New guidance for the development of wind turbine blades

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Summary: As wind turbines become larger and more complex, DNV firmly believes that there will be an increased focus on individual component reliability and safety from stakeholders, particularly for the offshore market. One of the more critical and complicated components of the wind turbine, is the blade. To provide further interpretation and guidance for the IEC WT-01 certification scheme, DNV will issue their new standard 'Design and Manufacturing of Wind Turbine Blades'.

DNV expects the continued extensive use of composite materials in blade design, and as a result has suggested a building block approach to composite structural substantiation that combines a process of iterative testing and analysis to more effectively utilise the benefits of composite materials. This approach is commonly used in the aerospace industry, and it expected to be an important tool for wind turbine blade manufacturers when conducting complex stress analyses and design optimisations.

This standard provides detailed guidance and supplementary standard interpretation throughout the blade development program, consolidating the vast amount of international experience present in the industry, and providing a basis for the blade designs of the future.

Key words: Wind Turbine Blades, Certification, Composites

1. Introduction

As wind turbines become larger and increasingly complex DNV believes that there will be an increased focus on individual component reliability and safety from all stakeholders. For wind turbines designed for the offshore market, DNV anticipates an even greater focus in these areas due to much higher maintenance and replacement costs when compared to onshore applications. One of the more critical and complicated components of a wind turbine is the blade assembly. The design and testing of wind turbine blades is to some extent covered by the current IEC WT-01 certification scheme, however with the high levels of innovation and change characteristic of the industry today, DNV believes there is a greater general need for further interpretation and guidance in this area.

For this reason, DNV will later this year issue their new standard 'Design and Manufacturing of Wind Turbine Blades' which provides principles, technical requirements and guidance for wind turbine blade development. This new standard will be an important addition to DNV's range of widely accepted standards and service specifications for ships, offshore structures and the wind turbine industry. This paper will provide an overview of the contents of the new standard, and the reasoning behind its development.

2. State and trends in the Industry

DNV have been providing third party certification services for the large wind turbine (greater than 7m diameter) industry in cooperation with RISØ for over fifteen years. Through this experience, DNV has observed the constant development of technology, and the high levels of innovations characteristic of the industry. Relatively short development cycles are typical for wind turbine blade projects, with numerous design iterations on a 'family' of blade types common.

This high level of growth is typified in the DNV type certificated turbine diameters over the past five years which is shown at Figure 1. This growth in turbine diameters can be attributed on a simple level to take advantage of the scale laws that govern power generation (power proportional to diameter squared). Conversely, as wind turbine blades are three dimension objects, their mass is also governed by scale laws (structural mass is nearly proportional to diameter cubed) leading to increasing masses. Generally speaking, this growth in turbine diameter can be associated with an increasing level of complexity in regards to load development, detailed structural design, materials, testing, and analysis techniques.

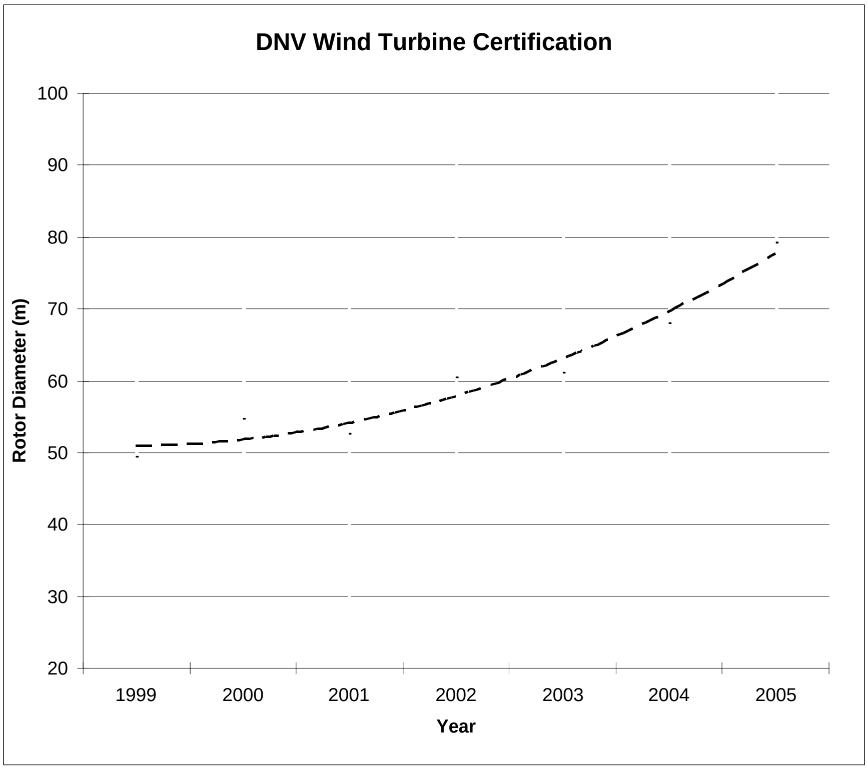

Figure 1 - DNV Certificated turbines by diameter (excluding prototypes)

There are a wide range of materials, and manufacturing techniques currently being utilised in the large wind turbine industry today. The material combinations used today in wind turbine structures are predominantly composite laminates, with a threaded root section providing the bolted connection to the hub or pitch bearing. Polyester, vinyl ester, and epoxy resins are common, matched with reinforcing wood, glass, and an increasing number of carbon fibres. A large range of manufacturing processes is also utilised in blade manufacture, encompassing: wet lay-up, pre-preg, filament winding, pultrusion, and vacuum infusion (with and without secondary bonding).

As manufacturers focus on the reduction of wind energy production costs, DNV expects that structural optimisation will be an increasingly important method of reducing material weights and manufacturing costs. To meet these demands, the design analyses and testing methodologies are also expected to develop in complexity to provide the same level of structural substantiation.

Considering this increasing complexity in design, analysis, and manufacture, the challenge for DNV is to provide a consistent level of structural substantiation for wind turbine blades, independent of the design and manufacturing methods.

3. DNV Blade rules

This new standard will be an important addition to DNV's range of widely accepted standards and service specifications for ships, offshore structures and the wind turbine industry. In 2004 DNV consolidated their large amount of industry experience, and released the now well established offshore wind turbine structural standard DNV-OS-J101 [4]. Now DNV is consolidating their knowledge and industry experience in wind turbine blades to provide the next standard in their wind turbine industry series: 'Design and manufacture of wind turbine blades'.

An IEC type certificate that includes blades certified by DNV to this new standard will provide a more consistent and thorough basis for the substantiation of wind turbines. Additionally, this will be an important milestone in DNV's offshore project certification, providing confidence for key project stakeholders in the safety and reliability of the offshore wind turbine project throughout the project life. These rules have the flexibility for experienced manufacturers, as well as the level of detail required for new entrants and less experienced manufacturers.

3.1 Background

DNV has been providing third party certification services for wind turbine manufacturers for over 15 years. These services are carried out in cooperation with RISØ, who began type approval of wind turbines as early as 1979 [2]. In 1991 DNV and RISØ began to carry out large wind turbine certification in accordance with national requirements, beginning in Denmark and closely followed by Germany and the Netherlands. Today more than 100 individual large wind turbine certificates have been issued by DNV, with current customers in Europe, the US, and Japan. Additionally, onshore and offshore project certificates are being issued globally.

In the early 1990s certification focused on addressing the critical areas in wind turbine engineering on a case by case basis, namely in the areas of: design and integrity of control and safety systems; development of design loads; control and safety system testing; blade ultimate and fatigue testing; and the measurement of power curve, noise and loads. Formalised requirements for these critical areas were subsequently developed based on industry experience in increasing detail.

In 2001 the international certification scheme IEC WT-01 was issued, with Denmark quickly adopting the scheme as part of their national requirements in 2004. DNV expects other national authorities to follow Denmark's lead and implement the IEC WT-01 certification scheme as part of their own national requirements. The IEC WT-01 certification scheme contains several detailed standards, covering both type certification as well as project certification.

For wind turbine blade engineering the requirements to structural safety and design loads are specified in the IEC 61400-1 [1] standard and requirements for full scale blade testing is specified in IEC 61400-23. The major manufacturers, laboratories, research institutions and certifying bodies have participated in developing these standards further; however the detailed qualification of blade materials, design, and manufacturing procedures are yet to be included. DNV has now taken the initiative and issued the new standard: "Design and manufacturing of wind turbine blades" that serves as detailed guidance to achieve IEC WT-01 certification for wind turbine blades.

In wind turbine blade engineering the qualification of materials, design and manufacturing procedures is dependant on the individual blade manufacturer. In DNV's experience, blade manufacturers utilise unique and individual materials, design approaches, and manufacturing processes – the details of which are often confidential. This is one of the major differences when compared to other industries, such as civil engineering and ship building, where the materials, design solutions and manufacturing methods are more or less common for each manufacturer.

The qualification of materials, design, and manufacturing procedures is usually inherent in the codes, such as the various Eurocodes for civil engineering, and DNV classification rules for ship building. In these cases, the detailed scientific basis for the rules is open and maintained by the research institutions, certification, and classification agencies. For wind turbine blades the scientific basis for qualification of the specific materials, design and manufacturing procedures has to a large degree to be maintained by the manufacturer. Standards for design and manufacturing of wind turbine blades are to focus more on the principles for qualification than on specification of specific materials and procedures. Such focus is implemented in the DNV standard "Design and manufacturing of wind turbine blades".

As with all DNV standards, this new standard has been developed with a rigorous process of both internal and external review, with key technical personnel from major blade manufacturers and research institutes providing critical review and input.

3.2 Key concepts

The standard includes detailed guidance for material qualification, design considerations and analysis procedures, qualification of manufacturing and test procedures, and the documentation requirements for detailed blade design. Additionally, the standard will capture and consolidate the key lessons learned from the EU funded wind turbine blade OPTIMAT program that DNV is currently actively involved with.

This standard provides detailed guidance and requirements in the following key areas of material qualification, design analysis, manufacturing and testing procedures, as well as design and manufacturing documentation requirements. Detailed requirements are shown in Figure 2.

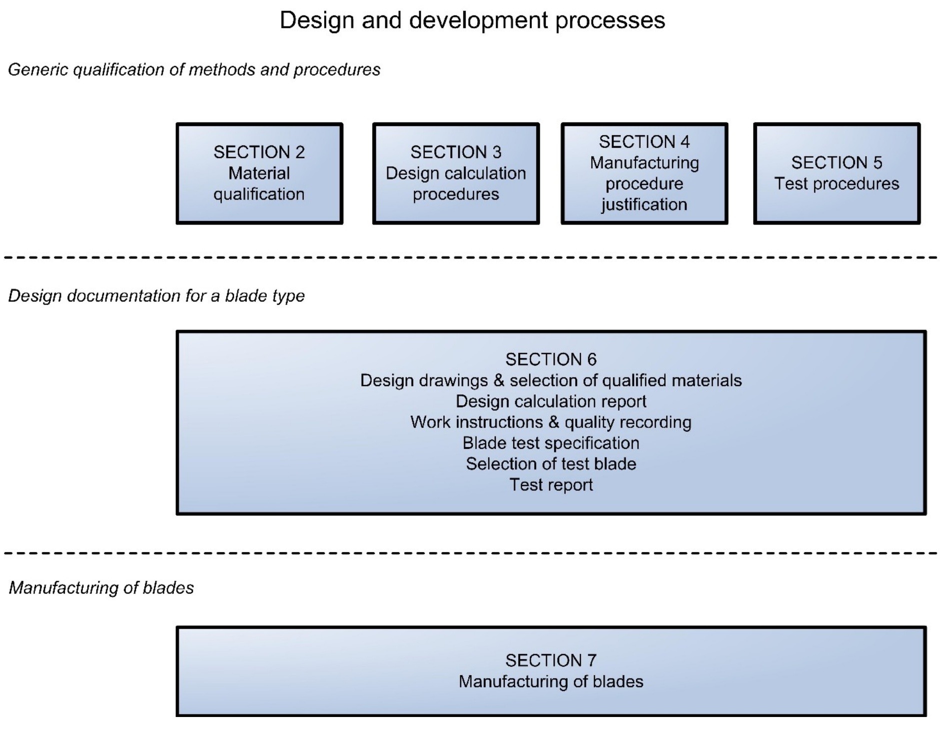

Figure 2- Wind turbine design and development processes

3.2.1 Material Qualification

Material qualification is a key area of this new standard, with guidance provided on materials commonly used in the manufacture of wind turbine blades. In addition to traditional metallic materials, additional guidance on the qualification of modern composite materials used extensively in wind turbine blades, in particular Fibre Reinforced Plastics (FRP), Carbon Fibre Reinforced Plastics (CFRP), laminated woods, paste adhesives, sandwich core materials as well as their associated paint and gel coat systems.

DNV expects the continued extensive use of composite materials in blade design, and as a result has looked to other industries to learn more about composite certification. Although composite materials are commonly used in numerous industries such as ship building, offshore, and transport; it is in the aerospace industry that composites have achieved wide spread use for critical structural applications - an application and context not dissimilar from wind turbine blades, and therefore serving as a valid comparative basis.

Based on the large amount of structural substantiation experience obtained in the aerospace industry, a new approach is suggested for composite material qualification. This approach, known as the *building block approach* [5], provides the framework for the development of a tailored composite material qualification program. The building block approach is characterised by iterative analysis and testing being conducted at increasing levels of structural complexity, and finalising in full scale static and dynamic tests - more effectively and intelligently utilising the benefits of composite materials. This approach has been accepted in the aerospace industry as state of the art by both manufacturers and certifying bodies. An overview of this approach is shown below in Figure 3.

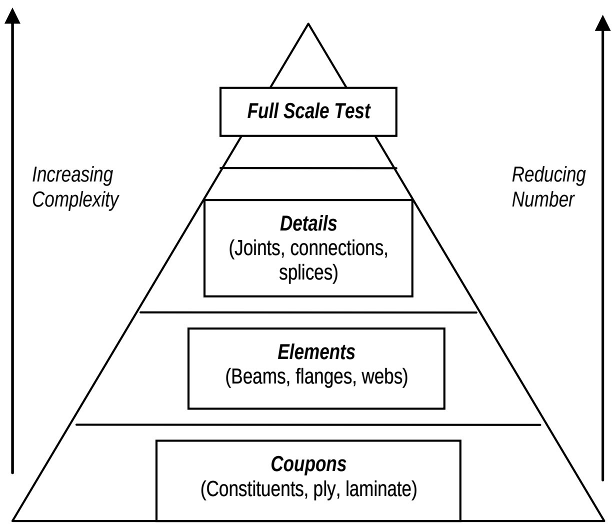

Figure 3- The Building Block Approach

At the coupon level, traditionally wind turbine blade manufacturers have focused their test programs on determining tensile strengths and fatigue response. However more complex material characterisation such as in and out of plane strengths, moduli, and Poisson's ratio, as well as Interlaminar strengths for the laminate are often neglected. These properties are becoming increasingly important for accurate stress analyses, and will be essential for conducting structural optimisation of the blade where the analysis of complex stress states are essential.

Through the establishment of the strength characterisation at the coupon level, accurate analyses can be conducted at higher levels (such as for blade beams or shells), and these calculations verified by test. In this way, the building block approach progresses in structural complexity through to the full scale test, with each test facilitiating design analysis iterations that increase confidence in the design. This progressive approach, in part, has been observed in recent years by DNV for numerous wind turbine manufacturers, and is expected to be adopted for structural optimisation purposes.

To more effectively use composite materials, a greater understanding of the structural complexity will be required than that which has traditionally been achieved. The building block approach provides an important tool in achieving confidence in structurally complex composite designs.

Due to both the inherent variability in composite materials when compared to traditional metals, and the uncertainties in the design analyses tools, the building block approach has been used by composite airframe manufacturers for decades. This approach typically requires extensive qualification testing, where for example the FAA certification of the Boeing 777 composite empennage assembly [6] involved over 8000 coupon and element level tests. The FAA simplified this approach for the general aviation industry (normal, utility, acrobatic, and commuter aircraft only) with the Advanced General Aviation Transport Experiment (AGATE) program [7]. Here, smaller manufacturers are able to benefit from the collected databases of composite materials in MIL-HDBK-17 Volume 2 and qualify their products through an approved manufacturing system, and a reduced set of mechanical property coupon testing (roughly 300 individual tests) to demonstrate their manufacturing system and any minor changes that they have made to the material or process. Large commercial airframe manufacturers however are continuing with their proprietary in-house composite material databases.

Is an aircraft level of safety for materials required for wind turbines however? A deeper look at the structural codes is required to properly answer this question. A comparison of FAR 25 [9] (structural code for commercial aircraft), and IEC 61400-1 [1] (structural code for large wind turbines) gives similar material allowable (characteristic strength) requirements. Both standards however require manufacturers to provide details of their design allowable strength, however it is in the detailed interpretation and application of these codes to develop the design allowable strength that differs.

Design allowables strength for aircraft structure are developed by individual manufacturers, however are typically based on MIL-HDBK-17-1E requirements [5]. Here, material strengths are determined through a comprehensive test program, and are usually driven by damage tolerance and holed strength requirements [8]. For comparative purposes only[1], an estimate can place these requirements at roughly 60% of material allowables. Further conservatism is also added during development of the aircraft material allowables where strength property testing considers additional environmental effects (at cold [-53C], ambient, and hot [+82C] dry/wet conditions [5]), where wind turbine blade materials assess these effects in a more qualitative manner, relying on conservative empirical assumptions.

The design allowable strength for wind turbine blades is typically determined from experience based empirical factors. The new DNV standard has now consolidated these empirical design allowable factors for common material types and manufacturing processes, based on industry and project experience, and tabulated these in the standard. However, the option to develop material design allowables through a dedicated test program is also provided for large wind turbine blade manufacturers.

[1] Aircraft loads [9] are also subjected to a safety factor of 1.5 compared with that of 1.35 for wind turbine blade aerodynamic loads [1], adding an additional margin for comparison.

To place these different material and design allowable approaches into perspective, both the aircraft and wind turbine approach is applied to a typical set of tensile static coupon test data from a generic wind turbine blade development program. The different levels of conservatism inherent in each approach is clearly visible in *(Note material A's actual test results: 729, 698, 730, 699, 662, 566, 489, 595, 566, 525 MPa; with μ=625 MPa)*

Figure 4.

Code	IEC 61400-1 §7.6.2.2 using DNV Blade rules	FAR25 §25.613(b.1) using MIL-HDBK-17E	FAR25 §25.613(b.2) using MIL-HDBK-17E
Application	Wind turbine blades	Primary aircraft structure	Secondary aircraft structure
Tolerance level for characteristic strength[2]	95%	99%	90%
Confidence level for characteristic strength	95%	95%	95%
Material characteristic strength for Material A	575 MPa	260 MPa	411 MPa
Partial safety factor for material capacity	2.2 for Polyester wet layup 1.7 for Epoxy prepreg	~60% for detail effects ~10% for temp/moisture	~60% for detail effects ~10% for temp/moisture
Design allowable strength for Material A	253 MPa (Polyester) 332 MPa (Epoxy)	141 MPa	222 MPa

(Note material A's actual test results: 729, 698, 730, 699, 662, 566, 489, 595, 566, 525 MPa; with μ=625 MPa)

Figure 4 - Material and Design Allowables

As it can be seen, even though the structural codes are quite similar it is the detailed interpretation by both industry and the certifying bodies that lead to different material and design allowables. The level of rigour and safety for wind turbine blade structural substantiation is not that of aircraft, however based on DNV's industry experience it is believed to meet the intent of the internationally accepted safety requirements of the IEC code [1].

3.2.2 Design Analysis

The new design analysis section provides an overview of the design development cycle, with detailed comments and experience throughout the text. Composite material failure modes and failure mechanisms are covered together with their associated design criteria, analysis, and partial safety factor development guidance. Supplementary ISO 9001 guidance for the design scope is provided, as well as additional information for the management of FEA software, and the people that use it.

The majority of design analyses reviewed by DNV involve simple beam and FEA of global blade models, with the assumption of dominant longitudinal laminate strains (ε_1). Failure criterions are

[2] The statistical methods in MIL-HDBK-17 rquire conservative data assumptions when compared to the simple statistical distributions typically used for wind turbine materials.

typically limited to simply longitudinal fibre strain failure. With the increasing size and complexity of wind turbine blades, DNV believes the next major step for manufacturers to reduce the cost of wind power will be to focus on structural optimisation techniques. Again, this is increasingly important for offshore wind turbines, as turbine weight reductions significantly reduce the support structure requirements and costs. Traditional simple single plane strain analyses are expected to develop in complexity to more accurately predict the local material responses, increasing from the simple single axis strain criterion to 2-D, and 3-D complex stress/strain states evaluating more complex failure criterions such as Hashin, Tsai-Hill, Tsai-Wu, and Puck's for various composite failure modes.

The design analysis section of the new DNV blade rules will provide the tools and requirements to conduct complex stress analysis, including the evaluation of some of the following major composite failure modes:

— Local buckling – focusing on Euler buckling of blade shell panels, and shear webs.

— Fibre failure –complex bi-axial, and tri-axial stress/stain states

— Matrix failure – analysis of the matrix in complex bi-axial, and tri-axial stress/stain states

— Interlaminar failure – the analysis of Interlaminar stresses in the laminate

— Sandwich failure – more detailed evaluation of sandwich failure modes

— Fatigue failure – providing detailed advice on the development of fatigue loads, analysis, and testing programs

Each failure mode is comprehensively discussed, with the analysis and testing requirements explicitly stated, with DNV accepted methods and procedures provided. Additionally, requirements for other design analysis considerations unique to wind turbine blades such as: erosion, environmental and corrosion protection, lightning strikes, impact tolerance, damage tolerance, and extreme temperatures are discussed in detail.

3.2.3 Manufacturing procedures

On the manufacturing side, further guidance is also provided in this new standard on how to build up an experience database for the rational control of manufacturing procedures, and how this data base is used during the certification process. DNV recognises the criticality of the manufacturing and quality systems in the final quality of composite components, and are providing guidance for its proactive management.

3.2.4 Static and fatigue type testing

Static and fatigue type testing will remain to be an essential element of DNV type certification, with the reliance on analysis alone not expected to be an acceptable method of structural substantiation. In order to provide valid static and fatigue type testing, there are three key areas that need to be addressed: the right loads, the right test specimens, and the right documentation.

— The right loads are addressed through the correct development of extreme and fatigue loads, the selection of the correct safety factors, and the correct setup and execution of the test program.

— The right test specimen is addressed through the selection of a representative test blade, and the inclusion of critical structural elements during the test.

— Finally, the testing program must be thoroughly documented, capturing the key information required to provide confidence in the test results, the design, and ultimately to achieve certification.

DNV provides detailed coverage and guidance of these key areas in this new standard based on proven testing experience.

4. Conclusion

Wind turbine blades are becoming larger and increasingly more complex, with a wide variety of materials and manufacturing techniques being utilised in their construction. The new DNV blade rules provide guidance detailed guidance and interpretation throughout the blade development program to meet the safety requirements of the internationally accepted IEC WT-01 certification scheme.

Composite materials in particular are used extensively in modern wind turbine blade design, and DNV believes that the complexity of structural substantiation will increase with increasing turbine sizes and structural optimisation. In order to manage this, DNV has learned from the aerospace composites industry, and recommended the widely accepted building block approach to composite structural substantiation that is based on iterative testing and analysis to achieve confidence in the final design.

This DNV standard provides detailed guidance and supplementary standard interpretation throughout the blade development program, consolidating the vast amount of international experience present in the industry, and providing a basis for the blade designs of the future.

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