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1 Mechanical reuse and recycling of composites

1.1 Introduction

Composite materials in the context of a circular economy are a challenging subject. On the one hand, these materials allow for efficient materials use and long product lifetimes, on the other hand reprocessing at end-of-use (EoU) remains challenging. The majority of these materials are made with thermosetting polymers that cannot be melted and therefore the original components (fibres, resins) cannot be recovered without degradation. How to process composite products at the end of their use?

This chapter describes the mechanical methods for reuse and recycling of EoU composites and in particular structural reuse and mechanical recycling. The chapter starts with an overview of circular strategies for composite materials in Section 1.2. The subsequent sections describe pathways for mechanical reuse and recycling of composite materials. This starts with an explanation of the product build-up of the most important EoU composites in Section 1.3. Section 1.4 describes the first phase of mechanical processing and transportation of processed parts. Section 1.5 covers structural reuse and retrieving construction elements, followed by processing the material into oblong reinforcing elements in Section 1.6. Section 1.7 describes mechanical recycling of EoU composite products by grinding them into particles and fillers. The chapter concludes with a discussion (Section 1.8) and conclusions on mechanical reuse and recycling of composite materials.

1.2 Circular economy strategies for composites

The circular economy is an economic and industrial system, which aims to eliminate waste through restorative use of resources [1]. Resources are retained in the system rather than wasted by focusing on product, component, and material reuse [2, 3]. The circular economy strategies are prioritised according to their capacity to preserve embedded value and apply directly to the reusing of composite products or parts. Composite materials enable a long product lifetime because of the resistance to corrosion and fatigue [4, 5] and provide opportunities for lifetime extension through maintenance and repairs [5, 6]. Although the practice is not yet widespread, there are cases of successfully reusing products by refurbishing and remanufacturing of composite parts.

Routes for reprocessing materials into raw materials show some distinct aspects [4]. Composite materials differ from homogeneous bulk materials in the way they are processed and created, which directly affects the characteristics of the materials re-

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covery processes. The majority of composite recycling processes tend to break down the composite into its constituent materials, thus losing the specific composite material properties [4, 7]. In addition to losing laminate architecture and fibre length, many recycling processes severely degrade materials, hampering the economic viability [7]. As a consequence, the majority of composite material goes to landfill or is incinerated, losing the material and its potential for reuse [8]. There is an urgent need for composite reprocessing solutions that can capture and retain material quality.

Structural reuse and recycling were identified as strategies to preserve material integrity. Structural reuse takes place through repurposing, resizing (segmenting), or reshaping the product. These actions discard the original product function, but maintain the unique structural properties, determined by the combination of material composition and structural design [9, 10]. Experts and the literature both note that this approach preserves material quality and value with a relatively small investment of energy and resources [5, 9, 11]. Keeping materials in use is an effective way to store resources for a longer time.

On a smaller scale, oblong elements like strips or flakes that are processed from EoU composite products can be used for making new composite products [12]. In that case, the elements are embedded in a virgin resin to form profiles or other structures with high percentages of retrieved content. The original composite structure contributes to the material characteristics of the new composite product. Although this method requires more processing steps, it offers more possibilities for reprocessing of large quantities [13].

Recycling of composite materials starts with mechanical downsizing into process able parts, followed by further processing. Thermoset composite reprocessing is usually based on polymer degradation, aiming to separate and extract fibres and resins. These processes can be generally classified as thermal, (electro-)chemical, or mechanical recycling. In mechanical recycling, addressed in this chapter, the composite is further processed into fragments or particle-based outputs.

Table 1.1 shows the overview of circular economy strategies for composite-containing products. These circular strategies are complementary to each other. For

Table 1.1: Circular economy strategies for composite materials.

Design aim	**Preserving product integrity**			**Preserving material integrity**	
Circular economy strategies	**Long life**	**Lifetime extension**	**Product recovery**	**Structural reuse**	**Material recycling**
Actions/processes	Physical-durability Long use Reuse	Repair Maintenance Adapt Upgrade	Refurbishment Remanufacture Parts-harvesting	Repurpose Resize Reshape	Mechanical Thermal Chemical Remould

example, a product can be reused and refurbished multiple times before reaching the end of use. Then, a composite part can find subsequent uses through repurposing, resizing, and recycling. The strategies presented in this chapter can be complimentary to each other as well as to those discussed elsewhere in this book.

1.3 Build-up of end-of-use composites

For effective mechanical reuse, a composite product waste stream has to meet a number of requirements. The material must be available in large volumes to set up an efficient recovery process. Collection and logistics have to be available and compatible with both material and processing facilities. Finally, the material must have residual mechanical properties that make it intrinsically viable for reuse. This pertains material characteristics at the end of use; thus load history and environmental degradation should be taken into account. In this section, the main sources of EoU composite material is first discussed, followed by the build-up of the three most relevant EoU product groups.

1.3.1 End-of-use volumes

Table 1.2 shows the main sources of EoU composite materials in the Netherlands and Europe. A significant volume of these sources is directly available for mechanical reuse. Wind turbine blades and polyester boat hulls represent the largest annual volumes, followed by roof panels and feedstock silos. The first two product types are widely recognised as significant EoU composite product streams. Various estimates have been made for the quantities of end-of-life wind turbine blades and boat hulls in Europe. It is estimated that the volume of blades reaching EoU – stage will increase from approximately 15,000 tonnes in 2019 to nearly 500,000 tonnes in 2050 [15]. For boats, less data is available, but it is estimated that between 120,000 and 145,000 tons of fibre-reinforced boats are in need of reprocessing per year in the EU [16, 17]. Roof panels and silos represent significant volumes in the Netherlands and given the widespread use of both, likely internationally as well. Printed circuit boards present a large volume but are, like other sources discussed in the next paragraph, unavailable for mechanical processing. Although the estimates vary in magnitude and timing depending on the assumptions made, it is clear that large quantities of composite materials need to be processed annually.

Various other composite applications result in large EoU product volumes but are unavailable for mechanical reuse. Printed circuit boards (PCBs), for example, are built on a substrate of glass fibre-reinforced composite. The recycling process of printed circuit boards is predominantly aimed at recovering precious metals rather than composite materials [19]. Also, approximately 145,000 ton of pipes and tanks are

Table 1.2: End-of-use composite in the Netherlands and Europe [14–18].

Composite product	EoU composite product (ton/year)	
	The Netherlands	**EU**
Rotor blades of windmills	1,300	15,000
Polyester boat hulls	1,400	120,000
(Corrugated) polyester roof panels	1,000	Unknown
Silos for feedstock of cattle	800	Unknown
Printed circuit boards	3,400	400,000
Total	**7,900**	**≥535,000**

produced annually in the EU, but these have not emerged yet as a significant EoU stream. Similarly, infrastructural composites (bridges and lock-gates) have been introduced in the market within the last two decades. Given the physical durability of composite materials in combination with the desired long lifespan of the design of such applications, these products are still in use and not yet available for waste supply. Other composite applications are too dispersed in the market, challenging efficient logistic collecting. For example, composites used in sport equipment (e.g. snow boards and bicycle frames), luxurious parts (e.g. special Jacuzzi's and yacht parts), building components (e.g. dormers and facades), and parts of cars, trains, and airplanes (e.g. skirts and stiffeners). Thus, a range of composite applications follow a different path of EoU treatment which makes them unavailable for mechanical reprocessing, even though these represent a significant waste stream. All these products and PCBs are therefore not considered in this chapter.

Most of the product groups presented in Table 1.2 are eligible for mechanical reuse. Wind turbine blades and polyester boat hulls are potentially suitable because of the high level of mechanical performance of the composite in these products. The same goes for silos. The properties of silos of over 40 years old are practically the same as when newly moulded. Polyester roof panels, however, are unsuitable because these panels are too thin-walled and degraded after many years of service. Eroded by sunlight and moisture they will therefore not be considered for mechanical reuse according to the method as described in this chapter. Wind turbine blades, polyester boat hulls, and silos as the main materials of interest for mechanical reuse and their build-up will be addressed in the following sections.

1.3.2 Build-up of wind turbine rotor blades

Wind turbines have grown considerably over the past decades, both in number and individual power. The hub height and rotor diameter increased steadily, enabled by developments in materials and engineering. In the early 1990s, a typical wind turbine would have a diameter of 20 m, and by 2010 this already grew to 100 m [20]. The largest blade produced measures 123 m in length [21]. Larger blades provide not only a larger swept area but also higher tip speeds. These increase the power generated by the wind turbine, but also the demand on the blade's structural properties.

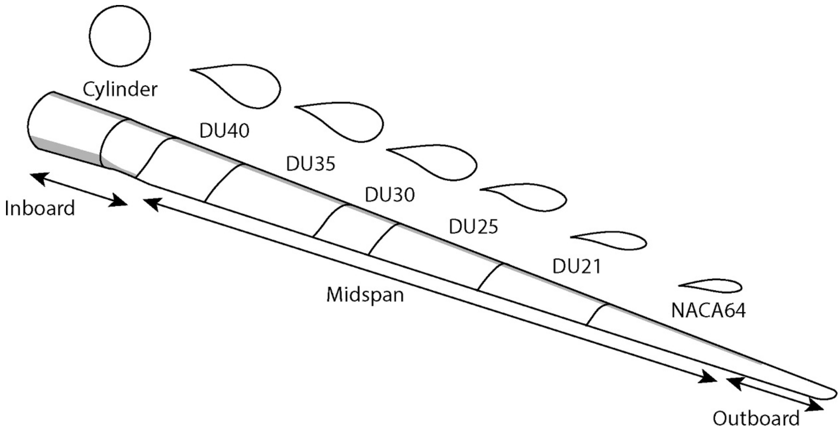

Figure 1.1: Schematic representation of NREL 5 MW blade, showing airfoils and main sections [10]. Reprint from Composites Part C: Open Access, 5, Jelle Joustra et al., Structural reuse of wind turbine blades through segmentation, 2021, with permission from Elsevier.

A wind turbine blade consists of three sections from root to tip: inboard, midspan, and outboard (Figure 1.1). The largest bending moment is exerted on the inboard section, where the blade is joined to the turbine axis. This is often a plain cylindrical shape made of a solid glass fibre-reinforced laminate. The midspan comprises approximately two-thirds of the blade length. A succession of airfoil profiles determines the blade's aerodynamic shape. 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.

When zooming in on the blade cross-section, the integration of aerodynamic and structural design becomes more apparent. The shells on the leading edge (1) and trailing edge (2), as well as the shear webs (3) use a sandwich structure to provide high stiffness for minimum weight (Figure 1.2) [22, 23]. The sandwich combines triaxial glass fibre face laminates with a core material, such as a polymer foam or balsa wood. The thickness of the sandwich panels decreases along the blade length. Gradually, by lowering the number of plies in the layup (ply-drops), or stepwise by selecting thinner core materials. The spar caps (4) have a monolithic, unidirectional layup to provide longitudinal stiffness to the blade. Adhesive bonds (5) join the upper and

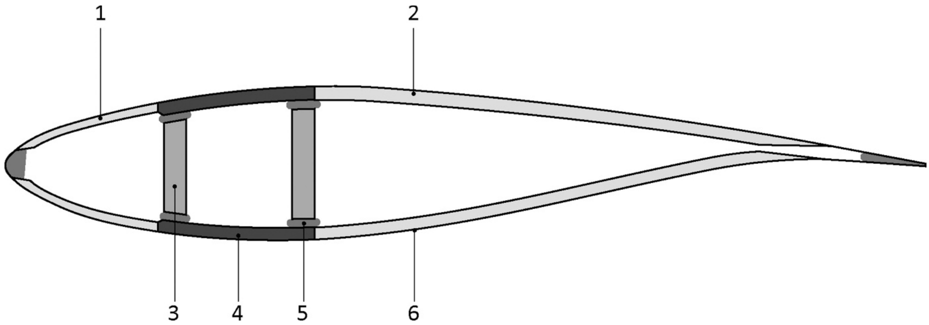

Figure 1.2: Sections in a blade cross-section: (1) leading edge shells, (2) trailing edge shells, (3) shear webs, (4) spar caps, (5) adhesive bonds, and (6) coating [24]. Reprint from Resources, Conservation and Recycling: 167, Jelle Joustra et al., Structural reuse of high end composite product: A design case study on wind turbine blades, 2021, with permission from Elsevier.

lower half of the blade, which are produced separately. A polyurethane surface coating (6) shields the materials from the environment and reduces wear.

Manufacturers use various material compositions, production technologies, and designs in their blades. While predominantly made of glass fibre-reinforced polymers, blades over 50 m in length also use carbon fibre [25] as unidirectional reinforcements in spar caps or hybrid weaves for the shells [23]. The variation is greater in terms of resins and clearly differs between manufacturers. Vestas uses epoxy, while LM Windpower mainly uses polyester [26, 27]. Covestro on the other hand develops and builds rotor blades based on polyurethane resins [28]. In conclusion, there is some degree of variation in compositions which may be relevant for reprocessing.

Technological developments in blade manufacturing are focused on increasing efficiency and lowering overall lifetime costs. While currently set at 25 years, some suggest extending wind turbine lifetime to 40 or even 50 years [29]. However, size and power increments described earlier also made repowering existing installations economically attractive [30, 31]. This means blades, or even complete wind turbines, may be replaced in favour of newer, more efficient models. Being replaced within their design lifetime, these blades are likely to be in sound physical condition when decommissioned.

1.3.3 Build-up of polyester boat hulls

Glass fibre-reinforced polyester (GFRP) has been the material of choice for many small watercrafts since the 1970s. The hull usually consists of a monolithic laminate reinforced with internal stiffeners [32]. The monolithic laminate of the hull is generally made of glass fibre-reinforced polyester. Various reinforcement types are used: random (laminated chopped strand mat or sprayed up mat), fabrics, and multi-axial reinforcement ("non-crimp fabrics"). The stiffeners are generally shaped on the wall-laminate using a core-material (most often foam based, but also other materials like wood, cardboard, or even old newspapers). Stiffeners can however also be pre-shaped and subsequently glued to the wall of the hull using a bonding paste.

Also, non-composite materials are incorporated into the boat hull and unfortunately in such a manner that they cannot be separated easily from the GFRP. These can be found below.

Coating outside: Onto the polyester "paint" on the outside of the boat (a so-called "gel-coat") often 2 K-PU-coating (DD-coating) are applied. In addition, an additional finishing layer of anti-fouling is often applied to prevent sea life (algae and molluscs) attaching to the hull.

In the wall of the hull: Inserts for connection purposes (metal, wood) and window-openings with rubber tightening can be found in the wall of the hull. (It is assumed that windowpanes have been removed.)

Inside surface: Boat interiors often use a polyester top-coating. Sometimes severe contaminations (grease, oil, etc.) are present on the inner surface that cannot easily be removed.

The polyester boat hulls have lengths that generally range from 4 to 9 m. The weight of GFRP of these hulls generally ranges between 400 and 3,000 kg per hull. As may be clear from the descriptions above, polyester boat hulls have very diverse build up and many other materials are connected to the GFRP of the hull. Sometimes also the deck is made of GFRP. Figure 1.3 gives an illustration of an abandoned polyester boat with an integrated GFRP deck.

Figure 1.3: Abandoned polyester yacht (obtained by ten Busschen).

1.3.4 Build-up of silos for cattle feed

Silos for cattle feed are present in the Netherlands in abundance (Figure 1.4). They all have a similar build-up but can be very different in size. The main body is a cylinder with a spherical cap on top and a conical bottom part for the outlet of feed. The silo diameters generally range from 2 to 4 m and a height ranging from 2 to 10 m. Volumetric capacities range from 4 to 120 m^3. The amount of GFRP in a silo (excluding steel pipes and steel support structure) ranges from 120 to 2,500 kg.

These silos are all built from GFRP. The cylindrical body is produced by quasi-tangential filament winding in combination with spray-up to achieve a wall-thickness ranging from 4 up to 10 mm. The spherical cap and conical bottom part are made by spray-up or hand lay-up. Tubes for filling and emptying may be of GFRP or of galvanised steel. The supporting frame is made of galvanised steel. The silo parts, support structure, and appendages are integrated by hand lay-up. Besides a relatively thin, UV-eroded outer surface these composites contain potential for structural re-use even after decades of outdoor exposure. Apparently, there is no structural degradation in the laminate. This is generally experienced by inspectors of old silos or producers of silos that get back old silos for refurbishment (e.g. Polem in the Netherlands).

Figure 1.4: Typical GFRP silos for cattle feed at a farm (with kind permission: taken from Polem, Industrieweg 7, the Netherlands).

1.4 First-phase mechanical processing and logistics

1.4.1 Logistics

For the EoU composite products considered for mechanical reuse, the first step is to transport the product from the location of use to a location where they are further processed. In the case of rotor blades there is a significant amount of processing necessary at the location of use before they can be transported to the location for further processing. The reason for this is that EoU rotor blades are very long (and will tend to be even longer in future) so transportation is very expensive. For polyester boats and silos for cattle feed this is generally not necessary as these can be transported on a truck without the need for processing first into smaller parts at location (Figure 1.5).

(a) (b)

Figure 1.5: Transportation by truck of a silo (a) (with kind permission: taken from Polem, Industrieweg 7, the Netherlands) and boat hulls (b) (obtained by ten Busschen).

EoU boats, silos, and segments of wind turbine blades can be transported to the location for further processing. The costs are determined by the number of trucks and distance of travel. Generally, a truck will cost a certain rate in Euros per hour (including driver and excluding VAT) and can transport a certain amount of EoU material in kg. With these parameters, the costs for transportation of the EoU material can be calculated.

The transportation time will strongly depend on the distance but also on the time for waiting, loading, and off-loading. The amount of EoU material that can be transported by a truck can be increased by diminishing the volume. Especially boat hulls and silos have a large volume as compared to the weight. They are relatively thin-walled and can easily be broken into smaller parts with standard waste treating equipment on a truck.

Wind turbine blades however have a relatively high density and need specialised processing equipment to be broken into smaller parts. As already indicated, transport of long blades is expensive over land. Such costs may be justifiable at the installation phase, but not necessary in the EoU stage. Preferably, rotor blade parts should have a length of maximum 6 m. In general, there are four methods of cutting a rotor blade on site for making smaller segments: crushing, sawing, grinding, and water jet cutting.

1.4.2 Concrete crusher

A concrete crusher is a large, hydraulically driven tool that is generally mounted on a truck with a crane (Figure 1.6). Demolition companies use it for crushing concrete structures. They are also effective in roughly cutting a rotor blade in parts. However, a lot of dust and particles occur in the process, and these can be distributed in the environment by the wind. The use of a concrete crusher also gives severe material damage (cracks, delamination) in the material surrounding the cut.

Figure 1.6: Concrete crusher mounted on crane vehicle (with kind permission: taken from Boverhoff, Molenweg 1, the Netherlands).

There are certain measures that can be taken to prevent the distribution of dust by surrounding the workspace with containers, thus forming a wall, and by blowing a water mist on the area where the rotor blade is crushed to prevent dust pollution.

1.4.3 Diamond saw

Like a concrete crusher, a diamond saw is also mounted on a truck with a crane. A rotor blade can thus be cut in a controlled manner leaving the material of the rotor blade undamaged (see Figure 1.7). During cutting some dust is however generated. Often, water is added to the process for cooling. If this is the case, the dust is immediately entrapped in the processing water. In general, it is not possible to cut a rotor blade all the way through from one position, and additional cranes are necessary to turn the blade or hold it in the right position for cutting. The cutting width depends on the thickness of the diamond-tipped blade and is generally between 4 and 8 mm.

Figure 1.7: Cutting of a rotor blade with diamond saw (obtained by ten Busschen).

1.4.4 Grinding belt

A grinding belt is a dedicated machine where a long belt with grinding capacity can saw through a rotor blade from one position (Figure 1.8). Similar to a diamond saw, the material of the rotor blade remains undamaged and grinding dust will only appear at the location where the blade is being cut. Because the grinding belt is water-cooled, the dust will be directly entrapped in the process water. Other machinery is needed to bring the rotor blade in position allowing the belt to cut through the complete cross-section. The width of the cut depends on the cutting width of the grinding belt and is generally around 10 mm.

When a rotor blade is positioned within a small distance from the ground, a grinding belt can cut a rotor blade into smaller segments without any further handling during the operation. For a medium size rotor blade (e.g. 40 m length) a cross-cut is made in 3–8 min, depending on the location in the length direction of the rotor blade.

Figure 1.8: Grinding belt (with kind permission: taken from Odolphi Technical Support, Marnchiem 14, the Netherlands).

1.4.5 Waterjet cutting

Water cutting, or "cold cutting" is done by projecting a high-pressure waterjet on the object to be cut. The pressure is very high, generally 3,000 bars and the water contains sand as an abrasive. Using water cutting practically all materials can be cut. To cut a rotor blade a mobile set-up is necessary. In view of safety, a guiding frame is first installed onto the rotor blade that can guide the cutting head in a controlled manner. As the width of the cut is very small with water cutting, generally 0.2–0.4 mm, very little dust is generated. Moreover, by nature of the process, this dust is directly entrapped by the processing water. Water jet cutting and a grinding belt both cut a rotor blade into neat sections, as shown in Figure 1.9.

In Table 1.3 an overview is given of some characteristics of the methods for onsite cutting of rotor blades. In all cases dust is generated, either entrapped in processing water or not. It is important that measures are taken to catch the generated materials and remove them to prevent environmental pollution.

Figure 1.9: Blade segments after grinding with belt (with kind permission: taken from Odolphi Technical Support, Marnchiem 14, the Netherlands).

Table 1.3: Characteristics of methods for on-site cutting of rotor blades.

Method	Dust generation	Particle generation	Product damage
Concrete cutter	Severe (*)	Severe (*)	Severe
Diamond saw	Moderate, controlled	Practically none	Not
Grinding belt	Moderate, controlled	Practically none	Not
Water cutting	Very little	Practically none	Not

*As mentioned earlier, the generation of dust and particles in case of the use of a concrete cutter can be controlled by measures at the working site. By using a water mist, a container wall around the workspace and cleaning up the water with the dust and the particles from a tight workspace floor the pollution of the environment can be prevented. This is brought in practice by e.g. Lubbers Logistics Group in the Netherlands.

1.5 Structural reuse of parts

Structural reuse is particularly interesting for composite materials as it preserves the original material composition and characteristics. Structural reuse can take place through repurposing, segmentation/resizing, or reshaping the product. These actions discard the original product function, but maintain the unique structural properties, determined by the combination of material composition and structural design. Structural reuse differs from product recovery in the sense that the parts are reused in other functions then initially designed for. Furthermore, structural reuse preserves material integrity, but differs from recycling processes in how it retains the original material structure. Structural reuse is therefore positioned as circular strategy between product recovery and materials recycling (Table 1.1).

1.5.1 Repurposing

Repurposing revolves around reusing the product as-is, or large parts of it, in another function. The composition of the material and product, as well as the overall geometry, is retained. Relatively few interventions are needed to make the product suitable for reuse. However, this does mean that the secondary application depends on the geometry and layup designed for the first application. On the one hand, this presents a challenge to match those applications as closely as possible in order to make the best use of the material. On the other hand, over-dimensioning secondary applications (i.e. using excess material to warrant a high safety margin) could even be considered desirable, as this increases the volume of materials being reused and "stored" in active stock.

(a) (b)

Figure 1.10: Bridge of blades, using two decommissioned wind turbine blades as load carrying beams [33] (With kind permission: created by Stijn Speksnijder, Trompstraat 334 G, the Netherlands).

Recent publications show a range of wind turbine blade repurpose concepts, where infrastructural applications play a major role. The most notable examples are bridges [33, 34], power transmission line poles [35], playgrounds, and sound barriers [36]. Some of these have been realised as demonstrator objects.

Bridges present a compelling reuse case for wind turbine blades. The Bridge of Blades (Figure 1.10) uses 75–85% of the blade length as load carrying beams [37].

Other studies report reuse percentages starting at 40%, depending on required span and load case [35]. To support engineering of blade bridges, Swedish research institute RISE developed a calculation tool and database to match bridge design criteria such as span and required stiffness with blade availability [38]. It is expected that the residual mechanical properties suffice for the loading scenario in a slow traffic bridge and will, as in a conventional steel bridge, have a lifespan of 60 years [34]. Such pedestrian and cyclist bridges are currently being constructed in Ireland and Poland [39].

To implement repurposing on a large scale, there are still a number of challenges related to the reverse supply chain and design. The reverse supply chain is currently still underdeveloped, which means there are still major challenges regarding the variation in materials supply (models as well as planning), the logistics associated with transporting large-scale parts, and reprocessing technology. In terms of design, there are challenges to properly deploy recovered materials and to anticipate repurposing as part of the product lifecycle in the design of the next generation of composite products. Although it is attractive to reuse large parts, finding suitable applications remains challenging.

1.5.2 Resizing and segmentation

To match the supply of EoU materials, recovery should be done on a systematic basis, preferably in larger series, or mass-production. Cutting larger composite parts, such as silos and blades, into practically usable construction elements is expected to expand the range of potential reuse applications. Construction elements like panels and beams are found across many applications in building and construction, infrastructure, and furniture industry. Initial experimentation showed that several high valued objects can be made, as furniture for example [24]. This requires a two-step approach (Figure 1.11). First, the structure is segmented into reusable construction elements like panels and beams. Second, the obtained elements are used in a next product lifecycle.

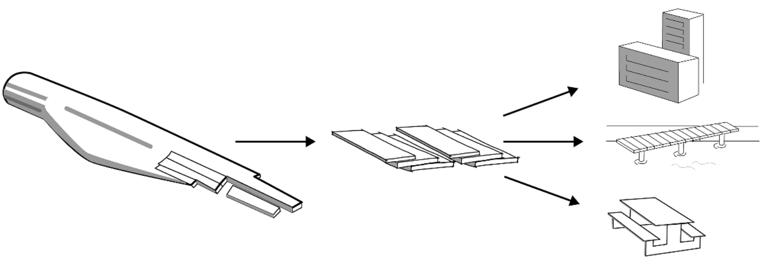

Figure 1.11: Structural reuse of a wind turbine blade: segmentation into construction elements and reuse in diverse applications [24].

The properties of the retrieved elements depend on the way they are cut from the original product. For the case of wind turbine blades, a number of cutting patterns were developed. Joustra [10] determined a cutting pattern based on timber standards and estimated that 55% of the blade midsection could be directly reused as panel or beam segment. The root and tip sections were not considered because of the thick laminate structure and strongly (double) curved surfaces. Another approach would be to section the blade into narrow strips or slats. Cutting into narrower strips has the advantage that curvature plays a relatively minor role and will thus increase the recovery percentage. However, it also results in narrow boards with a narrower scope of reuse. To better suit the construction industry, Pronk [40] therefore developed a cutting pattern based on standard timber trade dimensions. This segmentation procedure achieves recovery up to 60 wt.% (Figure 1.12). Depending on the chosen cutting pattern, the majority of a blade could thus be cut into panel or beam element.

Figure 1.12: (a) Cutting pattern and (b) obtained standard-sized panels and beams from a wind turbine blade [40] (with kind permission: created by Simon Pronk, Lisstraat 15A, the Netherlands).

Several application areas were identified for recovered construction elements, including construction and transport applications. In construction, the recovered elements could be used as structural parts in flooring, walls, or roofing. Sourcing from secondary feedstock and using elements with high specific mechanical properties, such as lightweight panels, provides interesting advantages in construction and transport. Structural reuse would make such high-end composite materials available at a favourable price. In transport, smaller planks and recovered elements could be used for lightweight, yet strong packaging, such as pallets. Both product groups can be produced centrally with appropriate processing equipment and dust extraction.

Figure 1.13: Design demonstrator: furniture made of wind turbine blade panels [24]. Reprint from Resources, Conservation and Recycling: 167, Jelle Joustra et al, Structuralreuse of high end composite product: A design case study on wind turbine blades, 2021, with permission from Elsevier.

Design case studies and demonstrators showed the feasibility of the structural reuse for wind turbine blades. The blade's aerodynamic profile causes minor curvature, twist, and bend of harvested segments. However, at the scale of construction elements, these were found to be well within conventional construction tolerances [10]. To test this, retrieved segments were used to construct a simple furniture product (Figure 1.13), which was presented at a design exhibition. Curvature and origins of the panels went unnoticed to most visitors, until it was pointed out to them. In the discussions that followed, the material was appreciated as construction element [24]. The segmentation and reuse approach are expected to be applicable to other composite structures as well. Wind turbine blades represent a durable, structural composite, which integrates mechanical performance and aerodynamic form. In practical terms, it is a large product that has no other functional use when its operational life ends. Similar characteristics are found for composite products in other sectors, such as boat hulls and silos. As such, it is to be expected that structural parts could also be reused in these product categories.

1.5.3 Re-shaping

Structural reuse is not restricted to thermoset composites. Thermoplastics based composites offer additional opportunities because they can be remoulded. Thermoplastic composites are often produced as flat panels (blanks), which are subsequently thermoformed into a product shape. The forming process forces fibre, resin, and plies to move into the composite, affecting its material properties. At the end of use, a similar process could be used to adapt a given shape to meet the requirements of a secondary use case. It is expected that such subsequent forming actions widen the scope for reuse applications, as the material is no longer bound to its original shape, which would have been the case with thermoset resins.

The re-shaping process is particularly applicable to panel-type products [41, 42]. Kiss [41] demonstrated flattening of a stamp-formed thermoplastic composite object to a panel. Retaining fibre orientation proved to be a challenge as it is difficult to effectively reverse the original forming process. Cousins [42] demonstrated a re-shaping process on an experimental wind turbine blade spar cap. The spar cap was flattened through thermoforming. It was suggested that such flattened panels could be planed to a desired thickness for use in construction or recreational goods. The re-shaping process is still highly experimental and needs further research to arrive at a scalable recovery process.

1.5.4 Material performance

Construction materials obtained by segmenting composite structures into smaller elements have favourable characteristics. Joustra et al. [10] modelled the material characteristics of panel and beam elements retrieved from a wind turbine blade. Regarding flexural modulus, the elements retrieved from a blade shell are comparable to wooden panels (Figure 1.14). On flexural strength, the panels perform similar to aluminium or even steel. The density of these panels, however, is relatively low compared to metals, partially because of the use of low-density core materials in a sandwich layup. Altogether, this makes for lightweight, yet strong and stiff panels, which outperform conventional construction materials when loaded in bending [10].

Wind turbine blades are generally considered safe to use in construction [9]. The secondary load case is often well within the original design specifications. However, cutting the original structure into reusable segments exposes core materials and otherwise enclosed interior parts to environmental conditions. To prevent ageing from UV-radiation and moisture ingress, suitable precautions must be taken. Surface treatments will generally suffice to protect the materials and prevent degradation [43].

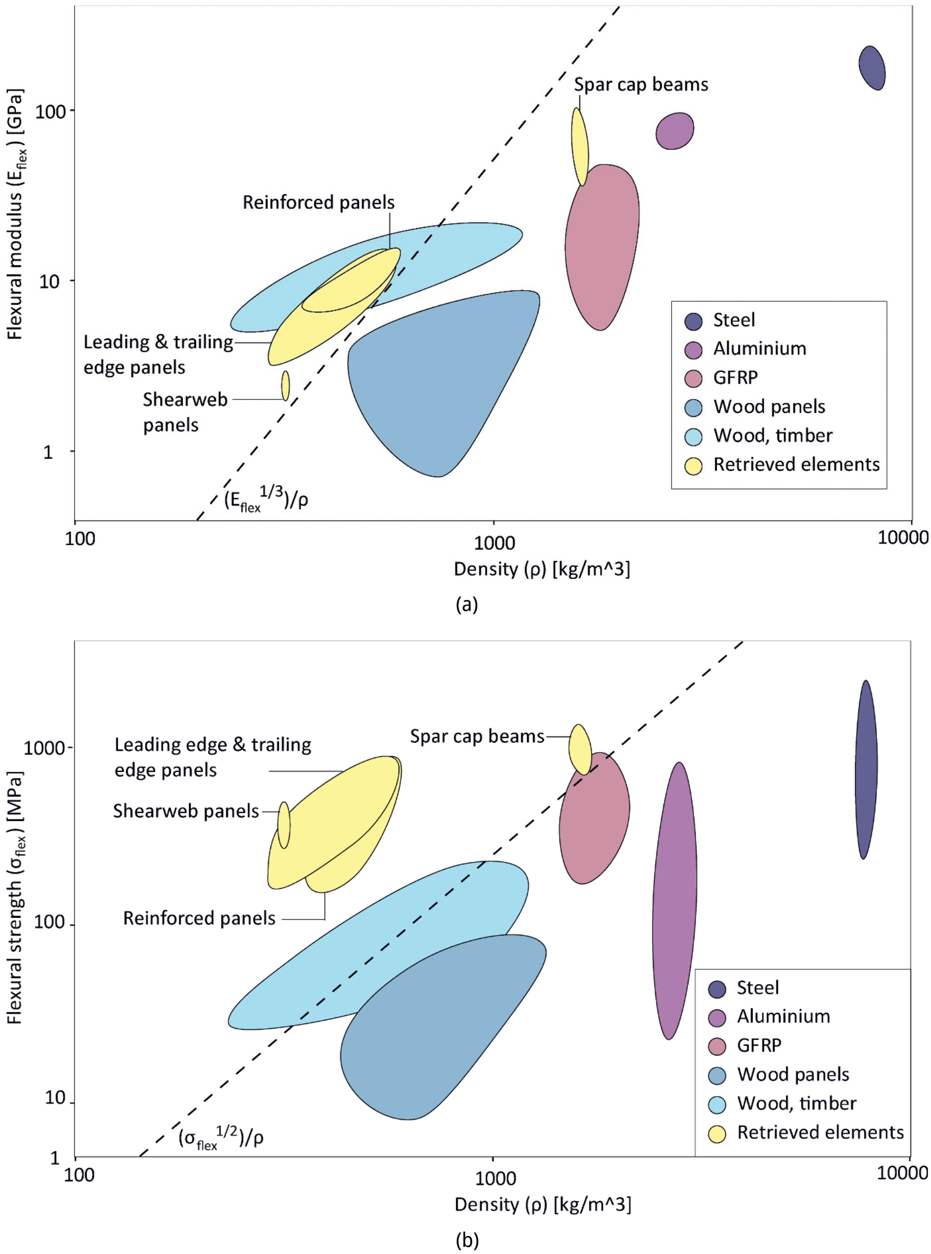

Figure 1.14: Material charts of density versus flexural modulus (a) and strength (b) of retrieved wind turbine blade materials [10]. Reprint from Composites Part C: Open Access, 5, Jelle Joustra et al, Structural reuse of wind turbine blades through segmentation, 2021, with permission from Elsevier.

1.6 Structural re-use of mechanical processed material

1.6.1 Principle of structural re-use with oblong elements

In Section 1.5, the structural reuse of parts is described. When EoU composite products are machined into substantial smaller elements, these small elements still have the intrinsic composite properties such as mechanical strength and resistance to corrosion [12]. They can be embedded in a virgin resin that binds the parts together. However, to use these elements as reinforcing elements in a new product and benefit from the mechanical strength of the original EoU composite product, the shape of these elements must be oblong. This is the result of the necessity of having sufficient length to load the ends of the element so that the middle of the element will have the same deformation (strain) as the surrounding material.

The mechanical loading of embedded reinforcing elements with finite length has already been described in 1952 with the shear-lag theory [44]. When an oblong, reinforcing element is embedded in a larger body that is strained, the part will build up the strain from the ends by shear stresses. When a part is considered, e.g. a strip with length L and thickness D that is embedded in a matrix material, the strain of the combination can be analysed. The shear-lag theory describes the occurrence of shear stresses, τ, as a result of the difference between strain deformation of the combination through an externally applied composite stress, σ_c, and the strain in the embedded element, resulting in tensile stresses in the embedded element, σ. The shear stresses enable the build-up of strain of the embedded element starting from the ends (Figure 1.15).

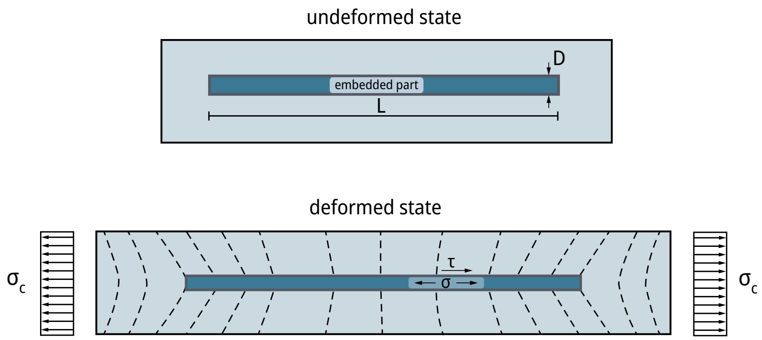

Figure 1.15: Loading of embedded element by shear deformation at the ends (obtained by ten Busschen).

From the figure it is clear that there is a transition region at the ends of the embedded element where the embedded element is not completely strained to the level of the composite strain. Over this region the tensile stress in the embedded element, σ, will increase from the externally applied composite stress, σ_c, to a maximum stress level in the middle of the embedded element. Figure 1.16 shows the distribution of shear stresses (τ) at the surface of the embedded element and normal stresses (σ) inside the embedded element.

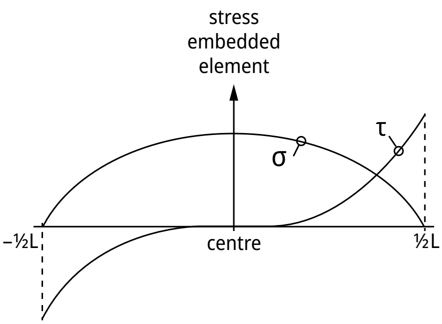

Figure 1.16: Distribution of shear stresses and normal stresses in the embedded element (obtained by ten Busschen).

1.6.2 Effect of L/D-ratio on composite properties

From literature it is extensively known that for composites reinforced with fibres of short length, the ratio between the (average) fibre length, L_f, and the fibre diameter, D_f, has a large influence on mechanical properties of the composite. Ning et al. [45] presented an elaborate literature review on this subject. The effectiveness of the reinforcement with fibres of short length can be studied for different mechanical performance parameters of the composite such as stiffness (E-modulus), static strength, impact strength, creep resistance, and fatigue strength. A specific mechanical performance parameter for a composite made with fibres of short length, P_s, is generally compared with the mechanical performance using endless (continuous) fibre reinforcement, P_c. An efficiency parameter, η, is introduced as the ratio between the mechanical performance parameter for a composite with short fibres and with continuous fibres:

$$\eta = P_s/P_c$$

The influence of the L_f/D_f-ratio on the efficiency of mechanical performance of the composite is very dependent on the mechanical performance parameter analysed. When plotting the efficiency parameter as function of the L_f/D_f-ratio on a logarithmic scale the following results are obtained for a variety of mechanical properties as schematically depicted in Figure 1.17.

For structural re-use of mechanically processed composite the effect of length to thickness on mechanical performance of a new product has been investigated. In the investigation a series of composite products were made that were built up from rectangular composite strips with a defined ratio between the strip length (L) and the thickness of the strip (D) [46]. New composite profiles were made with L/D-ratios of 8, 16, 40, and 200, respectively. The profiles were tested in three-point bending and

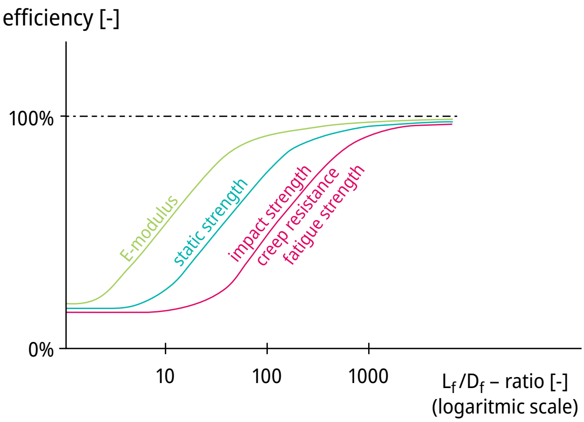

Figure 1.17: Typical efficiency curves for different mechanical performances (obtained by ten Busschen).

the effective stiffness (E-modulus) and effective bending strength were determined. Figure 1.18 shows the relation between the E-modulus and L/D-ratio. The mean value of the E-modulus ranges from 8.5 GPa for the lowest L/D-ratio to 9.5 GPa for the highest L/D-ratio. It is clear that considering the scatter in test results the dependence of the bending stiffness from the L/D-ratio is not very strong.

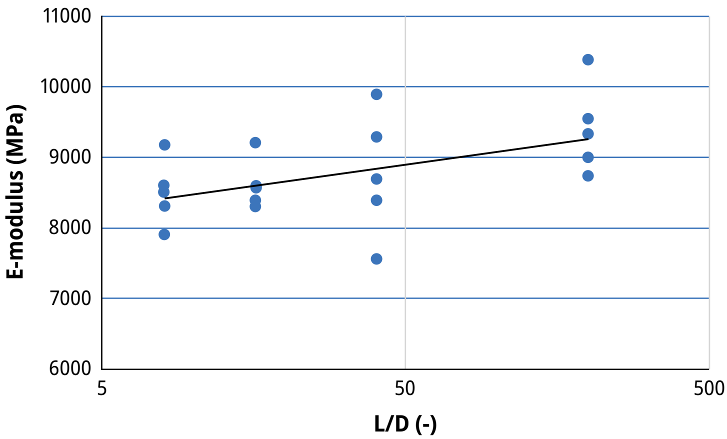

Figure 1.18: E-modulus of new product as function of L/D-ratio of strips [46] (obtained by ten Busschen).

Figure 1.19 shows the relation between the bending strength and L/D-ratio. The mean value of the strength ranges from 80 MPa for the lowest L/D-ratio to 200 MPa for the highest L/D-ratio. Clearly the effect of L/D-ratio on strength is strong. For a significant strength contribution of the reinforcing strips to the strength of the new product the L/D-ratio should preferably be 50 or higher.

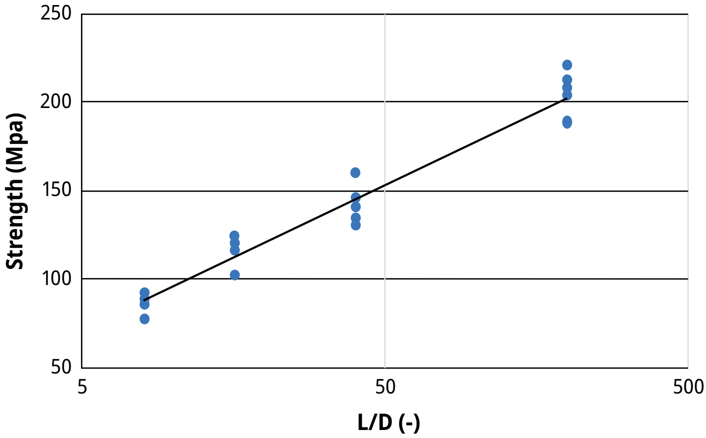

Figure 1.19: Strength of new product as function of L/D-ratio of strips (ten Busschen).

1.6.3 Processing into reinforcing elements

From composites that were exposed to outdoor conditions it is known that mechanical performance is preserved for a long time, generally much longer than the time that they are in use [47]. Thus, when EoU composites are processed into oblong reinforcing elements, there is strong potential to contribute to mechanical stiffness and strength in new products in the case of oblong reinforcing elements with a sufficient L/D-ratio. For significant strength contribution, the L/D-ratio should preferably be 50 or higher. Processing of EoU composite products into strips is in theory the best way to preserve and re-use mechanical performance of the composite. It was investigated how to process polyester boat hulls into strips and re-use them for new products.

Before a boat hull can be machined into strips, the hull must be machined into pieces that can be sawn. Figure 1.20 shows the breaking of a boat hull into such pieces. The necessary equipment for this process can be present on the truck used for transportation. With such equipment, polyester boat hulls can be broken into pieces with a surface-dimension in the order of 0.5–1 m^2. The complete operation is completed within 15 min for a medium-sized hull.

After the initial processing of polyester boat hulls into pieces typically in the order of 0.5–1 m^2, they can be sawn into strips using a diamond-tipped saw. Figure 1.21 shows plates obtained by tearing a boat hulland the resulting strips after sawing.

As can be seen in Figure 1.21, the resulting strips are curved. For small-scale production and testing, these strips can be processed into a new product but to date the processing of strips of EoU composites into new composite products was unfortunately not found to be suited for industrial, efficient production.

Figure 1.20: Photo of breaking a boat hull in smaller parts (obtained by ten Busschen).

(a) (b)

Figure 1.21: Plates from a boat hull (a) that are sawn into strips (b) (obtained by ten Busschen).

A better method for processing of EoU composites is shredding. A shredding process produces flakes with the required oblong shape. The advantage of flakes above strips is that they are smaller in dimensions and have a uniform distribution in size and shape. However, the requirement is still valid for these flakes to have a sufficiently high L/D-ratio to contribute as reinforcement.

Generally, shredding is carried out with a beater-mill (see Section 1.7 of this chapter) and the flakes can be sieved off when they are sufficiently small in dimensions. The drawback of shredding is the generation of dust. In case of a beater-mill, about

30 wt.% of the original EoU composite parts that are fed into the beater-mill is transformed into dust. This dust may be polymer-rich and can be used for pyrolysis into chemicals. Another outlet for the dust is to use it as filler in resins to make new composite products. The use of dust originating from EoU composite as filler is discussed further in Section 1.7.

The geometry of the flakes depends on the original EoU composite material. When this material consisted of random reinforcement (as is often the case for boat hulls), the flakes are plate-shaped, see Figure 1.22 left. When the original EoU composite had reinforcement with high orientation (as is generally the case for rotor blades), the flakes are spike-shaped, see Figure 1.22 right. Shredding silos will give a mixture of the two types of flakes because these products are composed of a combination of continuous filament-wound reinforcement and random reinforcement by spray-up.

(a) (b)

Figure 1.22: Flakes originating from boat hulls (a) and from rotor blades; (b) (obtained by ten Busschen).

1.6.4 Processing of flakes in new products

When the flakes are to be used as reinforcement in new products, they have to be bound together by a virgin resin. It was found that profiles or other products only consisting of flakes embedded in resin will show strength lower than expected. This is caused by the influence of the flakes at the surface of the product, which cause stress concentrations and crack initiation. To make profiles or beams based on flakes, the most optimal cross-section consists of a core of flakes embedded in virgin resin and an outer layer of virgin GRP. Using UD-reinforcement in this virgin GRP-layer, the mechanical properties can be tuned to the desired level of performance. Moreover, the use of UD-reinforcement can enhance creep resistance and fatigue strength significantly even when present in a relatively small amount. Figure 1.23 shows the principle of an optimum design of a cross-section.

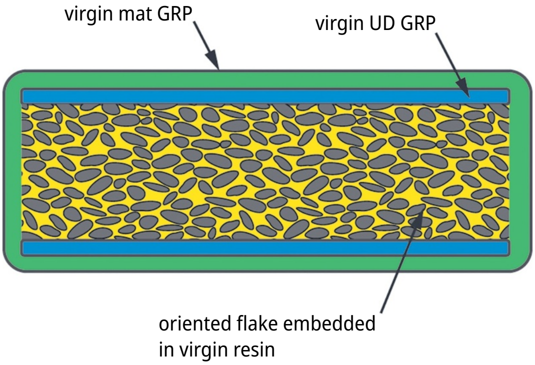

Figure 1.23: Principle of cross-section of optimum profile with EoU composite (obtained by ten Busschen).

A profile can be manufactured in a discontinuous manner. This can be done using an open mould in which the dry components are placed, followed by casting of a low-viscous resin. This is a good method for small-scale production and tests but not suitable for industrial production. Both labour costs and the costs for virgin resin become too high for a profitable business case because with this method over 50 wt.% of the total product is formed by virgin resin. Another discontinuous method is to use resin infusion methods such as vacuum infusion under foil, Vacuum Assisted Resin Transfer Molding (VARTM) or Resin Transfer Molding (RTM). Again, these methods are not suitable for industrial production. Although the virgin resin content is lower, it is still around 50 wt.% of the total product and too labour-intensive [12].

An industrial method to produce profiles or beams from flakes of EoU composite product is to use a so-called push-pultrusion process [46]. This is a continuous, pultrusion-like process pushing a core of oriented flakes between virgin reinforcement layers. This combination contains a surplus of virgin resin that gets pulled through a heated mould. The surplus resin is squeezed out and the package cures in the heated mould into a product. A schematic overview of the process is given in Figure 1.24.

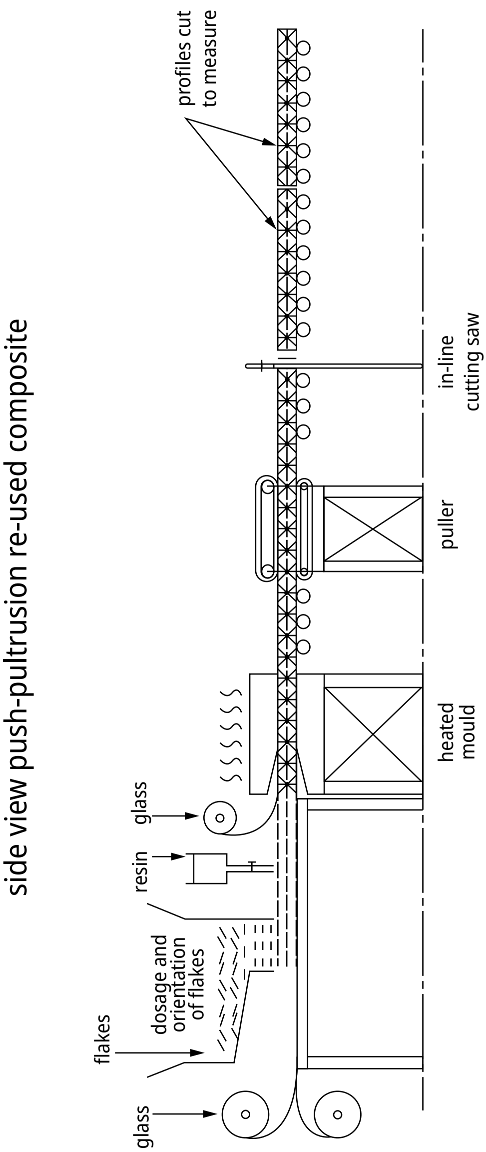

Figure 1.24: Schematic overview of push-pultrusion process (obtained by ten Busschen).

1.6.5 Demonstrators

Structural re-use of EoU thermoset composites enables products that are suitable for infrastructural applications. Panels, profiles, or plates can be manufactured that are strong and resistant to moisture. That these new composite products are not light weight is, generally speaking, not a problem in these applications. Demonstrator infrastructural projects from re-used EoU composite products are presented in the next sections.

1.6.5.1 Retaining walls

EoU composites profiles have been manufactured into retaining walls close to a lock-gate in the Netherlands [46]. Profiles with a length of 3.5 m have been produced by using vacuum infusion. The profiles cross-section measures 40 × 250 mm with a detailing that profiles fit in each other (see Figure 1.25).

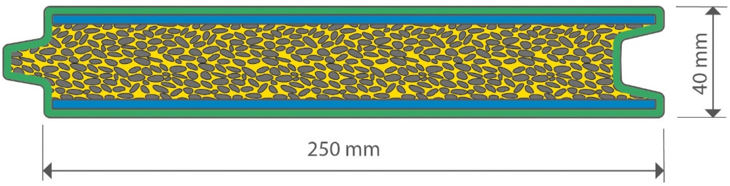

Figure 1.25: Cross section of retaining wall profile from EoU composite (obtained by ten Busschen).

The profile contributes to the wall with an effective width of 250 mm and has a thickness of 40 mm. The outside skin consists of a glass-reinforced polyester laminate made of virgin materials, containing a glass mat (in the picture-coloured green) and UD-reinforcement with 200 mm width on both sides (in the picture-coloured blue). Both reinforcements have a weight per unit area of 900 g/m^2. Inside the profile is filled with re-used EoU thermoset flakes embedded in a virgin polyester resin.

Prior to the vacuum infusion process, first the glass injection mat has been placed along with the first layer of UD-glass reinforcement in the open mould. On this, EoU flakes and strips have been deposited. A second layer of UD-reinforcement was placed on this and finally the glass injection mat was closed above it. After this, foil was place on this and made air-tight to the flange of the mould. Injection has been performed, using a polyester injection resin, with brown colour to give the profile a wood-like appearance. Further details can be found in the process description by ten Busschen [46]. Figure 1.26 shows the deposition of strips and flakes of EoU composite in the mould (left) and the product with infused with brown resin (right).

(a) (b)

Figure 1.26: Production of profiles using EoU composite by vacuum infusion under foil (obtained by ten Busschen).

The profiles have been tested in bending to confirm that the profiles have an equal bending strength as for a profile made of tropical hard wood that is normally used in these applications (azobé). The retaining walls were installed by driving the profiles into the soil using a vibrating hammer (see Figure 1.27). During the vibrating process no damage was incurred. Profiles were withdrawn two years after installation and showed no degradation or strength loss after inspection and tests.

1.6.5.2 Guiding beams

Guiding structures are placed in canals near bridges or lock gates to guide ships. Traditionally, these guiding structures are built up from frame of steel on which guiding beams are mounted horizontally. Traditionally these beams are made of tropical hard wood with typical dimensions 200 × 200 × 4,000 mm. In the project, guiding beams of re-used EoU thermoset composite were commissioned. These were used to replace the lowest two rows of four guiding structures, located near a bridge in the Netherlands [46]. The bottom rows of guiding beams are around and under the water level and therefore this is where tropical hardwood beams suffer most from rot. Re-used EoU thermoset composite will be far more durable at this location. Figure 1.28 shows one of guiding structures. The upper four rows of beams are made from tropical hardwood, and the lowest two rows are made or re-used EoU composite.

(a) (b)

Figure 1.27: Retaining wall installation by vibrating EoU composite profiles in the ground: (a) close up and (b) in distance (obtained by ten Busschen).

Figure 1.28: Guiding structure beams made from EoU composite (obtained by ten Busschen).

The guiding beams are designed to resist a possible ship collision. For this, a single beam has to have a static strength of 440 kN when loaded in bending when supported with a distance of 1,800 mm. The amount of UD-glass reinforcement in the beam was optimised to achieve this strength. A prototype beam was tested in three-point bending, supported with a distance of 1,800 mm. A maximum force of 515 kN was attained. Passing the strength test, guiding beams have been produced for the project with a total length of 112 m. This was done with RTM injection with an open steel mould with an upper composite mould part. Installation of the beams at the bridge in Delfzijl took place in October 2019.

1.6.5.3 Crane mats

Crane mats are used at building sites, creating a stable work area. Heavy cranes and other machinery can operate on this area. Crane mats generally are made of tropical hard wood beams, based on the requirements on strength, wear resistance and durability. Crane mats shown in Figure 1.29 have outside dimensions of 1,000 × 5,000 mm and are assembled from five beams of tropical hard wood that have dimensions 200 × 200 × 5,000 mm. The assembly is made using five steel bars, clamping the beams together.

Figure 1.29: Work place created with crane mats.

A crane mat was made of EoU thermoset composite beams. This was done in cooperation with Welex in the Netherlands. This company is a manufacturer of crane mats. For the production of beams made of EoU composite, RTM-infusion was used [46]. The process started with a glass injection mat (900 g/m^2) that was placed in the mould. This was followed by two layers of quadraxial glass reinforcement (1,200 g/m^2) and 10 layers of UD glass reinforcement (840 g/m^2). On this package flakes of EoU composite in combination with dry sand (1–2 mm grain) was deposited. The five holes with diameter of 30 mm for crane mat assembly were in-situ formed in the beams using inserts.

On the core another 10 layers of UD glass reinforcement was placed and the quadriaxial reinforcement layers and injection mat were folded over the top. Then the mould was closed for starting the resin injection process. With this RTM-infusion process, five beams have been produced and were assembled into a crane mat with traditional build up and dimensions. The crane mat was tested in various severe operating conditions. The EoU composite crane mat showed very good performance and good resistance to heavy vehicles and was easy to clean (Figure 1.30).

Figure 1.30: Crane mat of EoU composite tested with heavy vehicle (obtained by ten Busschen).

1.6.5.4 Bridge deck profiles

A deck of a bridge over canal had to be renewed. This was the Dinzer bridge in Friesland (the Netherlands). The old deck profiles were made of tropical hard wood, and in this case the new deck profiles were made from EoU thermoset composite. The profiles should resemble the original hard wood profiles by their dimensions (thickness 95 mm and width 245 mm) and their appearance and must be suitable for heavy traffic.

The profiles were designed with an outer layer of virgin glass fibre-reinforced polyester and a core build up from re-used EoU thermoset composite flakes embedded in virgin polyester resin. First prototypes of the profiles had to be mechanically tested to verify mechanical loading strength. Successful tests confirmed that the beam design fulfils the requirements for Dutch infra structural design [46]. The profiles that were made for the new deck, were produced using a method of resin casting in an open mould.

The profiles were mounted on a new bridge structure and give the appearance of a traditional deck made with wood deck profiles (see Figure 1.31). An important advantage of re-used EoU composite is that the service life is much longer, and maintenance is lower as compared with wood decking.

(a) (b)

Figure 1.31: Deck profiles of re-used composite at the Dinzer bridge: (a) installation and (b) result (obtained by ten Busschen).

1.7 Mechanical recycling by grinding

Mechanical grinding produces small size fragments and particles to be used as reinforcement or filler materials. The geometry and composition of the input material is less critical compared to the processes described in the preceding sections, and as such a grinding process is capable of absorbing materials which do not fit or are a by-product (i.e. cutting losses) of the other recovery processes described in this chapter. For these materials, and for reused products that cannot go through another use cycle, mechanical grinding is a viable option.

1.7.1 Process outline

Mechanical grinding breaks down composite scrap into smaller pieces to roughly separate fibre and resin fractions. The energy demand of mechanical grinding lies between 0.1 and 4.8 MJ/kg, depending on the used machinery and process scale. Powering the motor of the granulator or hammer mill machine constitutes most of the energy demand. The pre- and post-recycling stages, such as shredding and sieving, are not as energy intensive as the actual downsizing process [48].

Grinding does not use any chemicals and, if done in a controlled environment, does not cause atmospheric or water pollution. In addition, no high-end technical and expensive equipment is needed compared to other recycling methods, it allows for processing of larger amounts of waste at higher throughputs [49]. However, the inferior quality of recovered recyclate compared to the virgin product complicates finding market applications for the recyclate. Economically, the recyclate is hardly competitive with virgin raw filler materials [4, 49].

1.7.2 Process

In the mechanical grinding process, there are three main steps to be distinguished: shredding, grinding, and classifying (Table 1.4). First, the material is shredded down to chunks of 50–100 mm using a slow speed cutting or crushing mill. Shredding makes it easier to remove metal inserts and, if done at the waste location, the volume reduction makes transport easier. Secondly, the chunks are ground down further into fragments of 10 mm–50 µm using a cutting or hammer mill (see Figure 1.32 [50]). Both have their own benefits: cutting mills give more homogeneous fibre length distribution and longer fibres, whereas the blades of the hammer mills do not require sharpening, thus reducing wear and increasing the output. There is no significant difference between the two concerning the resin content of the recyclate [51]. Thirdly, the fragments are separated on their contents and size using cyclones and sieves [50].

Table 1.4: The mechanical recycling process ([7, 50]).

	1. Shredding	2. Grinding/milling	3. Classifying
Process	Reduce waste materials into pieces	Grind pieces into fragments	Separating the fragments into resin-rich powders and fibrous fragments
Particle size[a]	50–100 mm	10 mm–50 µm	–
Equipment	Slow speed cutting or crushing mill	High-speed cutting or hammer mill	Cyclones and sieves

[a]At the end of the step.

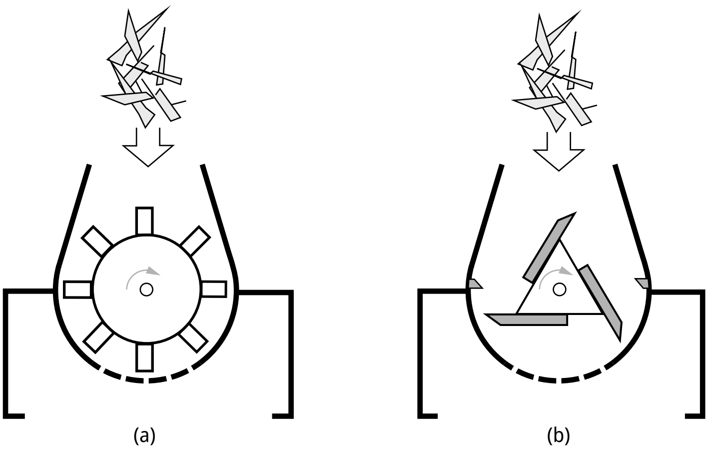

Figure 1.32: simplified diagrams of a hammer mill (a) and cutting mill (b) (obtained by Joustra from [52]).

1.7.3 Outputs

It is important to note that there is no complete separation of the two materials; the fragments will almost always consist of mixed materials. The recyclate of the mechanical grinding are mixtures of resin, fibre, and filler. In this, two main fractions can be distinguished: fine and coarse. The finer fractions are powders with a higher resin and filler proportion compared to the original composite whereas the coarser fractions are more fibrous with higher fibre content [50].

Resin-rich powder can be used as a filler. The powder contains a significant proportion of low-density polymer and as such has a lower density than conventional fillers. This could lead to weight savings compared to using calcium carbonate filler. Even though filler substitute recyclates are more expensive by weight than traditional fillers, the lower density means they are cheaper per unit volume [50]. This could be favourable for industries pursuing weight and cost savings, such as the automotive industry. However, the economic viability of the filler materials is challenged by the low cost of primary fillers (e.g. calcium carbonate or silica). Also, the incorporation level as a filler is quite limited (<10 wt.%) because of the deterioration in mechanical properties and increasing processing problems at higher content due to the higher viscosity of the compound [7].

Fibrous fragments range from powders, fibre-particulate bundles, and fibre tows to woven platelets. Each is a combination of resin and reinforcements, complicating assessment of recycled fibre properties. The length of the fragments varies depending on initial fibre length, composite type [53], and scrap feeding size. Bream and Hornsby [53] report that the structural integrity of the fibres is preserved, with fibres up to 10 mm being retained and 69% of the recyclate particulates greater than 1 mm in diameter. The fibres produced by ERCOM Composite Recycling in Germany range from <0.25 mm to 3–20 mm particle size or fibre length [50].

The fibrous recyclate can be used as filler, as reinforcement for new composites in short-fibre applications such as bulk moulding compound (BMC), sheet moulding compound (SMC) parts, or as inclusions in injection-moulded products [54]. Dutch start-up Extreme Eco Solutions developed paving stones based on ground wind turbine blade composites (Figure 1.33) [55]. The tiles promise to be lower in weight and to contain up to 85% of ground composite as filler [56]. Using the recyclate as reinforcement represents a higher value route as the reinforcing value of the fibre is (partially) retained, whereas the filler replaces very low value materials, and more energy is needed to grind to fine filler [48].

In general, recyclate performance in composites is inferior to virgin fibres [50]. Even with low reincorporation rates, the resulting mechanical properties of the new composite material are significantly impaired due to a poor bonding between the recyclates and the new resin [7]. To improve bonding, additional treatments such as grafting or coupling agents [57] or increased mixing times are needed [7]. Finally, it is important that in addition to the remainder of the virgin fibres, additional longer fi-

Figure 1.33: Paving tile based on ground composite material [55] (with kind permission: taken from Extreme Eco Solutions, Langestraat 37, the Netherlands).

bres are added, as these will compensate for the deleterious effect of the recyclate [50].

1.8 Discussion

Composites present a challenge in achieving a circular economy because of their inherent materials mixture and complicated reprocessing. Mechanical reuse and recycling contribute to closing the loop by reprocessing these materials and making them available for reuse. The need for such processes is evident given the increasing amounts of EoU composite material becoming available, especially in the construction, wind energy, and maritime sectors. Following the estimated volumes of wind turbine blades, boat hulls, and feedstock silos, 3,500 ton of GFRP material would need to be processed in the Netherlands and over 135,000 ton in the EU. The first step in mechanical processing is usually reducing large products to transportable and processable segments, these are then subject to further mechanical treatments.

In mechanical processing of composites, we distinguish two main strategies: structural reuse and material recycling (Table 1.2). Structural reuse focuses on reusing material as-is with the fibre-resin combination and (part of) the laminate structure intact. Recycling processes aim for fibre-resin separation or processing into particle fractions. The presented mechanical reuse and recycling processes are complementary to each other and can be applied in successive product life cycles.

Structural reuse can be used to slow the flow of materials through the economic system by extending the material lifetimes and thus pushing back the moment of recycling. As such, structural reuse can keep the materials in use until processing capacity and market are developed. From a materials flow perspective, structural reuse could meet the basic requirements for a successful recovery system. A successful recovery system should balance supply, processing capacity, and market for the recyclate [58].

Additionally, a continuous flow of waste is required to set up and run a mechanical recycling plant and to produce products from the recyclates. The viability of such an operation depends on, and is often hampered by, the availability of EoU composite materials [59]. With the expected composite waste volume from for example end of life wind turbines, the required waste volume will not be hard to achieve. However, without a viable new end-application for the recyclate, going through the whole process might not be justifiable or even sustainable.

Reuse across contexts and extending material use beyond its original design lifetime brings additional challenges in terms of performance, safety, and certification. Materials in use are subject to wear, most notably mechanical fatigue, and environmental degradation such as ageing and surface erosion. Therefore, the quality of the material is not always exactly known when taken out of use. In addition, reuse in another context changes the loading conditions. This can be dealt with by not using the material to its primary full capacity.

To optimise reuse and warrant safety of structural elements in terms of mechanical performance, an improved assessment of residual material quality is desirable. Three approaches to assess residual mechanical performance of composite materials are identified. The first approach assumes the material is still within its original specification when recollected. In the second, the residual material quality is modelled based on original documentation and in-use monitoring, which can be facilitated by progress in modelling fatigue behaviour of composites [60, 61]. The third approach considers testing samples of the acquired material to experimentally determine residual quality [62]. The first would provide a rough estimate, the second a good indication, and the third approach an actual, albeit local, and time-consuming, measurement of residual properties. The desired level of accuracy will depend on the intended reuse case and required safety margins.

Mechanical reuse and recycling can be used to realise several consecutive use cycles. Figure 1.34 illustrates five cases of glass fibre composite use and reuse, building on the case of wind turbine blades. First, the composite material is used as a wind turbine blade with a design life of 25 years. Second, major blade parts can be repurposed as load carrying beams in a slow traffic bridge, adding approximately 60 years to the material life. In a third step, the structure can be segmented (resized) for reuse as construction elements in e.g. furniture with an estimated lifespan of 15 years. Fourth, the GFRP can be processed into oblong flakes and used in retaining walls for another 60 years. Finally, as a fifth option, the materials can still be mechanically recycled, reprocessed, and used as a filler. These successive use cycles extend the potential material lifetime from 25 to up to 200 years. In addition to extending the material lifetime, reuse and recycling avoid use of primary materials such as steel beams for construction or wood for retaining walls.

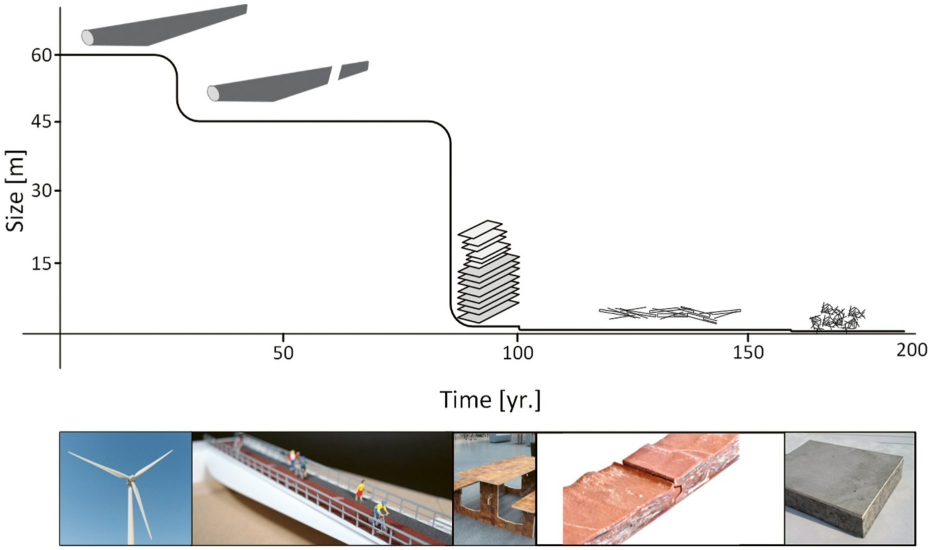

Figure 1.34: Structural reuse of wind turbine blades, extending lifetime and preserving value of the material (obtained by Joustra).

1.9 Conclusions

Mechanical reuse and recycling processes are attractive for composite products because of their capacity to preserve the material characteristics and prolong material lifetime at several levels of materials integrity. Repurposing and segmentation of large parts provides direct access to high performance materials at relatively low cost. Processing composites into flakes and embedding those in new products preserves the intrinsic strength properties. Grinding delivers filler material that could increase stiffness, while reducing cost and potentially weight for manufacturing new products. Thus, structural reuse, and to some extent recycling processes, retain the beneficial properties of composite materials and make it available for next use cycles.

The mechanical reuse and recycling processes described in this chapter are complimentary to each other. The material lifespan can effectively be extended by subsequently reusing parts, fragments and shreds. Next to such serial application of these recovery pathways, they may be used in parallel to ensure high reprocessing percentages. The offcuts and other “leftover” materials from repurposing or structural reuse provide immediate input for reprocessing into flakes or regrind. However, the general trend across these processes is a reduction in size and hence a reduction in material properties relative to the original use case.

The best planning of recovery actions will depend on the availability of resources, processing capacity, and potential market for the recyclate. Resource availability is starting to show, and the emerging return volumes are already reason for concern for some industry sectors. It is therefore necessary to get reprocessing capacity in place to deal with these increasing volumes of EoU composite materials. A key driver for development of recovery facilities is also the development of a market, or in other words, applications in which these recovered materials can effectively be reused. Development of such processes and materials can, in conjunction with product-level strategies and other recycling technologies, contribute to establishing a closed-loop for composite materials.

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