Rotor structures and materials – strength and fatigue experiments and phenomenological modelling

R. Nijssen, T. Westphal, E. Stammes[a], D. Lekou[b], P. Brøndsted[c]

[a] Knowledge Centre Wind turbine Materials and Constructions (WMC), Kluisgat 5, 1771 MV Wieringerwerf, the Netherlands, +31(0)227-504927/49, r.p.l.nijssen@wmc.eu
[b] Centre for Renewable Energy Sources (CRES), Wind Energy Department, 19th km Marathonos Av., GR-19009, Pikermi-Attikis, Greece
[c] RISØ National Laboratory/Danish Technical University (RISØ-DTU), Materials Research Department, DO 4000 Roskilde, Denmark

Abstract: This paper describes the tests, results and analysis carried out in the first phase of the UPWIND project, Work Package 3 (Rotor Structures and Materials). This phase focuses on testing methodologies for strength and fatigue. A universal reference geometry is defined, and its behaviour is extensively predicted, tested and documented. The reference specimen provides material data and a basis for comparison throughout the project. For instance, the influence of geometry on strength and fatigue life is investigated, including the use of compression fixtures. The data and their use in various analysis and prediction methods are presented in detail.

Introduction

Despite recent research efforts into strength and fatigue behaviour of fibre composites for rotor blades, this field continues to present interesting challenges. Fatigue characteristics of the “bulk” material were the focus of previous research projects such as the OPTIMAT BLADES project [1]. Currently, efforts are directed both at micro/meso-mechanical material behaviour (modelling composites on a fibre/interface/matrix level) on one hand, and on the other hand sub-scale structural behaviour (subcomponents with failure modes representative of blades, with more cost-effective testing). The combined research aims for more reliable design of wind turbine rotor blades.

Work Package 3 (WP3) of the UPWIND project is divided in three sub-tasks, which are concerned with the above topics. In WP3.1, most of the physical testing and phenomenological modelling is performed. WP3.2 investigates micro/mesoscale modelling. Subtask 3 investigates damage tolerance. Experimental data for all subtasks is collected in WP3.1. The long-term research objectives include comparison of various compression and shear testing methodologies; ageing and fatigue including the effects of temperature, humidity, and the interaction of temperature and frequency; testing of new and alternative materials; description of constant amplitude fatigue behaviour for life prediction methodology validation including long-life testing; testing of a series of subcomponents [2].

This paper presents the results of WP3.1, where a reference geometry was determined and its primary strength, stiffness and fatigue characteristics were established. These data provide a detailed description of a representative wind turbine laminate which is useful to both scientists and designers. Furthermore, they provide a sound basis for modelling, comparison with other laminates and different test methodologies.
Comparison of a limited number of compression geometries and methods, both numerically and experimentally, reveals quantitatively the importance of the boundary conditions for compression testing, notably in fatigue.

The reference specimen’s detailed strength and fatigue characteristics show good agreement with results from previous projects. Minor variations in specimen geometry have significant consequences for fatigue results at R = -1 (R = minimum load/maximum load).

Finally, the design for a suitable test-subcomponent and its relation with the reference material properties are discussed.

Reference coupon

For the UPWIND project, the reference coupon is a glass/epoxy (4-layers of Saertex 963 g/m^2 with 5% transverse reinforcement and Hexion L135i resin). This glass/resin combination was deemed representative for typical wind turbine blades by the project partners. Several candidate geometries were investigated in an extensive preliminary testing programme to find the best reference coupon geometry for this laminate. The candidates and considerations in this preliminary programme were discussed in [3] and [4]. The reference coupon finally selected for the test programme is the R08 geometry. This was based on a combined experimental comparison of R = -1 fatigue performance. From the experimental R = -1 fatigue results on the 4-layer and 6-layer specimens R08 and R07, fatigue behaviour of R08 was slightly better than of R07 (factor of 2 in life), see Figure 1.

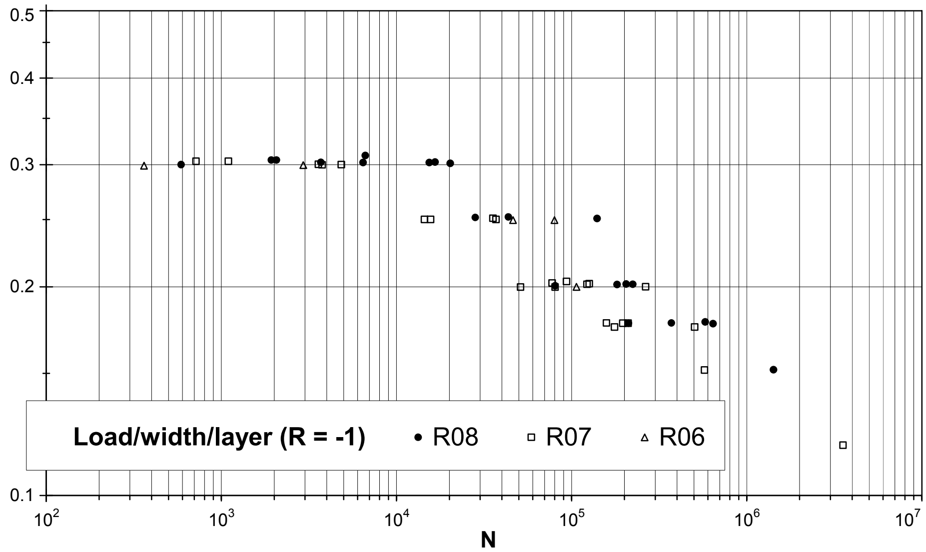


Figure 1: Comparison of fatigue behaviour for three different geometries. (For R08 see Figure 3; R06 is 25 mm wide, R07 has gauge length of 30 mm and is 6 layers)

The S-N data are presented on a double log scale. They are in the rather unusual format “load/width/layer”. However, this format is quite useful when comparing the behaviour of specimens with a different geometry, thickness, and number of layers, as was done during the preliminary programme aimed at defining the reference geometry. Since fibre volume fraction for these laminates can be tailored by varying the thickness of the laminate, it can also be used for this type of comparisons. As long as modulus, number of layers and geometry (width and thickness) are known, this parameter can be converted to any commonly used scale.

Some influence of tab thickness was seen for the R08 geometry. This influence is not seen for R07; eliminating the tabs did not result in inferior performance. The best tab thickness for the R08 geometry is 1 mm.

Table 1: Reference material constituent specifications (specimen has 4 layers of reinforcement)

Matrix	**Resin**	**Hardener**	**Mixing ratio**	**Density**	**Curing conditions**
	L135i	134i – 137i	100/30 by weight	1.15 (cured)	10h@70°C (T_g: 80°C)
Reinforce-ment	**Construction**	**Areal weight [g/m^2]**	**Tolerance [±%]**		**Material**
	total	963	5		UD
	0°	864	5		PPG2002 2400 tex
	90°	40	5		OC 111A 200 tex
	90°	41	5		PPG2002 68 tex
	stitching	18	5		PES
Tabs	Glass/epoxy electronic circuit board				

Numerical buckling predictions based on a finite element model of the different coupons indicated, that R06 and R08 were preferred for static compression (but that the recommended geometry is the dedicated combined loading specimen). Furthermore, R06 and R08 were recommended for R = -1 and R = 10 fatigue

[5]. The material properties required for this modelling were estimated from the then available data. In general, the values of the material parameters were in accordance with the later measured quantities.

A summary of the reference specimen constituents lay-up is given in Table 1.

The reference material is manufactured in a double-sided aluminium mould, using vacuum to impregnate the reinforcement, and automated mould heating to control the cure cycle. The fibre volume fraction can be adjusted by adjusting the spacers that keep the mould-halves apart. Prior to infusion, the liquid resin is mixed with hardener and degassed. The reinforcement is prepared and positioned in the mould. The mould is closed and sealed. The set-up is schematically shown in Figure 2.

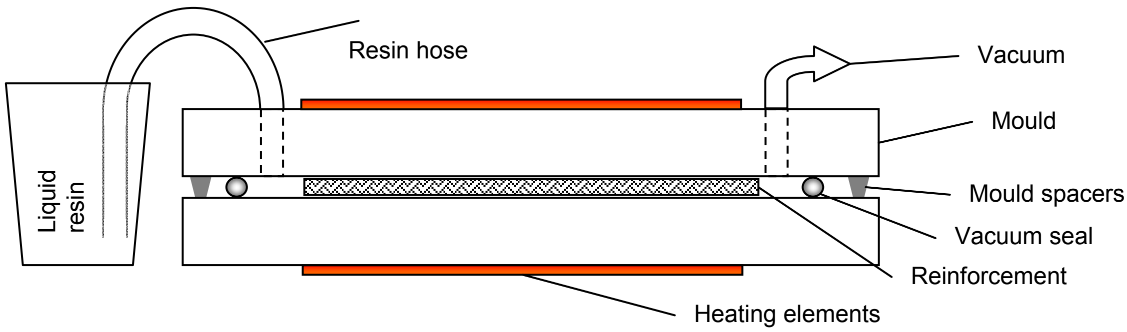


Figure 2: Mould for reference specimen production

Static characterisation
Static tests were done in various modes on the reference coupon. Results of the static tensile and compression tests are shown in Table 2.

All tests were carried out in displacement control, with a displacement rate of 1 mm/min. In the case of geometries I03 and I04, a special fixture was used (Combined Loading fixture according to ASTM D 6631, and an Iosipescu fixture as per ASTM D 5379, respectively). Geometry D01 is a dogbone specimen. If tab thickness or number of fabric layers is 0, then no tabs or layers of fabric were present. If the geometry ends with “9”, this means that the warp direction of the fibres was transverse with respect to the specimen and the load on the specimen. In the case of the shear tests, it means that the fibres were predominantly in line with the applied load.

Comparison of the dogbone geometry D01 and the reference geometry R08 in tension on the specimens of clear-cast resin is a measure for geometry influence on tensile strength. Apparently, performing the tests on a rectangular specimen means a knock-down on strength of about 50%. Surprisingly, including transverse fibres in the R08 clear-cast resin specimen (effectively performing a test on the transverse UD laminate using geometry R089) results in a strength that is 25% higher than the dogbone strength. One would expect a strength of about 5% of the warp-direction strength (because of the 5% weft fibres), but with a detrimental effect because of the “stress concentrations” formed by the warp fibres. Nevertheless, the transverse tensile strength is about 10% of axial strength. This may be partly attributed to the transverse fibres hampering transverse strain in a test, resulting in smaller Poisson contraction of the transverse laminate, and higher apparent axial stiffness.

In compression, there is an effect of number of layers on compression strength, even in the combined loading fixture (I03). Performing the compression test using the combined loading fixture increases the measured strength by ca. 12%. Comparing axial with transverse compression strength again shows that the transverse strength is higher than expected based on the percentage of weft fibres or the clear-cast resin strength. Transverse compression strength does not show dependence on using I0390 or R0890.

Shear strength was measured using a dedicated fixture and a notched specimen of geometry I04. Bonding paste (which is essentially the clear-cast resin with filler material) shows smaller shear strength, although the strength might be underestimated in this case, see further discussion on Figure 9. Shear strength where the direction of the test load is perpendicular to the fibres is higher than when the test load is parallel to the fibres, which can be expected. Near failure the warp fibres are “sagging” and can be expected to contribute to the apparent shear strength with a tensile fibre load component.

Table 2: Static characteristics of reference material and constituents

Test Type	Geometry	Tab thickness	Number of fabric layers	Fibre ; Resin	number of specimens	t [mm]	w [mm]	Load [kN]	σmax [MPa]	E_{avg} [GPa]	Poisson ratio [-]
Tension	D01	0	0	none ;RIM 135	5	2.84	22.41	4.5	70.6	3.6	0.341
	R08	1	0	none ;RIM 135	5	2.97	19.73	2.0	33.4	3.3	0.380
	R08	1	4	GF / UD ;RIM 135	9	2.93	19.97	53.2	907.9	38.3	0.262
	R089	1	4	GF / UD ;RIM 135	10	2.98	19.96	5.2	86.7	12.9	0.087
Compression	I03	0	0	none ;RIM 135	7	2.91	10.37	-8.2	-270.0		
	I03	0	4	GF / UD ;RIM 135	5	3.17	10.03	-19.9	-625.2		
	I039	0	4	GF / UD ;RIM 135	6	3.00	10.12	-4.9	-162.7		
	I03	0	6	GF / UD ;RIM 135	5	4.54	9.89	-30.1	-670.5		
	R08	1	0	none ;RIM 135	5	2.90	19.78	-4.8	-84.1	3.1	
	R08	1	4	GF / UD ;RIM 135	7	2.93	19.98	-32.6	-556.8	37.3	
	R089	1	4	GF / UD ;RIM 135	5	3.01	19.93	-9.5	-158.2	13.8	
Shear	I04	0	0	none ;RIM 135	5	2.83	12.43	-1.7	-48.7		
	I04	0	4	GF / UD ;RIM 135	12	2.89	11.92	-2.7	-77.2		
	I04	0	0	none ; Bonding paste	7	4.40	11.86	-1.8	-34.2		
	I049	0	4	GF / UD ;RIM 135	12	2.88	12.00	-2.1	-61.0		

R08=length x gaugelength x width x thickness=155 x 20 x 20 x 3
R089=idem, fibres in transverse direction
I03=136 x 10 x 10 x 3; I04=76 x12 x 3

The non-axial tests are indispensible for an accurate characterisation of structures and can be used as basic data in finite element models.

Fatigue characterisation
A summary of the fatigue behaviour of the reference laminate is shown in the constant life diagram of Figure 3. The S-N data were fit to a regression line of the commonly used type (N as dependent variable):

$$\log N = a \log s_{\max} + b$$

From the available S-N data, and by looking at detailed constant life diagrams from OPTIMAT and on axially dominated layups in the DOE/MSU database, there seems to be increasing evidence, that the CLD is bounded by a Goodman line for N = 100 to 1000, with the other constant life lines parallel to it. Without testing at R-values close to 1, the same philosophy that is behind the Goodman representation of the CLD dictates the designer to connect S-N data of the highest R-value to the Ultimate Tensile Strength. As more data become available, this seems to be both artificial and non-conservative: tensile-tensile loads with high mean and low amplitude may prove to be more damaging than expected. The right side of this constant life diagram is consistent with the formulation adopted by Brøndsted [9].

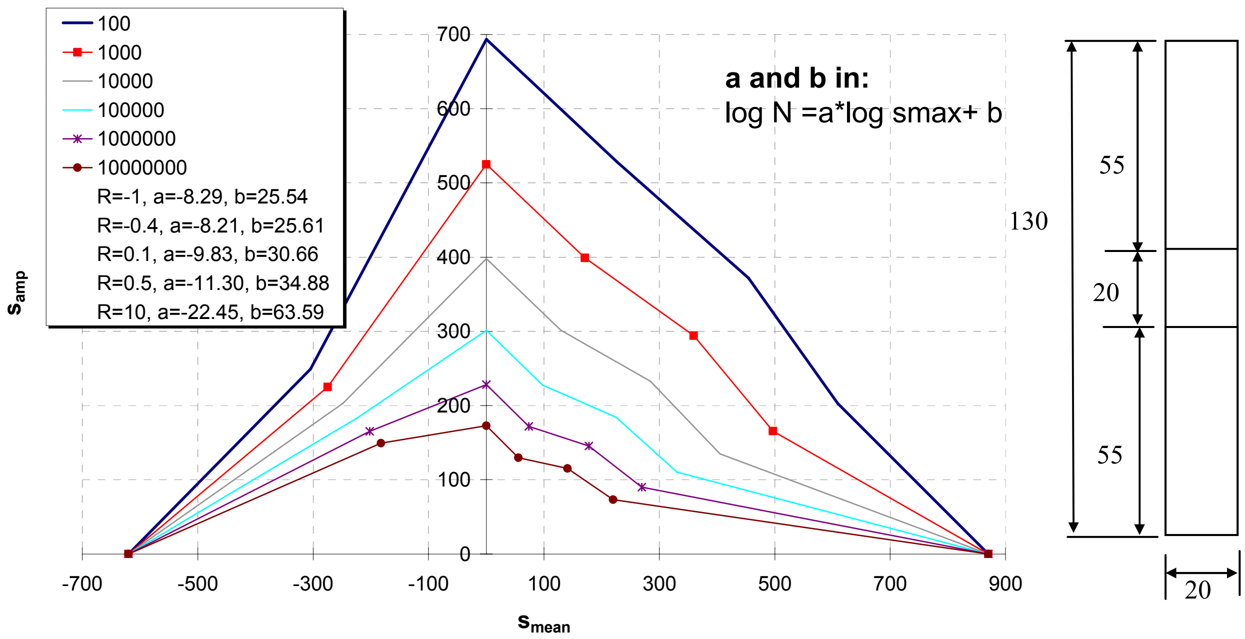
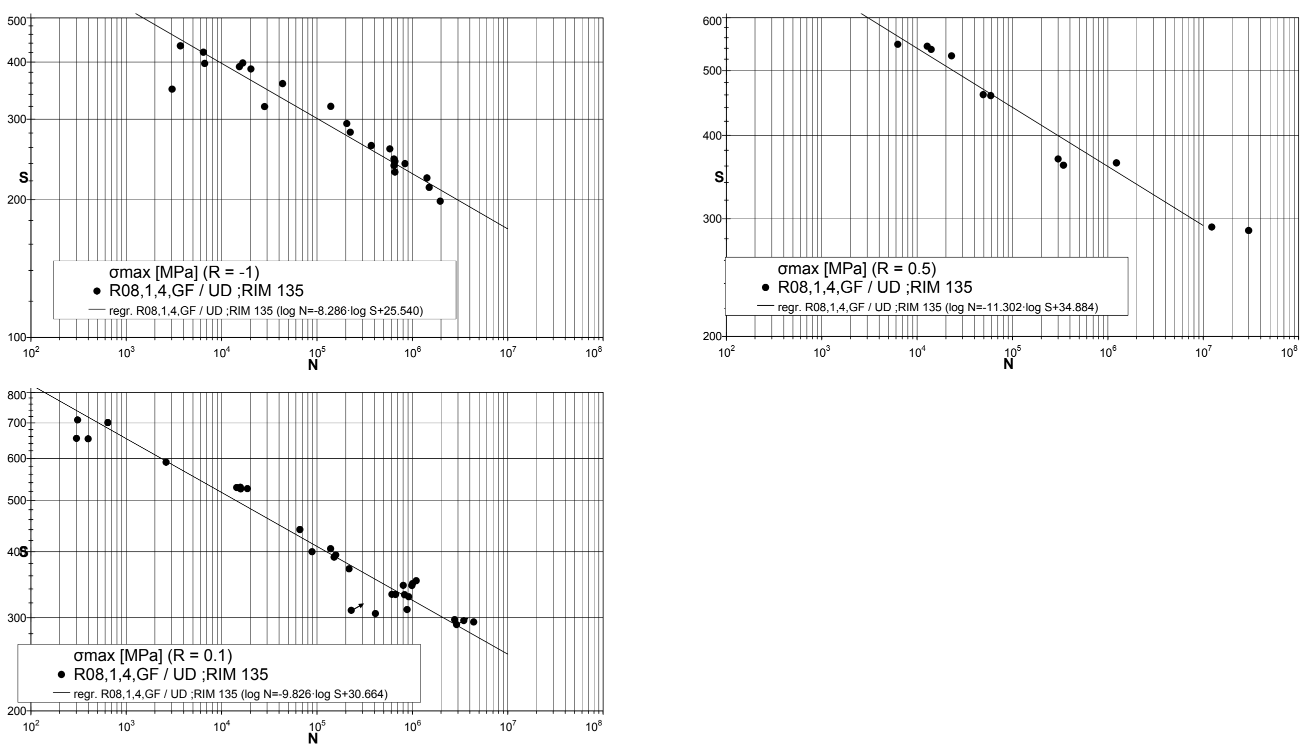


Figure 3: Constant life diagram of reference material, R08 geometry

S-N data for the most important R-values tested thus far are shown in Figure 4. Arrows indicate run-outs (specimens taken out of the test machine before failure).

More R-values will be used to fully characterise the material in constant amplitude fatigue and improve life prediction models.
As mentioned earlier, test geometry is of significant influence on performance. This is illustrated by Figure 5, where the performance of the same material is compared at R = 10. Geometry R08 is the reference geometry, R07 is the same material, but with 6 layers thickness and tested using a compression fatigue fixture. The fixture gives a slightly better slope of the curve, but the differences fall within the scatter.



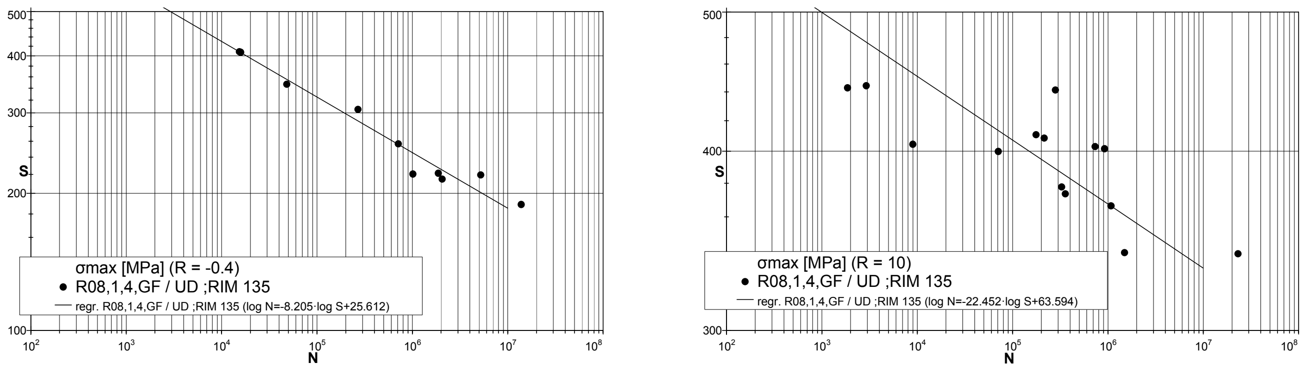


Figure 4: S-N data used to construct Figure 3

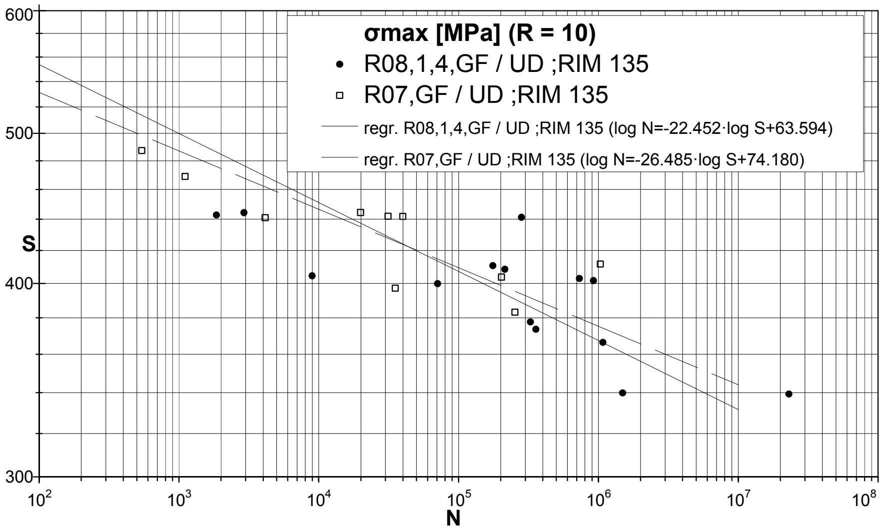


Figure 5: Comparison of 2 different specimen geometries at R = 10

Subcomponent testing

Philosophy

The objective of the subcomponent test programme is to develop a cost-effective test representation of a blade structure. Such a subcomponent can be used for various purposes, such as [6]:

- material tests
- validation of material models
- testing of repair methods
- -partial- replacement for full-scale blade tests

Structural details in a blade that could be represented in subcomponents are the blade root, trailing and leading edge, spar near root, transition of circular part to aerodynamic shape, sandwiches, repairs, flanges and shear web, spar structure (typically one (or two) I-beam(s) or box beam), bondlines and joints throughout the blade.

Some of these structural details are schematically indicated in Figure 6.

The blade root to hub connection is typically a bolted connection. This type of connection has been investigated extensively in previous projects.

Typically, the pressure and suction side of a blade are two separate components bonded together along the trailing and leading edge. Both extreme load conditions and fatigue loads are highly relevant to the trailing and leading edge bondlines.

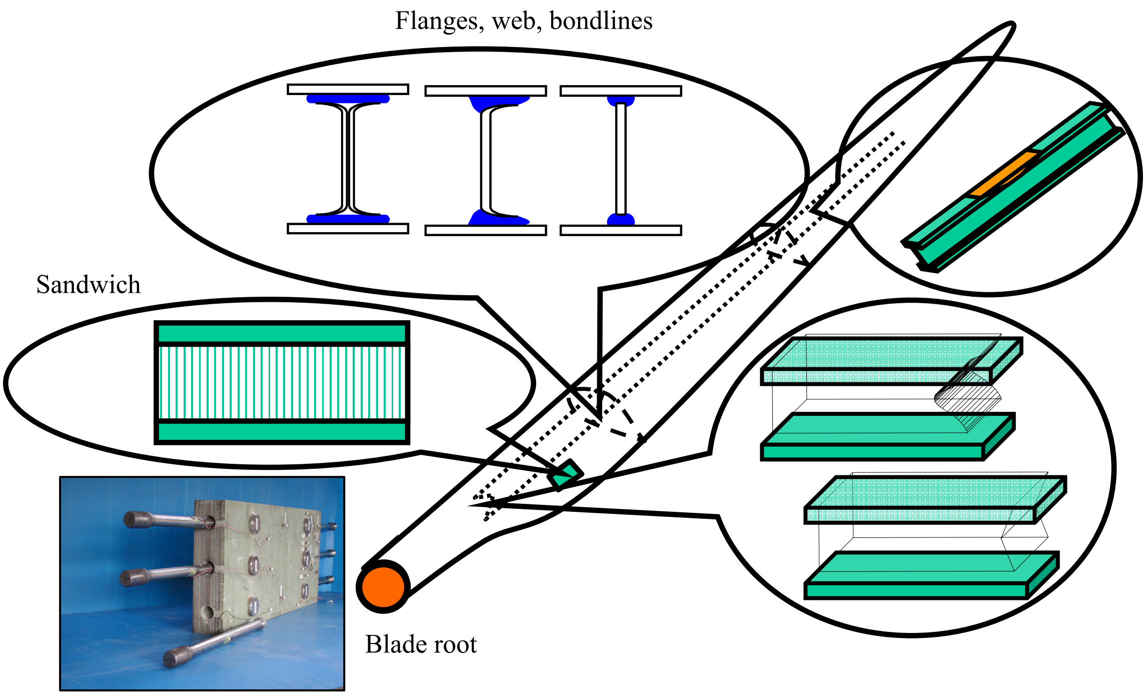


Figure 6: Parts of blade represented in subcomponents

The internal spar structure typically begins some distance away from the blade root. This is also typically one of the most complex and heavily loaded parts of the blade: it is in or close to the transition region; it is close to the location where the largest bending moments occur; it is a section where buckling is typically an issue, and where peel loads may exist on the bondline between web and flanges or skin.

(Shear) fatigue of sandwich material, and the structural design of the transition between laminates with sandwich and laminates without sandwich can be expected to be critical in some parts of the blade.

Previous projects such as OPTIMAT have demonstrated the effectiveness of repairs in terms of post-repair static and fatigue strength. However, these were tests on repaired uni-axial specimens only remotely reflecting the complex three-dimensional stress state in a realistic structural repair.

The first candidate subcomponent that springs to mind is a model blade. The downside of a model blade is its geometrical complexity (more difficult to manufacture and reproduce). Therefore, the blade needs to be reduced to a model structure that is easily reproduced.

Considerations for selecting an I-beam as generic subcomponent
From the description of the various regions of interest in a rotor blade it becomes clear that many different subcomponents are likely to be necessary to evaluate the above (non-comprehensive) structural behaviour. The design of structural details is obviously highly dependent on the respective manufacturer.

In the UPWIND project, various manufacturers are represented and should be able to utilise the results from the project. Furthermore, all interested research partners should be able to use the results from the subcomponent programme to perform the appropriate analysis and validate their models. As a consequence, an important prerequisite to the design of the subcomponent should be, that it is *generic*. This means, that the failure modes and test results are relevant to as many designs as possible (without representing a single manufacturers design philosophy), and that the subcomponent should be versatile (tailoring the design to accommodate as many types of test as possible). This also helps to control the size of the testing programme.

The definition of a single test geometry appropriate for subcomponent testing promotes wider acceptance among test laboratories, for whom it is impractical to acquire and maintain a whole range of specialised fixtures.

Some further topics to take into account are:

- Use as much reference material as possible in the subcomponent. For the reference material, very detailed information is available from tests, which is easily accessible, e.g. for modelling purposes. The inclusion of other materials in the subcomponent geometry might mean that additional tests will be required to obtain basic properties. This is in principle possible, but should be limited as much as possible
- Influence of manufacturing method; the manufacturing method, notably the formulation and application of adhesive bonds, should be representative for a realistic structure
- If the initial focus is on a single aspect, other objectives should still be taken into account in the design (dimensions and modelling) of the subcomponent. This means, that it should be possible to modify the subcomponent's dimensions and model to easily shift the focus of the research to another structural aspect.

At this point in the project, a model generic I-beam, consisting of a shear web and flanges bonded together, seems to be the most promising option, because it is/can:

- sufficiently versatile to represent to some extent almost all the structural details described above, except the blade root and trailing/leading edges;
- a straightforward geometry which can be relatively easily manufactured and tested in a three- or 4 point bending set-up;
- serve as a platform for various repairs.

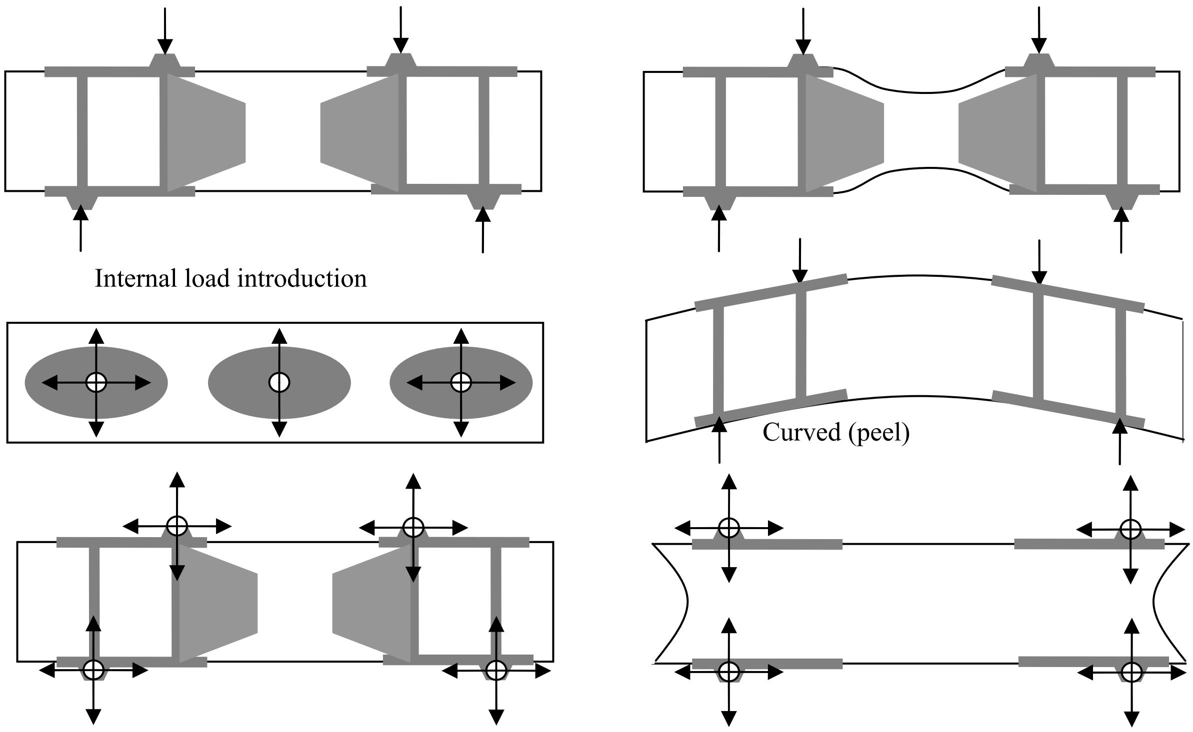


Figure 7: Candidate I-beam concepts (side view; arrows indicated loading direction, grey areas indicate extra reinforcement)

Testing of an I-beam can be done in various manners, using a three/four point bending set-up or a cantilever beam type of test. The dimensions of the I-beam may be tailored in length direction, to obtain the required combinations of shear, peel, and in-plane normal stresses in various locations of the subcomponent. Loads may be introduced in different directions and in some cases the load introduction may need to be shaped in such a manner, that reversing loads can be applied. In that case, external load application in one direction is not sufficient. Reinforcement of the load introduction points is necessary to avoid failure outside the area of interest. These considerations are visualised in Figure 7, which shows the side view of several candidate I-beam concepts. The grey areas indicate load introduction reinforcements, the arrows indicate loading direction.

Preliminary testing on the I-beam
The I-beam test programme consists of a preliminary test progarmme aimed at determining the best I-beam geometry. Apart from development of the “reference I-beam” geometry, it involves development of an appropriate test fixture, and numerous ancillary tests. For instance, the UPWIND reference programme has delivered various properties of the reference material, but the subcomponent is likely to contain other materials.

First, the focus is on bondline properties, so the bondline material should be fully characterised. Also, the characteristics for the materials used for the web should be available. In both cases, the shear strength characterisation is important.

Bondline characterisation
For determination of shear properties in adhesives, typically some type of lap-shear test is used. This test characterises shear strength of an adhesive by bonding two substrate plates together and pulling them apart, loading the bondline in shear. This method gives a severe underestimation of shear strength, since shear initiates at the stress concentrations coinciding with the edges of the bondline, and this stress concentration is not straightforward to analyse.

In the current project, a different method is proposed and implemented. A tubular specimen is manufactured. This type of specimen is often used in validation of bi-axial failure criteria [8]. This specimen is cut through the mid-plane and adhesively bonded using the adhesive under investigation. By applying a pure torque load on the tube, the shear strength on the bondline can be measured. Since the bondline is “infinite”, the strength is not underestimated because of bondline edges.

The tubular specimen used for the first bondline tests is shown in Figure 8.

Initial investigations indicate, that the tubular specimen (which is significantly more complicated to manufacture than a flat specimen) can be re-used up to a limited number of times by cutting away the bonded –and any damaged– section and duplicating the test on a reduced bonded tube.

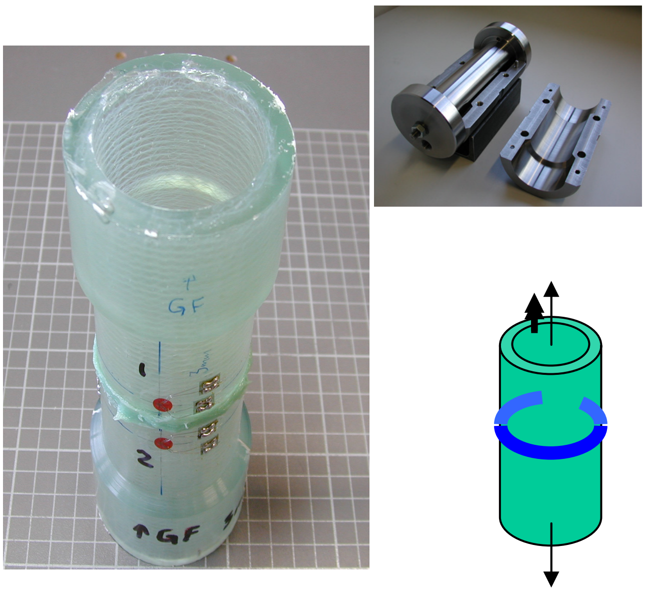


Figure 8: Tubular specimen for bonding paste shear testing, mould and loading concept

Some disadvantages are more complicated manufacturing and testing procedures and hardware. Also, as in the lap-shear test, measurement of shear modulus is best done via a displacement measurement instead of a more appropriate direct strain measurement. The advantages are better characterisation of the shear strength, and more realistic representation of the substrate-adhesive combination because the orientation of the fibres in the tube can be tailored to best represent the situation in the bonded subcomponent. In principle, the top and bottom halves of the tube can have different laminate orientations, by combining two halves from different tubes.

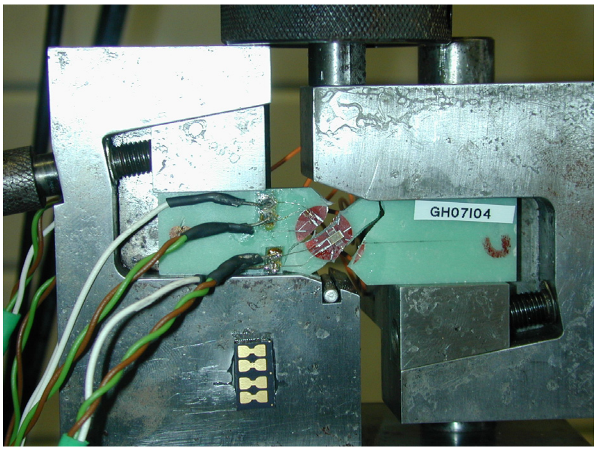


Figure 9: Shear strength testing on bonding paste

Shear modulus is best measured by fabricating and testing dedicated shear specimens out of bonding paste, such as the commonly used Iosipescu specimen. Whether this geometry is always useful for shear strength determination is questioned e.g. by Figure 9, where a failed bonding paste Iosipescu specimen is shown. In this test, failure may have been initiated in tensile mode at voids or irregularities in the notch. Nevertheless, this geometry does allow for application of strain gauges.

Concluding Remarks

The UPWIND programme uses experience from previous material fatigue research programmes, such as OPTIMAT. The reference specimen philosophy was adapted, a suitable reference testing geometry was found, and results from the reference characterisation are presented, including an assessment of geometry influence.

The behaviour of this glass-epoxy is quite similar to that of previously tested materials., which may imply that universal models may be defined to describe the fatigue behaviour of any unidirectional wind laminate. Additional factors that influence behaviour must be further investigated to determine the number and values of parameters in such a model.

In the subcomponent programme, an I-beam with bondlines has been selected, and tests on subcomponents and adhesives have started.

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