

## CONNECTION METHODS IN WIND TURBINE ROTOR BLADES

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Status: Public  
Project no.: S17-002  
Report no.: WMC-2017-109  
Issue: 00  
Date: 15 October 2018

Title: Connection methods in wind turbine rotor blades

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Date: 15 October 2018

Year of first issue: 2017



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# 1 INTRODUCTION

Mechanical and structural connections in wind turbines are among the most heavily loaded connections in engineering applications, and are in several cases connections between different materials, i.e. 'hybrid' connections.

This report is one of two literature reports, created in the framework of the TKI-WIIP (Topconsortium Kennis en Innovatie – Wind Innovatie Impuls Projecten) 'Structural connections' project, with RVO reference number TT\_WIIP1\_1601\_WMC. A similar report focuses on the support structure connections<sup>1</sup>. This report gives a literature overview of wind turbine blade connections. The TKI-WIIP project has the overall objective to identify knowledge gaps as a basis for a research programme on this topic.

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<sup>1</sup> Van Es, S., Pijpers, R., van der Putten, S., 'TKI-WOZ WIIP - Joints for offshore wind applications - Report on failure mechanisms of bolted ring flange connections', TNO report, May 2017

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## 2 CONNECTIONS IN ROTOR BLADES

Wind turbine rotor blades are integral composite structures, for which typically it is avoided as much as possible to incorporate any connections other than the interface between the fibres and resin of which the rotor blades are manufactured. Nevertheless, for manufacturing and installation, and occasionally for operation, it may be required to include connections in rotor blades such as:

- The connection between prefabricated parts within the composite blade structure;
- Split blade/modular blade connections, which are connections between different pre-manufactured blade segments;
- The blade root connection, which is the bolted connection between the blade and the turbine interface.

Typical rotor blades are hollow composite structures, manufactured with glass-and/or carbon fibres in an epoxy, polyester, or vinylester thermoset matrix. They are produced in large scale vacuum-infusion moulds, and a most common way to do this is to separately manufacture two halves (pressure side and suction side), and a central spar, and to join these with thick adhesive pastes ('bonding paste').

A variation of this concept include splitting up the pressure and/or suction sides, for instance in the case of a box beam central spar.

Another variation of this concept is a one-shot process, avoiding splits and bondlines as much as possible (Siemens and Cartflow).

In most manufacturing cases, the aerodynamic geometry of the blade may be compromised in case blade parts and bondlines have tolerances that are outside specification.

Rotor blades obviously need to be connected to the wind turbine hub, and this is most often achieved through bolts in the mostly circular blade root section.

For transport reasons, but with larger blades also for manufacturing reasons, blades may be split up into two or more spanwise sections: modular blade designs or split joint designs. Mostly this is done with a bolted connection, however recently techniques are available based on bonding or semi bolting/bonding.

Several other, less prevalent connections may exist in modular blades, such as replaceable blade tips and trailing edge root fairings.

These connections in wind turbine rotor blades have the following in common with each other:

- They are 'primary' connections;
  - if they fail, severe power loss or blade failure will entail;
- The connections are subjected to severe fatigue loading;
  - a rotor blade is designed for ca. 20 years of life, in which it will suffer ~100 million load cycles due to wind shear, gravity loading, and gusts;
- Blades, and thus their connections are designed for minimal maintenance;
  - For the owners and operators of wind farms, reliability of the entire wind farm is important, since maintenance and standstill do not contribute to cost-effective operation of the power plant;
- Connections increase sensitivity to crack growth and damage;
  - they provide locations for crack initiation, growth, and paths for ingress of moisture;
- They add mass to the blade;
  - Steel inserts may be used;

- Additional material must be applied to account for e.g. loss in net stress cross-section;
- Connections are in practice not equipped with sensors for long-term monitoring of e.g. pre-stress;
  - Technologically this would be possible;
- Cost is induced due to:
  - Use of additional material;
  - In some cases: relatively complex multi-material details, to transfer the loads between components and to account for the above loads and sensitivities;
  - Uncertainty on behaviour of the connection (e.g. creep, fatigue);
  - Time for (on-site) assembly;
  - Additional tooling;
  - Certification.

In the past two decades, a continuous trend for upscaling wind turbines is seen, which has for a part been enabled by more material-efficient rotor blade designs. Rotor mass and mass-induced mechanical stresses on a rotor blade are very sensitive to scaling (they scale with an exponent of 3 and 1, respectively, according to classical scaling rules).

In view of the above, the main aims of research into rotor blade connections can therefore be summarised as: mass and cost reduction and improved efficiency/reliability.

In the following, research into improvement of rotor blade connections is discussed, mainly to identify topics that need deeper or more elaborate research to enable further improvement in rotor blade technology.

This literature research is organised along the lines of rotor blade topology, i.e. which part of the blade contains the connection, but first a general qualification of connection types is discussed.

Connection methods can be qualified based on the type of connection (mechanical, adhesive, welded, or friction-based). Per type, the same general behaviour and sensitivities can be relevant to different application areas or blade parts. Subsequently, per blade part, examples of different connection solution types are treated in more detail, in order to identify the potential for improvements in connections. Thus, where this information is given or can be estimated, the connections are investigated with a focus on the added mass, added cost and added uncertainty.

The above is particularly aimed at horizontal axis wind turbines. A special case of wind turbines in terms of connections is vertical axis wind turbine rotor blade connections. Vertical axis wind turbines seem to occupy the relatively low rated power and built environment niches, although for deep-water wind turbines they spark renewed interest in recent years after much research and prototyping in the previous century.

### 3 COMPOSITE-COMPOSITE CONNECTIONS

Connections between composite parts in a rotor blade are typically made with bonding paste adhesives. This chapter does not go into the connection between lamina in a composite, although delamination within a composite or between sandwich cores and –face sheets may be an issue in some laminates (for which techniques such as through-thickness stitching may improve resistance to crack growth, see e.g. [1]).

In a rotor blade, typically several structural adhesive connections are present, joining different materials. These connections have several commonalities:

- The adhesive in the bondline is often ‘thick’ (>3mm). Bondlines between blade shells may be used to compensate for manufacturing tolerances in the blade components and are therefore up to ~1 cm thick. For this reason, the adhesives used are ‘bonding pastes’, sometimes even glass-powder filled epoxies with high viscosity;
- The adhesive is loaded along multiple axes. Trailing edge and spar cap bondlines are loaded both in shear and along the blade spanwise direction.

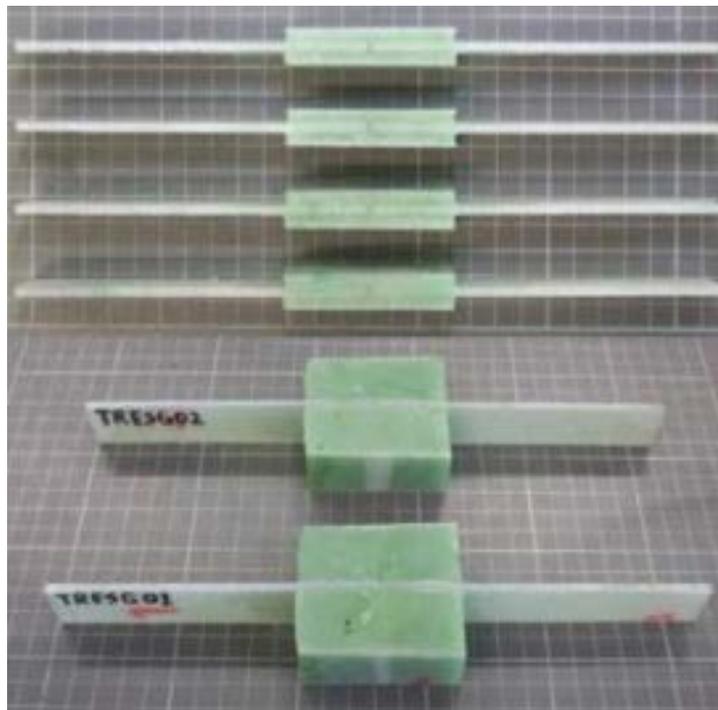


Figure 1: double lap shear test specimens with different bonding thicknesses

#### 3.1 Spar-cap – shear web connection

Spar caps (thick laminates dominated by unidirectional fibres in spanwise direction) and shear webs (sandwich panels with foam or balsa cores) are typically made separately (prefabricated) and joined with a bonding paste. At that location, the load on the connection comes from various sources that are in turn a consequence of the operational blade loads:

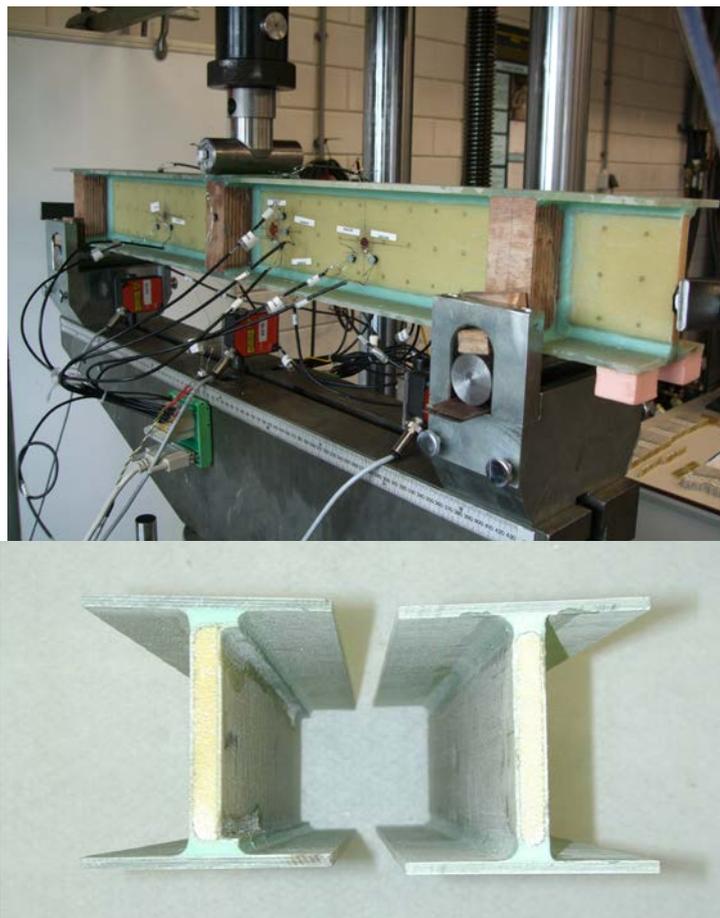
- Shear load from beam bending and beam torsion
- Peel load from cross-section ovalisation and cross-section shear distortion

Thus, the stress state in the bondline is typically multi-axial, and, of course, fatigue loads should be taken into account.

### 3.1.1 UPWIND beams

In the European UPWIND project, a subcomponent test was developed in an attempt to realistically represent the stresses in the bonding paste layer in a bondline between spar caps and shear webs. See Figure 2 for the set-up tested at WMC. Various other configurations of this concept were numerically modeled and tested in the laboratories of Fraunhofer IWES, CRES, Rutherford Appleton Laboratory, and VUB. The main advantages of using a beam test set-up for bondline characterisation are:

- the substrates correspond to the actual materials joint by the adhesive;
- the multi-axial stress state in the adhesive can be manipulated by modifying the dimensions and shape of the beam structure



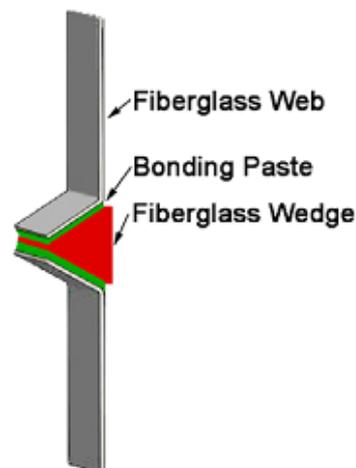
**Figure 2: UPWIND beam test set-up at WMC. Two different cross-sections were tested**

An overview report of all beam tests can be found in [2], with recommendations on subcomponent testing for validation of bondline details in [3].

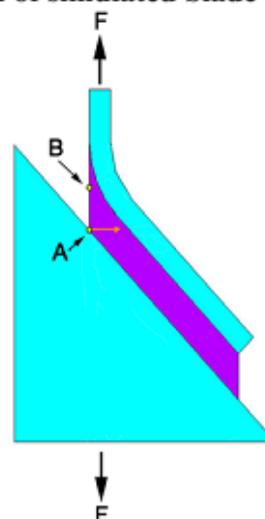
### 3.1.2 Sandia/MSU bondline research

In [4], relevant work is presented on the static and fatigue strength of bondlines that are representative for blade joints. The structural detail geometries tested are reproduced in Figure 3. Failure modes and effects of manufacturing flaws were observed and modeled. Through the geometries of these structural detail tests, both tension (peel) and shear was introduced, especially in the 45° geometry. Despite the difference in geometry, quasi-static and fatigue tests showed similar strength and life in tensile fatigue. Crack initiation was in the adhesive in both

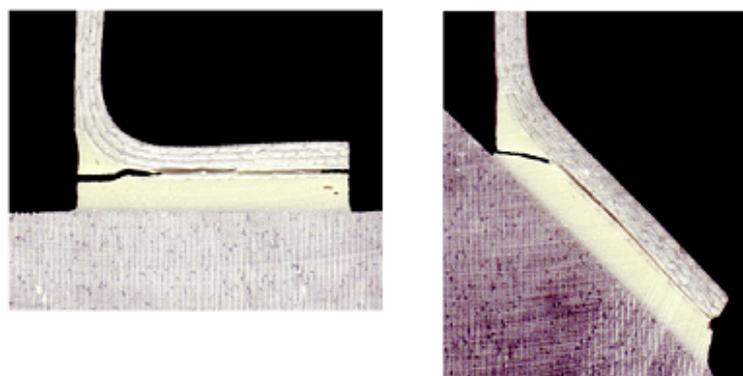
cases, and this may explain the similarity between the fatigue behaviour of geometries A and B.



**Figure 1. Illustration of simulated blade adhesive joint coupon.**



**Figure 2. Geometry and location of points of interest and line plot axis.**



**Figure 3: Geometries tested (left is B, right is A in the lower illustration) in quasi-static and various fatigue modes in [4]**

### 3.2 Trailing & leading edge connections

Operational experience has sparked more research into trailing edge buckling and failure. The industry together with blade testing experts, have intensified their relevant test development.

The trailing edge adhesive joint suffers from the following load types:

- Loads or stresses related to the production (curing, shrinkage);
- Strains in longitudinal or blade length direction;
- Strains in chordwise direction;
- Panel buckling load;
- Shear flow load;
- Deformation of the panels resulting in peeling loads.

Adhesives are composed to withstand these load types individually, but a combination of loads in the complex 3D structure may lead to crack initiation and this will lead to a split trailing edge having mostly the consequence of a panel buckling failure. Such failure calls for a significant repair or might lead to blade destruction.

As this is a geometry-dominated very specific failure mode, the trailing edge behaviour can potentially be well-represented in a subcomponent test [5], which could be used a.o. to verify engineering models, test design modifications without the need for a full-scale test.

In the framework of the IRPWIND project, different test set-ups were developed at RISØ-DTU, Fraunhofer IWES and WMC, see Figure 4 - Figure 7.



**Figure 4: Test set-up for trailing edge buckling at DTU [5]**

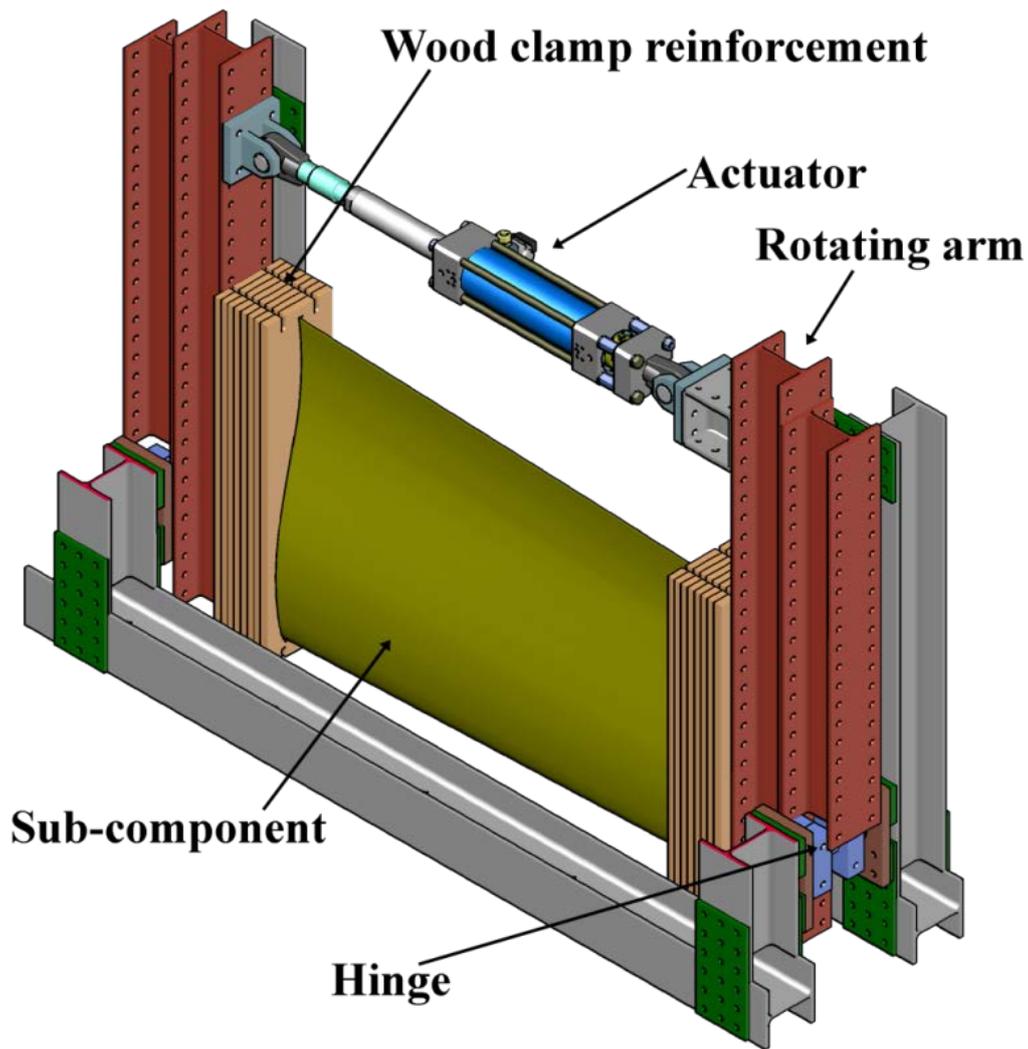


Figure 5: Trailing edge buckling test set-up schematic (WMC)

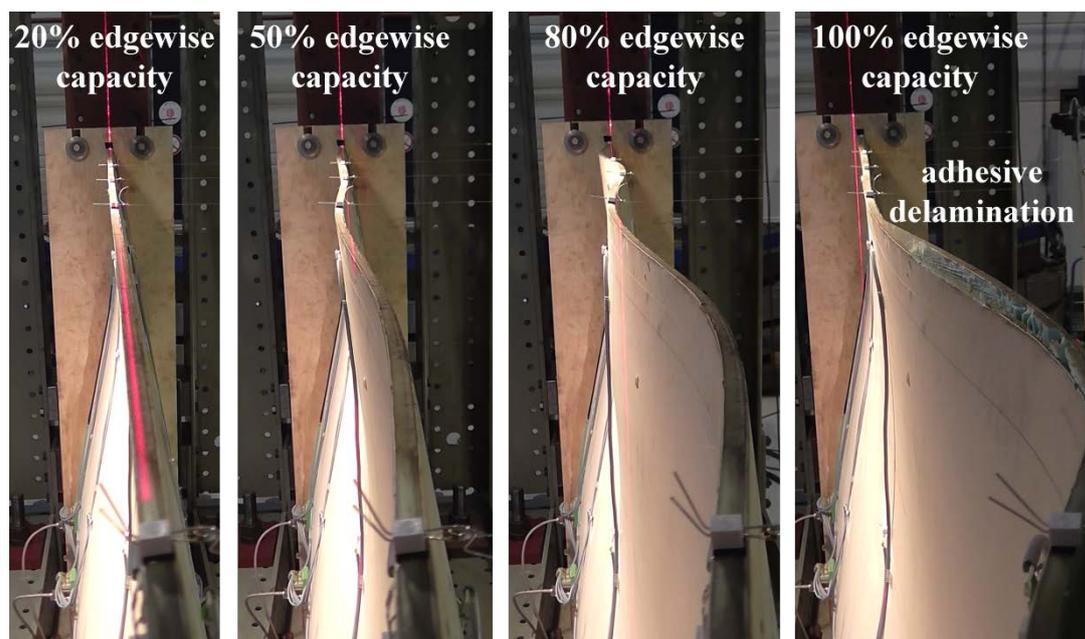


Figure 6: Quasi-static trailing edge buckling behaviour in trailing edge test at WMC [6]

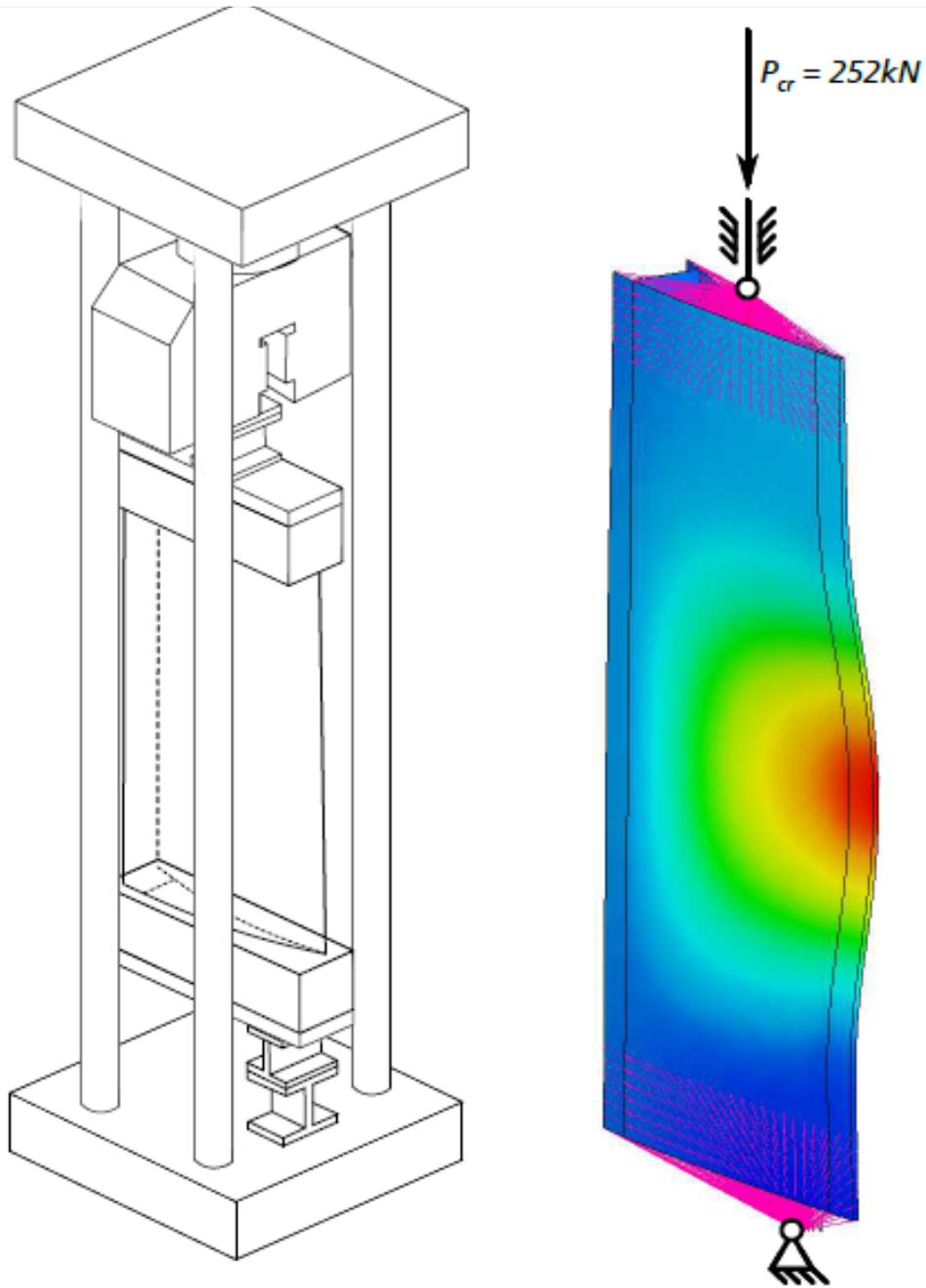


Figure 7: Trailing edge buckling test set-up in universal testing machine [7]

## 4 COMPOSITE – STEEL CONNECTIONS

Designers of composite-to-steel connections in rotor blades face various challenges. First of all, the connection is more or less by definition going to increase structural mass because of three reasons:

- 1) Most composite-to-steel connections in rotor blades involve composites with predominantly unidirectional fibre orientations, that need to be connected to another (part of the) structure. The fibres do not continue across the connection, which means that the loads very often need to be transferred through shear stresses in adhesives and in the resin of the laminate itself. Since the shear strength and stiffness of composite resins are at least an order of magnitude lower than the axial strength of composites, this means that relatively much composite material should be added around the connection to cope with the load transfer;
- 2) Even if the load could be transferred by directly coupling the steel part with a UD composite part, there would be a difference between part thicknesses in strength-based designs. Any UD glass-fibre structural cross-section is capable of transferring 1 to 4 times the load compared with a steel part (the tensile strength of steel is 1-4 times lower than that of glass fibre). Thus, to connect parts with equal thickness, the UD composite part will have to be made thicker than necessary based on strength (for stiffness-based designs, this would be the other way around, as a UD glass-fibre has a 6-8 times lower Young's modulus than steel);
- 3) In order to transfer loads, metal inserts or holes will need to be included in the composite and steel parts, requiring additional material to enable load transfer.

Further challenges are:

- Stresses due to mismatch in coefficient of thermal expansion. It is assumed that this is most detrimental in adhesively bonded steel-to-composites connections such as in the case of embedded inserts;
- Stress relaxation in the composite should be taken into account when designing a pre-stressed connection.

Within the composite-to-steel connections in wind turbine blades, a generic distinction can be made between:

- Split blade connections, or modular design connections;
- Blade root connection, blade to turbine interface connection.

Below, an overview is given of research and development projects aimed at addressing the abovementioned challenges for these two connection types.

### 4.1 Split blade connections

To cope with dimensional constraints in transport, or even to cope with the manufacturing for large blades, the long blades may be produced in parts. Terms encountered in the literature on this topic include split blades, multi-piece/-section, sectional, modular, split joint or segmented blades. An added benefit of this type of blade that is sometimes mentioned is exchangeability of one of the blade parts, although in practice the advantage of split blades depends on the effort associated with dismounting and mounting of part of a blade vs the entire blade.

A comprehensive overview of split blade connection methods is given in [8].

The rapid growth of maximum blade length already sparked research interest as early as ca. 1995. Some relevant research projects are:

- 1997-2000: Sectional blades
- 1997-2002: Bladeco
- 2004-2011: Upwind: Channel fittings
- 2013: INdeModular joint @ CENER

Further, several patents are applicable.

Apart from these research programmes and patent files, also a clear interest and need for development from the engineering and production market is noticed. The latter resulted in the actual launch of commercialised available solutions, which have implications for the development of connection technology.

Examples of market available or introduced solutions are:

- Aerpac: tip mechanism;
- Enercon: partial span pitch, chordwise inboard;
- Envision: partial span pitch;
- Sinowind: bolted split joint;
- Nabrawind: bolted split joint;
- We4Ce-TRES4: beam with ribs.

Elements from the above timeline are discussed in slightly more detail below.

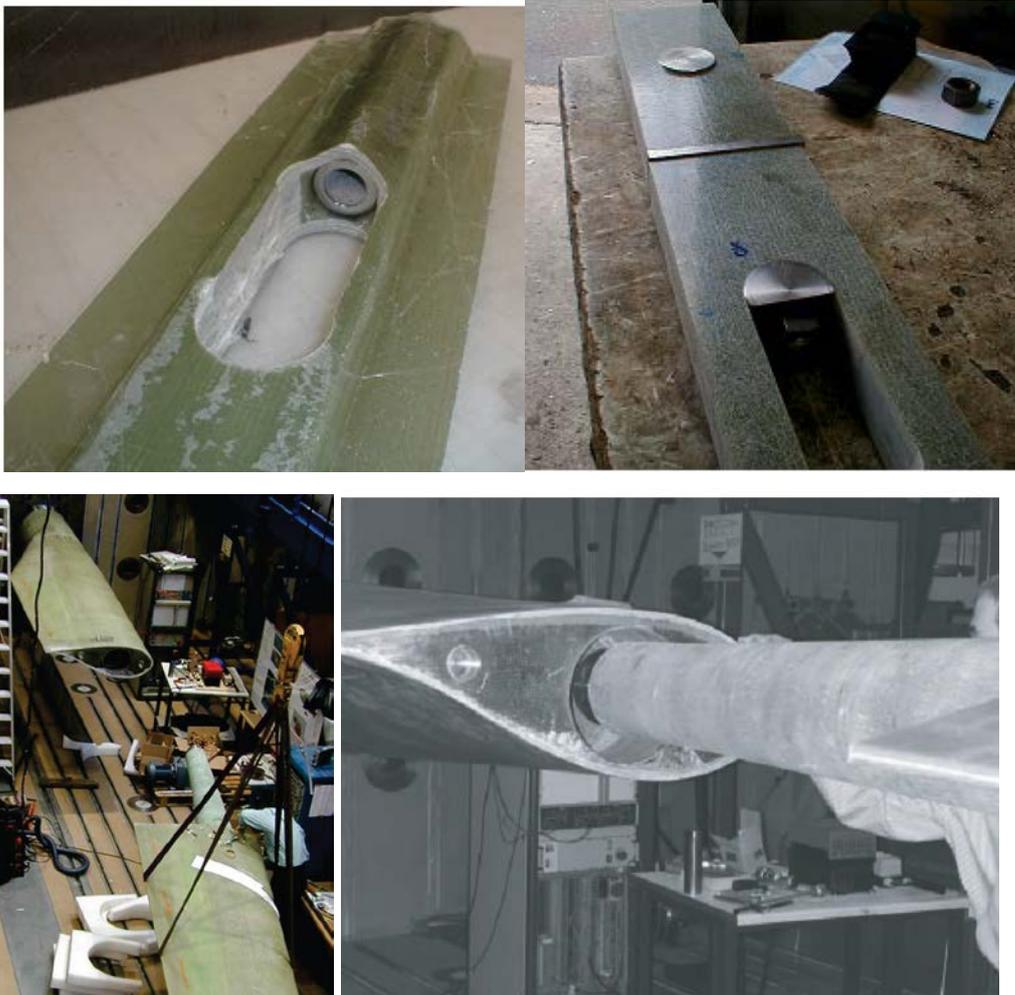
#### 4.1.1 Sectional blades

In the late nineties, a European project 'Sectional blades' focussed on the development of blade connections outside the root. The background was the rapid growth of blade length and the resulting perceived need for building blades in a modular fashion to promote transportability.



**Figure 8: preparation of a full-scale 23.3m blade test**

Within the project, three blade connection concepts were tested as subcomponents, and a scaled blade test and full-scale blade test was performed. In several publications, the results and implications are described, including strain- and damage evaluations using thermo-elastic stress evaluation (TSE) with a SPATE-device, see e.g. [10] - [13].



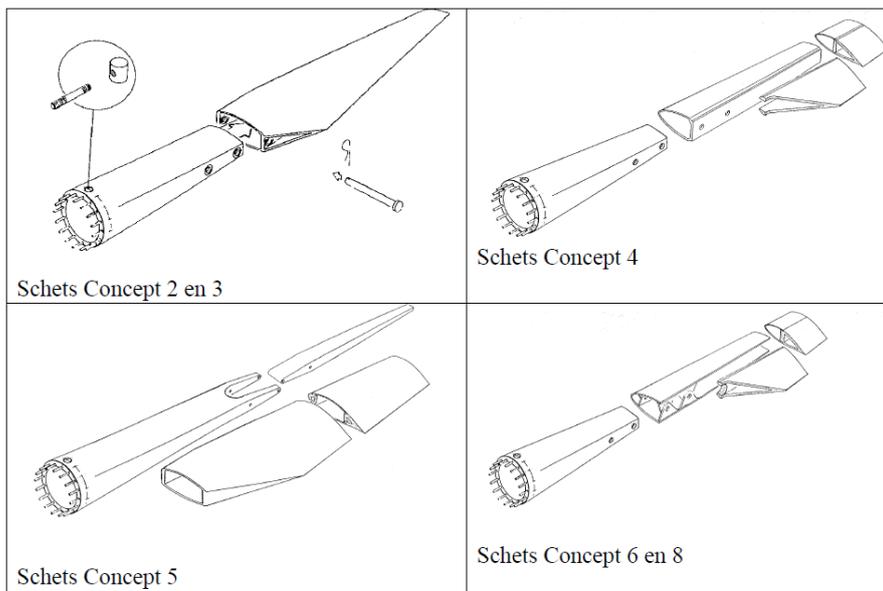
**Figure 9: Bushing, and T-bolt subcomponents, and connecting tube scaled blade specimen (latter tested at DLR) [12]**

Limited static and fatigue testing showed that the T-bolt connection was similar in strength and fatigue life as the embedded stud. The embedded stud is harder to manufacture to narrow tolerances.

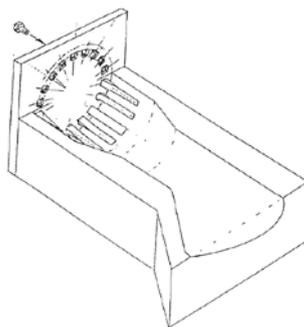
The project reported an increase of blade costs for a 23.3m blade of 68%, and 19% cost increase for a projected 60m blade. Transport costs were estimated to increase by 5% for an unsplit blade; thus the additional material and production cost with a mid-span T-bolt connection was not estimated to be compensated fully by a reduction in transport cost. On the other hand, more sites will become accessible for a split blade. The financial benefit of this increased site accessibility was not investigated.

#### **4.1.2 Bladeco**

The Bladeco project, where the main industrial partner was Aerpac (blade manufacturer until 2003) aimed at lowering cost of rotor blades and environmental impact through application of natural materials, modular design (easier to recycle), and automated manufacturing ([9]). Several brainstorm sessions on modular design were held, resulting in a multitude of modular blade concepts (Figure 10), but no detailed analysis of performance criteria was made due to lack of time. Two concepts (bolted and bonded joints) were tested in the framework of the project.



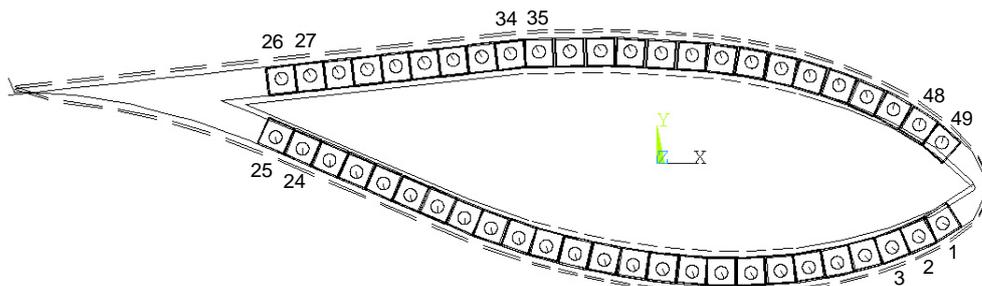
**Figure 10: Results of brainstorm for modular blade design with innovative connections [9]**

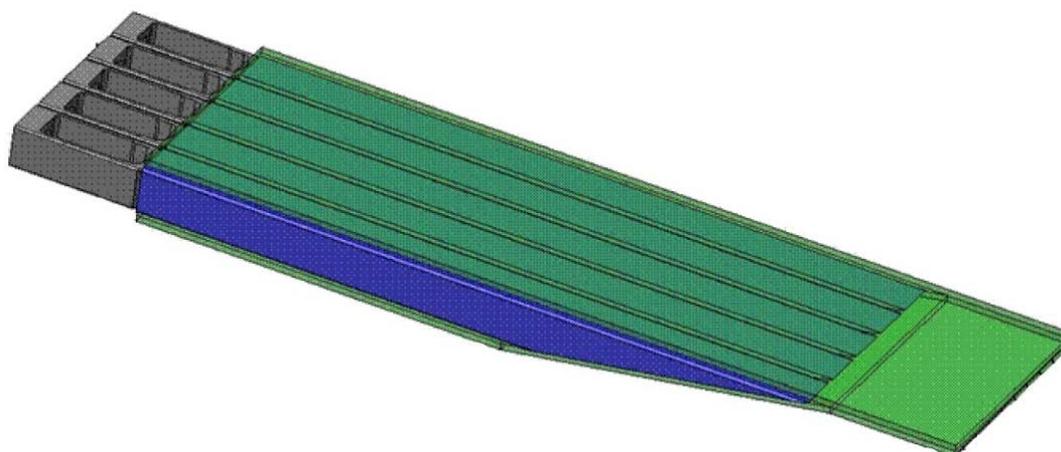


**Figure 11: Embedded stud connection concept from Bladeco project [9]**

### 4.1.3 UPWIND

In the UPWIND project (2004-2011, [14]), a bolted connection was investigated in detail. As can be seen in Figure 12, the concept consists of metal fittings which form the interface between blade parts; the fittings are embedded in a pultruded carbon profile (blue part in Figure 12), which is laminated into the blade (tapering the thickness to accommodate the fitting elements). The validation of the joint's final configuration has been established through detailed 3D FEM simulations and a series of tests. These tests were specifically designed to test the strength and fatigue resistance of the bolted and bonded joints.

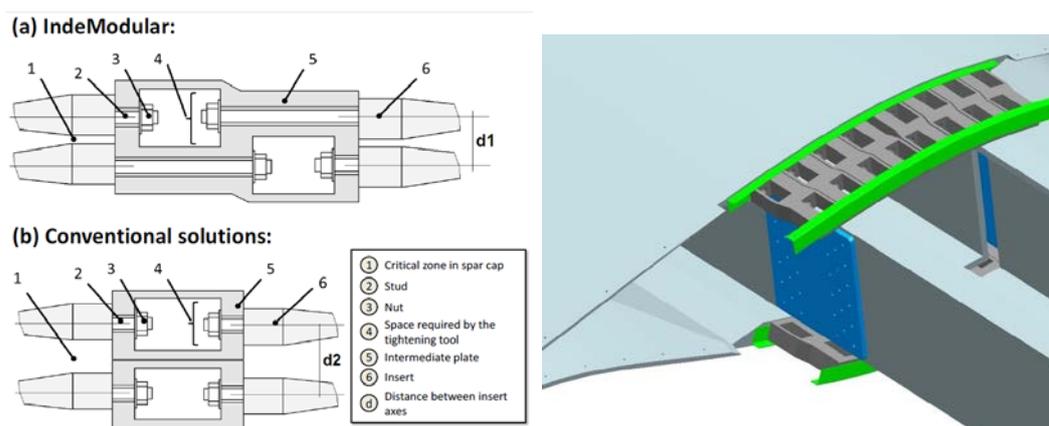




**Figure 12: UPWIND bolted fitting concept**

#### 4.1.4 INDEOL CENER modular joint

A method to bolt together the sections of a wind turbine blade, which is similar to the method described in the UPWIND report, but where minimisation of the bolt pitch is achieved, is described in [15][1], see also Figure 13. Smaller bolt pitch is achieved as the access openings (required for bolt tightening and pre-stressing) are staggered.

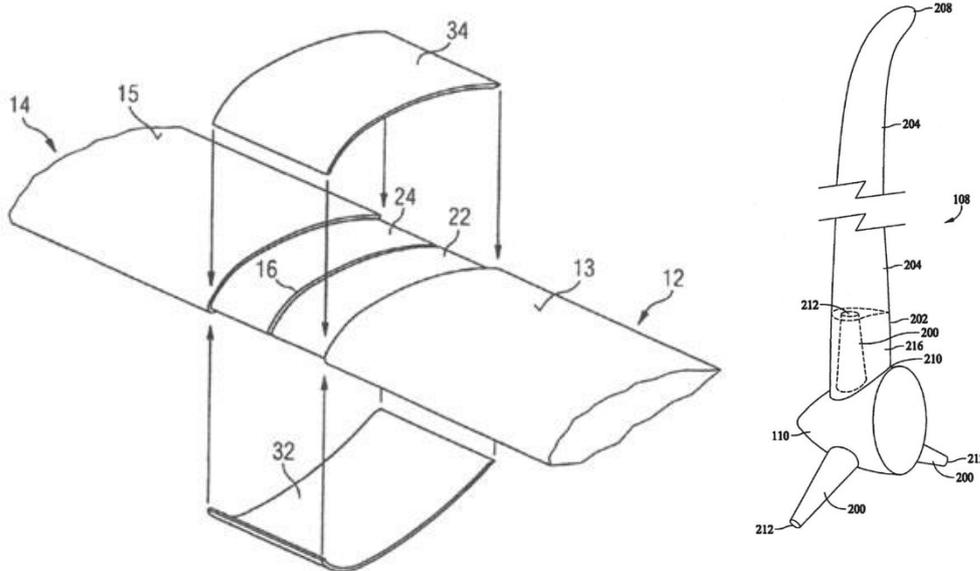


**Figure 13: Overview of Indeol/CENER Indemodular concept ([15])**

#### 4.1.5 Various patents

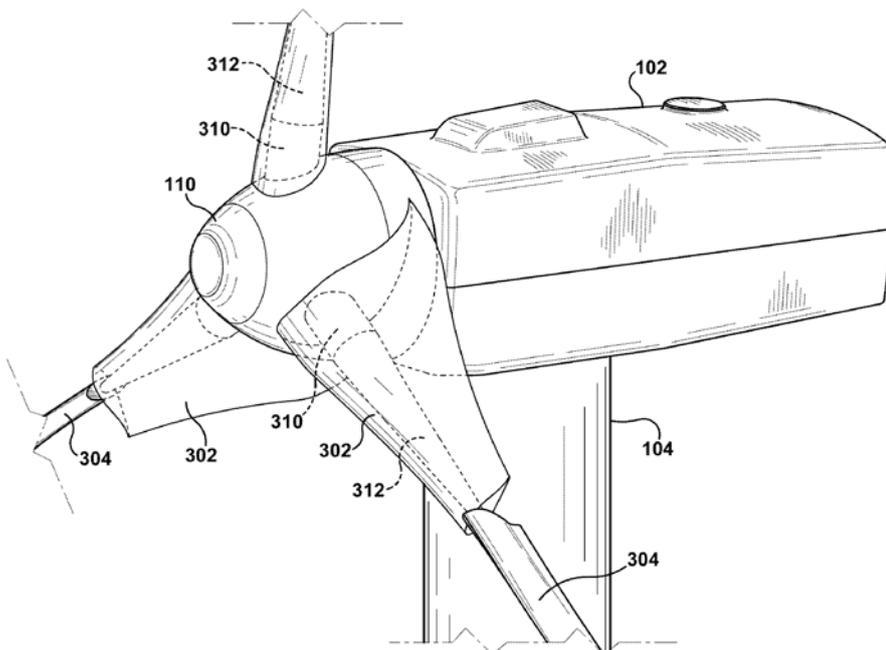
In [16], it is noted that in the period 2003-2005 several patents were filed that seemed to emerge from Vestas, GE, and Gamesa. This could be considered an indication at the time that industrial R&D into multi-piece blades had the interest of several manufacturers.

This included a GE-patent on bonded multi-piece blades, where the gap between connection panels on the outside and the blade structure on the inside would be kept open and flooded with adhesive, to ensure consistent bondline thickness with minimal void inclusions, see [17].



**Figure 14: Bonded multi-piece blade and multi-piece blade design with hub extender (from patents [17], [18][19], respectively)**

GE also filed a patent on a design including a hub-extender, which put the pitch bearing at ca. 30% of blade length, and allowed for easier transport as well as replacement of outboard section to change blade design during turbine operation (right side of Figure 14). A very similar patent was filed in 2007, see Figure 15 ([19]).



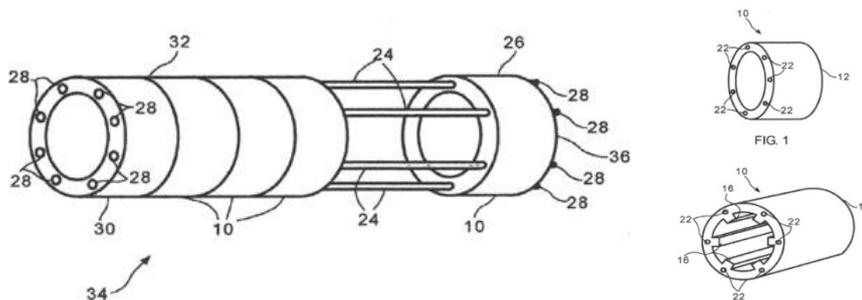
**Figure 15: multi-section wind turbine blades [19]**

Later, the Envision company actually built a two-bladed rotor with the pitch bearing at 35% of the blade length, see Figure 16.



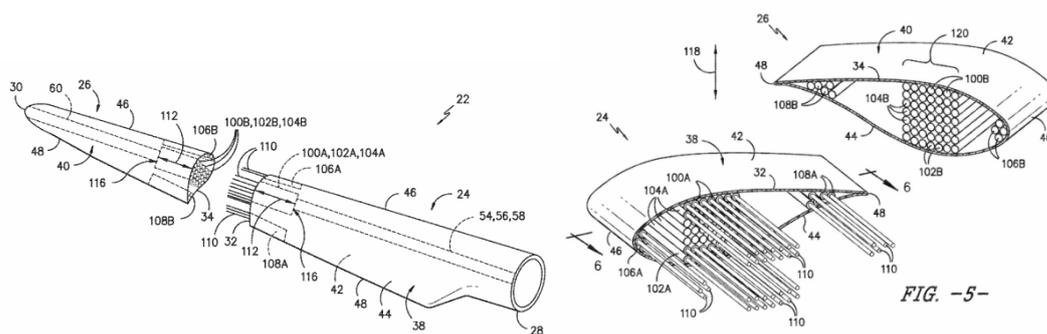
**Figure 16: rotor blade with pitch bearing at ca. 23m rotor radius (blade length 63m) [20]**

Another patent involved connecting multiple blade parts with tensioned cables, see Figure 17.



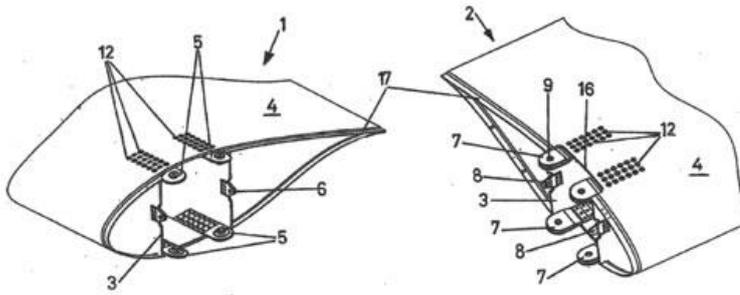
**Figure 17: multi-part blade connection using tensioned cables ([21])**

A more recent patent by GE features rods and tubes that are placed inside the aerodynamic shell and fit into each other and are fixed by e.g. adhesive or resin infusion, see Figure 18 .



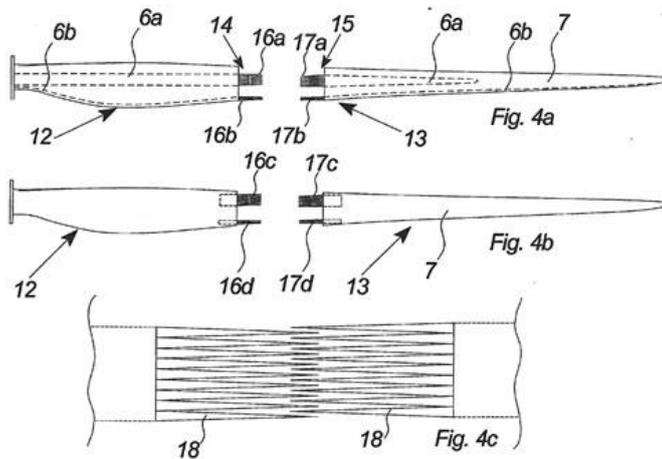
**Figure 18: rod and tube connection patent ([22])**

A patent, supposedly originating from Gamesa, proposed blade part connections with lugs. Within the UPWIND project (see 4.1.3), Gamesa and various R&D partners also pursued split blade connection methods, but then concluded that embedded channel fittings were a better option.



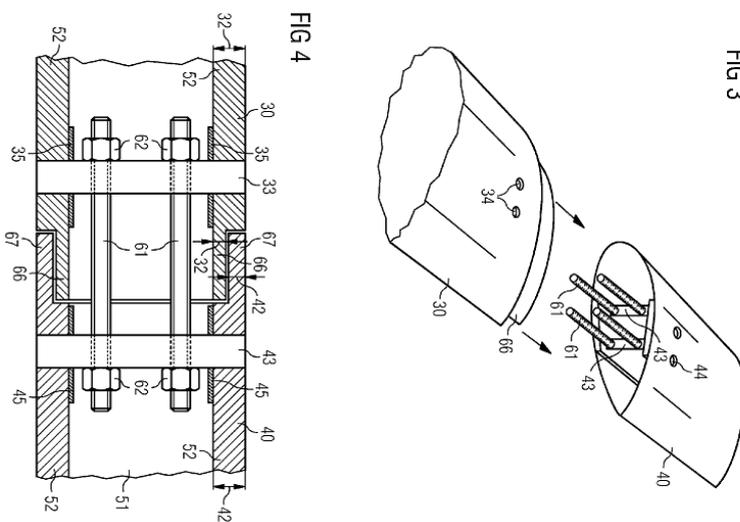
**Figure 19: Blade part connection with lugs [23]**

An adhesively bonded solution was also proposed in [24][1], where both blade parts have triangular extensions that fit into each other and can be bonded together over a significant length to transfer blade loads, see Figure 20.



**Figure 20: bonded connection with interlocking triangular blade part extensions [24]**

A recent patent application for a bolted connection, where the laminate does not locally need to be made thicker to accommodate the bolts is described in [25], and illustrated in Figure 21.



**Figure 21: Bolted connection with no shell thickness modification [25]**

Also of interest are the patents launched by Vestas and Astrium (Figure 22 and Figure 23):

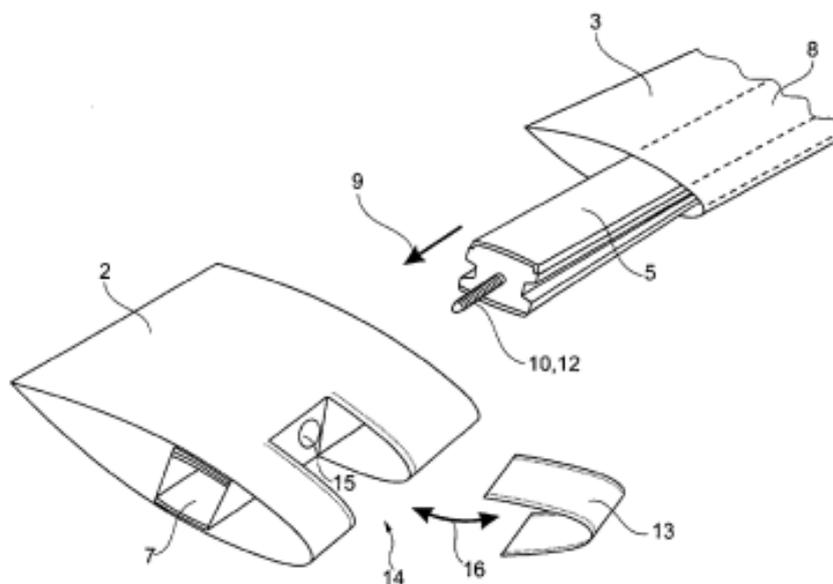


Figure 22: Vestas patent [26]

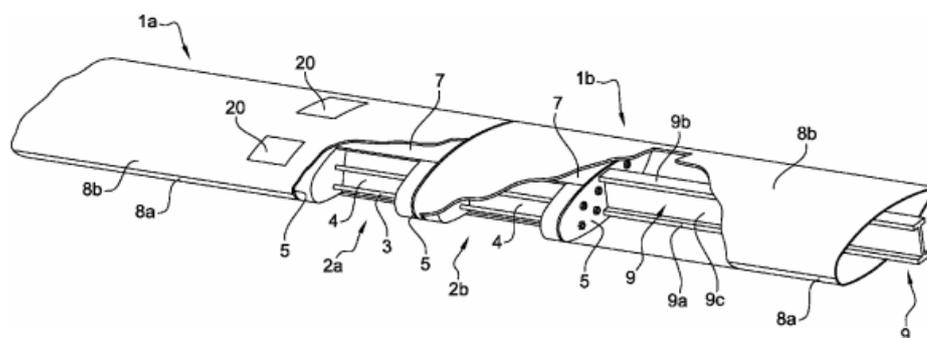


Figure 23: Astrium patent [27]

An overview of relevant patent applications is shown in Table 1.

Table 1: Modular blades patent applications summary

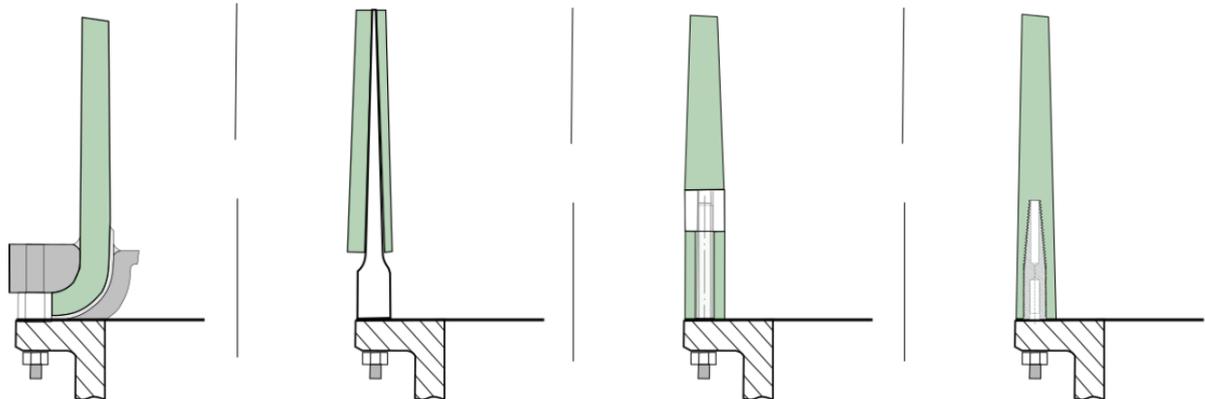
Applicant	Patent number	Subject	Date
<b>ENERCON (A. Wobben)</b>	WO2001 48378-A;	Joint for rotor blades of wind turbine consists of series of connecting plates which are fastened to two sections of blade by bolts at their ends	22/12/2000
<b>ENERCON (A. Wobben)</b>	WO2007 131937A1	Rotorblatt für eine windenergieanlage	11/05/2006
<b>GAMESA EÓLICA, S.A.</b>	WO2005 100781, EP1584817 (A1)	Wind turbine blade for use in manufacturing plant has connectable ends consisting of lugs respectively affixed to independent modules and arranged in coinciding positions, with hole that receives joint e.g. bolt between facing lugs	31/03/2005

Applicant	Patent number	Subject	Date
<b>GAMESA CORPORACIÓN TECNOLÓGICA, S.A.</b>	WO2006 103307-A2	Blade for wind powered generator, is divided transversely into blade segments which are equipped with aerodynamic wall and inner longitudinal reinforcing structure	20/03/2006
<b>GAMESA CORPORACIÓN TECNOLÓGICA, S.A.</b>	EP21387 16	Blade insert	
<b>SIEMENS AKTIENGESELLSCHAFT</b>	WO2006 056584-A1	Method and connecting piece for assembling windmill blade sections	11/24/2004
<b>SIEMENS</b>	US 201502924 77 A1	Segmented rotor blade with a bolt connection	18/08/2015
<b>BOREAS NT</b>	WO2008 084126A1	Modular joint based on inserts.	08/01/2007
<b>MESSERSCHMITT-BOLKOW-BLOHM</b>	US43891 62; DE292115 2-A1;	Wind generator rotor blade - consists of sections fitted together and adjustably tensioned longitudinally between anchor plates	13/05/1980
<b>VESTAS</b>	WO2006 002621	Wind turbine blades made of two separate sections, and method of assembly	
<b>GENERAL ELECTRIC CO</b>	US20071 05431-A1	Modular joint based bonded parts.	10/11/2005
<b>M TORRES MARTINEZ</b>	WO2000 73651-A;	The invention relates to a blade for an aerogenerator, which is formed by assembling one, two or more longitudinal sections, each of which comprises a core formed by a longitudinal carbon-fiber tube (2) on which a series of carbon fiber or fiberglass cross	31/05/1999
<b>SHIN MEIWA IND. CO. LTD.</b>	JP20040 11616		6/11/2002
<b>MITSUBISHI JUKOGYO KK</b>	JP20061 23277	The fiber reinforced plastic structure (5A) is formed by stitching and integrally bonding junction portion (53) of the fiber reinforced plastic materials (51,52) by tension material (20), and arranging reinforcement material (10) over junction portion of	10/27/2004
<b>MAKKU KK</b>	JP20032 14322-A	Assembling method of blade of windmill, involves joining several blade segments, at windmill installation site, to form blade, and reinforcing blade surface with carbon fiber sheet	1/24/2002
<b>GENERAL ELECTRIC</b>	US20060 67827-A1	Assembly method for rotor of wind turbine, involves shipping unassembled parts of multisection rotor blade to wind turbine site, and assembling multisection rotor blade at site	30/09/2004
<b>GENERAL ELECTRIC</b>	US 201700893 23 A1	Segmented wind turbine rotor blade with rod and tube joint connection	30/09/2015
<b>Anton Bech</b>	US 200800696 99 A1	Wind Turbine Blades Made of Two Separate Sections, and Method of Assembly	30/06/2004

Applicant	Patent number	Subject	Date
<b>Baker, Myles; Arendt, Cory</b>	WO2008 115265	Lightweight composite truss wind turbine blade	13/07/2007
<b>GOUGEON BROTHER, INC.</b>	US44745 36-A	Wind turbine blade of wood resin composite - has hollow sections joined by inserts adhered flush in mating slots	09/05/1980
<b>MESSERSCHMI TT-BOLKOW- BLO</b>	DE31095 66-C2; DE310956 6-A; DE310956 6-C	Wind turbine rotor blade - formed in separate segments for ease of handling held together by expansion screw	13/03/1981
<b>FUJI JUKOGYO KK (FUJH-C); FUJI HEAVY IND LTD (FUJH-C)</b>	EP15619 47-A2; JP2005220 805-A	Separable blade for wind turbine, has metal plate electrically connected to joints of inner and outer blades, in-blade electrical conduction wire arranged to extend from metal plate through blade root of inner blade to outer side of blade	05/02/2004
<b>GAMESA INNOVATION &amp; TECHNOLOGY, S.L.</b>	WO2007 051879 A1	Split-blade for wind generators	28/10/2005
<b>Nabrawind</b>	WO2017 174828 (A1)	Device for joining a modular blade	12/10/2017

## 4.2 Blade root connection

Peeters et al. distinguish 4 types of blade root connections, see Figure 24:



**Figure 24: flange root, hub type, T-bolt and stud [8]**

These are all for cylindrical blade roots. Apart from these, also the clamped friction joint of Lagerwey or WES can be considered. These deal with a “squared shaped” rather than “cylindrical” root.

The flange root was used e.g. in the Nedwind 40 blades (with additional shear pins connecting the inner and outer metal parts). A variation where fibres loop around a blade hub (see Figure 26), thus enabling a connection with continuous fibres, may result in a fatigue resistant and lightweight connection – albeit with manufacturing challenges that have not been overcome to date.



Figure 25: clamped root

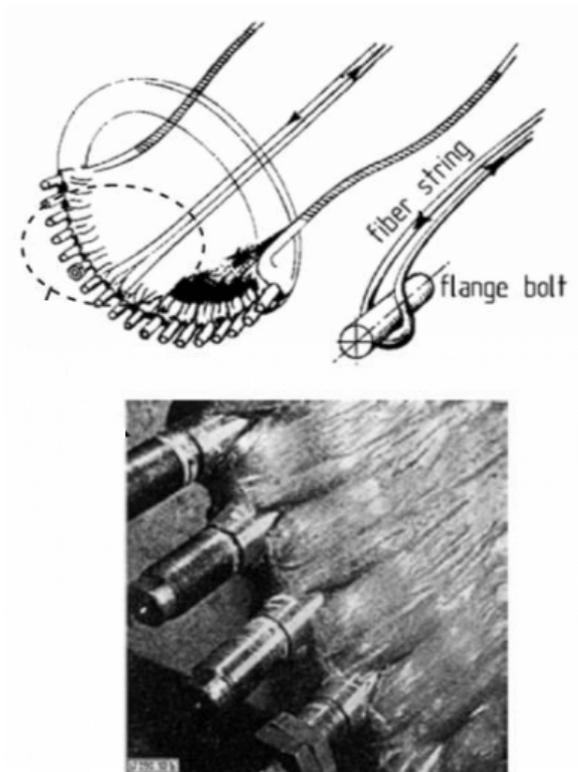
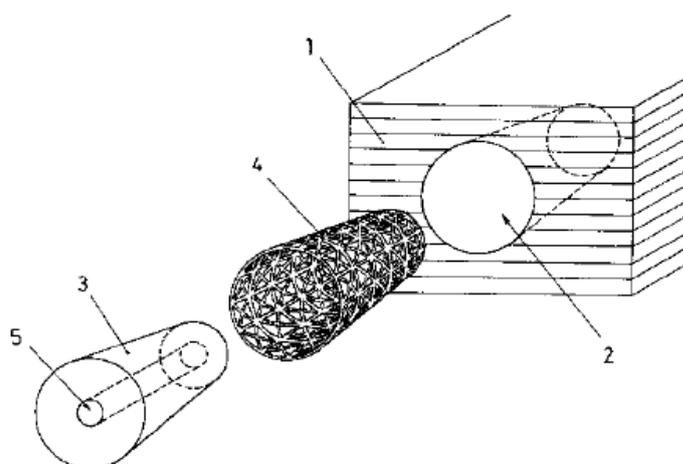


Figure 26: Hütter looped fibre blade root connection concept

The hub type is similar to the stud bolt, in the sense that a metal part is bonded to or inside the blade root.

The T-bolt is a well known and commonly used type also referred to as “IKEA” connection. Blade manufacturers like Aerpac, NOI (SINOI), Suzlon use this connection type.

In the case of connections based on inserts, classically two types of manufacturing systems are available: bonded inserts or embedded inserts. As an alternative to bonded inserts, resin infused inserts [28] with a 3D biax fabric as interface between the insert and the laminate cavity were proposed and successfully tested. The advantages were related in terms manufacturability, reduction of the bonding thickness and elimination of voids in the adhesive.



**Fig.1**

**Figure 27: Infused insert in a 3D biax fabric. 1: laminate, 2: cavity, 3: metallic insert, 4: 3D fabric 5: internal orifice to infuse the resin [28]**

#### 4.2.1 T-bolt connections



**Figure 28: T-bolt blade root connection (TRES4) [29]**

A T-bolt connection is used to bolt thick laminates to other structures, such as the blade hub. It is a widely applied connection method. The connection consists of an axial bolt and a cylindrical or barrel nut mounted perpendicular to the laminate. The

advantage is that installation is relatively simple (automated solutions exist for bolt and nut hole drilling in blade roots); a main disadvantage is that the laminate is locally damaged, thus extra material needs to be added in the laminate. Therefore this is not the most lightweight solution. Various experimental and numerical studies have been done into the behaviour of this connection method. A typical test specimen is shown in Figure 29. Some motivation for this test specimen shape:

- The specimen is symmetric, giving the opportunity to test two sides simultaneously and avoiding clamping issues on the unbolted side;
- Having three bolts in a row allows for testing the center bolt while applying pre-stress on the outer bolts, giving realistic boundary conditions for the center bolt.



Figure 29: Typical T-bolt test specimen (WMC)

Ideas for variations on the T-bolt connection are shown in Figure 31 and Figure 31.

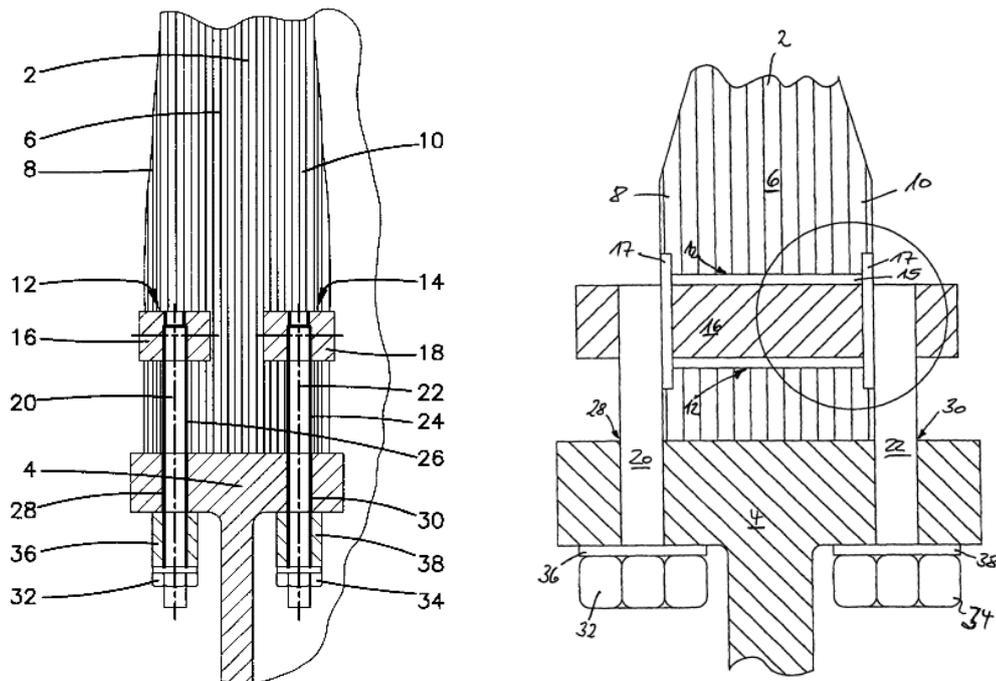


Figure 30: Variations on the T-bolt connection, from [30][31]

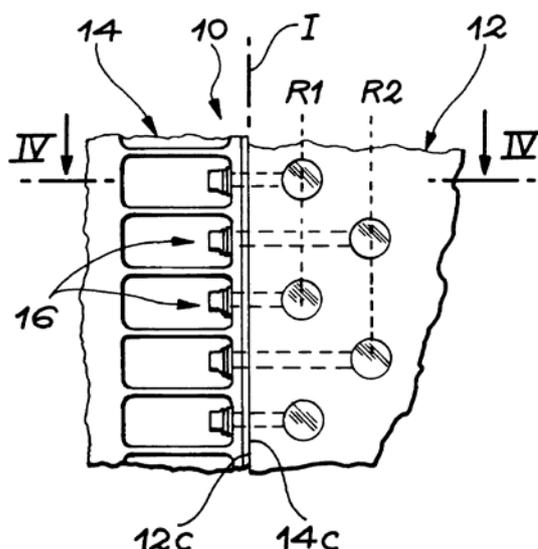


Figure 31: Variations on the T-bolt connection, from [32]

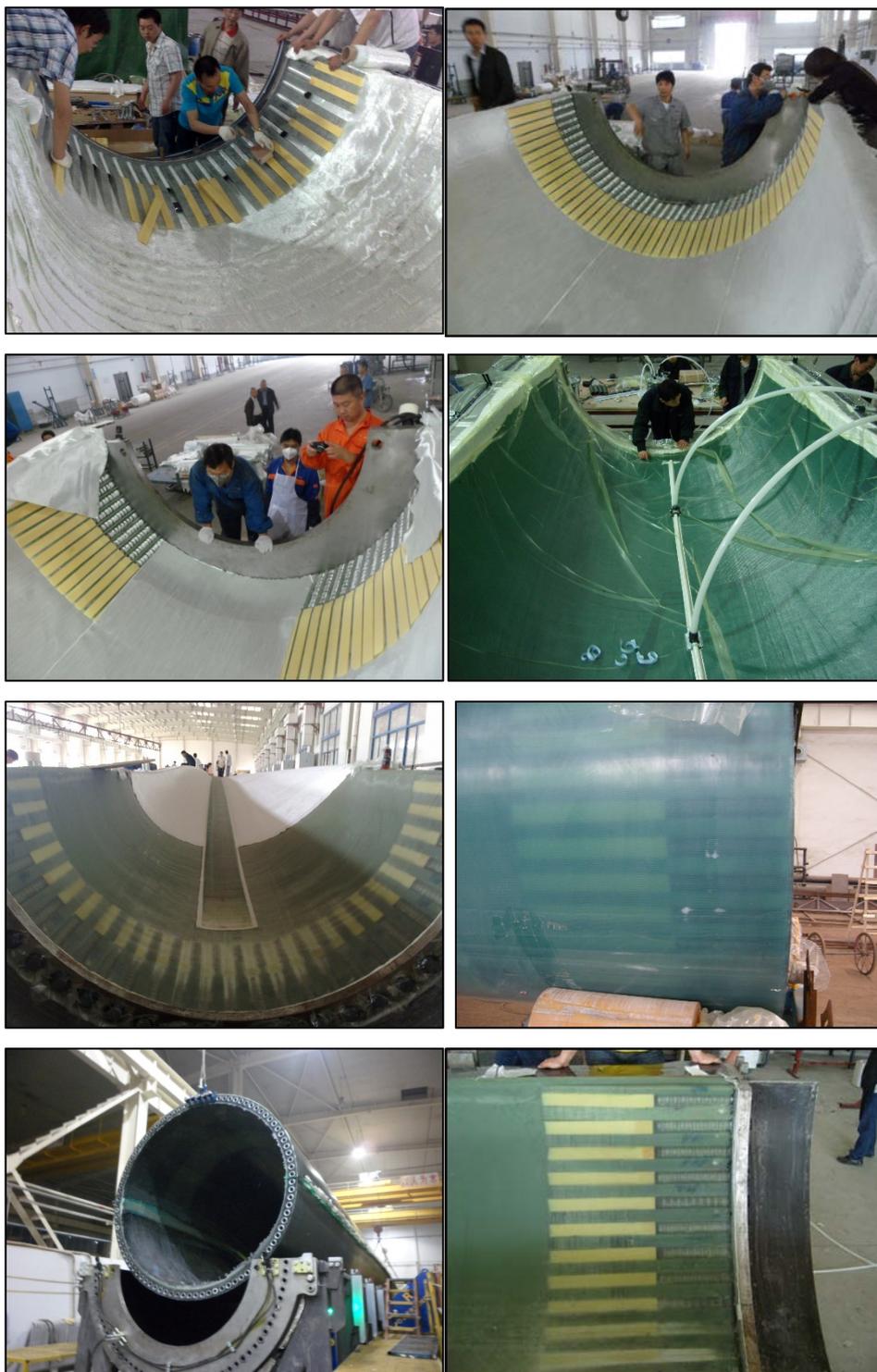
#### 4.2.2 Insert connections

Within wind industry blade design, root inserts (a.k.a. stud connections, bushing connections) are an often used alternative to T-bolted connections. The advantage is that compared to the conventional T-bolt connection about 35% more bolts (strength) can be implemented. Further no damage by drilling is required, and another potential advantage is that inserts can be included as prefabricated parts in a remaining root infusion. Root inserts by TRES4/We4Ce were certified with pull-out and fatigue tests, see Figure 32. The bushing designs features a 'ribbed' outside of the insert being filled with UD-roving, such that both adhesive and mechanical joining of the insert in the root laminate can be achieved.



Figure 32: Test on rotor blade insert (left) and insert details (right)

The TRES4/We4Ce bushing process is shown below.



**Figure 33: Blade root with embedded inserts (TRES4/We4Ce)**

For this system, TRES4/We4Ce filed patent NL2012326.

A patent from Blade Dynamics ([33]) includes a novel, 'high-performance' insert ([34]) that employs a helical threaded outside to improve fixation to the root laminate, requiring shorter inserts and thinner root laminates, resulting in a lighter blade root.

### 4.2.3 Fibre-metal laminates in bolted connections

The blade root connection using T-bolts potentially suffers from stress concentrations around the cylindrical nut, leading to damage in the brittle GFRP. A method to avoid this is to intersperse the composite layers with much stiffer metal layers. Thus, the metal layers will transfer the bearing stress to the composite layers via shear. The principle is shown in Figure 34 [35], and was investigated recently for the root region of a wind turbine blade in the Lenah project for glass-fibre composite with steel foils ('Lifespan extension and lightweight construction optimisation thanks to nanomodified and hybrid material systems in rotor blades', 2015-2018). Comparable work in titanium-CFRP hybrid laminates is found in [36].

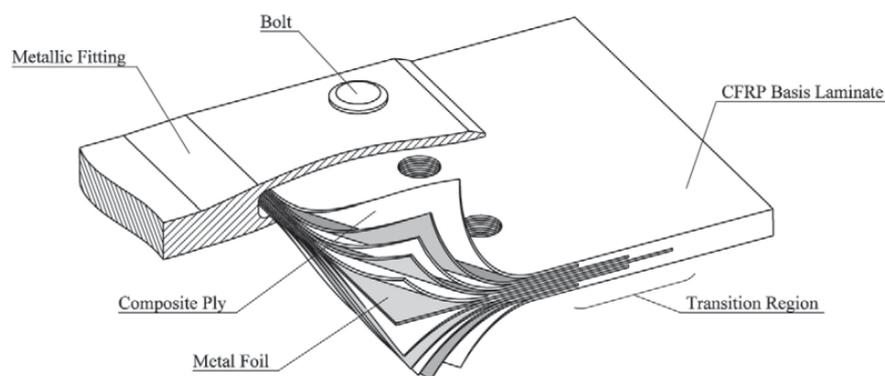


Figure 34: Composite metal laminate with bolted connection

## 4.3 Other connections

### 4.3.1 Innotip

In the recent Innotip project [37] investigations into blade (tip) add-ons were done: can existing blades be equipped with power-improving or noise-reducing tips. Basic quasi-static tests were performed, but detailed investigation into the structural performance of the add-ons was outside the scope of this predominantly aerodynamic study. A back-of-the-envelope calculation estimates that shear stresses in an adhesive used to fix the add-ons to the blades can be designed to be below 1 MPa (not taking into account any peel stresses or stress concentrations). On the other hand, consequence of failure can be high, so follow-up research may be required.

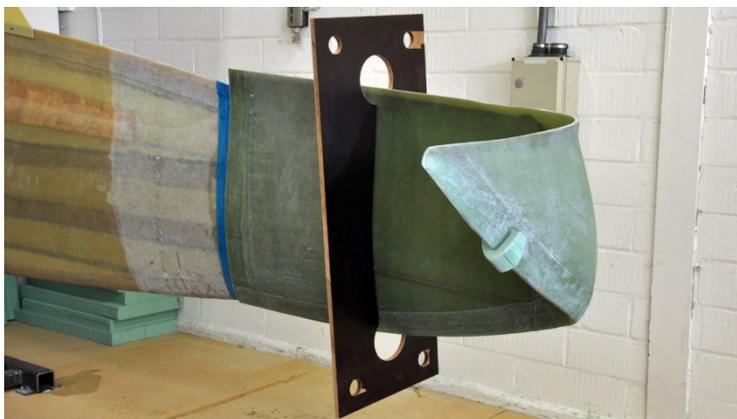


Figure 35: Add-on winglet from TKI-Innotip project

### 4.3.2 Shear studs

Using embedded shear studs, as e.g. described in [1] and schematically shown in Figure 36], might give an improvement for steel-to-composite connections, in the sense that:

- they are not solely reliant on the shear properties of the adhesive;
- no cutting of fibres is involved;
- the loads in the shear studs are converted into tensile and shear stresses in the reinforcement fibres, which is more benign than shear only or compression;
- this concept seems to be especially useful for thin laminates.

The concept was later elaborated by the institute for welding and joining in Aachen, [39], Figure 37.

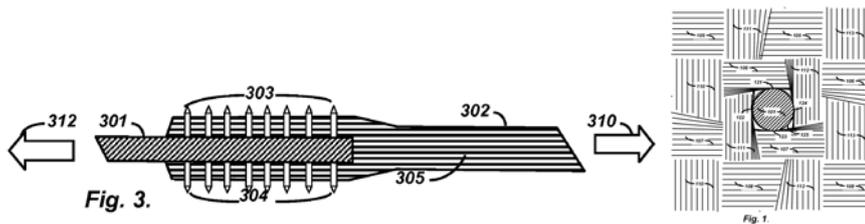


Figure 36: shear stud concept [1]

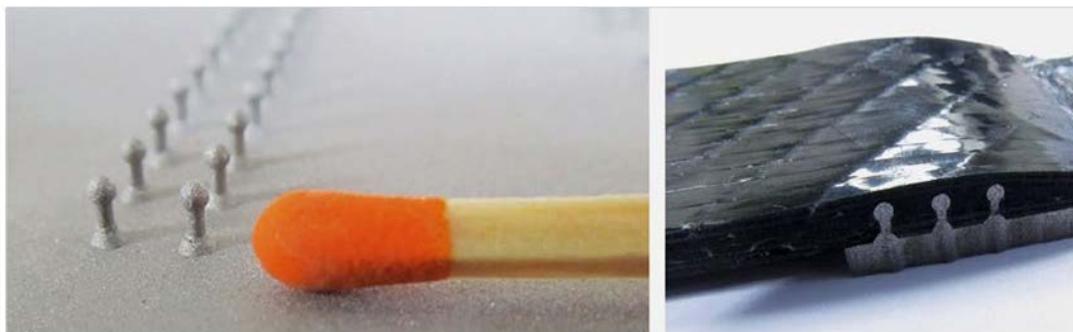


Figure 37: metal shear pins [39]

### 4.3.3 Loop connections

Research at Fraunhofer IFAM investigated using metal parts with loops, which allow carbonfibres to be looped through to connect the metal part to the composite.



Figure 38: Hybrid connection between Aluminium part and carbon fibres using titanium loops [40]

#### 4.3.4 Injection bolts

Tests on performance of injection bolts in pultruded profiles was reported in [41]. The injection bolt concept consists of an ordinary bolted connection, with oversized bolt holes which are injected after bolt installation with e.g. an epoxy resin. This limits the play between bolt and was shown to lead to stiffer connections with improved reversed loading fatigue behaviour. It can be argued that injection bolts at least partly mitigate the need for bolt pre-stressing.

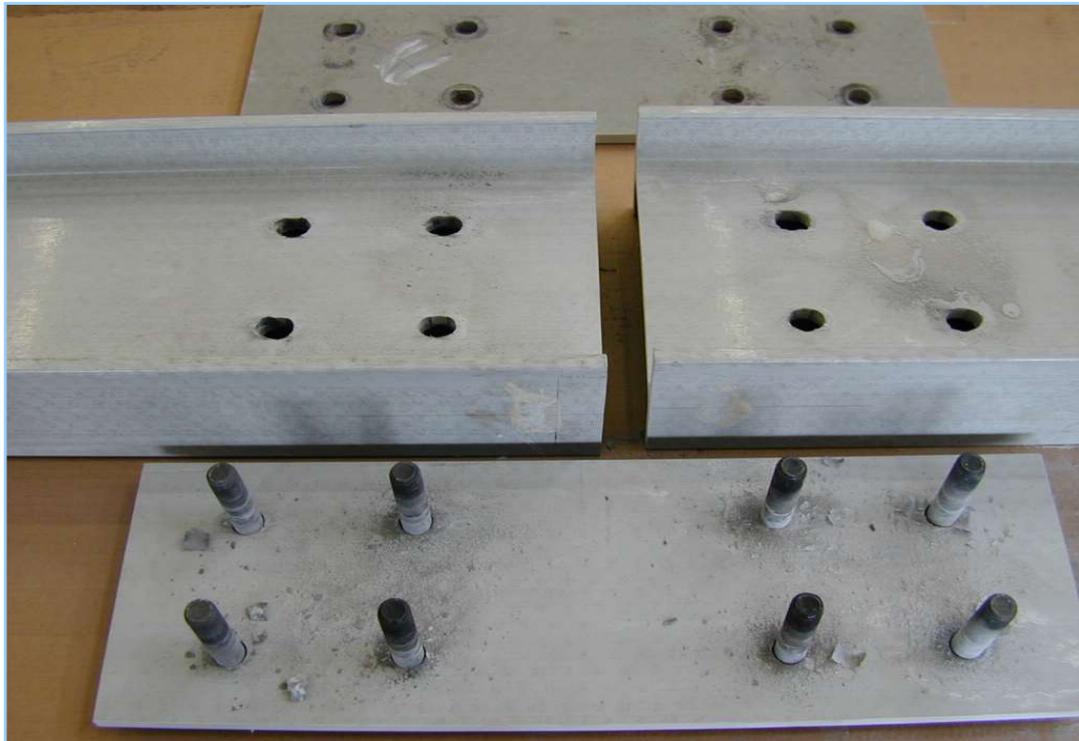


Figure 39: Pultruded profile with connector plates and injection bolts after test [41]

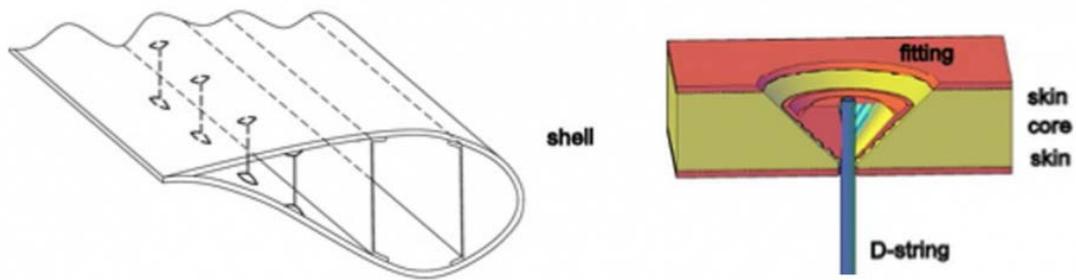
#### 4.3.5 Blade structural add-ons

The Bladerna company of Copenhagen, Denmark, has developed various innovations in collaboration with RISØE-DTU, to augment rotor blade structures and counteract non-linear effects such as blade 'breathing' a.k.a. the Brazier effect (where the shape of the blade cross section expands and contracts due to blade loading), and shear distortion (where the cross-section deforms in shear due to e.g. blade torsion). Some of their add-ons and function are shown in Figure 40 - Figure 43. Essentially, the add-ons provide additional connection of structural elements, to partly relieve the stresses on e.g. the trailing edge bondline in the case of the D-string. The add-ons themselves employ mostly adhesive bonding for installation, and can be installed also after blade manufacture, albeit with the requirement of e.g. drilling holes in the trailing edge sandwich panels.



**Figure 40: D-stiffener, to counteract buckling failure [42]**

A similar solution to the D-stiffener is the D-string, which Bladerna claims is running in 8 different blade types [43].



**Figure 41: Bladerna D-string, to counteract trailing edge splitting [43], [44]**

Damage due to cross-sectional shear distortion is claimed to be counteracted by the X-stiffener configuration, where the top and bottom of both spar caps (in a two-webbed spar beam configuration) are connected with pretensioned wires, see Figure 42.



**Figure 42: X-stiffener, to avoid longitudinal bondline cracks due to cross-sectional shear distortion [45]**

Other add-ons by Bladena include the caps stiffener (Figure 43), and a shear web that is to be installed in the root area and is positioned perpendicularly to the traditional shear web .



**Figure 43: Bladena cap stiffener, to facilitate spar cap reduction**

#### **4.3.6 Rivets, roller bearings and bushings**

Rivets, roller bearings and bushings are a type of connection not generally use in wind energy. These types of connection are common in aerospace and automotive industry.



**Figure 44: Rivet connections for composites [<http://www.gesipa.com>]**

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## 5 CONCLUSIONS AND RECOMMENDATIONS

- Adhesive bonding and bolting are the most commonly applied connection methods;
- Scaling of connections may be an issue in some cases;
  - Most available literature is available for bondlines incorporating very thin adhesive layers, often non-paste types, whereas rotor blades show ample use of glass-filled adhesives (bonding pastes), applied in layers several mm thick with limited fillet control;
- T-bolt connection testing and insert testing are becoming common practice in industry, whereas first efforts in trailing edge bondline testing have been seen only in the last couple of years;

Based on these conclusions, several recommendations may be made. These are categorised below.

### 5.1 Monitoring

Virtually no information was found on the monitoring of e.g. pre-stress in a bolted connection or damage growth in an adhesive connection. Structural health monitoring techniques specific for blade joints should be further investigated to improve operational robustness.

### 5.2 Testing

Scaling effects inserts/bushings needs to be investigated. The market shows trends towards bigger inserts like M42, but also smaller for southern Europe like M20.

Hence recommendation is given to investigate M20-M30-M36-M42 and show scaling trends or relations in strength.

Testing of connections is recommended to be done on simplified connection subcomponents, taking into account the appropriate structural and loading boundary conditions. Standard test methods are not available, but aligning some test methods based on connection type will enable the design community to build a database/expertise on connection testing and certification.

### 5.3 Manufacturing defects

It is recommended to improve testing of manufacturing effects in inserts. Especially looking into the DNVGL-ST-0376 edition 2015 standard there is a market need for including manufacturing defects in the test coupons insert/bushing tests.

It is recommended (market need) to particularly target manufacturing defects in the testing and modelling of connection methods. Thus, designers can improve robust bondline design as well as better funded assessment of manufacturing defects involving e.g. bondlines, and including alternative adhesives such as MethylMethacrylates (MMA).

### 5.4 Novel connections

A couple of conceptual studies have referred to the possibility of connections involving continuous fibres, such as loop connections. Manufacturing automation could facilitate cost-effective implementation of such connections. More research is required to develop the connections themselves as well as the manufacturing,

testing and (numerical) modelling, also taking into account alternative design concepts including e.g. pultruded prefabs.

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