Review

The concept of segmented wind turbine blades: a review

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Abstract: There is a trend to increase the length of wind turbine blades in an effort to reduce the cost of energy (COE). This causes manufacturing and transportation issues which have given rise to the concept of segmented wind turbine blades. In this concept multiple segments can be transported separately. While this idea is not new, it has recently gained renewed interest. In this review paper the concept of wind turbine blade segmentation and related literature is discussed. The motivation for dividing blades into segments is explained and the cost of energy is considered to obtain requirements for such blades. An overview of possible implementations is provided, considering the split location and orientation as well as the type of joint to be used. Many implementations draw from experience with similar joints such as the joint at the blade root, hub and root extenders and joints used in rotor tips and glider wings. Adhesive bonds are expected to provide structural and economic efficiency, but in-field assembly poses a big issue. Prototype segmented blades using T-bolt joints, studs and spar bridge concepts have proven successful, as well as aerodynamically shaped root and hub extenders.

Keywords: wind turbine blades; segmented/split blades; modular design; blade joints;

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1. Introduction

Over the past decades wind turbines have been developing rapidly. Most notably, the size of the rotor diameter and the corresponding power output has been increasing steadily to rotor diameters of up to 180 m, with rated powers as high as 9.5 MW [1–3]. This up-scaling trend is still ongoing, especially offshore and is motivated by an expected reduced cost of energy (COE) for larger rotors as a result of increased economies of scale [4–7]. However, this up-scaling leads to issues which can cause a steep increase in costs related to the production and handling of blades, to the extent that further up-scaling may no longer be beneficial. As a consequence, optimal rotor sizes exist for on- and offshore turbines which can increase as a result of technical improvements [2]. Furthermore, methods to reduce the loads on the rotor have proven successful for reducing the COE. The increase in size of the blades has led to interest in the concept of so-called "segmented" blades. Instead of the conventional single piece blades, these are manufactured as a number of segments, which can be transported individually and assembled at the site of the turbine. While the "segmented", "split" or "modular" blade concept is not new, it has recently gained increased interest. This paper intends to provide the reader with an overview of the concept. Design options include span-wise or chord-wise segmentation, the purpose and location of the division as well as the use of a static joint or a variable mechanism. The available options are discussed along with their advantages and limitations. Furthermore, the feasibility of different methods is discussed.

2. Wind turbine blade manufacturing

While initially, aerospace methodologies were used, most modern wind turbine blades are manufactured from composite materials using methods derived from ship building [8,9]. Large clamshell moulds are used to manufacture separate pressure sides (PS) and suction sides (SS) and a number of shear webs. This is done using processes such as the lamination of pre-impregnated material, bladder moulding, wet-layup or vacuum assisted resin transfer moulding (VARTM) [10–12]. The material is currently placed manually but can be automated [13,14]. Most frequently the separate components are joined together using thick adhesive bonds [15]. As the blade size increases this leads to issues. Firstly, tolerances increase resulting in thickness variations of the adhesive bonds which add weight and cause stress concentrations [16]. Secondly, heating and temperature control become more difficult while very thick laminates give exothermic reactions which can damage the blade [17]. Thirdly, defects become more severe and prevalent in larger volumes resulting in a lower strength than assumed from coupon data [18]. These defects lower the load-carrying capacity of the blade and may require scrapping the part, which is more expensive for a larger blade [19,20]. Lastly, modern blades are often designed with a pre-curved shape, to ensure sufficient tower clearance under extreme load without using a very stiff design [21].

Modifications have been suggested to counter the issues with manufacturing large blades. Typically, these allow production in separate components, allowing better quality of the individual pieces. Frequently, a separately cured spar structure is used [18]. Furthermore, Hayden [22] suggested to build the spar cap out of thin pultruded planks glued on top of each other to avoid thick laminates. Hayden [17] suggested producing the blade root in multiple segments for better temperature control. Kontis [23] suggested producing large parts of the blades separately and joining them together using adhesive bonds before transport. This approach has the advantage of manufacturing segments and avoids the difficulty of on-site assembly. Additionally, to improve the quality of the adhesive bonds at the shear webs, Sorensen [24] advocated producing the internal spar of a blade in two pieces, of which the height can be adjusted to order to obtain the desired bond thickness.

3. Transportation of wind turbine blades

In general, wind turbine blades are manufactured at a production facility and subsequently transported to the installation site [25]. Due to local legislation, the total number of transports and various other factors, transportation costs are highly route dependent. Every haul requires investigation of the optimal route and transportation method [26]. While wind turbine blades are frequently transported by road, typically, lengths of over 45m need to be transported as oversized and overweight (OSOW) load requiring specialized trucks with rear steering escorted by service cars [27]. The route has to be analysed to ensure blade transport vehicles can be accommodated [27]. Furthermore, modifications to the road may be required and local regulations may restrict road transportation to night-time, specific weather conditions and may impose special licenses [28,29]. Licenses with a limited validity period introduce lead-times and additional costs in the case of a delay [30]. Wind turbine blades can also be transported by rail. While blade lengths are not limited to the size of a single rail car, trains have to go slower when part of the blade is hanging over board [31]. Further, blades are also transported over waterways and seas. However, to prevent twisting of the ship from damaging the blades, expensive fixtures, custom to every blade type, have to be used [29]. As a last resort, blades can also be transported by air lifters. Because helicopters are expensive and risky, blimp like air lifting devices are under development [26,32]. Increased difficulty of transporting larger blades results in a non-linear increase in costs. Beyond certain breakpoints there is a sudden steep increase [26]. On the road, transportation costs rise sharply for blade lengths over 46m and can be prohibitive for blades longer than 61m [18]. Furthermore, there are actual limitations to the dimensions of components that can be transported for each method [33]. These apply to the bounding box surrounding the blade. As can be seen in Figure 1, the height and width of the box is determined by

Table 1. Maximum allowed dimensions and weights for the transportation of wind turbine blades, based on [26].

transportation method	max. weight (tonne)	max. length (m)	max. height (m)	max. width (m)
rail	163	27.4	4	3.4
road (over weight)	36	45.7	4.1	2.6
water (barge)	>200	76.2	-	16.5

the blade's maximum chord length and the blade root diameter as well as the amount of pre-bending and pre-curving. An overview of the maximum allowed dimensions and weights is given in Table 1.

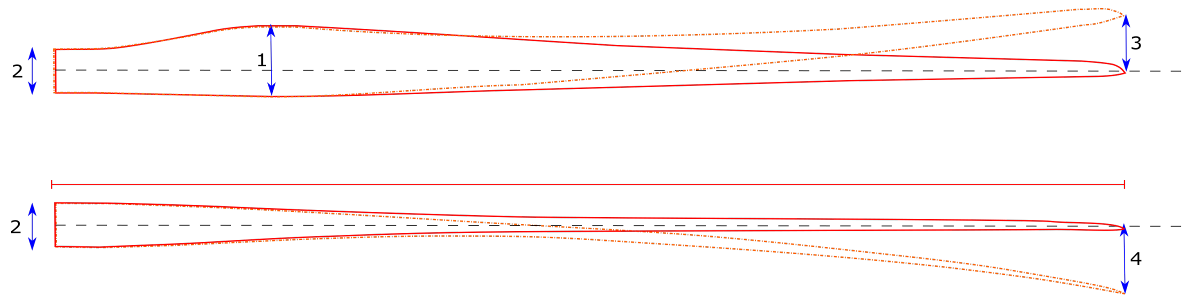
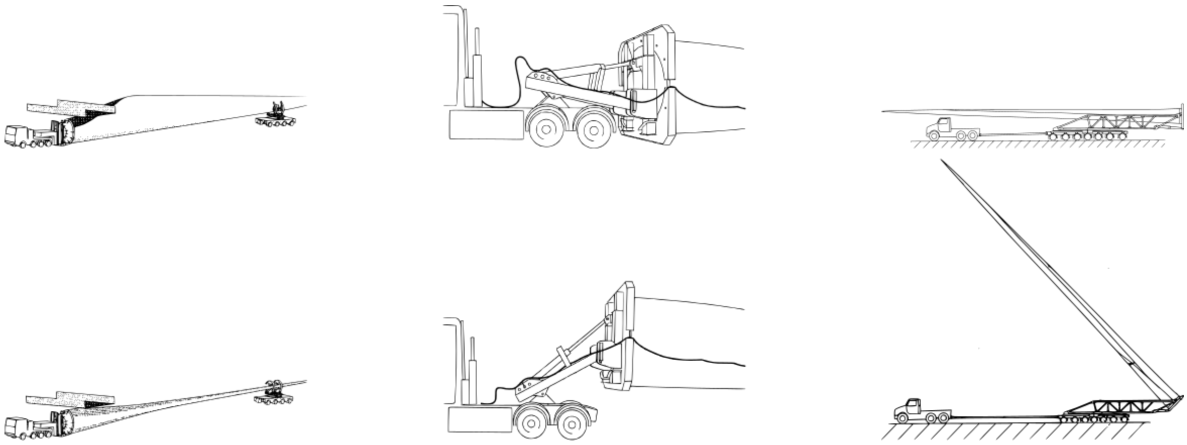


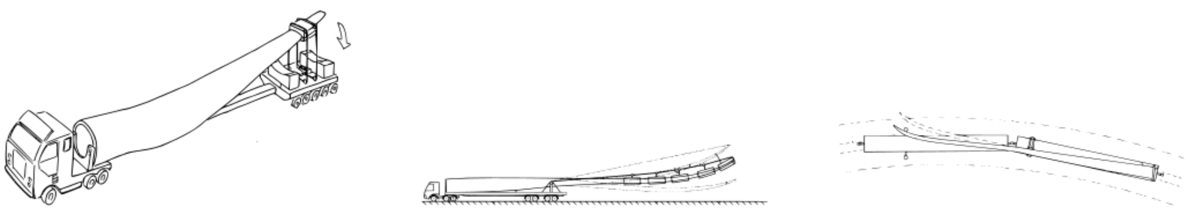
Figure 1. Top and side view of a modern wind turbine blade, giving an overview of blade transportation critical dimensions. The solid line shows a blade without pre-curving or sweep, while the dashed line shows a swept and pre-curved blade. 1) maximum chord length, 2) blade root diameter, 3)blade sweep, 4)blade pre-curving

Various improvements have been made to the conventional transportation methods. One possible approach is to make the position in which the blade is carried variable. Jensen [34] suggested a system where the blade is suspended at both ends, which can each be lifted. This allows the blade to be lifted over small obstacles. Similarly, Wobben [35] suggested to rotate the blade to pass under obstacles such as bridges. These systems can be seen in Figure 2. Likewise, Kawada [36] proposed connecting only the blade root to a truck with a system that enables tilting the tip upwards. This allows larger blades to get past a narrow corner. Furthermore, Nies [37] suggested tilting the blade and reducing the length of the carrying vehicle. Additionally, Pedersen [38] improved upon these tilting concepts, allowing the blade tip to be in front of the truck while using a lighter vehicle. To allow larger blades to be transported by rail, Landrum [39] proposed using two coupled rail cars and using a sliding support. Another approach is to deform the blade to alter its dimensions. Modern wind turbine blades are often pre-curved and swept. For larger blades however, the amount of pre-curving is less than desirable, due to the difficulty of transport [40]. This issue could be reduced by applying a load to "straighten" out the blades while they are transported [40]. In addition, to improve blade transportation by rail, Schibsbye [31] advocated using bumpers to bend the more flexible outboard portion of the blades during turns so that there would be no overhang. An overview of these methods can be seen in Figure 3. Further, the transportation of blades over water is less restricted. Grabau [29] proposed to take advantage of the similarity between blades and composite boats. When all gaps are sealed, the blades can float in the water and towed behind a ship. Alternatively, Berry [41] investigated producing blades in a small on-site factory using material kits prepared at the main factory. However, there were difficulties with handling the blades at the temporary facility.



(a) (b) (c)

Figure 2. Blade road transportation solutions that temporarily change the way the blade is handled a) Solution where the blade can be rotated to pass under obstacles such as bridges or tunnels. [35] b) system where the blade can be lifted to pass over low obstacles [34] c) system where the blade can be tilted at the root [42]



(a) (b) (c)

Figure 3. An overview of blade transportation solutions that deform the blade to ease transportation. a) straightening of the pre-curved blade to simplify transportation [40] b) temporary deforming the blade to simplify transportation c) Deforming the outboard portion of the blade during rail transportation to prevent overhang during turns [31].

4. The cost of energy: requirements for segmented blades

4.1. Cost of energy components

The overall aim of the wind energy industry is to provide energy at the lowest possible cost. This cost is affected by segmenting. The cost of energy (COE) can be modelled as suggested in [43], as can be seen in (1). The COE depends on the fixed charge rate (FCR), the initial captial cost (ICC), the net annual energy production of the turbine(AEP_{net}), the land lease cost (LLC), operations and maintenance ($O\&M$) cost and the levelized replacement cost (LRC).

$$COE = \frac{FCR \cdot ICC}{AEP_{\mathrm{net}}} + LLC + \frac{O\&M + LRC}{AEP_{\mathrm{net}}} \tag{1}$$

4.2. The initial capital cost

The ICC depends on manufacturing transportation and installation cost of the turbine. Manufacturing costs increase because of the additional material, labour and production steps required for producing the joint and reinforcing the inboard part of the blade [44]. On the other hand, a cost reduction is possible due to economic benefits. Production facilities can be smaller [44–46] and components can be standardised. For example, a single root segment can be combined with different tip segments to obtain blades for different wind conditions [47,48]. Additionally, using different materials at different locations along the span is economically interesting but requires a difficult transition. This can be simplified by segmenting [49,50]. Furthermore, segmentation simplifies quality assurance [49]. Blade segmentation can decrease transportation costs [44]. Moreover, many sites that are suited for wind turbines are located in complex terrain with poor infrastructure. Their development may become cost effective with segmented blades [51,52]. Installation costs increase because of additional assembly steps required to make the final blade. In this respect, speed and simplicity of assembly are important.

4.3. Operations and maintenance cost

The cost for operations and maintenance ($O\&M$) increases because of additional inspections or maintenance. It may be required to verify the pre-stress of bolts or the protection against water ingress [53]. Minimal additional maintenance and good access and inspectability to the joint are required to limit this cost increase. Therefore, sensors can be included to monitor the joint [54].

4.4. Levelized replacement cost

The use of a detachable joint could allow replacement of a single segment rather than the complete blade in the case of damage [55,56]. This would allow a reduction of the LRC, which represents the cost of replacements over the life of the turbine.

4.5. Net annual energy production

Further, the annual energy production (AEP) has a very strong influence on the COE since it has to offset all the costs including those not related to the rotor. The performance of the rotor will decrease by alterations to its outside shape. Therefore, joints should use holes that can be covered or blind holes from the inside of the blade [50]. Furthermore, a lower rotor inertia makes it easier for the control system to keep the ratio of the rotational speed of the rotor to the wind speed optimal under fluctuating wind conditions, thereby resulting in a higher AEP [57]. The additional inertia resulting from the joint may therefore reduce the AEP. Additionally, the AEP will be decreased if a local stiffened portion is included [58].

4.6. General considerations for segmented blades

In order to minimize the COE resulting from a segmented blade the different cost components have the following considerations based on [44,59].

- Initial capital costs
  - manufacturing costs
  - tolerance requirements
  - production complexity and accuracy
  - ability to use with conventional production methods
  - quality control
  - positioning accuracy and speed of assembly
- Annual energy production
  - reliability
  - aerodynamics
  - weight of the joint
- Annual operating expenses
  - requiring minimal inspection
  - easy to repair during service
  - possibility of disassembly for replacing segments

Table 2. An overview of blade segmentation strategies.

Segmentation strategy	Type of division	Advantages	Drawbacks
Reducing component lengths	Span-wise	Potential cost reductions	Goes against historical trend Slender blades reduce available space Optimal split transport/structure differs. Division of structural spar
Reducing component width/height	Chord-wise	No division of structural spar.	Transfer of edge-wise loads
Obtaining variable rotor loading	Span-wise: telescopic blades	Increased power output.	Division of structural spar
	Chord-wise: trailing edge flaps	Reduced extreme and fatigue loads. No need to divide structural spar.	Increased complexity

4.7. *Cost effectiveness of blade segmentation*

Segmenting blades is useful if this results in a reduced COE. For example, Dutton [44] reported an expected increase in blade cost of approximately 19% for a 60m blade, while the transportation costs decreased only about 5% of the total price of the blade, thus overall resulting in an elevated COE. However, from Dutton [44] it is clear that the relative added cost of segmenting a blade decreases with the size of the blades. Further, at a turbine level, the optimum scale is determined by the ratio between capital costs and other costs [2]. Because the fixed costs are significantly higher for offshore turbines than for their onshore counterparts, the optimum size for offshore turbines is larger than onshore [2]. Additionally, for land based turbines, transportation costs may be extremely high for certain sites that do allow for a high AEP. Therefore, segmentation is most likely to be cost effective for either very large, typically offshore turbines or on-shore turbines that are installed on sites that allow a high yield but are otherwise difficult to access.

5. Blade segmentation strategy

Blade segmentation can be done following different strategies. These are detailed in the following sections. An overview is provided in Figure 4.

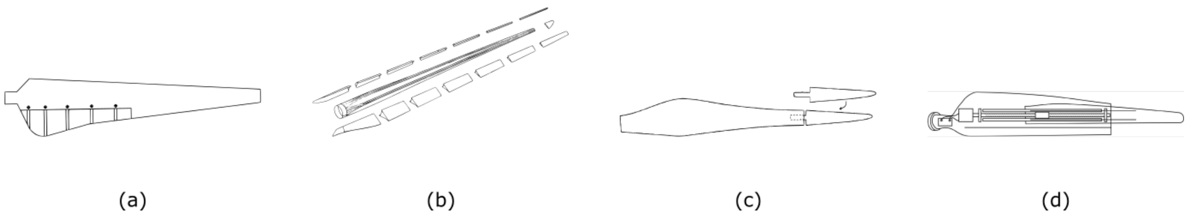


Figure 4. Different segmentation strategies. a) Blade with a separate TE-segment to reduce the blades width b) Blade with separate LE and TE panel segments to reduce the blade width. c)Blade divided to reduce the length of the components. d) Telescopic wind turbine blade.

5.1. *Segmenting to obtain a reduced component length*

Large blades cannot get past narrow corners. This issue can be alleviated by splitting the blades into in-board and out-board segments. However, such a division requires the use of highly loaded structural joints to transfer loads between the segments. Introducing such additional joints goes against the historical trend in aerospace and wind energy of reducing the number of components [18]. Furthermore, fatigue design is better off without joints [60]. Additionally, there is a trend to produce more slender blades with higher tip speed ratios (TSR) and reduced chord lengths resulting in less space for a segmentation joint [61,62]. While the split location may be determined as to minimize transportation costs, it may also be influenced by structural consequences. The blade loads increase non-linearly towards the root. Meanwhile, modern blade designs use very thick airfoils near the root, where structural requirements dominate the design and very thin ones toward the tip, where aerodynamic performance dominates. As a consequence, the ratio of section forces to the available cross-section is the highest around the center of the blade [59]. At this location, a very heavy joint would be required. The ratio of section forces to the available cross-section is lower towards the tip portion and towards the root portion, with the tip region expieriencing the lowest section forces. However, while this was also true for the 61.5m blade considered in [48], a mid-span location was still selected.

5.2. Segmenting to obtain a reduction in width and height of the components

On straight roads, the width and height of the blade's bounding box are the main limiting factors. The area of maximum chord length is typically critical since it can easily reach a size of 6m [50]. To counter this problem, [63] tried to alleviate the transportation issues by truncating a blade around the area of the maximum chord length. However, in this particular study, the prototype blade was found not to perform as expected. More beneficially, the blade can be segmented to obtain a separate trailing edge segment [50,64,65]. This segmentation strategy can be applied without dividing the blade's structural spar. As a consequence the segmentation joints are not highly loaded and typically the trailing edge segment does not transfer loads coming from the tip region to the root. Alternatively, the blade can be split in a load-bearing structural spar and a non-structural aerodynamically shaped skin to reduce the width of the structure. Multiple authors [66–71] have suggested to consider the blade as a structure consisting of a load-bearing part (the spar) and an aerodynamic skin. In this approach it is possible to maintain a single part for the load bearing component, while making separate segments for the blade skin. However, conventionally, the skin transfers shear loads between the spar and trailing edge reinforcements originating from edge-wise loads. The decoupled skin concept should avoid to break up the structure that handles the edgewise loads [18].

5.3. Segmenting to obtain a variable rotor loading

Control strategies such as varying the blade pitch or the rotor speed are used to produce the maximum amount of energy while limiting the load to the turbine's rated power. Additionally, various strategies are used to reduce the extreme and fatigue loads on the rotor. Reducing the loads on the rotor can affect the loads on other components such as the bearings, gearbox and generator and could reduce the *COE*. Such strategies include cyclic pitch, individual pitch control and aeroelastic tailoring [72]. Alternative strategies using the relative displacement of different blade segments are possible. One such approach uses telescopic blades. In that case, one segment is retracted into the other to vary the swept area of the rotor [73–76]. This allows the turbine to produce more power at low wind conditions while avoiding the extreme loading at high wind speeds. However, this requires a mechanism to perform the retraction that has to transmit all the loads from the outboard segment to the inboard segment. Alternatively, various active 'smart' control strategies are under development [72]. These use distributed sensors and actuators along the blades. The actuators include trailing edge flaps. Castaignet [77] demonstrated this concept on a turbine with 13m long blades. The average flap-wise blade root moment decreased by 14% along with 20% of the amplitude of the 1P loads. [78,79] tested trailing edge flaps on a turbine with 9m blades. An average load reduction of 14% was reported.

6. Adhesive joints in segmented blades

6.1. Cost of energy

Adhesive joints can be structurally efficient, light and cheap. They have low stress concentrations and good damage tolerance. However, when used in segmented blades they result in high installation costs due to the the need for specialized equipment and the number of added time consuming steps during on-site assembly. Various improvements have proposed approaches to alleviate these issues. One problem is the lack of inherent self-alignment of adhesive joints. This increases the complexity and time required to assemble the blade from its segments [80]. Baker [81] presented a system to align blade segments on different carriers using laser positioning. Alternatively, Zirin [82] suggested using brackets attached to the spar caps to ease alignment, after which the adhesive bond can be

Table 3. My caption

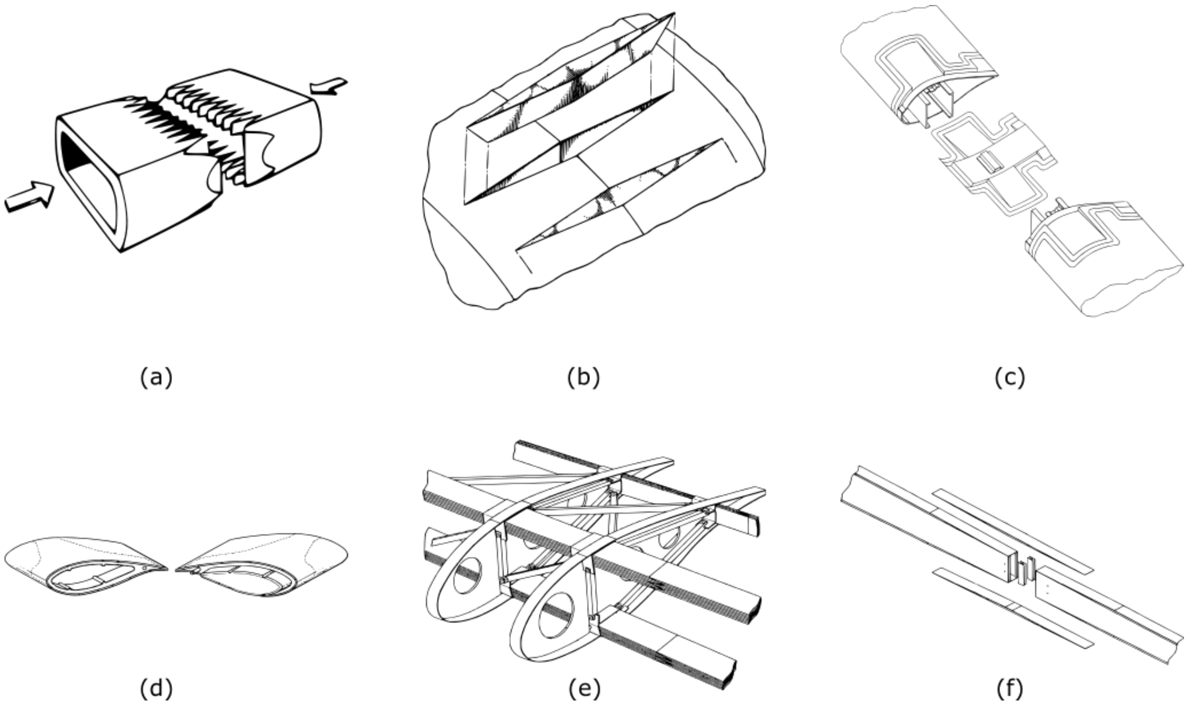
Adhesive joint issue		Suggested remedies
Time of assembly:	Alignment of the segments	-Alignment using laser-positioning
		-Brackets attached to spar cap
		-Alignment pins
		-Overlapping portions
	Curing of the bonds	-Resistance heated bonds
Bond-quality	bond thickness	-Bonding grid
		-Shims
		-Producing the segments in a single mould
	air entrapments	-Flooding of a cavity
		-Infusion

formed. Livingston [83] proposed using alignment pins. Additionally, Baehmann [84] and Riddell [85] suggested using different types of overlapping portions to ease alignment. Further, Kyriakides [86] proposed using joint portions that are offset in span-wise direction to create an overlap.

A second issue is the difficulty of producing a high quality bond on-site compared to under controlled conditions [56]. Surface preparation, temperature and humidity affect the quality of adhesive joints [16]. Good control over the bond thickness is important to avoid stress concentrations. In [87] the use of a bonding grid is proposed. This grid is incorporated into the joint to obtain a very accurate bond thickness. Zirin [82] suggested using shims to ensure a constant minimum distance between the parts to be adhered. To ensure a perfect fit between two segments, Riddell [85] advocated producing the segments in a single mould. By folding in a vacuum bag with release agent the two adjacent segments can be manufactured while in contact with each other. Afterwards, they can be separated easily and will have a very good fit at the interface. Further, air entrapments can drastically reduce the strength of adhesive joints. Arelt [88] suggested to put the connecting surfaces in place first, creating a cavity which can subsequently be flooded or infused to create the joint while avoiding air entrapments. Similarly, Baehmann [84] suggests a segmented blade with overlapping spar caps, which cause the formation of a spar cap cavity, which is subsequently filled with adhesive. Another issue is the assembly time and requirement of specialized equipment such as ovens, heat tents and heater blankets to cure the bonds [89]. Up to ten hours at elevated temperature may be required to fully cure the adhesive [88]. Driver [89] suggested the use of resistance heated bonds to alleviate these issues. Also, the O&M costs are lower for adhesive joints compared to mechanical connections.

6.2. Implementations

Blade segments can be joined using structural adhesive bonds. An overview is given in Figure 5. The efficiency of the joint depends on the chosen geometry. Finger joints were used in the wood-epoxy blades of the MOD-5A turbine [90]. However, the use of this type of joint in modern fiberglass blades may be impeded by the higher modulus of elasticity and strains as well as issues with tooling. Similarly, diamond shaped splice-inserts can be adhered to the segments to form the joint [91]. Likewise, Bech [92] improved upon this approach by using longer connections providing higher stiffness and strength. Bhat [93] used finite element modelling to investigate the option of bonded strap plates. For general geometries, scarf joints and stepped lap joints have the highest efficiencies [94]. Concepts using scarf joints were suggested by [82–84,87]. To avoid fragile protrusions, Hayden [95] proposed using a double scarf joint. Segmentation using stepped lap joints was suggested by Baker [81]. Further, Frederiksen [96] suggested not infusing the fibres in the joint areas when fabricating the segments, so that they can be joined by overlapping, infusing and curing the dry fibres.



(a) (b) (c) (d) (e) (f)

Figure 5. Blade segmentation concepts using adhesive bonds. a) Finger joint b) Splice insert joint [90] c) Adhesive cavity joint d) Single lap joint [85] e) Stepped lap joint [81] f) Double scarf joint [95]

Table 4. My caption

Blade root connection	Advantages	Drawbacks	Implementations
Flange type	-	Inferior fatigue behavior	
Hub type		Heavy	
T-bolt type	Cheap and simple	Packing limitation of the T-bolts	DEBRA, JOULEIII, MEGAWIND
Stud/insert type	Allows for the lightest joint		UpWind,

7. Mechanical joints in segmented blades

7.1. Cost of energy

Mechanical joints are heavy and expensive, but are fast and easy to assemble [44,46]. Furthermore, they are easy to inspect but require some maintenance.

7.2. Experience from blade root connections

Conventionally wind turbine blades are attached to a steel hub using a detachable mechanical joint. These root joints are highly loaded and experience a very high number of load cycles. Because of the existing experience in this field and the similarities with the joints for segmented blades these joint types are candidates for blade segmentation. The most frequent root types are seen in Figure 6.

7.2.1. Flange type

Blades with a flange type root have a flange formed by moulding the material outwards. This flange is then bolted to the hub. Bundles of fibers can be looped around bushings with the flange to capture them mechanically. This type of root is known as the Hütter root connection [8,97].

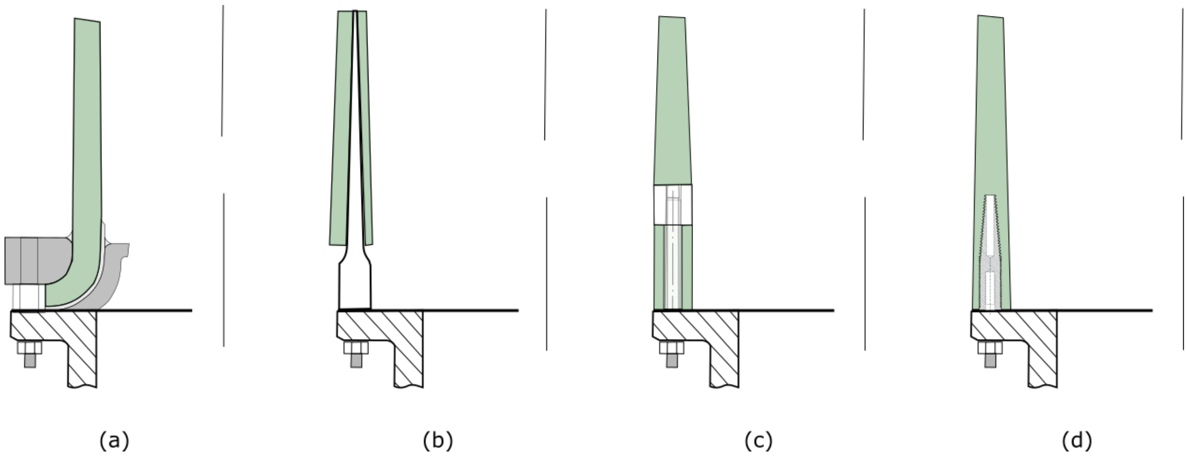


Figure 6. An overview of blade root joints. a) Flange root connection b) Hub type root connection c) T-bolt root connection d) Stud root connection.

7.2.2. Hub type

The hub type root connection uses a tapered metal cylinder embedded or adhered to the root laminate and bolted to the hub. Assuring correct bond thickness is difficult, but critical for the performance of the joint[41]. Strain incompatibilities are present, resulting in large stress concentrations. Furthermore, in some implementations the hub has a lower diameter than the actual root [97]. This reduces the second moment of area of the section trough which the loads are transferred, reducing the structural efficiency of the joint. Hosseini-Toudeshky [98] investigated the progressive debonding of a hub type joint using finite element methods. It was demonstrated that an overloading such as a gust can cause damage to the bonding of the root joint, which grows due to fatigue loading. The used method was able to predict the life reduction of this joint caused by various loadings.

7.2.3. T-bolt joint

T-bolt joints have cross-bolts positioned perpendicular to the root cylinder surface. Longitudinal bolts connect the hub to the cross-bolt [99]. T-bolts rely on the contact between the cross-bolt and the laminate to transfer loads. Martinez [100] investigated the T-bolt joint both numerically and with experiments and concluded that the T-bolt joint is reliable and cheap but has a low structural efficiency, resulting in a high weight compared to other solutions such as inserts. Packing limitations exist and lead to a significant laminate build-up. Furthermore, the load factors of the bolts are critical to the integrity of the connection. Multiple improvements to the conventional T-bolt joint have been suggested. Harismendy [101] suggested the use of two longitudinal bolts for each cross bolt outside the blade laminate. While Quell [102] suggested using other shapes of cross bolts than cylindrical. Additionally, Doorenspleet [103] suggested using multi-row T-bolts in order to increase the packing limit.

7.2.4. Stud/insert type

The stud or insert root joint relies on longitudinal bolts attached to studs or inserts. Typically, the inserts are female threaded and made of steel, causing a thermal and flexural mismatch [104]. This is countered by tapering the studs on the out or inside and by using a thicker laminate [104]. Hayden [104] suggested to use a threaded insert made from a composite tube to improve compatibility to allow a reduced root wall thickness. Furthermore, to reduce the stress concentration at the tip of the inserts, Vronsky [105] suggested using inserts of different lengths. Often, the studs are glued into the blade. In wood composite blades the studs are placed in holes that are drilled, while in glass fibre blades the holes are preferably formed during fabrication [41,106]. Positioning of the stud is vital to the quality of the joint as a non-uniform adhesive thickness causes stress concentrations [107]. Typically, fixtures are used to position and bond the studs simultaneously. Often, the adhesive is injected into the hole around the insert by using a secondary hole or through the gap between the laminate and the stud. Alternatively, modified studs can allow the adhesive to flow through the center of the insert to form the bond through the stud [41]. Additionally, the joint quality can deteriorate because of macroscopic voids [41]. To avoid these voids, Raina [107] suggests to improve the tru-stud bonding method to allow vacuum infusion by adding a second channel to the stud. Alternatively, the studs can be directly embedded during the lamination process. This requires less fabrication process steps, tooling and allows the root laminate to be much thinner, but increases the complexity of the lamination process [41,108]. Sorensen [109] suggested using a holder with spaced recesses to hold the bushings. As an alternative, Bendel [110] and Kildegaard [111] both suggested inserts that can easily be positioned and form a smooth outer and inner surface onto which the fibre mats of the root laminate can be applied. In general, to provide sufficient pull-out strength, inserts have to be long. Various improvements have been suggested to increase the pull-out strength, allowing shorter, lighter inserts. Grove-Nielsen [112] suggested to include longitudinal grooves on the outside of the inserts to increase the contact area with the laminate. Further, in similarity with the Hütter root, Mcewen [108] proposed to capture the inserts mechanically by looping fibres around it. Additionally, Feigl [113] suggested putting fibres in between the inserts for a better contact, whereas Schmidt [114] suggested stitching together the fibres surrounding the bushings.

7.2.5. Comparison

The blade root design is mainly driven by cost as it represents between 7 and 20 percent of the total blade cost [100,115]. The weight of the joint is less important, since it is added close to the hub and the center of rotation. As a consequence it does not have a big impact on the blade's eigenfrequencies, and edge-wise and dynamic loads. This is different for blade segmentation joints which are placed further outboard. Due to the superior fatigue performance of T-bolts and studs other blade root designs have become rare. Jackson [116] performed the preliminary design of a 50 m blade. Blade roots were designed considering a T-bolt joint and a stud joint. The stud connection allowed a larger number of connections because of packing limitations of T-bolts. This lead to a reduced root laminate build-up resulting in a lower weight and price, despite cheaper T-bolt hardware.

7.2.6. Implementations in segmented blades

The T-bolt joint has been used in several prototype segmented blades, seen in Figure 7. It was first used on the DEBRA 25 wind turbine [117]. T-bolts joined the blades to the hub and connected the C-spars of the two 8.5 m blade segments. The turbine was successful and needed only limited additional maintenance to verify bolt pre-tension. Dutton [44] also investigated the use of a T-bolt joint for a segmented blade by using a single row of T-bolts in a prototype 23.3m blade. The blade survived both static and fatigue testing. Later, Vionis [51] also investigated the use of a T-bolt joint by using a double row of T-bolts in a 30 m segmented blade. The blade survived static testing but bolts at the spar caps failed during fatigue testing at one fifth of the 1E6 load cycles. Prototypes using inserts have also been made, as shown in Figure 8. Within the UpWind project, a 42.5m sectional blade using inserts was developed [118]. Furthermore, Saenz [48,119] developed a joint for blade segmentation that increases the number of connections by alternating long and short bolts. The joint was used to design a 61.5 m segmented blade since this was the optimal location for blade transport.

7.3. Experience from blade root and hub extenders

To use existing blades on turbines at sites of a lower wind class than the blades were designed for, blade root extenders are placed in-between the hub and the blade roots, increasing the rotor diameter [120]. Blade extenders are generally made out of metal but can also be manufactured from composite material [121]. They can incorporate a pre-coning [122] or sweep [123]. In a similar approach, the hub

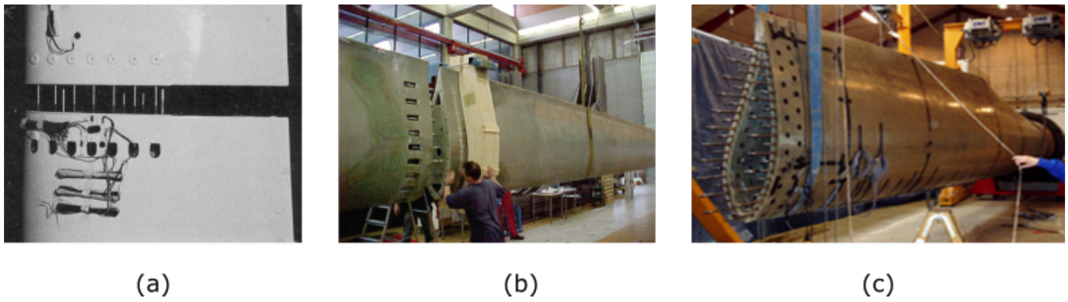


Figure 7. Prototype segmented blades using a T-bolt joint. a)DEBRA-25 blade [117]. b) split blade tested under the JOULEIII project [44] c) blade tested under the MEGAWIND project [51].

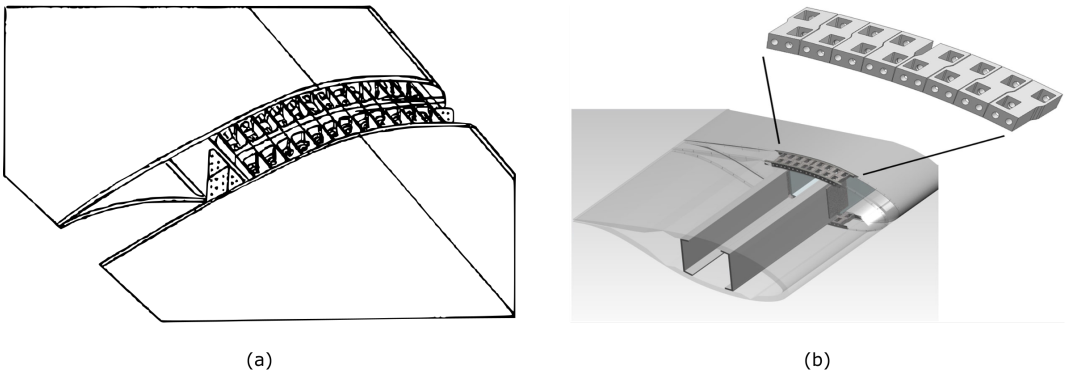


Figure 8. Prototype segmented blades using inserts. a) blade joint developed during the UpWind project [54]. b) Blade joint with alternating long and short bolts [48].

is extended, placing the pitching mechanism further out-board forming a hub extender or partial pitch system [124]. This concept was already used in the NASA Mod-2 turbine [125]. Lu [126] investigated a segmented blade of which the inboard portions were essentially blade extenders connected by a truss structure to reduce loads. Furthermore, to provide sufficient solidity at the blade root, an aerodynamic shape with a large chord length is required. This can be made feasible by using a root extender with an aerodynamic shape as suggested by Curtin [127]. An overview of these methods is shown in Figure 9.

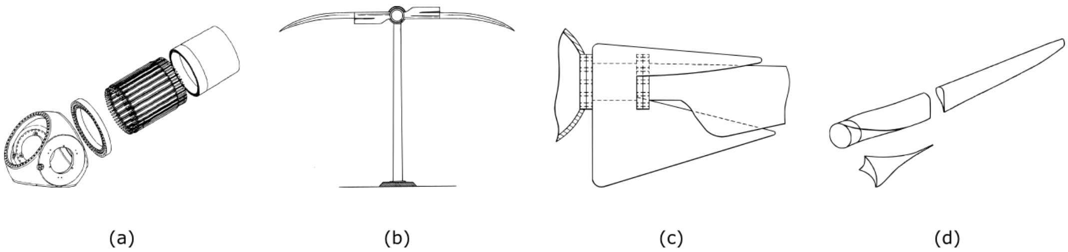


Figure 9. Blade extension methods. a) Blade root extender [120] b) Partial pitch mechanism [124] c) Blade root extender with an aerodynamic shape [127] d) Segmented blade with the inboard segment made from steel.

7.4. Experience from rotor tips and glider wings

To reduce turbulence at the tips, aircraft often employ winglets. Similar tips are used on wind turbines to limit noise production [128]. However, such angled blade tips form delicate components during transportation and make manufacturing more complex and expensive. Therefore, they are often made as separate components and connected to the blades at the installation site. The blade tips can be connected by means of tubular guides and locked by means of a bolt, either transversely to the joint as suggested in Olthoff [128] or longitudinally as suggested in Hoffmann [129]. Furthermore, in the past, tip brakes were used to prevent over-speed on rotors with stall control [8,97,130]. These can rotate 90 degrees to create a drag. They are typically connected by means of a tube. Similarly, Moroz [49] suggested to alleviate loads with a segmented tip. In addition, the fabrication methods, structural layout and slenderness of gliders and wind turbine blades are similar making joints used in gliders suitable candidates for blade segmentation [117]. Gliders often have detachable wings to allow easier transport and storage [131]. Modern glider carry-trough structure configurations have one or two tongues next to each other to transfer bending loads [132]. Similar spar-bridge strategies with one or more protrusions have been suggested and tested for segmented blades. For example, Rudling [133] suggested a segmented blade that relies on joining the shear webs of a number of structural spars with shear pins. Loads are distributed using shear blocks attached to the webs. Segmented blades using spar-bridge joints were suggested in various studies [134–137]. Further, Dutton [44] designed and tested prototype of a segmented version of a 13.4 m blade with a connecting tube. The tube was attached to the blade using two bulkheads similar to the concept suggested by [138]. The blade underwent three static load tests (flap-wise towards the suction side and both edge-wise directions) followed by a 5 million cycle fatigue test in the flap-wise direction after which the static tests were repeated. It was concluded that no damage occurred in the blade, but that the loads were sometimes transmitted trough the locking device instead of via the fitting which had resulted in fretting corrosion.

7.5. Other concepts

7.5.1. Cables

Some blade segmentation concepts cannot directly be traced back to a particular other application. An overview of these methods can be seen in Figure 10. There are a number of segmentation joints that rely on cables to form a connection. [139] suggested using pre-tensioned straps to hold together eccentric transversal bolts, attached to neighbouring segments. However, due to friction the pre-stress accuracy is limited and difficult to ensure [56]. Furthermore, this concept leads to high stress concentrations [88]. Alternatively, pre-tensioned cables can be used to hold the different segments together by pulling them towards the root. Kootstra [140] proposed to incorporate a joining segment that is pulled towards the root using a pre-tensioned cable. Similarly, in Doellinger [141] using pre-tensioned steel cables running through channels in the skin and shear webs as an alternative to a structural spar is suggested. The cables are attached at the blade root and fastening points on every blade segment. Likewise, Cairo [142] suggested using pre-tensioned cables running through conduits in the blade skin. Further, Klein [143] suggested using U-shaped cable loops embedded into the laminate.

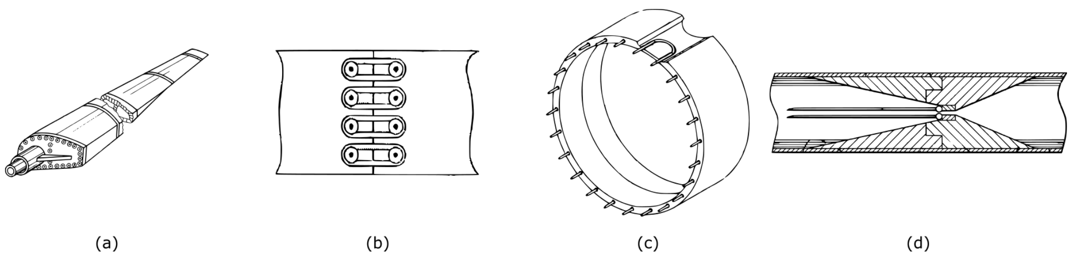


Figure 10. Unique blade connections relying on cables to connect the different segments. a) Blade using pre-tensioned steel cables to hold together the different segments as an alternative to a spar structure [141]. b) Joint using pre-tensioned straps around eccentric bolts [139]. c) U-shaped loops [143] d) Segmented blade joint relying on pre-tensioned cables to pull the outer segment towards the hub [140].

7.5.2. Joints using transverse fasteners

Joining the segments with fasteners in a transverse direction has also been considered. Torres [144] suggested joining the blades by riveting. Petri [55] suggested transversely bolting overlapping plates to the segments. To increase laminates the bearing strength, Birkemeyer [59] suggested using fibre metal laminate (FML) in the region of the joint. Llorente [145] suggested using lugs to connect the spar of adjacent segments. These methods can be seen in Figure 11.

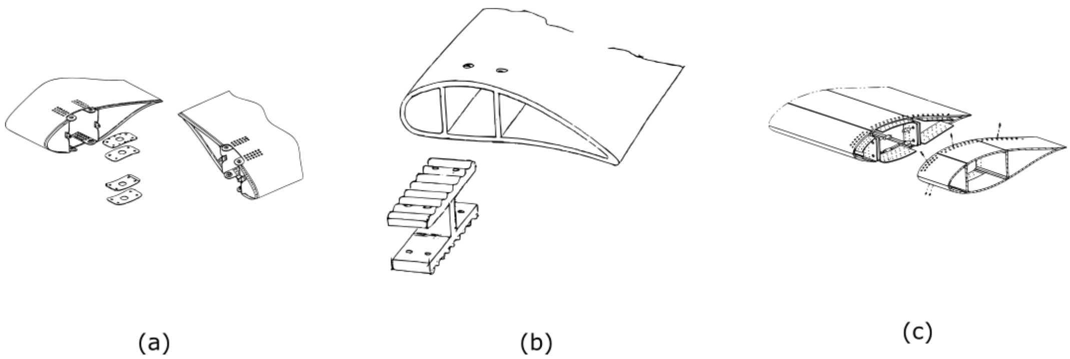


Figure 11. Transverse joining concepts. a) Segments joined with lugs [145] b) segments joined by intermediate pieces [55] c) Segments joined with rivets [144]

8. Conclusion

The feasibility of a segmented blade largely depends on the risk of the chosen concept. In this respect concepts that require only limited changes from existing approaches pose less risk and are more likely to succeed. For example, concepts that do not require division of the blade's main structural components such as the use of separate leading or trailing edge segments are only small modifications since these require only limited loads to be transmitted across the connections. For this reason, active trailing edge flaps are more likely to succeed than telescopic blades. Similarly, aerodynamically shaped root extenders pose only a small modification from existing root extenders, which are well known in the industry. Furthermore, concepts incorporating a spar-bridge are close to joints used in sail-planes and tip brakes and have been shown to be feasible. Joints using longitudinal bolts have also been successful and are well known from the blade root design. The fact that large modern blades typically prefer the use of inserts to form a lightweight joint indicates that such joints are better suited for segmentation than flanged, hub type and T-bolt joints. On the other hand, breaking up the blade's main structural components poses significant challenges regarding production, maintenance costs and reliability. The failure of the T-bolt prototype blade in Vionis [51] and the unfavourable cost calculation for the T-bolt prototype blade in Dutton [44] indicate the difficulty of making this approach successful. Adhesive joints are also well known in the industry and are sometimes preferred because of their structural and economic efficiency [46]. However, the step from controlled conditions to in-field production of such connections is large. Yet, it may be possible to assemble the blade segments using local, perhaps temporary facilities. Furthermore, to avoid air entrapments, such adhesive joints would most likely be produced using vacuum infusion. The issues related to the manufacturing of larger blades are already being countered by manufacturing separate blade components. These are mostly assembled in the factory using either adhesive or mechanical joints. While blade segmentation poses serious challenges, the wide variety of possibilities and the potential benefits are bound to lead to further developments in this field. Furthermore, segmentation appears most likely to be cost effective for very large, offshore turbines or on-shore turbines promising conditions but accessibility issues.

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