20th International Conference on Composite Materials
Copenhagen, 19-24th July 2015

Bridging the gap between coupon tests and full-scale blade tests

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Keywords: wind turbine, rotor blade, subcomponent, test, certification

ABSTRACT

The current certification process for rotor blades of wind turbines starts out by performing coupon tests for establishing the material properties, as is the case for structural designs in most other industries. However, the next step does not consist of testing structural details, but skips directly to a full scale blade test to check the validity of the design of the blade by subjecting the fully built blade to a number of static and dynamic loads which exceed the design loads.

The paper starts out with the backgrounds involved and outlines the project between DNV-GL and Fraunhofer IWES aimed at establishing practical guidelines for the testing of subcomponents and their use in the certification process of wind turbine blades. The project aims to establish a “catalogue of blade details” and their appropriate testing options. In order to check the validity of this approach, “certification tests” on two blade details: the bond line between spar cap and shear web and the trailing edge are foreseen, so as to verify the practical problems in application of the catalogue and use the knowledge gained to improve the descriptions in the detail catalogue. As an example in this paper, the beam test representing the bond line between spar cap and shear web is presented.

Due to the high cost pressure in the industry, the need for a high reliability and the relative short time to market for new developments the certification process is a crucial step in the development of new products.

1 CURRENT BLADE CERTIFICATION PRACTICE

The current certification process for rotor blades of wind turbines starts out by performing coupon tests for establishing the material properties, as is the case for structural designs in most other industries. However, the next step does not consist of testing structural details, but skips directly to a full scale blade test to check the validity of the design of the blade by subjecting the fully built blade to a number of static and dynamic loads which exceed the design loads experienced, see Figure 1.

The all but complete omission of intermediate subcomponent level tests at many manufacturers, and the lack of support in the standards cause major problems with the development of new concepts and ultimately becomes a major obstacle for the further development of the industry. The current practice where a few larger players develop some in-house testing practices, which are not shared with the industry at large and where the test results are not guaranteed to be recognized by the certification bodies is not an acceptable situation for this industry which has gained so much traction in such a short period otherwise.

A number of challenges face the industry here, such as manufacturing of realistic test specimens, setting up correct boundary conditions and interpretation of the results. The manufacturer needs to establish a catalogue of details with their static and fatigue behaviour, which, coupled with for instance FE analyses, can help to underpin the design of future blades and establish confidence in the results and allow for a deeper understanding of the effect of structural changes on the performance of the blade.

This paper starts out with the backgrounds involved and outlines the project between DNV-GL and Fraunhofer IWES aimed at establishing practical guidelines for the testing of subcomponents and their use in the certification process in blade design. The project aims to establish a “catalogue of blade details” and their appropriate testing options.

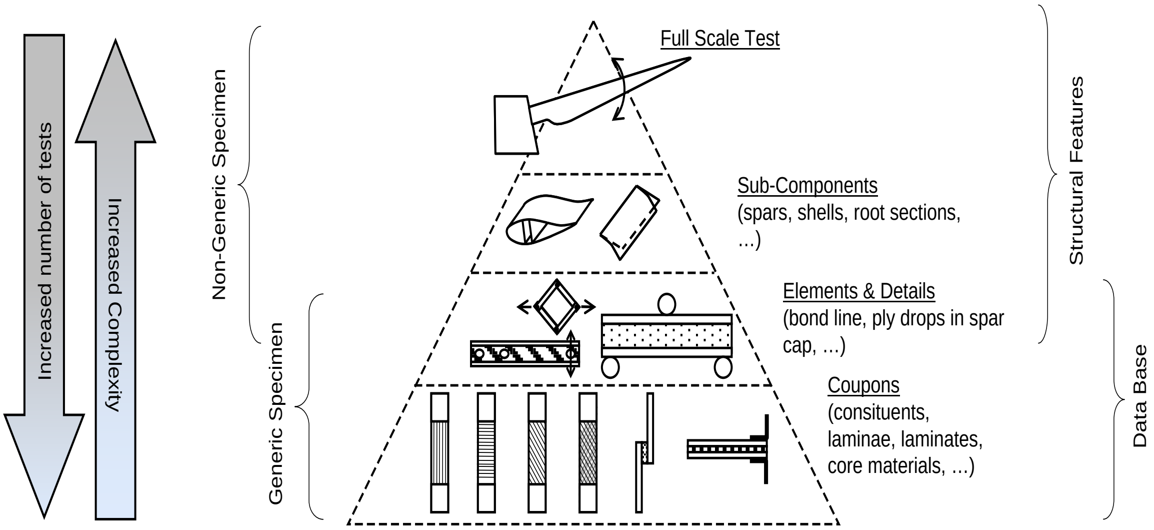


Figure 1: Comparison between wind, aviation and automotive industries [3].

The current backgrounds to the blade certification practice are described in an earlier ICCM paper [4] and will only be shortly repeated here for readability. This paper concentrates on the backgrounds involved and outlines the project between DNV-GL and Fraunhofer IWES aimed at establishing practical guidelines for the testing of subcomponents and their use in the certification process in blade design.

2 MARKET PERSPECTIVE: COMPARISON WITH THE AVIATION AND AUTOMOTIVE INDUSTRIES

Figure 2 gives a qualitative comparison of the wind industry, relative to aviation and automotive industries. Although the relative points are certainly open for discussion, the overall picture highlights that rotor blades are about the largest, highest loaded and the cheapest fibre-reinforced parts manufactured today. The largest rotor blades today, at over 80 m long, are longer than the complete wingspan of an A380, weigh over 30 to and cost less than 5% of the price per kg of aviation parts. This means that, although it is certainly worthwhile to compare to other industries, a 1:1 transfer is typically not feasible.

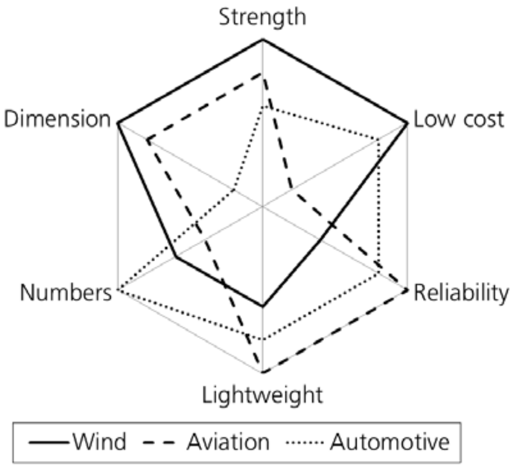
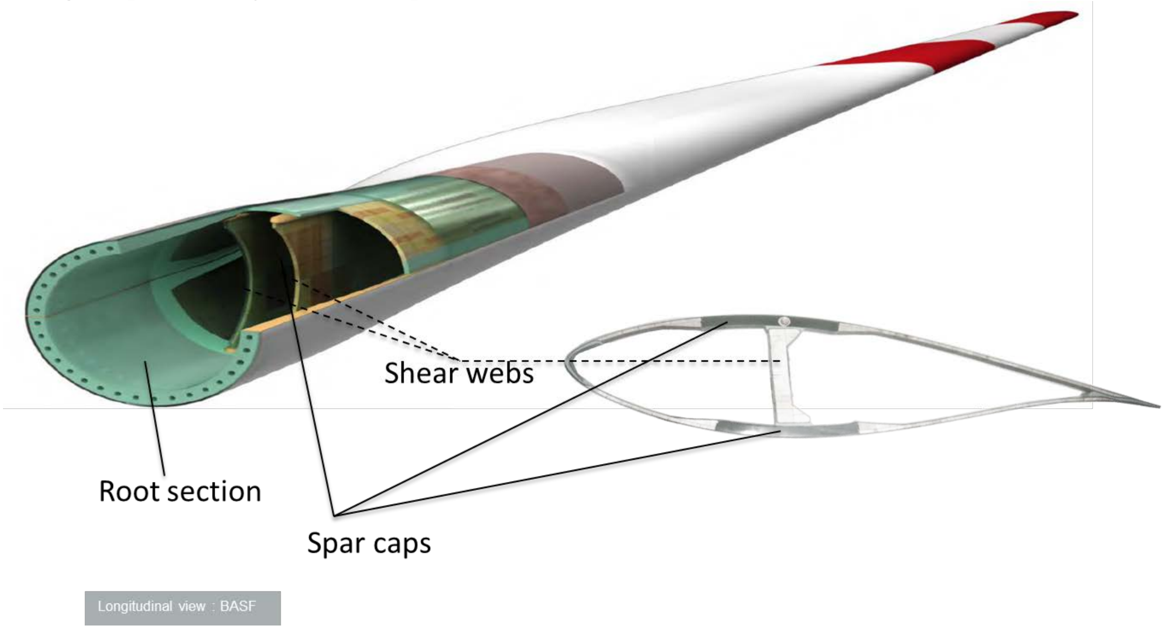


Figure 2: Comparison between wind, aviation and automotive industries.

The blades are typically made in two halves which are bonded together and have 1 to 3 shear webs bonded in between, see Figure 3. Although some parts of the halves, such as the spar caps and the root inserts, can be made separately, all parts of a half shell are typically bond together into one part and testing the inlay parts as such does typically not bring much insight, for instance because of the bonded and shafted connections between the various parts.

Contrast this situation to an airplane wing, where the various pieces are mechanically fastened and often can be tested at a “natural” subcomponent level. Also, in aviation, safety is such an overriding priority that other aspects, such as costs become relatively less important and much more testing per prototype is possible (and necessary).

On the other hand for cars, the various parts may be tested as well. In that case, the numbers of products produced are thus high that more prototypes and parts thereof can be tested without overly taxing the profitability of the final product.



Longitudinal view : BASF

Figure 3: Typical structure of a rotor blade.

3 INSPIRATION FOR TESTING STANDARDS

Even something seemingly straightforward as a static tensile test for fibre reinforced plastic, such as ISO 527, in practice it can be hard to carry out correctly. Furthermore, establishing any test method is a slow and convoluted process. Thus, establishing a standard for blade components may seem a truly daunting task. However, an example is available here, namely the whole blade test according to IEC 61400-23, see also [4]. The description is aimed at what needs to be tested, rather than how it should be tested, comprising static and fatigue tests combined with natural frequency and weight measurements [4].

Although IEC allows for other options, a typical blade test is contains following steps:

1. Determination of the dead weight, and centre of gravity of the blade. This step serves as a first check whether the blade is manufactured according to the design. Higher weights can occur for instance by bonding past and additional parts (for instance lightning protection) compared to the design, or by incorrect assumptions regarding the material density, but can also indicate deviations on the number of layers of material.
2. Preparation for a number of strain, load and deflection measurements, such as by strain gauges on the blade, sometimes also on the bolts that connect the blade to the pitch bearing or adaptor plate.
3. Measurement of the natural frequencies of the blade. Often, this measurement is repeated after the fatigue test as an indication of fatigue damage.
4. A static blade test, typically in 4 directions at 90º (flap_{min}, flap_{max}, lead-lag_{min}, lead-lag_{max}).
5. Fatigue tests, typically in 2 directions, (flap- and lead-lag-wise). Note that this procedure leaves the

blade areas at 45° essentially under-loaded and thus not fully tested. An alternative is a biaxial test, which loads the full cross section of the blade.
6. The static test of step 4 is repeated after the fatigue test as the blade should also be able to withstand a storm at the end of its fatigue life.

It is worth noticing that some labs carry out the static tests with winches and the fatigue tests with eccenters or linear accelerators on the blade, whereas other labs use hydraulic actuators for both static and fatigue tests. Some labs test vertically, using the dead weight of the blade as part of the load, whereas other labs test horizontally. Even the number of load directions (in practice typically 4 directions, about perpendicular to each other) and the directions themselves are not prescribed.

Blades are designed to withstand quite a large number of load cases, including the two major load cases: wind perpendicular to the rotor plane and the effect of the dead weight of the rotating blade, which occurs millions of times over the lifetime of the turbines, but also special cases such as grid failure and emergency stops which can cause major loads on the rotor as well in the rotor plane. These loads are analysed in terms of the bending moment distribution on the blades and the envelope of the various bending moments in various directions is established and augmented by various factors which represent the uncertainties.

The loads are typically concentrated in one or more cross sections of the blade. For instance in case of static tests at Fraunhofer IWES, the load introductions consist of wooden load frames around the blade attached to cables which are pulled by hydraulic actuators. In principle, the load frames can be positioned at will, so as to create a multi-linear bending moment distribution, which in addition with the dead weight forms the test load. In practice, the load frames locally support the blade against buckling and apply concentrated forces, so that an area on both sides of the loaded cross section is not correctly tested. The IEC allows for this, but fairly cryptically states that “All critical areas should be loaded at a minimum to the target loads”. Unfortunately, it is typically unknown which areas are truly “critical” since in that case the designer would likely opt to reinforce these areas until they are no longer critical. In practice still about one quarter of the blades tested today suffers major or catastrophic damage during the test, typically caused by manufacturing errors. It should be remembered here that the IEC blade test verifies whether the blade – if manufactured according to the design – can withstand the design loads.

It can be concluded that the standard for rotor blade testing is quite broad compared to for instance material test standards, allowing for a wide variety of test and measurement practices. Currently, an initiative is underway by the IEA Wind task 35 to see how the current test standards can be expanded and improved to cover the developments within the field, for instance by considering torsional testing and looking at subcomponent testing, health monitoring and non-destructive inspections.

4 STANDARDISATION PROJECT: KOMPZERT

The project KompZert (COMPonent CERTification – in German) which is being carried out between DNV-GL and Fraunhofer IWES aims to lay the foundation for a subcomponent-based methodology for blade development and certification.

Aim of the project is the augmentation of the current standards in wind turbine testing, the IEC 61400-x series, by a separate standard for subcomponent testing. A major application would be in case of modifications of an already certified blade, where it would be possible to drastically reduce or even omit the full scale blade test altogether. Two points are deemed essential to establish this standard, namely the definition of a catalogue of rotor blade details test options, followed by implementation of these options into standards, since it is vital that the test results are accepted by the certification parties. Having this rather modest project, €400,000 over 3 years with just two parties, namely DNV-GL and Fraunhofer IWES, assures a small, focused project that may serve as kick-starter for more elaborate projects, within the IEA, IEC or for instance the EU, which in turn could provide the basis for a future IEC standard.

In spite of having only two partners, having the major certification body on board allows for a fast track access to both the DNV and GL standards, which will likely be merged. On the other hand, IWES is one of the world’s foremost test institutes for rotor blade testing. Both parties are active in the current IEC 61400-5 committee for manufacturing of rotor blades. Thus, together these partners could prove to be a powerful nucleus for the task at hand.

A major problem, as outlined by the various blade manufacturers is that the load factors on material and subcomponent tests tend to be higher than for full-scale rotor blade tests, which all but prohibits manufacturers from using subcomponent tests to augment their current material and full scale blade tests. A possible way out here would be the use of options to lower load factors.

The current draft of the IEC 61400-5 states: "Where a dedicated test program has not been conducted, the partial safety factor is to be calculated by an empirical approach using the partial safety factors listed below".

$$\gamma_m = \gamma_{m0} \cdot \gamma_{m1} \cdot \gamma_{m2} \cdot \gamma_{m3} \cdot \gamma_{m4} \cdot \gamma_{m5} \tag{1}$$

The partial safety factors for ultimate limit state (ULS) and fatigue limit state (FLS) depend upon the level of modelling and testing, see Table 1.

factor	Description	ULS_{min}	ULS_{max}	FLS_{min}	FLS_{max}
γ_{m0}	"Base" material factor (to be included in all analyses)	1.20	1.20	1.20	1.20
γ_{m1}	Environmental degradation (non-reversible effects)	1.10	1.35	1.10	1.35
γ_{m2}	Temperature effects (reversible effects)	1.00	1.10	1.00	1.00
γ_{m3}	Manufacturing effects	1.00	1.40	1.00	1.40
γ_{m4}	Computation and validation methods	1.00	1.30	1.00	1.56
γ_{m5}	Resolution of load components	1.00	1.20	1.00	1.32
γ_m	Resulting partial safety factor	1.32	3.89	1,32	4.67

Table 1: partial safety factors in the draft IEC 61400-5.

In particular $\gamma_{m1,}$ γ_{m2} and γ_{m3} lend themselves to subcomponent testing, since tests after accelerated aging, at extreme temperatures and for manufacturing effects, is quite feasible for subcomponents, but close to impossible for full scale blade tests. Also γ_{m4} can be addressed by sub-component testing, as the damage models in the blade simulation can be experimentally validated in relevant load situations. Such tests would allow the lower partial safety factors to be used, which would overcome the problem of the subcomponent test partial safety factor.

5 PRINCIPLES OF SUBCOMPONENT TESTING

In order to be effective, a subcomponent test would have to fulfil a number of criteria:

1. Cover the most critical details and load cases in the blade or blade detail, or in case of a modification to an existing blade, the modification.
2. Adhere as much as possible to a certain "standard" so that manufacturers, certification bodies and test institutes alike know what to do and what to expect and gain comparison material and experience in the test alike, without having to reinvent the wheel with every new test.
3. Manufacture the relevant parts in a representative way, so that residual stresses, stress concentrations and defects may occur in a similar manner as in the blade strucure4. Prove that the subcomponent test carried out is relevant for the load case studied.

Note that the subcomponent test is essentially used to verify and augment the numerical models, so a complete 1:1 incorporation of the complete boundary conditions that occur in a blade subcomponent often is not required. However, the test results combined with the numerical results should be usable to gain confidence that the loads in the blades and their effects can be adequately covered. In practice this is a very difficult requirement and it is to be expected that a significant effort will be needed to establish a solid basis for future standards.

In order to check the validity of this approach and determine where the major problems will occur in establishing the framework for the standard, "certification tests" on two blade details: the bond line between spar cap and shear web and the trailing edge are foreseen, so as to verify the practical problems in application of the catalogue and use the knowledge gained to improve the descriptions in the detail catalogue.

6 EXAMPLE: BONDING PASTE PROPERTIES

In order to illustrate the application of a subcomponent test, a test established in cooperation with Henkel will be shortly described here. Bonding paste cannot really be treated as a “material” to be tested. Rather, it is essentially a structural property, determined by both the bonding paste and the bonded parts. According to current standards, one relevant test to show the suitability of an adhesive for wind turbine blades is the lap-shear test, e.g. according to ASTM D5868. Although relatively simple to manufacture and test, the boundary effects, large peeling forces and lack of longitudinal forces make it difficult to see any kind of relation between the test and the loading of bond lines in a rotor blade. Figure 4 shows the result of a non-linear FE simulation of a Lap-Shear specimen. The given strains show for the applied loading and used adhesive a stress concentration factor of almost 5 at the edge of the adhesive.

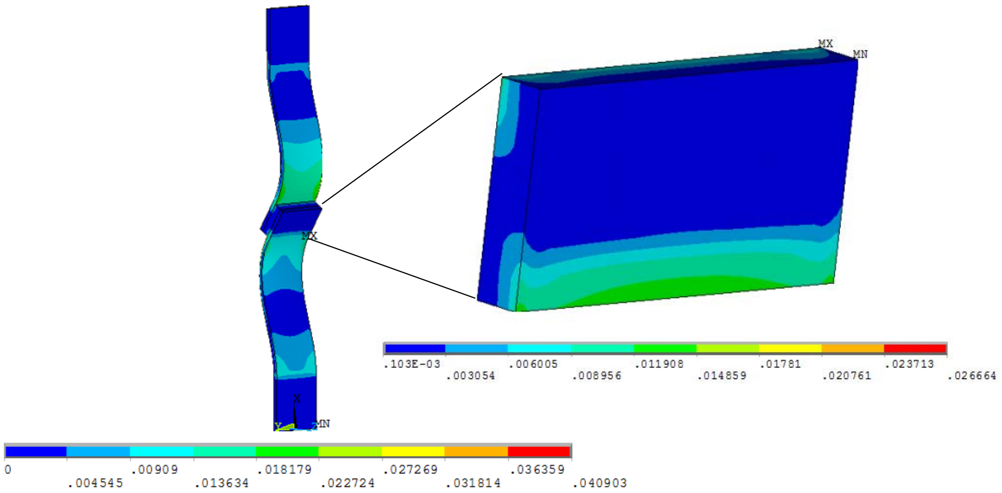


Figure 4: Schematic FE-calculation of strains in the adhesive in lap-shear specimen

(non-linear material behaviour)

In order to access the structural properties of a bonding paste between the spar cap and the shear webs in a rotor blade, the large shear and normal stresses in the direction of the bond line should be adequately modelled in the test. The solution consists of an asymmetric 3 point bending beam with a tailored geometry to allow for careful introduction of loads and supports and with a similar ratio between shear forces and bending moments, as shown in Figure 5.

Figure 5: test set-up for a subcomponent test of a bond line between shear web and spar cap.

A typical fatigue failure in a rotor blade after N_f cycles to failure occurs as follows:

1. Transversal cracks (mode I), 10% N_f
2. Cracks extend into laminate, longitudinal crack (mode II), 60-70% N_f
3. “kissing” cracks: ultimate failure, N_f

The failures occurring during the first two test phases correspond to those seen in full scale rotor blade tests and bear no obvious relationship to failures occurring in the lap-shear test, see Figure 6.

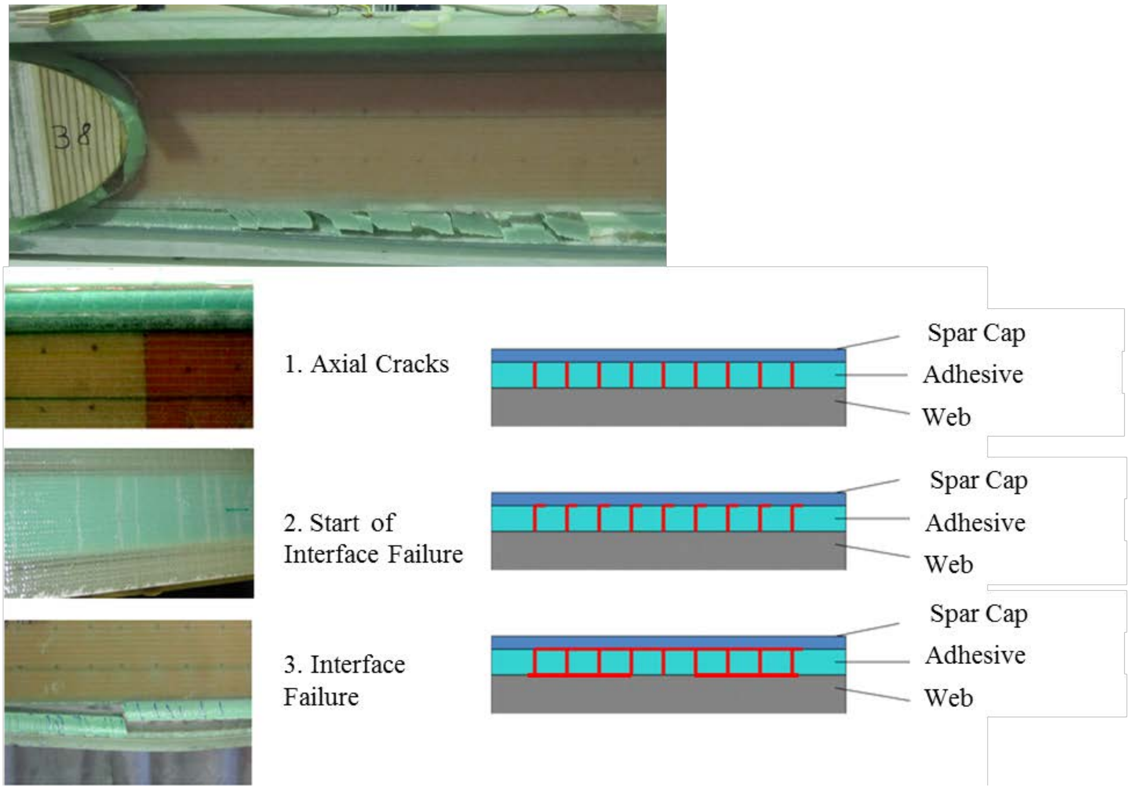


Figure 6: Failure of bonding paste in a subcomponent test.

Once this test specimen geometry and set-up is established, it is possible to test at elevated temperatures, check the effect of for instance voids in the bonding paste and make S-N lines of the detail in ways that are difficult to do for a full scale blade test. Moreover, variations in the geometry can be separately tested see Figure 7. In fact, this kind of “what-if” comparison has been a major driving factor in the development of other industry – but a full scale blade test where tens of millions have been invested into is hardly a suitable occasion to try “something different”.

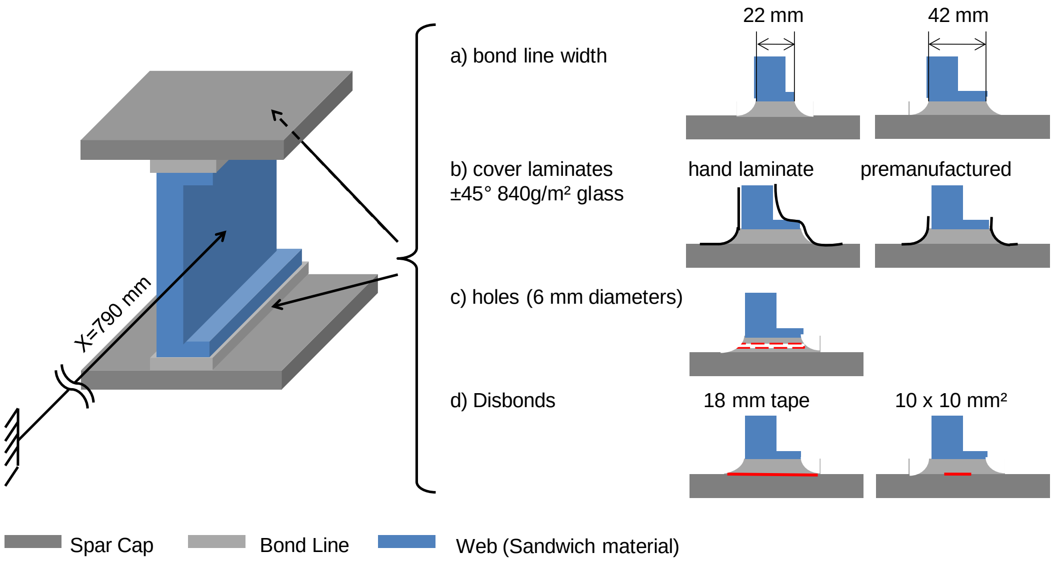


Figure 7: Variations of a structural detail in Henkel-subcomponent tests.

Tests conducted with the details/defects in Figure 7 are plotted in Figure 8 for an equivalent strain of 0.5%. It can be seen that the details do have a significant influence on the structural behaviour. However, small damages and defects in the bond line do not necessarily have a negative effect on the final structural failure.

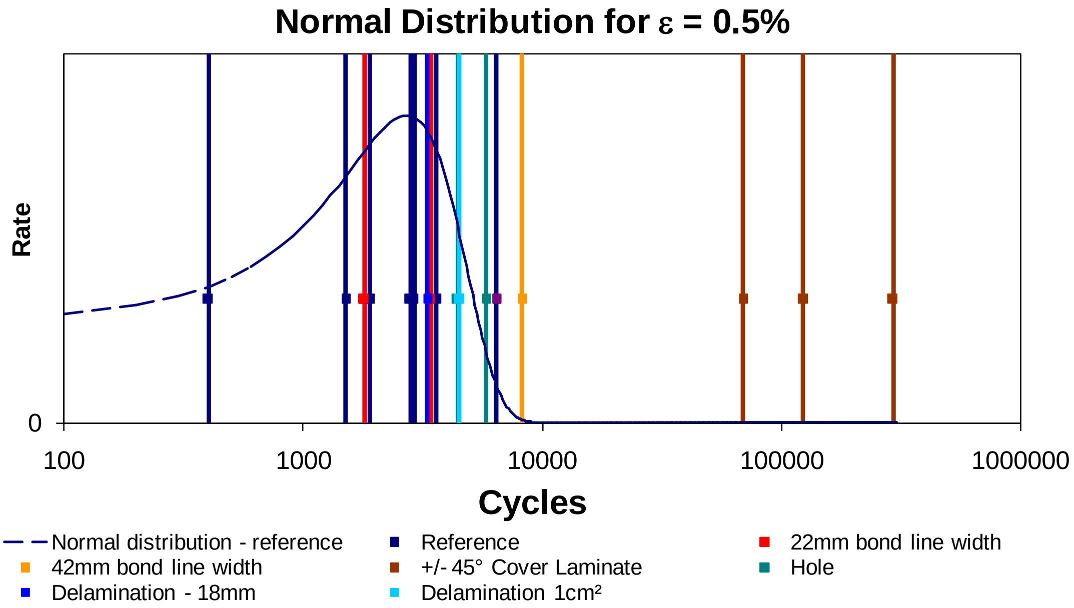


Figure 8: Statistic Evaluation of fatigue test results at normalized strain of 0.5%.

7 CONCLUSIONS

Due to the high cost pressure in the industry, the need for a high reliability and the relative short time to market for new developments, the certification process is a crucial step in the development of new products. Due to the monolithic nature of the blades, but also due to the lack of standards and obstacles in the certification process, the use of subcomponent tests within the rotor blade has been limited to date and mostly open to larger parties with a lot of experience. Opening the option of testing subcomponents in lieu of a full scale blades and acknowledgement of the results by the certification bodies with adequate partial factors will be a tremendous boost for the whole industry and help achieve to same tremendous growth that has marked the industry to date, coupled with an increase in quality and reliability necessary for tomorrow's blades.

ACKNOWLEDGEMENTS

The support by the Federal Ministry of Education and Research of Germany for this project is gratefully acknowledged.

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