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Structural reuse of wind turbine blades through segmentation

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A R T I C L E I N F O

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A B S T R A C T

Composite materials offer many advantages during the use phase, but recovery at the end of a lifecycle remains a challenge. Structural reuse, where an end of life product is segmented into construction elements, may be a promising alternative. However, composites are often used in large, complex shaped products with optimised material compositions that complicate reuse. A systematic approach is needed to address these challenges and the scale of processing. We investigated structural reuse taking wind turbine blades as a case product. A new segmentation approach was developed and applied to a reference blade model. The recovered construction elements were found to comply to geometric construction standards and to outperform conventional construction materials on specific flexural stiffness and flexural strength. Finally, we explored the reuse of these construction elements in practice. Together, the segmentation approach, structural analysis and practical application provide insights into design aspects that enable structural reuse.

1. Introduction

Composite materials, known for their lightweight properties, are often used to make products more sustainable. Lightweight designs reduce fuel consumption in transport applications, and thereby effectively reduce the carbon footprint [1]. Lightweighting also allows efficient material use, and makes large spans in building and architectural applications possible [2]. Composites are used to maximise performance of these structures. However, when the complete lifecycle is taken into account, the environmental advantage of using composite materials becomes less evident [3,4].

The lifecycle perspective is central to the Circular Economy (CE) concept. The CE aims to preserve resources by keeping products and materials 'in the loop'. This can be done through extending product lifetime and recovering products, components and materials when they reach their end of operational life [5]. Maintaining product integrity, through e.g. reuse, repair or remanufacturing, is considered most desirable. Material integrity, i.e. recycling of material, is a necessity when products can no longer be kept alive. Preferably, recycling retains material properties and avoids downgrading [6,7].

Composite materials enable long product lifespans and require little maintenance. High quality repairs can be made *in situ*: restoring original strength and appearance [1,8]. Reuse at product level is more difficult because the material composition is often optimised to a specific application. This maximises the performance in the use phase, but complicates reuse in another context. For example, wind turbine blades cannot readily be exchanged between wind turbines. Consequently, material recycling remains as the only recovery option.

Recycling composite materials is challenging due to the way in which various materials are structurally combined at a sub-millimetre scale. Thermoset resins and glass fibres, Glass Fibre Reinforced Polymers (GFRP), constitute the majority of composite materials in today's market [9]. For these materials, co-firing in a cement kiln remains the advised recovery route [10]. However, the energy gain is low, the material is lost for further use and the economic perspective is limited [11–13]. Thus, much of the material is landfilled, resulting in a loss of materials and value; and as such landfilling is at the bottom of the waste management hierarchy. To prevent such loss, landfilling of composites has already been prohibited in a number of countries [14,15].

There are various explorations into circular systems for composite materials. For example, current research programs include demonstrators for circular composite products [16,17] and recovery of End of Life (EoL) wind turbine blades [18]. Moreover a number of companies have developed new reprocessing methods to close the composite material loop [19–22]. At a governmental level, the increased use of composite materials is likely to lead to new policy targeting recycling [23–25]. In the meantime, composite products nearing their EoL present a pressing problem. Current recycling capacity is insufficient while in coming decades the composite waste volume will increase strongly [26,27]. Better solutions to deal with EoL composite products are therefore urgently required.

Structural reuse, also referred to as structural recycling, is an attractive alternative solution for EoL composite materials [28–32]. Rather

Abbreviations: CE, Circular Economy; EoL, End of Life; GFRP, Glass Fibre Reinforced Plastics; UD, Uni-Directional; DB, Double-Bias.

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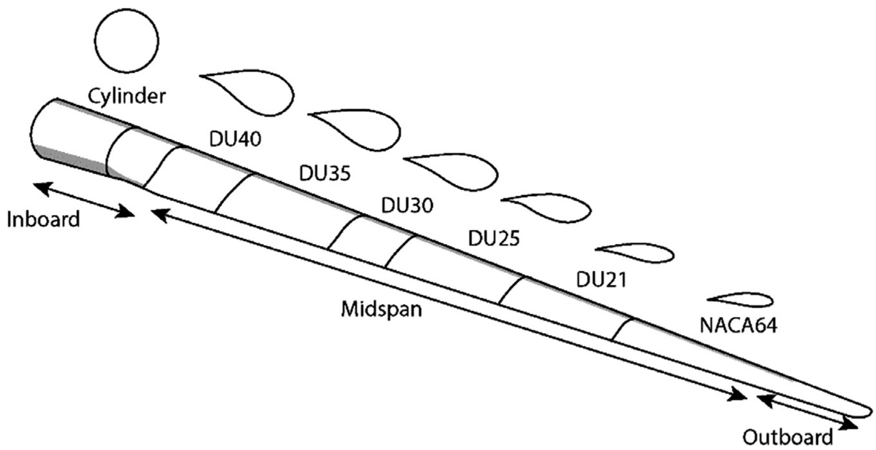


Fig. 1. Schematic representation of NREL 5MW blade, showing airfoils and main sections [36,40].

than shredding the product and attempting to separate reinforcements from the matrix, as is done in current recycling processes, the composite is reused as a structural material. Compared to current recycling practices, structural reuse requires relatively little reprocessing effort and, to a large extent, retains the material quality [29]. As such it is a compelling alternative route to recapture value and extend the lifetime of the material. Reuse can be done by directly harvesting large parts or by cutting construction elements from the EoL product.

Structural reuse has been demonstrated for wind turbine blades, see e.g. [29] for an overview. Blades are interesting objects for this reuse approach as they retain high structural quality, even after 20 years of use. Moreover, blades consist of multiple materials and layup types, which can be reused in many different applications.

Large structural parts have been repurposed for example for outdoor applications such as street furniture and a playground [33]. However this practice is regarded as being difficult to upscale. The large size, complex shape and complex material composition all restrict reuse opportunities [34]. It is expected that cutting-up these large structures into practical and usable construction elements like beams and panels will diversify the potential applications [28].

In an earlier design study we explored the reuse of construction elements from a wind turbine blade [35].We found structural reuse to be feasible, but new segmentation approaches need to be employed to deal with the product's complex shape and structure. In addition, we expect that the yield of reusable construction elements from a blade can be higher and, with a good patterning approach, the reuse process can be made more efficient. This gave rise to the following questions concerning structural reuse of composite product, which are addressed in this paper:

- How to determine a segmentation pattern to obtain reusable construction elements?
- How to compare structural quality of recovered construction elements to conventional construction materials?
- Which design aspects enable or limit structural reuse?

2. Materials and methods

For this study, we took wind turbines blades as case product as these represent a real and pressing recycling problem. We studied structural reuse of composite materials from a wind turbine blade using the following approach. First, segmentation patterns for construction elements were determined based on the structural and geometric specifications of the wind turbine blade. Then, the structural properties of these construction elements were evaluated and compared to conventional construction materials. To test the reuse approach, a relatively simple product was made from retrieved panels. Observations made during this process were then related to design insights.

2.1. Materials

A reference blade model was used to analyse blade design and to determine segmentation patterns and structural properties of recovered materials. The blade model was developed by the National Renewable Energy Laboratory (NREL) and Sandia National Laboratories, based on a study by the Dutch Offshore Wind Energy Converter (DOWEC) project [36–38]. This model was used, because in contrast to commercial blades, this blade was developed for research purposes and its specifications are publicly available [39]. The blade measures 61.5 m in length and was designed for a 5MW turbine. Turbines of this size are found both onshore and offshore, which makes it representative for current installations [27,37].

The blade consists of three sections from root to tip: inboard, midspan and outboard (Fig. 1) [36]. The largest bending moment is exerted on the inboard section, where the blade is joined to the turbine axis. This section starts at rotor radius r = 1.8 m (taking hub diameter into account). It is a plain cylinder with a wall thickness of 61 mm, made of a solid glass fibre reinforced epoxy laminate with a triaxial layup. The midspan starts at r = 10 m and ends at r = 54.5m. The shells, made with a sandwich layup, taper from 100 to 25 mm thickness. The spar caps taper from 48 to 20 mm. The layup consists of triaxial GFRP skins, foam core and glass fibre as well as carbon fibre UD reinforcements. The midspan section comprises six airfoil profiles, five of which were selected from the Delft University (DU) systematic airfoil series. The aerodynamic profile tapers towards the tip to meet aerodynamic and structural requirements. The outboard (tip) section has a relatively flat airfoil profile because it has to cope with high air speeds. In commercial blades, this section is often pre-bent to prevent collision with the tower when the blade deflects under load.

The structural and aerodynamic performance primarily determine the design (Fig. 2) [34,37]. The spar caps (3) and shear webs (4) make up the main structural elements of the blade and function as a box beam to provide longitudinal stiffness. The panels of the leading edge (2) and trailing edge (5) give the blade its aerodynamic shape. The trailing edge has additional reinforcements (6) to alleviate edge-wise bending moments. The blade top and bottom shell are produced separately and joined at the leading edge (1) and trailing edge (7), as well as on top and bottom of the shear webs (4). The panels (2, 5, 6) and shear web (4) are made with a sandwich structure. Spar caps (3) are made with a monolithic carbon fibre laminate and covered with the same GFRP face laminate as the panels.

We retrieved material properties for calculating the structural characteristics of blade segments from the original blade design specifications [37]. Specifications missing from the design report were supplemented with values from equivalent materials in the CES Edupack level 3 database [41]. Table 1 lists the materials and specifications. Density

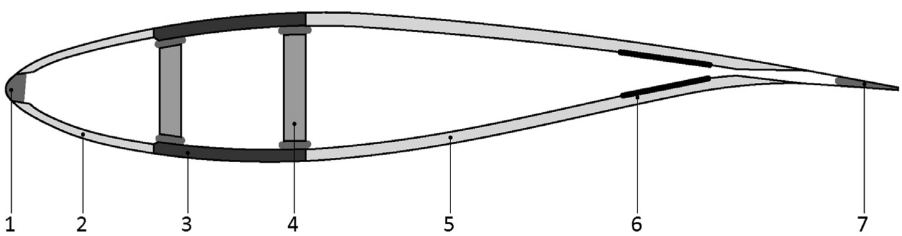


Fig. 2. Cross-sectional profile of a wind turbine blade, showing parts and structural design.

Table 1
Properties of materials used in 5MW blade [37] used to calculate mechanical properties of recovered construction elements. Values marked (a) are supplemented from CES database, (b) calculated from material datasheets.

Material	E-modulus [MPa]	Shear modulus [MPa]	Poisson's ratio [-]	Density [Kg/m^3]	Tensile strength [MPa]	Compressive strength [MPa]
GFRP UD	41,800	2630	0.28	1920	972	702
GFRP Triax	27,700	7200	0.39	1850	700	292_a
GFRP DB	13,600	11,800	0.49	1780	144_a	213
Foam	256	22	0.3	200	5.6_a	4.4_a
CFRP UD	114,500	5990	0.27	1545_b	1546	1047

of carbon fibre UD was calculated using from the material datasheets using the rule of mixtures [42–44].

2.2. Methods

We investigated structural reuse by developing a segmentation pattern, analysing the structural performance of the retrieved elements, and exploring their application in practice. Using the segmentation approach, we can explore various cutting patterns and calculate how effective they are in delivering reusable construction elements. The structural analysis allowed a comparison of the retrieved elements with conventional construction materials. Exploring the application of reused construction elements gave insight into its practical feasibility and the role of design.

2.2.1. Segmentation patterns

The NREL 5 MW model was analysed for recovery of construction elements by evaluating the structure and form. The NuMAD wind turbine blade design tool [45], was used to calculate the weight of individual parts like leading edge panels and spar caps. The calculated properties were verified with distributed blade properties provided by Sandia [37]. In addition, a physical decommissioned blade was inspected to investigate practical implications of construction and recovery which were not addressed in the design report [37].

The succession of aerodynamic profiles along the blade length indicates where the cross-sectional profile is constant or where shape transitions occur. Changes in pitch and chord length indicate the twist and tapering of the blade surface. The twist is constant for the majority of the blade length, but the cross-sectional curvature needed to be calculated.

We calculated the closest distance between a point and a line using vector calculus [46]. The calculation started with a set of 3 points: start point A, endpoint B and intermediate point C (Fig. 3a). Here, length AB corresponds to the segment width w and the maximum perpendicular distance from line AB to a point C on the curve AB corresponds to segment deflection d. The objective of the function was to achieve the largest possible segment width w for a given curvature d/w or deflection d (Fig. 3b).

We applied two segmentation approaches to determine panel segmentation patterns based on curvature and deflection (Table 2). The first approach is governed by d/w and delivers panels with equal curvature [47]. The second approach is governed by d and delivers panels with equal segment deflection. The cutting pattern is aligned with the blade's longitudinal axis, perpendicular to the airfoil section.

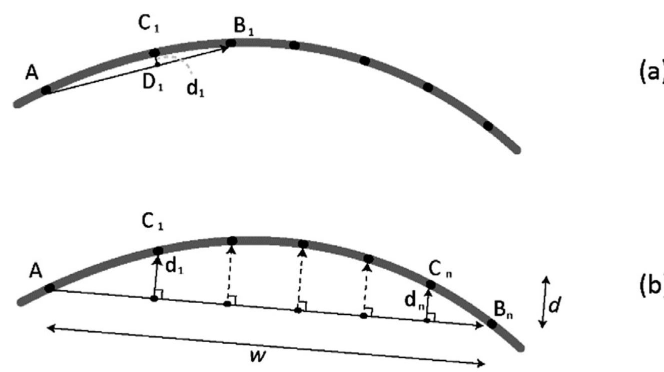


Fig. 3. Calculating panel deflection d between points A and B on the airfoil profile.

Table 2
Boundary conditions for dimensional deviation of a curved construction element, based on NEN 5461 timber standards [47].

Dimensional deviation	NEN 5461	Curvature d/w	Deflection d [m]
Small	d/w <0.02	d/w <0.02	d<0.02
Medium	0.02<d/w<0.04	d/w<0.04	d<0.04
Large	d/w>0.04	d/w <0.08	d<0.08

The dimensional standards for construction timber were used as boundary conditions as standards have not yet been established for the recovery of composite materials. Timber element shapes depend, like the recovered composite segments, on raw material shape as well as prospective application areas. The tolerances are given in Table 2. The goal of the segmentation was to obtain panels with a width and curvature suitable for reuse as construction material.

The cross-sectional segment shape also depends on the cutting angle, for example perpendicular to the local blade surface, airfoil chord or panel chord. Although this affects the cross-sectional shape of the resulting panels, calculation shows minimal effects on cutting losses (<<1wt%). Furthermore, the alignment does not affect segmentation patterns or material performance, and is therefore not further detailed in these analyses. In practice, the alignment will depend on the processing context (i.e. cutting tools and handling equipment) and intended panel reuse applications.

2.2.2. Structural properties

The material properties of the recovered elements were calculated and compared to conventional materials. The goal was to evaluate the material's performance and identify potential application areas. The materials were compared using the level 3 database of Granta CES Edupack 2019 [41]. Properties of the recovered materials were calculated using the Granta CES Hybrid Synthesizer and the blade design specifications given in Table 1. The sandwich material model was used for all parts and properties, except for the density (ρ) and flexural modulus (E_{flex}) of the trailing edge reinforcements. There, the multilayer model was used to account for the additional UD layers. The calculation used a distributed load condition and a segment length of 4.1m, which corresponds to the spacing between consecutive aerodynamic profiles in the blade model.

To evaluate structural quality at end of use, we considered a range of material properties, rather than a single value. For the minimum value, we assumed the blades can still operate under the design load case at the point of decommissioning. For the maximum value we used the original design specifications, which included additional safety factors. Thus to get the minimum values, the original design specifications for stiffness and strength were divided by their respective safety factors. To reflect the blade design specifications, we used the safety factors as stated in the original design report: 1.485 for stiffness and 1.755 for strength [37]. The material density remains constant along the product lifespan.

The calculated values were then plotted on material property charts to enable comparison with conventional construction materials. The materials were compared based on density (ρ), flexural modulus (E_{flex}) and flexural strength (σ_{flex}) [44]. These properties combined indicate the performance of the materials for lightweight constructions loaded in bending [44].

2.2.3. Application

To explore the implications of structural reuse in practice and the role of design, we conducted a design study on a decommissioned wind turbine blade [35]. Panels from a blade were used to design a simple furniture product, which was subsequently built and evaluated. The study followed a research through design approach [48,49] which provided rich data on recovery, design and manufacturing, as well as on user acceptance of the resulting construction materials. The design and reuse of the blade were evaluated using a preliminary set of design aspects [32]. Together, the segmentation approach, structural analysis and practical application provided insights into design aspects that enable structural reuse.

3. Results and discussion

The structural reuse of composite parts was evaluated using a reference wind turbine blade. The segmentation approach starts by assessing the product shape and structure, followed by a more detailed approach, which takes local curvature into account. The segments are then evaluated for their structural performance. The segmentation and structural evaluation provide insight into design aspects that facilitate structural reuse.

3.1. Segmentation patterns

The blade midspan section, which comprises nearly three-quarters of the blade length, offers the best opportunities to retrieve continuously shaped construction elements. In this section, all profiles are selected from the same systematic airfoil series. The linear decrease of chord length (3 cm/m) and twist angle (0.25°/m) indicate continuous tapering and twist of the blade towards its tip (Fig. 4). Together, these form factors allow for smooth shape transitions along the blade length. Thus, construction elements recovered from the midspan section will have relatively straight shapes, despite their aerodynamic origins.

To find the types of construction elements and their properties, the blade structure was reconstructed for Section 8, as shown in Fig. 6 and Table 3. This section is positioned in the middle of the blade, at radius r=28.15m (Fig. 5). Here, airfoil DU25-A17 is used with a chord length of 4.01m. Two composite layup structures were used: a sandwich layup for the panels and shear webs (2, 4, 5 and 6), and a monolithic laminate for the spar caps (3) as well as bonding areas at Leading Edge and Trailing Edge (1 and 8). This structural design provides a starting point for segmentation.

As a starting point for the patterning, the blade cross-section can be divided into two types of construction elements: panels (63 wt%) and beams (33 wt%). Panels can be recovered from the leading edge panels, shear webs, trailing edge panels and reinforced trailing edge (2, 4, 5 and 6). Beams are found in the spar caps (3). Alternatively, the spar caps and shear webs can be retrieved as-is, to be reused as box-beam. In this study, we chose to take them as separate parts, as this permits a clearer structural comparison.

Some cutting losses will occur, caused by the adhesive bonding areas (3 wt%), tapering of the panels due to decreasing chord lengths (1 wt%) and processing (minimal). The adhesive bonds at the leading edge and trailing edge (1 and 8) obstruct recovery of construction elements. These

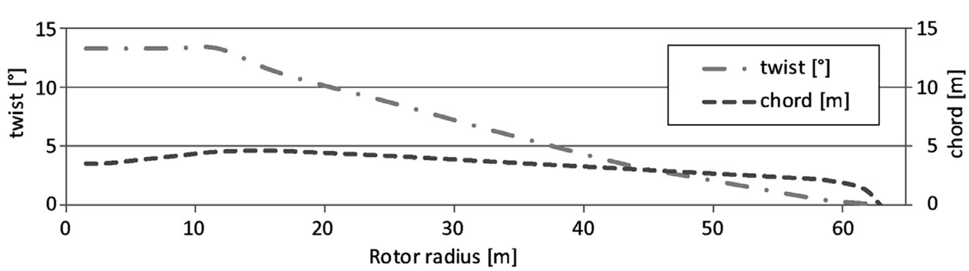


Fig. 4. Twist angle [°] and chord length [m] of the airfoil profiles along the blade length.

Table 3
Parts, weight, weight percentage, structure and construction element types found in blade segment 8.

#	Part	Materials	Mass [kg]	Weight [wt. %]	Element type
1	Leading Edge	Solid GFRP, adhesive	17	2%	None
2	Leading Edge Panels	Sandwich	151	14%	Panel
3	Spar caps	Solid GFRP & CFRP	340	33%	Beam
4	Shear webs	Sandwich	132	13%	Panel
5	Trailing Edge Panels	Sandwich	304	29%	Panel
6	Reinforced Trailing Edges	Sandwich	73	7%	Panel
7	Cutting losses (tapering)	Sandwich	16	1%	None
8	Trailing Edge	Solid GFRP, adhesive	9	1%	None
	Total		1042	100%	

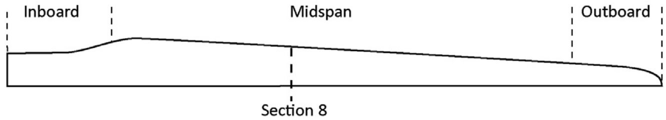


Fig. 5. Sketch of the blade and its sections. Cross-Section 8 is used for further analysis.

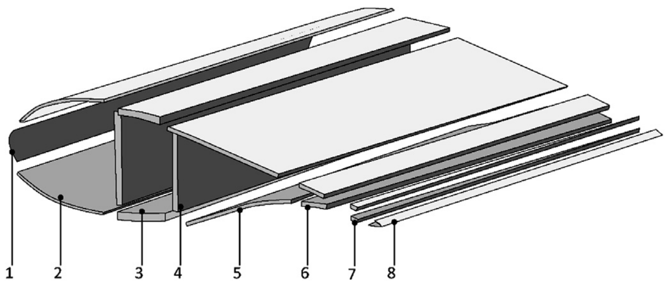


Fig. 6. Structural segmentation of the blade.

parts have a mixed materials composition, a strong curvature, and the structure transitions from sandwich to monolithic. Moreover, physical inspection of a decommissioned blade revealed poorly defined bonding areas and abundantly applied adhesives, which challenges the recovery of uniform materials. Tapering of the blade results from decreasing airfoil chord lengths and causes triangular shaped offcuts (7). For the weight calculation, we assumed these to be deducted from the trailing edge reinforcements. The processing losses were found to be negligible; the waterjet cutter used in the application test had a jet diameter of 0.7 mm, and thus minimal cut losses. As such, these were not further taken into account. Still, even after excluding these bonding areas and offcuts, 96% of this section could be cut into reusable construction elements.

However, it is not realistic to assume that 96% of the complete blade can be reused; this estimate is based on a profile in the blade midspan, which constitutes 58% of the complete blade mass. The blade root (40 wt%) and tip (2 wt%) cannot be directly segmented into construction elements. The root is a cylinder with an average diameter of 4m and length of 10m, it is challenging to cut due to its thick and solid GFRP walls. The blade tip is made of relatively flat airfoils but is pre-bent to prevent tower collision. This pre-bend adds to the shape complexity and thereby complicates segmentation and reuse. Thus, focusing on the blade midspan, and accounting for offcuts, we expect up to 55 wt% of the blade can be segmented into construction elements.

The original design determines what kind of construction elements can be recovered in terms of size, shape and structural layup. These properties gradually taper towards the tip of the blade which leads to a large distribution of properties of the recoverable construction elements. In addition to properties imposed by the original design, the reuse application can also present design requirements. These requirements are usually defined in terms of size, mass, stiffness and strength, accompanied by tolerances and safety factors. These can then be used as boundary conditions for the segmentation pattern. To extend reuse opportunities beyond a single product, we used construction industry standards for this purpose [47].

The spar caps (3) and shear webs (4) are positioned directly above and aside from the blade reference axis, which is aligned with the maximum airfoil thickness. Along the midspan, the spar caps have a constant width of 0.6 m. The shape of these elements is predominantly determined by blade twist and layup thickness. A beam, cut from the spar cap will twist 0.002m per metre length, which corresponds to a “very small” dimensional deviation [47]. Thus, beam elements can be recovered directly from the spar cap. The surface panels (2, 5 and 6) however, have a more complex double-curved shape and need further assessment. Table 4 and Table 5 show the results for segmentation using the two boundary conditions, based on curvature

Table 4
Segmentation patterns using curvature *d/w* as boundary condition.

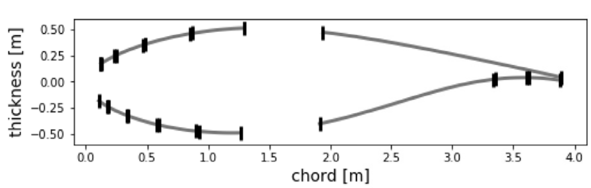
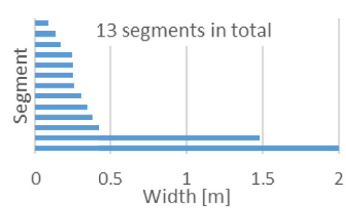
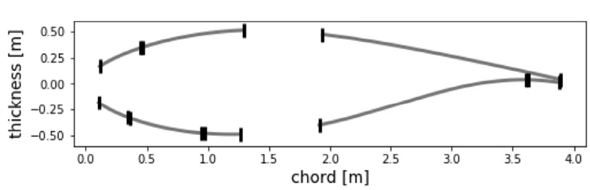
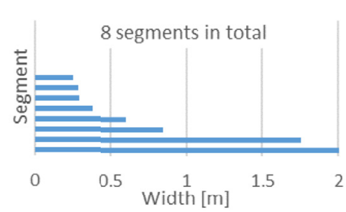
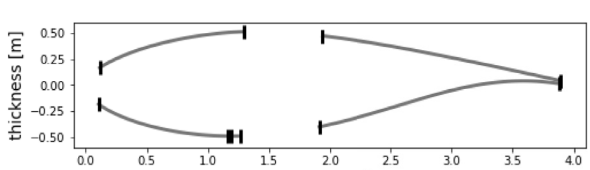
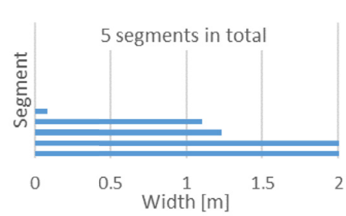
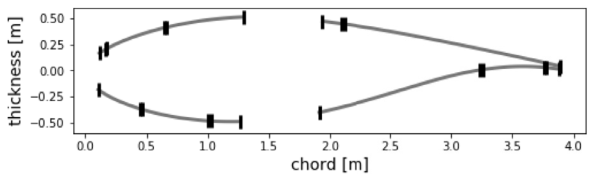
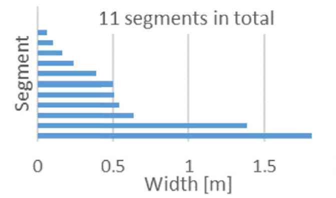
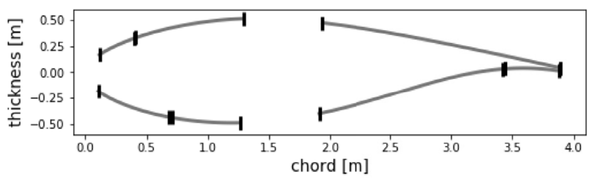
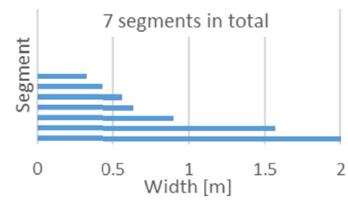
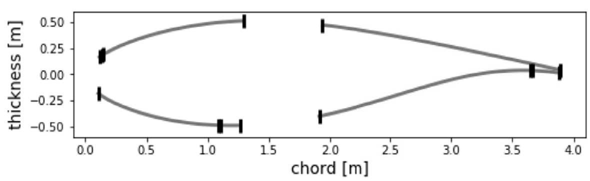
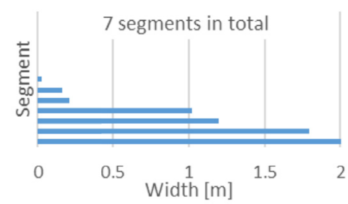
d/w	Segmentation pattern for maximum curvature, *d/w*	Segment width *w*
0.02		
0.04		
0.08		

Table 5
Segmentation patterns for maximum panel deflection *d*.

d [m]	Segmentation pattern for maximum deflection, *d*	Segment width *w*
0.02		
0.04		
0.08		

d/w and deflection *d,* for tolerance criteria small, medium and large, respectively.

Table 4 shows the segmentation patterns and resulting segment widths for blade Section 8 with *d/w*<0.02, 0.04 and 0.08 respectively. *d/w*<0.02 results in 13 segments, ranging in size from 0.08 to 2.0 m . The strongly curved leading edge section is divided into 9 panels with widths under 0.5 m. In the trailing edge section, we find two large panels of 1.5 and 2.0 m and two smaller segments. This clearly shows how curvature affects segment width: a strong curvature makes for narrow segments. *d/w*<0.04 results in 8 segments, with four small panels around 0.3 m wide, two medium-sized of 0.6 and 0.8 and two large panels of 1.8 and 2.0 m. For *d/w*<0.8 we found 2 panels of about 1.2 m and the trailing edge divides into two panels of 2 m. Unexpectedly, this pattern also delivered the narrowest segment for these boundary conditions, just 0.08 m wide.

Such a narrow segment is the result of the chosen patterning approach. The leading edge panel is now divided in a panel with a curvature of 0.08 and a small “leftover” piece. This indicates an opportunity to improve on the segmentation pattern; by not going for the maximum possible width, the leading edge panel could be divided into two or more smaller panels with a lower curvature. This is shown in the cutting patterns for *d/w*<0.04 and *d/w*0.02.

As was to be expected from the airfoil curvature, the narrow segments are found at the leading edge, and the wider segments at the trailing edge panels. The maximum width remained the same for all tolerance bounds, as this part is confined between the spar cap and trailing edge bonding area. Where the lower tolerance criterion results in a set of distributed widths, the upper tolerance level results in a segmentation pattern that almost directly follows from removing spar caps and bonding areas. However, this increased width comes at a cost; the wide panels have a large curvature which may limit application areas where the panels can be reused.

The boundary condition on deflection *d* showed similar results. Table 5 shows the segmentation patterns for Section 8 with a maximum deflection *d* of 0.02, 0.04 and 0.08 m. *d*<0.02 m resulted in a pattern of 11 segments, most of which were below or just above 0.5 m wide. The trailing edge section delivers two wider panels of 1.4 and 1.8 m. *d*<0.04 m resulted in 7 segments with widths almost evenly distributed between 0.3 and 2.0 m. Lastly, *d*<0.08 m also has 7 segments, two of them are around 0.2 m wide, two around 1.1 m, and the largest at 1.8 and 2.0 m. Here again, the largest tolerance bound resulted in the narrowest segment, just 0.02 m wide. Considering the tapering of the blade and cutting tolerances, a narrow strip like this is likely to be lost in processing.

The narrow segments found in *d/w*<0.08 and *d*<0.08 m were for the same reason: the leading edge panel deflection was just outside of the given tolerance bound, and was thus divided in a piece of maximum width, and a very small remainder. A better option would be to divide the panel into two or more elements with a lower deflection. Thus it may be beneficial to apply multiple boundary conditions on a given cross-section to optimise the cutting pattern.

The varying segmentation patterns provide insights in the relation between boundary condition and panel width. The segmentation approaches show that the blade panels can be reused within standardized tolerances. However, it also resulted in a range of variable panel widths and some un- or barely usable segments. Thus, to deliver practically reusable panels the boundary conditions need to be refined. To do so, commonly used panel widths can be imposed as an additional boundary condition. These standard widths can function as ‘bins’ when calculating the optimal pattern. Combining the boundary conditions of curvature and panel size will result in a segmentation pattern for construction elements with standard size and accuracy. The boundary conditions can then be used to explore patterns to find one that optimally uses the available material and delivers readily reusable construction elements.

3.2. Structural properties

With regard to the structural properties, we found four sandwich panel layups and one solid laminate beam in the blade mid span. Only the leading edge panel and the shear web have a constant layup along the blade, the other parts taper towards the blade tip by reducing the thickness of the core material and the number of plies. Table 6 shows the resulting ranges for thickness, density, flexural modulus and flexural strength of all blade parts. The minimum and maximum thickness are given for each part, because the thickness of the core material (foam) largely determines the effective material properties.

The following charts compare the blade segments to conventional construction materials, using the equivalent material properties. Fig. 7 sets out the Flexural modulus (E_{flex}) to the density (ρ). This charts shows that the blade materials have a flexural modulus comparable to timber. Fig. 8 plots the Flexural strength (σ_{flex}) versus density (ρ). Noteworthy is that the blade elements are characterised by their high specific strength (σ_{flex}/ρ). The spar caps are positioned in the top-middle in both charts, indicating a relatively high specific stiffness as well as strength compared to conventional materials. Both the panels and the beams do not fully overlap on both characteristics with other structural materials, thus direct substitution of other materials by the retrieved blade materials is not evident.

Using material indices, we compared the performance of the material in specific functions: panels and beams. The performance indices for a beam and panel of minimum mass, loaded in bending, are $E^{\frac{1}{3}}/\rho$ for stiffness limited design and $\sigma^{\frac{1}{2}}/\rho$ for strength limited design [44]. These indices are plotted as lines with respectively slope 3 (Fig. 7) and 2 (Fig. 8). The lines connect materials that have equal performance regarding stiffness and strength, respectively. Materials above the line exhibit better performance, while materials below the line perform less well.

For stiffness limited design (Fig. 7) timber is the only material with a material index similar to the recovered blade segments. As such, the retrieved materials outperform all other conventional construction materials for lightweight constructions loaded in bending. This indicates that structurally reused composites can be used to substitute timber panels and beams in bending-dominated structures, and that they will enhance performance compared to other materials.

For this reason, Ashby [44] and Beukers [2] argue for the use of composites in architecture. High-rise buildings especially require materials with a high structural efficiency, which composites can fulfil. Architects have now adopted composite panels for cladding building façades [8] and composites are gaining ground in infrastructural projects, for example in bridges and lock doors [50]. However, thus far the cost of composites in comparison to today's bulk construction materials remained prohibitive for large-scale implementation. Structural reuse however, has the potential to lower the material cost and as such unlock composites for application in building applications.

Fig. 8 shows performance for strength limited design. The blade panels are above the performance index line, the beams and timber are intersected by it and all other materials fall below. Thus, the blade panels outperform all other materials for constructions loaded in bending. The CFRP spar caps perform equal to some timber types. The spar cap position, to the top-left of GFRP materials, shows the higher strength and lower density of CFRP compared to GFRP.

Table 6
Properties of blade parts, calculated from blade design specifications, including safety factors, using Granta CES Edupack 2019. The equivalent density, flexural modulus, and flexural strength depend on the thickness of the sandwich, which is dominated by core material thickness.

Part	Thickness [mm]	Density ρ [x10^2 kg/m^3]	Flexural modulus E_{flex} [Gpa]	Flexural strength σ_{flex} [x10^2 MPa]
Leading & Trailing edge panels	26	5.6	9.8 – 14.6	5.1 – 8.9
	96	3.0	3.2 –4.7	1.6 – 2.8
Trailing edge reinforced panels	26	5.9	15.1	5.1 – 8.9
	103	4.1	6.7	1.6 – 2.8
Shear web panels	54	3.2	2 – 3	2.8 – 4.9
Spar cap beams	20	16.5	37.1 – 64.9	7 – 11.7
	48	16.1	52.2 – 99	8.1 – 13.3

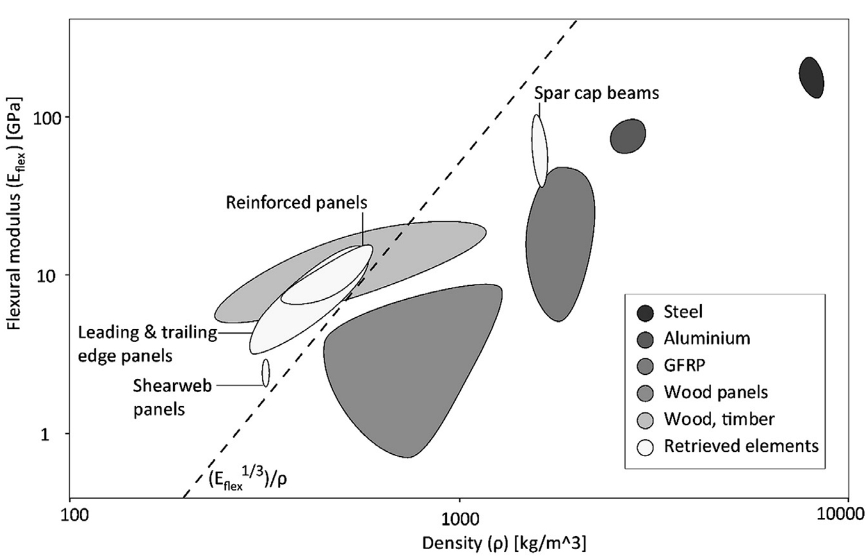


Fig. 7. Comparing conventional construction materials to retrieved blade elements on Flexural modulus (E_{flex}) vs. Density (ρ).

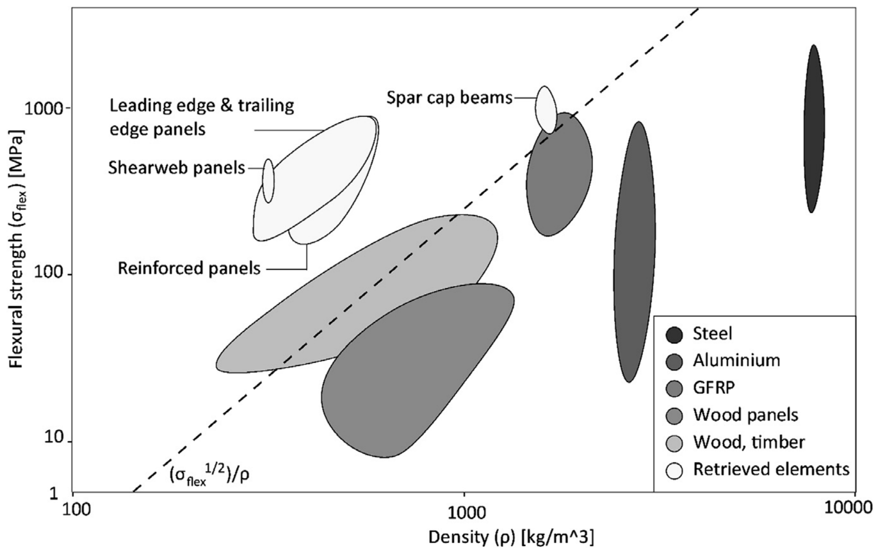


Fig. 8. Comparing conventional construction materials to retrieved blade elements on Flexural strength (σ_{flex}) vs. Density (ρ).

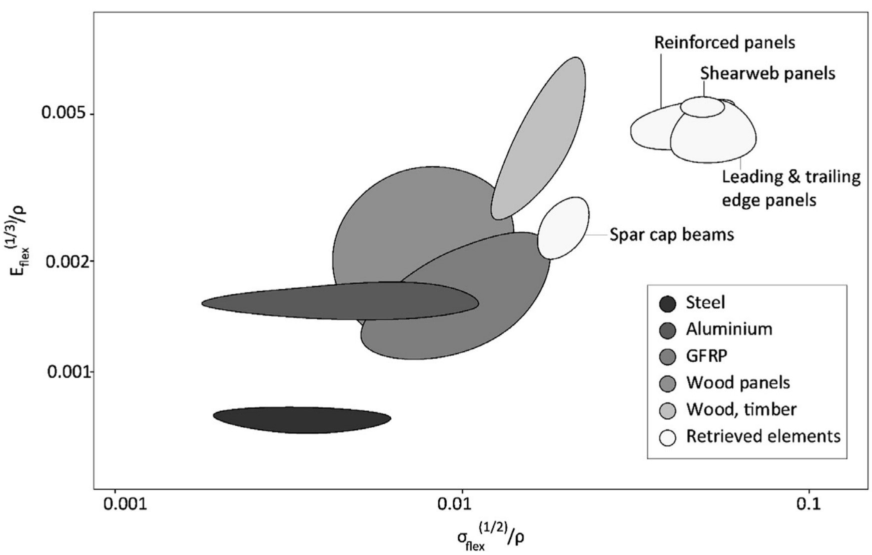


Fig. 9. Comparing the stiffness and strength performance of conventional construction materials to retrieved blade elements for a construction loaded in bending.

Fig. 9 sets out the material indices for lightweight design; the vertical axis for stiffness-limited design, and the horizontal axis for strength-limited design [44]. The best performance, minimum mass for a prescribed stiffness and strength, is found when maximising the indices; at the top-right of the chart. Even though timber can achieve higher performance for stiffness limited designs, the blade panels excel in strength-limited designs. All panels are found at the top-right of the chart, which indicates these provide the best combination of stiffness and strength for lightweight designs. As such, the retrieved construction elements outperform all other materials for a lightweight construction loaded in bending.

The shape and material properties of the retrieved segments are most reminiscent of panels and beams found in construction, infrastructure and, in smaller sizes, furniture. Indeed, the occasional applications for which these materials have been used are mostly found in these sectors [28,29]. This “occasional” application is attributable to the restrictions imposed by the original size and shape.

The safety factors were used to calculate the expected range of material properties. These were used on the assumption that the blade would still be in safe operation at the point of decommissioning. Still, the material will have suffered from fatigue and potential impact damage. This range could be further narrowed down through modelling and inspection [51]. However, determining the degradation of material properties through fatigue and the extent of damage is challenging for composites [52,53]. Insights from the fields of fatigue life prediction, structural health monitoring and damage inspection could improve the definition of post-use material properties. Also, identified weakened areas could then be excluded from the cutting pattern.

Using curvature to determine a segmentation pattern and to evaluate structural quality using material indices were promising first steps that can be developed further. Structural analysis shows that the retrieved materials have excellent properties in comparison to conventional construction materials. However, the structural shape of the composite product is already defined, while that of raw materials can still be chosen. In the structural comparison charts, shape factors can be used to expand the material envelopes [54], but such an extensive comparison is outside of this paper’s scope. The defined shapes also affect finding the right application for the construction elements, a process that needs to be further explored.

3.3. Applications

In addition to the size and structural performance, we need to consider the practical usability of the material. For reuse in practice, the

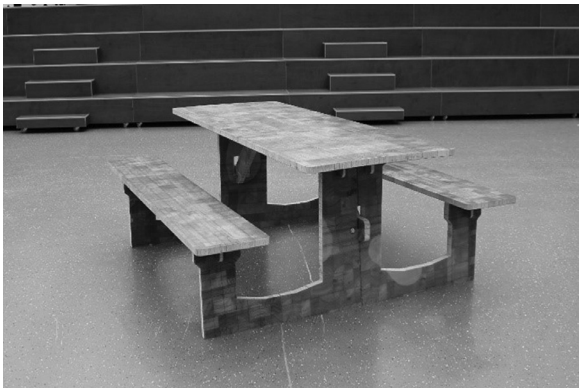


Fig. 10. Picnic table, made of recovered blade segments.

construction elements will have to be machined (cut to desired size and shape), joined and finished. We tested structural reuse in practice, by designing and building a simple furniture product from a wind turbine blade, retrieved from a recycling company (Figure 10).

Cutting cured GFRP laminates requires specialised equipment. When developing the furniture, we consulted a number of workshops for producing the prototype, but none was willing to process the material. The main objections were: tooling degradation, personal health and safety, and contaminating the dust extraction system and machinery with GFRP residue. This reflects the concerns raised on reprocessing wind turbine blade material in earlier studies [28,29]. We found waterjet cutting to address these concerns; there is no risk of tooling degradation, and dust is collected in the water filtration system.

The prototype was produced in two steps. First, the blade parts (spar caps, shear webs and panels) were separated using a portable waterjet cutter at the recycling company. Then, we had the components cut out from the panels using a CNC waterjet cutting table. These cuts were made perpendicular to the panel chord, which resulted in near-rectangular part cross-sections, especially for relatively flat panels. Overall, we found that waterjet cutting delivered good cutting quality, high accuracy and few cutting losses (the jet diameter was 0.7 mm.). The piercing points however, where a cutting track starts, needed to be predrilled, to prevent pressure build-up between core and bottom laminate, and thereby delamination of the GFRP faces from the core material.

Three connection types were used in the construction of the table, where special attention was paid to preventing water ingress during use and maintaining structural integrity. Slotted joints were used to minimise screw holes, and adhesive bonds were used to eliminate joints on exposed, horizontal surfaces. Fasteners, placed on unexposed positions, were used to facilitate dis- and reassembly.

This construction was chosen because the largest threat to the product in its use phase is the environmental exposure. The core material of these sandwich panels was balsa wood, which is prone to moisture degradation. And the matrix material, epoxy, is sensitive to UV ageing. So by ensuring no holes on exposed surfaces, the risk of water seeping in was minimised. A coating will shield the materials from humidity and UV radiation. The loads during use will not cause any problems, because these are well below those in its initial application in the wind turbine and the material safety limits.

The picnic table can be disassembled at the end of its use phase. Then, large parts can be reused, because these are still structurally sound and largely unaffected by the cutting pattern, smaller components can be processed in the GFRP recycling stream, as no additional or foreign materials are added or connected. From this application, we learned structural reuse is feasible in practice. The blade delivered reusable construction materials, which were processable with high accuracy, using the right tooling.

Prefab building could be another application area for the recovered construction elements. A typical timber frame building uses timber beams and wood panels. These parts are fabricated to specifications, enabling quick assembly on-site. The segmentation pattern complied to timber construction standards, and panels sizes were in line with trade standards. The panels can substitute the timber as well as wood panel parts given their structural performance. The need for specialised cutting equipment is solved by pre-fabricating parts and eliminating on-site rework. The gains made in weight come to the benefit of transport and installation. Prefab construction sees wide-spread use in various building types, including roofing and industrial warehouses, as well as public buildings and housing. Thus, concerning dimensional standards, structural quality, processing and scalability, we expect prefab building to be a promising sector for reuse of blade segments.

The segmentation patterning method, structural analysis and application example provide insights into what is needed for structural reuse. The reuse of construction elements relies on the availability of product specifications. Determining segmentation patterns requires data on overall dimensions and (aerodynamic) shapes. The structural comparison needs materials and layup schedules which also implies identification of the product and collaboration along the value chain, to retrieve this information. These factors may seem evident, but in industry practice, intellectual property and commercial considerations may prevail over sharing information among stakeholders. Moreover, the use phase inflicts wear, damage and fatigue on the product, introducing additional uncertainty about residual material quality at end of use. Additional information on the material state, e.g. through (embedded) monitoring, inspection and certification may reduce these obstacles.

The design of wind turbine blades is driven by aerodynamic and structural performance; there is no room for design adjustments that impair these elements. The design aspects presented here do not need to have adverse effects on product performance, as they are largely contextual and easy to implement. Thus, the recovery potential for a such a complex composite product as a blade, can be improved by relatively simple interventions:

1) Documenting product specifications
2) Enabling traceability through identification
3) Sharing information along the product value chain

3.4. Future research

To improve on the proposed approach, further research could expand on additional product (sectors), more detailed product features, boundary conditions and design for reuse. Other sectors, like marine and aviation, also use high end composite parts, and face similar end of life challenges. Further research could detail structural reuse of parts from these sectors. Additional product features to include could be composite layup schedules, 3D shapes, connections and sub-assemblies. The segmentation boundary conditions could also be expanded to meet requirements for successive applications more accurately. Where possible, elements of the approach could be implemented in the design of new products, to prepare them for reuse.

The presented structural reuse process could be adapted to variations in blade design and materials composition, which vary per model and manufacturer. For example, the NREL blade used safety factors for onshore deployment based on IEC standards [55]. These factors will have to be adapted for analysis of blades using other standards, such as DNVGL-ST-0376 [56]. Also, as blades get larger, use of carbon fibre reinforcements increases in spar caps and shells [34]. This improves the mechanical performance of the recovered segments, and thereby their economic value. Also, the size, configuration and number of shear webs may increase with blade length [57]. This affects the boundary conditions of the cutting pattern (i.e. cutting lines along the spar caps) as well as the reuse opportunities. Bank (2018) explored direct reuse of these as doors and window frames [58].

A segmented blade concept [59] may facilitate reprocessing, while at the same time introducing bonding areas which are difficult to reuse. An integrated blade concept by contrast, could improve the reuse rate by eliminating bonding areas at the leading edge and trailing edge [60]. Although the presented segmentation approach could be adopted to meet these variations, this further signifies the need for available design documentation at the reuse stage, in order to define optimal segmentation patterns.

To improve the reuse rate, recovery of the root and tip sections need to be further investigated. This could be structural reuse as other construction element types or applications, which are in line with the geometry and material characteristics. Alternatively, other recovery routes may need to be found in the domain of thermal, chemical or mechanical recycling.

Future research could also pursue more ambitious applications for structural reuse. The reuse case in this study, furniture, served to evaluate the process and manufacturing in practice. The expected loads were well within the material specifications. Building on the insights of the structural property evaluation and additional materials testing or modelling will enable reuse at the materials full potential.

Structural reuse adds another use cycle, and thereby extends the material lifespan. This preserves energy and value embedded in the composite, and potentially substitutes use of virgin materials. To fully close the resource loop, recovery routes in terms of reuse or reprocessing of the construction elements need to be further investigated.

4. Conclusion

In this study, we explored a systematic approach for structural reuse of complex composite materials. Structural reuse is complicated by the large size, complex shape and complex material composition of composite products. To address this, a systematic method was needed to define segmentation patterns and evaluate structural quality.

We proposed an approach for the structural reuse of complex composite products through segmentation, structural analysis and reuse applications. We applied this approach to a typical wind turbine blade made of glass and carbon fibre composite. The segmentation pattern showed that high accuracy construction elements can be cut from a double-curved product, in such a way that 95% of the analysed blade section, and 55% of the complete blade are eligible for reuse. The structural analysis revealed good performance in terms of flexural stiffness and flexural strength in relation to weight, with the retrieved panels exceeding the performance of conventional construction materials for constructions loaded in bending. Reuse of blade panels in another product showed the need for specialised cutting equipment, and delivered accurately dimensioned parts.

A number of design aspects limit retrieval of construction materials from end of use wind turbine blades. Converting a large structure into smaller, reusable segments, relies on availability of model details to generate cutting patterns. The materials' fatigue behaviour and (variations in) operating conditions complicate determining residual structural quality, signifying the need for structural health monitoring. These design aspects are mostly contextual in nature, and could be addressed without infringing the performance of the blade in its initial use.

To facilitate recovery of construction materials, designers can address structural reuse by documenting product specifications and facilitating traceability. During product life, reuse is supported by collaboration along the value chain and reducing uncertainty about the product's state through e.g. monitoring or inspection. Testing the structural reuse approach in a furniture application showed its feasibility. In addition to identifying relevant design aspects, the presented segmentation and structural analysis approach brings a new perspective to structurally reusing composite products.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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