Re-use of wind turbine blade for construction and infrastructure applications

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Abstract. To achieve a more resource-efficient society with a future with reduced carbon dioxide emissions, new technological challenges must be dealt. One way to reach a more sustainable world is to start re-using end-of-life structures and waste and give them a "Second Life" with a new function in the society. As composite structures are lightweight, strong, stiff and durable materials, there is great potential to re-use decommissioned composite for new resource-efficient solutions in the building and infrastructure sector. The present paper investigates innovative solutions in re-using wind turbine blades as elements in new bicycle and pedestrian bridge designs. Several conceptual bridge designs where wind blades utilized as load bearing elements were developed and studied. The main design requirements for pedestrian bridges were considered and assumptions regarding wind blades quality and their mechanical properties addressed based on interviews with industries working with wind turbine blades repair and recycling. The aim of this paper is to contribute to a sustainable use of fibre reinforced polymer (FRP) waste and at the same time provide a more cost-effective FRP bridges. In a larger perspective, the authors would like to highlight the economically profitable potential of recovering and reusing / re-manufacturing end-of-life glass FRP composites.

1. Introduction

In 2017, 1118 kilotons of glass fibre reinforced polymer composites (GFPRs) were produced in Europe, of which 40 kilotons in the Nordic region, which showed an increase of 10% since 2012. At the present, GFPRs represent 98% of the composite market in the boat and wind turbine sectors [1]. In the wind turbine sector only, it is estimated that the amount of GFPR products reaching their end-of-life (EoL) in the coming decades will be considerable [2]. This is a major concern in terms of sustainability as reuse or recycling of GFPR is rarely considered in the industry today. Current EoL GFPR parts are either incinerated to produce heat (over 100€/ton) or are discarded in landfills with detrimental effect on the environment [3-5].

Wind energy is currently one of the fastest growing renewable energy sources and is expected to increase in the future. The lifetime of a wind turbine, whose blades are mainly made of GFPRs, is approximately 20-25 years, which will lead to a large number of decommissioned turbines in a near future. By 2025, about 36 000 blades in Europe are expected to be dismantled, which corresponds to 240 000 tons of polymer composite waste [6]. Today, there is no sustainable and efficient solution to recycle these structures, as they are complex to recycle [7-8]. If the EoL treatment is not addressed in a sustainable way, wind energy cannot be fully considered as sustainable energy source. Therefore, new solutions to undertake these growing issues must be developed [9]. These challenges are global, and solutions used currently are far from the idea of considering waste as a resource (figure 1)
Figure 1: Landfill of EoL wind turbine blades in USA [10].

The recent EU directive from 2015 (2000/53 / EC) suggests that 95% of the EoL/waste should be reused or recycled. In addition, new strict EU directives against landfill have been legislated. Therefore, new technical solutions for reusing and/or recycling of GFRP composites must be developed. Considering the low cost of new glass fibres (1-2€/kg), re-use of EoL GFRP seems to be a more economically promising and viable alternative.

Simultaneously, an increasing demand on FRP lightweight structures has been observed in transport and infrastructure applications in the last decade [11]. In addition, the market for pedestrian and bicycle bridges is rapidly growing in Europe as policies promoting shift to healthy and sustainable mobility are introduced. FRP bridges are proven to be the one of the best alternatives for infrastructure owners when considered in LCCA (Life-Cycle Cost Analysis) [12]. In remote locations the lightweight FRP bridges are the perfect solution due to little needed maintenance, and in highly populated areas due to their fast installation where they offer significantly reduced traffic disturbances. However, the initial investment cost is often a barrier for selection of this solution [13].

The development of “circular economy-based design of FRP bridges”, where decommissioned GFRP parts are used as base production material, will address both the issue of sustainability in dealing with GFRP waste handling, as well as decreasing investment cost for FRP bridges. The possibility of prolonging the service life of GFRPs while at the same time minimizing their impact on the environment is considered highly favorable and industrially relevant. To this end, investigations to develop innovative pedestrian and bicycle bridge concepts where the base material is EoL wind turbine blades has been carried out.

2. State-of-the-art

So far, very few research projects have been investigating this area. The reason probably being that the problem related to managing EoL wind turbine blades was not as obvious as it has become today. A thorough and inspiring study investigating conceptual design in reusing wind turbine blades for a slow traffic bridge was presented in 2018 at Delft University [14]. The conceptual design included connectors, railing, deck, as well as preliminary structural analysis for performance and safety.

Re-Wind project is an ongoing collaborative project between US and Ireland. It investigates the conceptual re-use of FRP wind turbine blades for housing, buildings, infrastructure, landscape and public art applications [15-16]. The results of the study showed a great potential for the construction industry, and the process of re-purposing decommissioned FRP parts such as wind turbine blades is shown to be a very sustainable way of handling FRP parts reaching EoL. However, the authors clearly indicate that further studies should be conducted to clarify aspects such as structural analysis, logistics, detailing, cost and ease of dis- and re-assembly; social accessibility and acceptability, together with quality control were also identified as paramount aspects to investigate.

Wild project is another ongoing project in Aalborg, Denmark, where two decommissioned blades are planned to be used for the construction of a pedestrian bridge, see Figure 3b [17]. The procurement
procedure has been conducted by the municipality of Aalborg. This could be the first pedestrian bridge of this type in the world. In both projects, industrial partners are actively participating, showing a clear industrial interest of finding a solution to the management of EoL blades.

Figure 2: Concept Design of a bridge made of wind blades [14, Stijn Speksnijder].

Figure 3: (a) Concept bridge – Re-Wind project; (b) Blade bridge in Aalborg – Wild project; (c-d) Playground and benches in the Netherlands (Superuse Studios, Denis Guzzo)

Some companies have already realized the potential of “mining” their raw material in the mountain of decommissioned blades to come. Innovative design solution is the key as geometry and properties are already assigned. Superuse Studios, a Netherlands based company has developed some interesting designs and construction of structures made of re-used wind turbine blades, see figure 3c-d. These constructions are the only projects within re-using wind turbine blade in new application that have been built. Other projects are mostly at the conceptual design phase [18].

In Sweden, the need to develop knowledge and increase the expertise on recycling processes for FRP composites to reduce the future environmental impacts has also been identified [19]. At the present, the biggest problem for the recycling of FRP is the economic factor, therefore more basic research must be given priority in order to enable the development of new technical solutions that increase resource efficiency and thereby the new players’ interests.

In parallel, we observe a rapid growing interest in using FRP for new infrastructure applications, mainly due to a large number of bridge structures which are in need for immediate and costly maintenance work [20]. In Sweden today, about 2500 bridges are in need for major deck rehabilitation or replacement [20]. These figures underline the fact that the low maintenance and sustainability aspects must be central for future bridges.
Several projects investigating FRP bridges and recycling of FRP material have been conducted by the authors during the past years. The recently concluded research project FALCON [13] investigated Future Lightweight Composite Infrastructure in Sweden and created the condition to build Sweden first FRP bridge in Malmö in June 2019. In the pilot project RECYTAL [21], investigations on the potential of recycling / reusing defective and EoL GFRP composite insulators as reinforcement in cement and new composite products were carried out. It was demonstrated in the project that FRP elements can be ground down and used as additive materials both in new composite products and in concrete. However, the economic potential was identified somewhere else, through a short investigation on the re-use of these composite insulators as load-bearing components in the construction industry where several tons of EoL FRP materials can be consumed in one application. Four partners of the FALCON project are today working on the RECINA project [22] based on the result obtained from RECYTAL. The focus is on reusing the decommissioned composite insulators to design a composite pedestrian bridge deck.

Reuse means to either extend the products lifetime, or to reuse it in a new product by taking advantage of its original design purpose. The most promising solution for decommissioned wind turbine blades today is refurbishing [23]. This solution is also consistent with the European waste hierarchy where reuse is the second best alternative. Indeed, the blades show good mechanical properties after 18 years in service according to Sayer et al. [24]. The polish-based company Anmet also performed a full-scale test of decommissioned blades and the results showed that the blades still had a lot of capacity left [25].

The intrinsic mechanical properties and value of decommissioned blade is still high, while handling of waste is expensive for the manufacturers and producers. This clearly creates an incentive to find a new function for the blades in a secondary market. Wind turbine blades are designed to withstand shear and bending stresses along their entire length, a property that is useful in pedestrian bridges. In this study, the focus will be on the development of preliminary conceptual design for pedestrian bridges.

3. Conceptual designs of pedestrian bridges

3.1. Typical wind turbine blade material and structure, and the Sandia blade model

Wind turbine blades are mostly made of glass fibre reinforced polymers (GFRP), but newer blades contain even stiffer carbon fibres that allows the design of longer blades. High strength and stiffness, lightweight and durability are features that differentiate polymer composites from other materials. High costs are usually associated to the use of carbon fibre, but glass fibres are available at very competitive cost. The matrix used is a thermoset of different types (epoxy, polyester, vinylester ) depending on the blade manufacturer. The full list of components contained in the blade is almost never disclosed, which complicate the EoL processing. In the case of re-using the blade for structural applications such as pedestrian bridge, one of the challenges will be to determine the quality of the blades and its mechanical properties, without knowing the exact composition.

For most in-service blades today, the construction is made of a shell structure and a load bearing structure. The shell structure is often made of sandwich GFRP, with core materials at different position made of balsa wood or foam material such as PVC. The load bearing stiffeners, that are positioned along the whole length of the blade, give the blade its stiffness and strength. They can be of three different types, mainly single shear web, double shear web or box beam. Adhesive bonding is usually used to attach the shell structure to the stiffeners [14].

The initial idea in the current study was to work with Vestas-V90 which is the most common type of wind turbine in Sweden. However, due to the insufficient information about this blade, it was decided to work with the open-source blade model from Sandia National Laboratories where geometry, material data and FE models are available for research studies. The blade model used in the current study is the SNL100-00 from [26]. This blade has three shear webs and integrated spar caps. To get a comparable size to the Vestas-V90, the model of the SNL100-00 was scaled down to half. Estimations were made on the material thickness, and a parametric study was performed to obtain a range of results (deflection and frequency).
3.2. Brainstorming, ideation and evaluation of potential concepts
To identify as many potential design concepts as possible, a brainstorming with architects was conducted. The pros and cons for each concept were analyzed and the most promising concepts were thereafter investigated more thoroughly. Generally, all the concepts had a 20 m span and a 4 m wide deck as it is the recommended width for a shared pedestrian and bicycle paths.

| Concept 1: Use four blades that carry the load in the edgewise direction. Beams will be placed transversely between the blades to make the blades work as a unit. |
| --- |
| **Pros:** The vertical positioning of the blades provides the largest available bending stiffness. Also, more blades are re-used in this design. This is desirable as finding a purpose for the decommissioned blades is the origin of the problem. |
| **Cons:** The construction height. The full chord width of the blades needs to be considered, which is approximately four meters. Even if the smallest part of the blades is used, the chord length would still be approximately two meters. The conclusion drawn from this is that the blades should be positioned in the flatwise direction instead to reduce the construction height. The connection between the blades is also anticipated to be complex and time consuming to manufacture. |

| Concept 2: Use two blades placed in the flatwise direction as beams - bridge deck on top of the beams. |
| --- |
| **Pros:** The main advantage with this concept is a simple construction with a relatively low height. The blades are also positioned in a way that highly utilize their design intention. Furthermore, there is no connection between the blades which simplifies the construction. |
| **Cons:** As the blades have a varying cross section and are positioned in the opposite direction of each other, the cross section of the bridge will be asymmetric. The blade will deflect more on one side of the bridge deck and torsional forces in the bridge deck are introduced. Furthermore, due to the uneven shape of the blades the connection to the bridge deck becomes even more complicated. This concept also needs uneven level of supports. |

| Concept 3: A suspension bridge created out of four blades. The blades are leaning towards each other connected at the top to transfer shear forces between the blades and making them work together. In order to transfer the moment forces to the abutments, the blades have a fixed connection at their root. |
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| **Pros:** Large and spectacular construction, with an innovative design. This construction allows for longer span lengths as the blades can be used as cantilevers as they were designed for. |
| **Cons:** Probably the most complex of our concepts. Crucial details need to be addressed: The connections between the blades as well as the connections between cables and bridge deck are difficult and expensive to produce, maintain and inspect. In addition, large bending moments needs to be handled in the abutments. |

| Concept 4: An attempt to create a slender structure. Similar to concept two, although this connects the same section out of four blades to create a more constant and lower cross section. |
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| **Pros:** This concept has the lowest construction height out of all the concepts. Since the blades are joined together at mid-span, transportation of the blades to the site will also be simplified due shorter components. |
| **Cons:** Clamped foundations, which are used, are a more complex and expensive solution compared to having a simply supported bridge. The clamped foundation will be on both sides of the bridge which is not optimal from an economical point of view. |

| Concept 5: The two blades are attached to each other to create one single beam. By removing a part of the shell, the shear webs can be connected directly to each other. Mechanical connectors or adhesive bonding solution could be investigated. The bridge is intended to be simply supported. |
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| **Pros:** The two blades are working together. This leads to a simpler design for the bridge deck. |
| **Cons:** Complex joining of the blades, regardless of the method chosen (mechanical or adhesive joint). Adhesive requires planar surfaces, and bolts requires labor inside the blade where space is limited. |

| Concept 6: Two blades span the whole length. The blades are positioned the wide parts on one side and the narrow on the other. The thick end of the blade is clamped to the abutment while the other end has a roller support. |
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| **Pros:** This concept is clamped on one side which simplifies the construction. The bending moment curve follows the cross section of the blades. |
| **Cons:** Clamped foundation is an expensive and complicated solution, with complicated connection to the blade. The two blades are working separately. |
When choosing the concept for further studies, several aspects needed to be considered. A life cycle perspective was therefore applied where factors as initial cost, transportation, production method, usage and maintenance were roughly evaluated for each concept.

Concept one was eliminated in an early stage due to the unrealistic construction height. Concept three, the suspension bridge, was also eliminated early due to its complex details. These details would probably have led to an advanced production process as well as high construction and maintenance costs. The remaining concepts, two and four, were then further evaluated and improved to find the most promising alternative. This process resulted in concepts five and six. The connection of the two blades in concepts four and five was analysed as too complicated to construct and thus these concepts were eliminated. Concept six was realized to be the concept with the least complicated details as well as the simplest structural system. This is economically favourable as the production and maintenance costs will be kept low. The detailed design of concept six was therefore conducted.

4. Concept design detailing and preliminary analysis

As the final concept was chosen, all the details needed to be further analysed and designed. This involved how and where the bridge would be assembled, how it would be affected by the transportation and how to handle the boundary conditions as well as all the connections. During this process, it was realised that the initial clamped foundation was probably not necessary as it is more expensive and complicated than the simply supported solution. Therefore, the bridge was set to be simply supported to create a material efficient and economically attractive solution.

Apart from the blades which have been the focus in the concept design, the bridge deck, railing and connectors have also been investigated:

4.1. Bridge deck

The selection of a bridge deck depends on factors such as structural requirement, weight, initial cost, maintenance requirement and EoL management. Most of the time, the cost factor prevails, especially the initial cost. A pultruded FRP deck with box section was chosen due its strength and lightweight properties, its low maintenance cost and easy prefabricated production process as it simplifies the connections between the deck and the blades. Furthermore, a closed section reduces the wear caused by the surrounding environment and reduces the need for maintenance. On top of the bridge deck an acrylate coating will be used to achieve a suitable walking and biking surface.
4.2. Railing
The railing will be made of FRP. This is mainly to keep the self-weight low and the material in the bridge concept consistent. The railing is mounted on top of the bridge deck with a bolted connection.

4.3. Connectors
Wind turbine blades have a very irregular shape and thus a material to fill the void between the flat bridge deck and the curved blades is required (e.g. polyurethane support components). This can be achieved by casting on-site, 3D-scanning the blades and produce the part off-site or cutting a solid block to fit. A bolted connection can efficiently be used to connect the deck to the blade.

4.4. Preliminary numerical analysis
A preliminary numerical analysis was conducted on the blade. Both static and frequency analysis were carried out. The material data from [26] were used.

The analysis for the serviceability limit state showed that the deformation was well below the requirement whereas the fundamental frequency was lower than 5 Hz (4.1 Hz) so further studies on dynamic behaviour need to be carried out. Further analysis on the acceleration needs to be done. The thicknesses are in relation to the full Sandia blade model SNL100-00.

5. Conclusion and Future work
This paper reports the preliminary results of an investigation on the conceptual design study of a pedestrian bridge made of decommissioned wind turbine blades.

Based on the results obtained and knowledge gained, building bridges out of decommissioned wind turbine blades is considered as a promising solution. However, detailed calculations, and further investigations on the remaining capacity of the blades have to be conducted in order to validate the concept. There is especially a need to investigate closer the dynamic loading as the preliminary fundamental frequency was lower than 5Hz.

Even though reusing the blades in bridges is an efficient way of extending the lifetime of wind turbine blades, the problematic of waste management is only postponed during the lifespan of the new bridge. Developing a cost-efficient method to recycle the material in parallel is therefore still needed.

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