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What Goes In, Comes Out

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For wind turbine blades, generally two main root connection types exist to connect the rotor blade to the hub of the turbine: the T-bolt connection or bushing technology. Where for small size rotor blades both connection types are frequently used, for the large multi-megawatt turbines the bushing connection technology is becoming very interesting because of the potential to have longer blades with smaller roots.

Figure 1. Cross section of the assembled We4Ce bushing solution, post inspection after test

In this article, the bushing connection is discussed. The article points out the two different principles and the development steps of the We4Ce bushing. Further it clarifies the aspects that need to be considered to have a successful connection type in the future.

The Bushing Replaces the T-bolt

We4Ce is a provider of blade root bushing technology. The development of the We4Ce bushing solution started in 2008. It was designed in such a way that the laminate thickness of a traditional T-bolt connection could be replaced one to one by the subcomponents of the bushing solution. Since the strength of the bushing does not depend on the strength of the laminate net area like in a T-bolt connection, the design that uses bushings is able to contain approximately 35% more bolts with the same geometry. This leads to a high root strength and substantially longer blades for more energy capture. It also limits the root geometry, which has a positive effect on the rotor blade transportation costs.

Fundamental Bushing Concepts

Within bushings, different fundamental concepts exist. These are related to the failure mode. A first concept is the bushing that is bonded with the blade by means of drilling and applying a bonding paste between the steel insert and the composite part. In the early days of the wind industry this type was referred to as the 'carrot' solution.

The second method is where the connection between the bushing and composite is made during the resin infusion process and where the strength is determined by the strength between the bushing and prefabricated elements being positioned adjacent to the bushing. An example of this connection type is the 'dog bone' solution.

A third method is also based on the resin infusion process; however, the

Figure 2. 180 degrees 2.8m pitch circle diameter for 3.XMW, with We4Ce bushings

Panel	Full ID	Description	Characteristic strength [%]
S1C	W4C-S1C	Roving to UD bar We4Ce	100
S3	W4C-S3	Roving to Biax side of root laminate package	132
S4	W4C-S4	Roving to UD side of root laminate package	101
S6	W4C-S6	Prefab Biax to Biax	217
S8	W4C-S8	Prefab UDbar We4Ce to Biax	195
S7	W4C-S7	Biax side of root laminate package to UD pultruded (Supplier 1)	156
S1A	W4C-S1A	Roving to UD bar pultruded (Supplier 1	84
S1B	W4C-S1B	Roving to UD bar pultruded (Supplier 2)	98

Table 1. Interface shear test results for different interfaces

load transfer from the blade to the steel bolts is achieved by the majority of the inner and outer laminate. The We4Ce bushing is based on this methodology.

The Design of the We4Ce Bushing Connection

A typical cross section of the We4Ce bushing solution is shown in Figure 1.

From bottom to top (Figure 1), the bushing solution consists of the first part of the root laminate package, followed by the bushing assembly and ending with the second part of the root laminate package. The bushing assembly consists of a steel bushing with glass fibre reinforcement (rovings) wrapped around it, core wedges and composite prefabricated unidirectional (UD) bars between the bushings. The root laminate package is a triaxial glass fibre layered fabric .

What You See Is What You Get

For the T-bolt connection, 'what you see is what you get' generally counts. In other words, the level of quality and strength is secured by means of the mechanical locking part of the cylindrical nut and by the cross-sectional strength of the laminate net area between the cylindrical nuts. Proper flatness is required to avoid bolt failure. If the T-bolt connection is produced well, the end user will witness this instantaneously.

For the bushing connection, although 35% more strength can be reached, the statement 'what you see is what you get' is not always true. If materials are selected differently from the specs, if a non-proper vacuum tightness is applicable, or different assembly tolerances are used, then the end user might not visually notice. To guarantee that the design lifetime is controlled, the end qualification is to be made by means of a more thorough and in-depth inspection of the materials and processing applied at the manufacturer. For the bushing 'what goes in comes out' counts.

The Strongest Interface

Together with TNO Structural Dynamics in Delft, the Netherlands, We4Ce has performed double lap shear tests for different glass epoxy material combinations used in the bushing solution. The tests were witnessed by the certification body TÜV Rheinland and were based on the ASTM D3528-96 standard. The tests were performed under the RVO Dutch funding scheme referred to as 'PMRB within HER '(HERnieuwbare energy). PMRB stands for Prefab Modular Root Bushing.

Table 1 shows the interface strength results. The yellow marked interfaces are the ones applicable for the We4Ce bushing.

The interface between the roving and the UD bar gives the lowest result. Hence the connection between bushing reinforcement (wrapped roving) and UD bar is the weakest link. Compared with the use of pultrusion for the UD bar, the We4Ce UD bar showed significantly higher strength results.

High Level Intermediate Tests

Of all the interfaces, the weakest link in terms of shear strength is between the roving and the UD bars. The UD bars need to be selected carefully.

The ultimate and fatigue load level of the bushing assembly is determined by the highest load-to-strength ratio of each of the components and interfaces. Multiple full-scale coupon tests for M20-M30-M36 have been performed to empirically determine the ultimate and fatigue load levels. Post inspection showed the failure mode.

Based on tests starting from 1,000 cycles up to 10 million cycles, several Goodman diagrams for fatigue were created, including the load range as well as the mean level.

Figure 3. Pre-assembled root ring with We4Ce bushings

Certification

With the interface tests and intermediate load level tests up to 10 million cycles, We4Ce has reached certification according to the GL 2010 Guideline, the DNVGL-ST-0376 Standard (edition 2015) and the IEC 61400-5:2020 Standard.

Certification of the We4Ce bushing assembly is reached empirically and on a unit load level for the complete bushing assembly situation. As a result, the solution is used extensively for different sizes of circular wind turbine roots as well as in several projects where non-circular geometries are required. Examples are partial-span pitch rotor blades and the rotor arms of vertical axis wind turbines. Depending on the size, the certification covers the first 500–1,500mm of length.

Manufacturing effects by means of tests and analytically are considered in the material knockdown factors to reach the final engineering values. Clear specifications for construction compatibility on the shop floor and tolerance constraints can be given, leading to a uniform working method.

Confirmation of the engineering properties is finalised with a confirmation statement received from TÜV Nord for the M36 and TÜV Rheinland for the M20 and M30.

Lifetime Extension

A logarithmic relation exists between strength and lifetime. The fatigue design curve of a bushing has a smooth 'strength vs number of fatigue cycles' relation.

A small difference in strength leads to a big difference in lifetime. For example, a 10% strength difference gives a lifetime difference of a factor of 2.

A small reduction in the strength can therefore lead to a big impact in the lifetime. This also counts the other way around – a small improvement in strength leads to a lifetime extension and with that a lowering in the cost of ownership.

Within the Modular Adaptive Root Solution programme, We4Ce is aiming for lifetime extension with controlled improvement steps in the bushing assembly. ■

Edo Kuipers is one of the co-owners of We4Ce. He has 22 years of experience in rotor blade design. His main responsibility is the engineering department for rotor blade design and he is a specialist in the bushing connection. Edo has a Bachelor of Engineering degree in Aeronautical Engineering from the Netherlands.

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