Chapter

Industrial Re-Use of Composites

Albert Ten Busschen

Abstract

The amount of obsolete composites is increasing on a global scale, for example yacht hulls from a growing leisure industry and large rotor blades from wind energy production. Until now it has not been possible to recycle or disassemble thermoset composites into their original constituent parts of fibre reinforcement and resins. Subsequently a new method of re-use has been developed. This method involves machining the obsolete composite product into strips or flakes for re-use as reinforcing elements which, when combined with fresh resin and fibre, enable the production of a brand new component. This, in effect, preserves and re-uses the mechanical properties of the original obsolete composite. This method has been proven in manufacturing retaining walls, also guide beams for canals, crane mats and bridge decking, all using the strips or flakes from end of life composite products. For use on an industrial scale, a positive business case is imperative. In order to prove the industrial technology, new products have to contain a sufficiently high percentage of re-used composites in combination with automated processing. This has been achieved with "push-pultrusion" which is in essence a further development of the long established pultrusion process.

Keywords: composite, thermoset, fibre reinforced, end-of-life, rotorblade, re-use

1. Introduction

By definition a composite material is a material that is build up from two or more different components. For example, concrete is a composite material because it is build up from cement, sand and aggregates. However, with the name 'composites' often a category of materials is indicated that can be described as fibre reinforced plastics. In the following, 'composites' will refer to these fibre reinforced plastics. Fibres provide the reinforcement of the plastic, and the result is a strong but light material. These properties, when combined with the freedom to mould them into curved shapes has resulted in composites being used in many applications, notably: wind energy, aerospace structures, transportation, building and infrastructure, sport, yachting and various marine applications.

Industrial production of composite products started during the 1939–1945 World War and involved the use of epoxy or polyester resins reinforced with glass fibres. In the 1980's carbon and aramid fibres became available allowing the manufacture of stiffer, stronger and lighter structures. After the millennium, other reinforcement fibres became commercially available: high-oriented PE, basalt and natural fibres (e.g. flax and hemp). Despite these material innovations, glass fibre remains the volume material due to its excellent price to performance ratio.

Polyester and epoxy resins are thermosets. This means that they are initially liquid and solidify after a chemical cross-linking reaction. This liquid state enables the impregnation of the fibres and in this wet form they can be easily positioned into a mould without using pressure or elevated temperatures. The thermoset resin then solidifies and results in a strong fibre reinforced plastic product that can be subsequently removed from the mould. This combination of materials shows very good resistance to water or other corrosive environments. This results in composites having a long service-life with little or no maintenance. Even in outdoor applications a service-life of composite products is between 60 to 100 years [1].

Since the 1980's thermoplastic polymers have also been used for manufacturing composite products. Initially they were used only in short-glass fibre reinforcement for injection moulded parts (e.g. casings for tools). Typically the thermoplastic polymers PP, PA6, PA66, PBT and PET are used for these products. Thermoplastic composites require both a high temperature and pressure to achieve fibre impregnation. When producing composite parts using the injection moulding process, the high viscosity of the thermoplastic melt means that the impregnation of the fibres can only be achieved by a compounding step in an extrusion process. This results in a reinforcement with a short fibre and with such high pressures required, the size of the products is limited because of the need to use heavy steel moulds and high closing forces.

The commercial use of long-fibre thermoplastic composites has increased in the last twenty years. The production is a two-step process because of the difficulties in impregnation with the viscous thermoplastics, similar to the problem with the short-fibre thermoplastics. The long fibres are first impregnated with a melted thermoplastic polymer into plates or tapes, followed by a second step in which the pre-compounded materials are reheated and shaped into the desired form. This is achieved by hot-press moulding or laser-assisted tape laying. When cooled the product becomes solid. Long-fibre reinforced thermoplastics require PP or high-performance thermoplastics such as PEI, PPS and PEEK. Long-fibre thermoplastic composites are relatively small in volume compared to the total composite market but they are growing [2].

2. End-of-life thermoset composites

Despite their longevity, thermoset composites do eventually come to an End-of-Life (EoL) stage. This can be because of esthetical reasons, damage, or the end of their *guaranteed* structural safety. Generally the composite material itself is still viable. Particularly in the case of rotor blades from modern windmills that are guaranteed for safe use for a period of 20–25 years. When rotor blades are decommissioned (**Figure 1**), the composite material still has very good properties.

The major volume of EoL thermoset composites consists of boat hulls and windmill rotor blades, and these waste streams are expected to increase in the coming years [4]. Boats are a fashion leisure product and as such are periodically replaced and, as mentioned, the dismantling of windmills occurs when the period of guaranteed of structural safety ends or, as rotor blade size increases, for reasons of efficiency.

3. The composite recycling challenge

Thermoset composites are very hard to recycle into the original components (fibres, resin, fillers and core materials). To separate the components, the cross-linked resin must be decomposed because it cannot be melted. Decomposition can be achieved by burning or by dissolving in a chemical substance that can

Figure 1.
Obsolete windmill rotor blades [3].

depolymerize the thermoset polymer. These methods have been extensively investigated since the 1990's, but to date there is no industrial method that is financially viable.

The burning method to regain the fibres is only a partial (caloric) recycling of the material because the resin and organic core materials are not being recycled. In addition, the fibres that are regained from this process are of a very limited value. The glass fibres experience a dramatic loss of fibre strength as reported by Thomason et al. [5]. The coupling agent on the glass fibres (binder) is also destroyed by the burning process. With regard to carbon fibres the situation is slightly more positive because the burning process does not affect their strength. In both cases, however, the after-burning result is not a suitable material for general industrial use.

Two development programmes were set up in the 1990's using the burning process to regain glass fibres from composites in automotive applications, mainly from Sheet Moulding Compound (SMC) and Bulk Moulding Compound (BMC) parts. One programme from the automotive industry in Germany was developed by ERCOM Composite Recycling GmbH that started in 1990 [6]. This development did not lead to a successful industrialisation and stopped in 2004. The other development was the VALCOR-process from the automotive industry PSA in France. This development also did not lead to success and was duly stopped.

Grinding the composite products into a filler was also investigated. Although the resulting filler can be re-used in new products, this method did not lead to a positive business case. This was because virgin fillers that are available on an industrial scale (e.g. limestone, talc, sand) have a very low price level in the range of € 0,10 to € 0,20 per kg. The processing costs to grind the composite products lead to a much higher price level, so competition with traditional fillers is not possible. Over the past years several companies have developed composite grinding methods but they have not been a lasting success.

The burning method was further developed into the 'cement-kiln route' [7]. In this method, EoL composite is fed into a cement oven and the organic components are burned off providing the caloric value to heat the oven. The inorganic components, especially the glass fibre, remain as a filler in the cement. Although not technically a recycling of the composite, some useful components are retained in the form of energy and the fibre remainders that can serve as a filler. The cement kiln route has been accepted in Europe from 2012 to present day as a recognised method for the recycling of composites [8]. This method, however, is expensive: the EoL composite has to be processed into small pieces and to be brought to the cement oven in Bremen, Germany and then there, a gate fee of € 160, −per metric ton has to be paid.

To improve composite recycling, several initiatives in the last 20 years were undertaken to recycle composites into their original components but none have resulted in an industrial process yet. Comprehensive overviews have been given of these initiatives and have been described [9, 10] and presented by the ACMA [11].

4. Principle of structural re-use

In 2015 the Professorship for Polymer Engineering (Windesheim University of Applied Sciences) began to develop the principle of the structural re-use of EoL thermoset composite products [4, 12]. This method is based on keeping the composite structure of the End-of-Life product intact but machining it into smaller parts, e.g. strips or flakes. These smaller parts must have an oblong shape enabling it to act as reinforcing elements once embedded in resin while making new products. In this manner the good properties of the EoL composite, mechanical strength, stiffness and water resistance, remain unimpaired and can be used in the new product. An illustration of the use of EoL composite strips and flakes as reinforcing elements in new composite products is given in **Figure 2**.

To embed the strips or the flakes, additional virgin resin is required. This method implies that the new products will be relatively heavy and can only be simple in shape e.g. profiles, beams or plates. This combination of properties: high strength, high water resistance, relatively heavy and straight-shaped are extremely suited to infrastructural applications. Thermoset composites materials have outstanding resistance to outside conditions [1] and therefore will result in products with a long service life. The method of structural re-use of EoL thermoset composite products has been successfully proven in infra-structural demonstrators like retaining walls, guiding structures that funnel boats into canal locks, crane-mats and bridge decks as will be shown further on in this chapter.

5. Structural re-use in practice

The method starts with the machining of the product into smaller parts, prior to the making of strips or flakes. In **Figure 3** an example is shown where an obsolete polyester boat is broken up into large panels.

In the second step, these panels are sawn into long strips or shredded into flakes, see **Figure 4**.

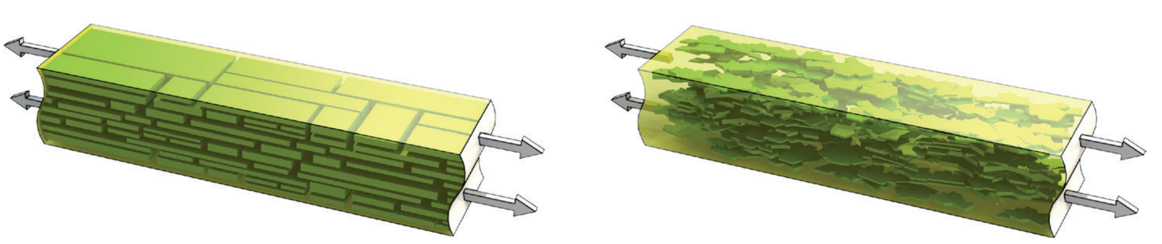

Figure 2.
New composite profiles reinforced with EoL composite strips or flakes [4].

Figure 3.
Breaking up of a polyester boat into panels [4].

Figure 4.
Panels sawn into strips or shredded into flakes [4].

The processing of heavy and large windmill rotor blades into strips or flakes involves more effort than a thinner polyester boat hull. Abolished rotor blades are currently in the region of 30 meter long. Future lengths of abolished windmill rotor blades will be much longer still because currently windmills are installed with rotor blades of over 100 meter length. Abolished rotor blades must therefore be pre-cut preferably on location into transportable sizes, e.g. by mobile waterjet cutting ('cold cutting'), by concrete breaking tools or by diamond blade cutting. These pieces can then be transported to a location where they can be reduced in size still further before eventual shredding.

When rotor blades are shredded, a different material is obtained compared to shreds from boats, because a large part of this composite consists of high-oriented reinforcement. After the shredding process, the material is more needle-like, see **Figure 5** left, than when products with a more random reinforcement are shredded, such as boat hulls, the latter results in a more flake-like product, see **Figure 5** right.

During the process of machining the composite product into strips or flakes, other side products are obtained. First of all, dust is formed during cutting and shredding. But also other components occur originating from the original product such as adhesives, coatings, core materials (foam and wood) and metal parts. Also contaminations that were present on the product can be found back such as dirt, oil and specifically for boat hulls: anti-fouling and growth of shells. Generally these other components are not very harmful for the properties of the end product, provided their percentage is limited. Moreover, the harmful substances will not leach out because it is completely embedded in virgin ('fresh') resin. The company CRC in The Netherlands is specialised in industrial processing of EoL thermoset composites into grades of flakes that can be re-used for making new products.

Processing the strips or flakes into a new product can be done by different techniques. All techniques have in common that the re-used material (strips or flakes) is

Figure 5.
Shreds from rotor blades (left) and from boat hulls (right).

embedded in virgin resin that binds it together. In most cases also a virgin composite layer is formed around the outside of the product.

6. Mechanical performance of re-used composite

The principle of structural re-use of EoL thermoset composite products is based on the possibility to partially benefit from the strength that is still present in the material. The so-called L/D-ratio of the parts that are re-used (strips or flakes) as reinforcing elements is an important parameter. In this ratio L represents the longest dimension of the re-used composite part and D represents the smallest dimension. Although the role of the L/D-ratio on elastic properties of fibre reinforced materials is described already long ago with elastic models [13], the influence of the L/D-ratio of reinforcing elements on strength of the complete reinforced material or product is more difficult to model.

The influence of the L/D-ratio of reinforcing elements on the strength of the new product that is made with it has been further investigated with a well-defined shape: a rectangular strip. To investigate the effect of the length of strips on reinforcement, a series of panels was produced and tested. To allow for a good comparison, instead of EoL-material, virgin glass mat reinforced polyester laminate with a constant quality was used as a base material to produce the strips.

The base material for making the strips for the investigation was a glass mat reinforced polyester laminate with a thickness of 5 mm. For the glass mat reinforcement 6 layers of continuous glass fibre mat (CFM) of 450 g/m^2 were used (Unifilo U813, OCV). As resin a low-viscous DCPD polyester resin (Synolite 1967 – G 6, AOC) was used. This laminate was made by vacuum infusion resulting in a glass content of 37 wt%. The laminate was made with peel-ply on both sides that was removed after curing for improved adhesion lateron.

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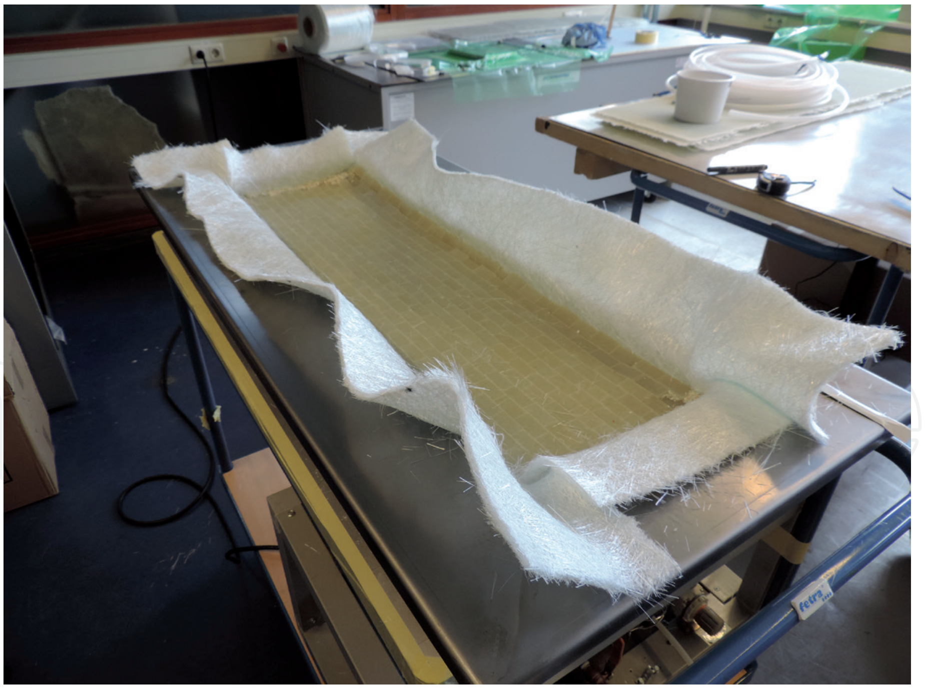

Figure 6.
Layers of GRP strips as core in a test panel in preparation for infusion [4].

From the laminate, strips were cut with a diamond-tipped blade to a width of 20 mm, that were used as reinforcing elements in a test panel with the dimensions L x W x T = 1000 x 300 x 24 mm. Incorporating four layers of these strips positioned flatwise resulted in a reinforcing core of 20 mm. A surrounding shell of about 2 mm thickness was created by wrapping the core in an infusion glass mat (Polymat HI-FLOW M03P Core, Scott & Fyfe, consisting of 2x 450 g/m^2 glass mat reinforcement layers). The final panels were produced by means of infusion with the same DCPD polyester resin as for making the 5 mm laminates. The reinforcing strips were used in the core with lengths of 40 mm, 80 mm, 200 mm and 1000 mm, respectively. The photo in **Figure 6** shows the flat-wise incorporation of the fourth layer of 40 mm strips just before it was covered with the infusion glass mat.

To investigate the effect of adhesion between strips and embedment resin, a test panel was produced with 40 mm strips with flat surfaces (by omitting peel-ply layers, resulting in smooth surfaces with relatively bad adhesion). Moreover, a test panel was produced using 1000 mm strips, that was cut from a polyester boat hull without any surface treatment. Finally, a test panel was produced with 200 mm strips placed vertically on their sides instead of flatwise. In all test panels strips were oriented in length direction of the test panel and the strips were placed staggered with respect to the neighbouring strips (both horizontally and vertically). **Table 1** gives the overview of tested configurations.

Length of strips used as reinforcement of core (mm)	40	80	200	1000
Virgin GRP strips with peel ply, 4 layers placed flatwise	X	X	X	X
Idem, but without peel-ply (bad adhesion)	X			
Virgin GRP strips with peel ply, 1 layer placed vertically			X	
Strips of 5 x 40 x 1000 mm from boat hull, placed flatwise				X

Table 1.
Combinations of materials and strip lengths tested.

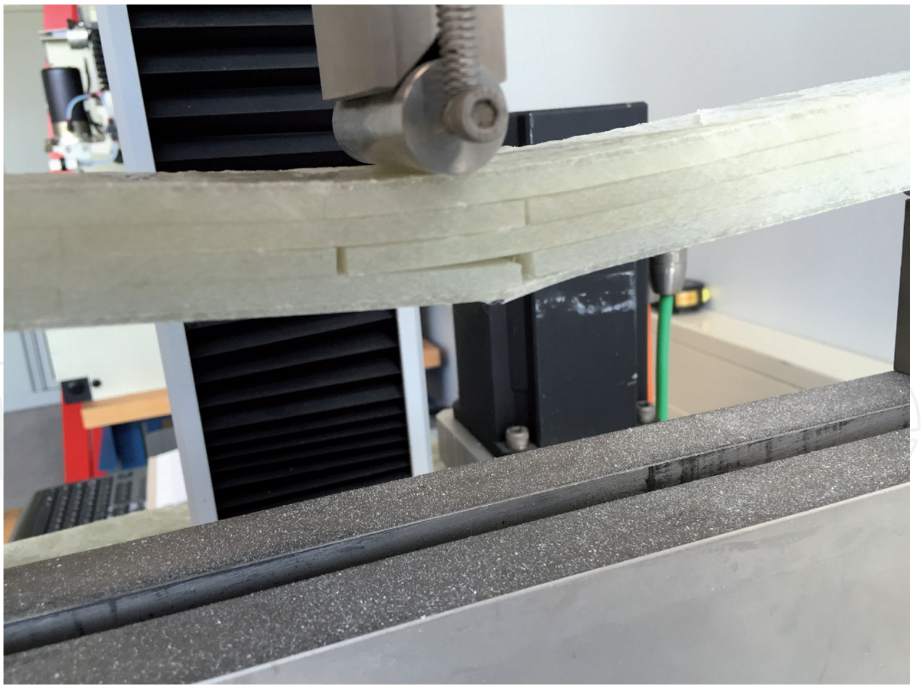

Figure 7.
Bending test of a specimen made with 80 mm strips [4].

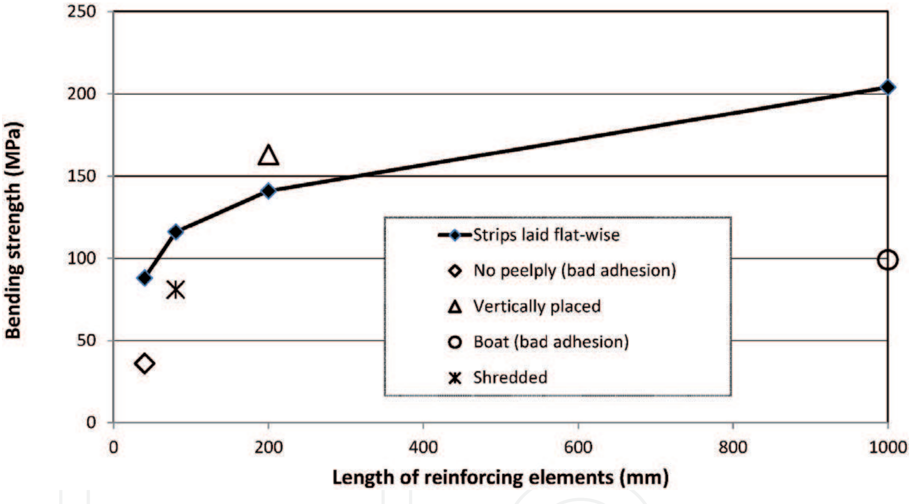

Figure 8.
Mechanical strength as function of strip length for different test materials [4] (markers indicate the mean value of 5 tests).

From each test panel samples were cut in length direction (i.e. in de direction in which the strips are oriented) with the dimensions L x W x T = 360 x 50 x 24 mm. Tests were repeated 5 times. The samples were tested in three-point bending in accordance with ISO 178. The photo in **Figure 7** shows the testing of a sample with four layers of strips of 80 mm in length, placed flat-wise.

The graph in **Figure 8** shows a clear correlation between the bending strength and the length of the strips in the core for flat-wise laid strips with good adhesion. With a 1000 mm strip length the bending strength reaches 204 MPa. The negative effect of bad adhesion on bending strength is seen in the case of the 40 mm strips where the peel-ply has been omitted: the bending strength is as low as 36 MPa, less than half of the strength with 40 mm strips with good adhesion (88 MPa). Also a relatively low strength of 99 MPa is found when using strips cut from a polyester boat-hull, which can be attributed also to bad adhesion. During the test these strips that were obtained from abolished boats, delaminated at the gelcoat side, showing a smooth delamination surface, which is an indication of a relatively bad adhesion. By placing the 200 mm strips vertically, a higher bending strength is observed (163 MPa) as compared to the flat-wise placement (141 MPa).

With the set-up of strips laid flat-wise and a good adhesion with the embedding resin, the effect of the L/D-ratio is considered. It is assumed that the panel strength with strip lengths of 1000 is the maximum attainable panel strength in this set-up (204 MPa). At a strip length of 40 mm (L/D-ratio of 8) only 43% of the maximum attainable strength of the panel is found. With increasing strip length the bending strength of the panel increases in a degressive manner. At a strip length of 200 mm (L/D-ratio of 40) a panel bending strength is found that is 69% of the maximum attainable panel strength. From these considerations it can be concluded that a significant part of the possible maximum panel strength is obtained for a L/D-ratio which is of the order of 50 or higher.

In the graph, also at the location of 80 mm length, the strength of a panel made from flakes is shown. That strength was found to be 81 MPa. The flakes were made by shredding EoL thermoset composite in such a way that a mean flake length of roughly 80 mm was obtained. It must be remarked that the lower strength as compared to the strength of 80 mm strips (116 MPa) can partly be attributed to the lower content of reinforcement (higher resin content).

Shredding may be a more economical way of machining EoL thermoset composites into reinforcing elements than sawing or water cutting, although this has to be investigated further. Shredding is a very promising method because a large quantity of EoL composite products can be machined at relatively low cost. However, the flakes that result from the shredding process must have a quality level that makes them suitable for the re-use in new products, e.g. sufficiently high L/D-ratio, dry, dust free and good adhesion properties with the embedment resin.

7. Demonstrators

The methodology of structural re-use of EoL thermoset composites results in products that are especially suitable for applications in building and infrastructure. Profiles, plates or panels can be made that are mechanically strong and resistant to moisture. The fact that the new products made from EoL composites are not light-weight is generally not a problem for this field of application. In the following section, demonstrator projects are described from re-used EoL composite products.

7.1 Retaining walls

EoL composites profiles were manufactured for retaining walls near the Beatrix lock-gate in Almere, The Netherlands [3, 14]. 80 separate profiles, each with a length of 3.5 metres were produced using two steel moulds. The cross-sectional

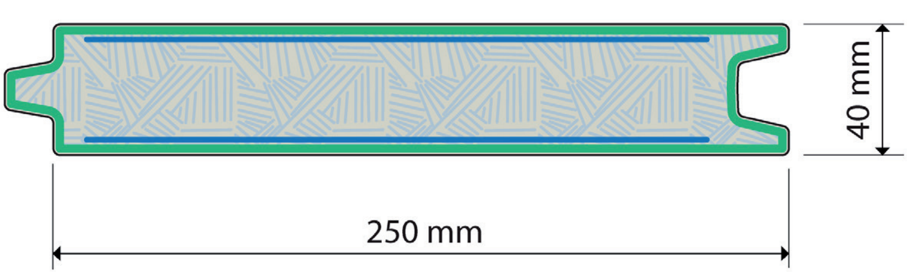

Figure 9.
Cross section of profile for retaining wall built up with a core of EoL composite [3].

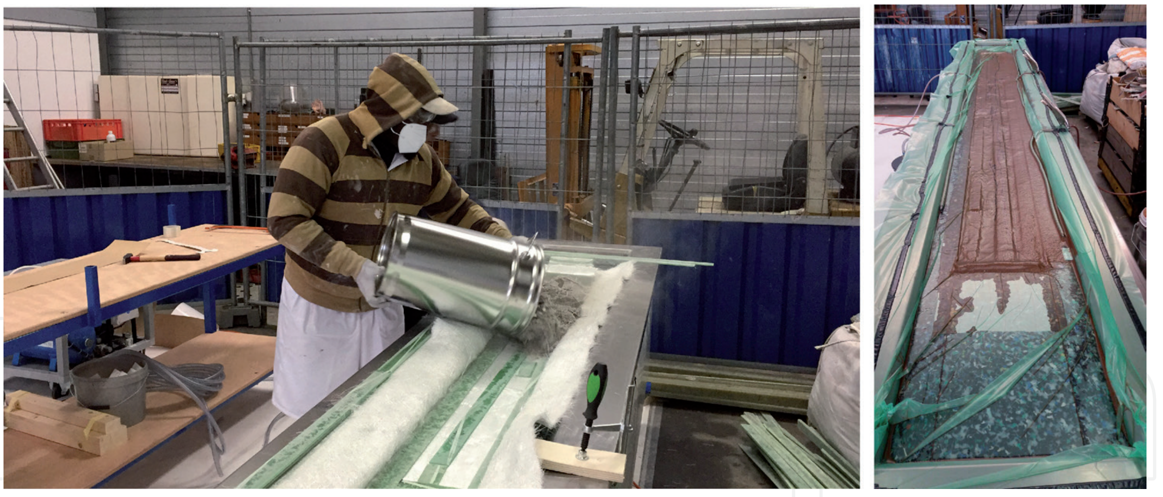

Figure 10.
Production of profiles using EoL composite by vacuum infusion under foil [3].

dimensions of the profiles were 40 x 250 mm with a tongue-and-groove detailing. A drawing of the cross-section of the profile is given in **Figure 9**.

The profile has an effective width of 250 mm and a thickness of 40 mm. The outside skin is build up from a virgin glass reinforced polyester laminate containing a 900 g/m^2 random reinforcement (glass mat, green in the picture) and a 900 g/m^2 UD-reinforcement of 200 mm width on both sides (blue in the picture). The core is formed by re-used EoL thermoset flakes that are bound by a polyester resin.

For this demonstrator, the profiles were made by means of vacuum infusion under foil in steel moulds. Into the mould, the glass injection mat was charged (Polymat HI-FLOW M03P Core, Scott & Fyfe, 900 g/m^2) along with the first layer of 200 mm wide UD-glass reinforcement (UNIE840, Selcom 840 g/m^2) on which the EoL flakes and strips were applied. On top of this, a second layer of UD-reinforcement was placed and the glass injection mat was closed around it. Then the vacuum foil was applied. A brown pigmented polyester DCPD resin (Synolite 1967-G-6 of AOC) was injected, giving the profile a wood-like appearance. **Figure 10** shows the charging of the mould with strips and flakes of EoL composite (left) and the product that is infused with brown pigmented resin (right).

Figure 11.
Installation of retaining wall by vibrating profiles with EoL composite in the soil [3].

Figure 12.
Guiding structure with two lowest rows of beams made from EoL composite [3].

The profiles were tested mechanically and the same bending strength was found as for the same profile geometry made of azobé wood, that are commonly used for these applications. The profiles were installed in 2017 by vibrating into the ground without any damage being incurred on the profiles, see **Figure 11**. Inspections and tests on profiles withdrawn from the ground in 2019, two years after installation, showed no signs of degradation nor loss of strength.

7.2 Guiding beams

Guiding structures are placed near bridges or lock gates in canals to guide ships and prevent damaging the infra structure. Traditionally, these structures consist of a steel frame with horizontal guiding beams. These beams are normally made of tropical hard wood (e.g. azobé) and typically have dimensions of 200 x 200 x 4000 mm. In 2019 guide beams were made from re-used EoL thermoset composite to replace the lowest two rows of four guiding structures at Groningen Seaports in Delfzijl, The Netherlands [3]. Because the lowest two rows of guiding beams in a guiding structure are located around and under the water level, this is the location where normally tropical hardwood beams suffer most from fungi attack and re-used EoL thermoset composite will be more durable. **Figure 12** shows a photograph of one of the four guiding structures. The four rows above the water level are made from tropical hardwood.

The strength needed to resist a possible ship collision for a single beam is defined for a single beam as 440 kN when mounted at a support distance of 1800 mm. To achieve this, additional layers of UD-glass reinforcement had to be incorporated into the beam. A prototype beam was tested in three-point bending with a support distance of 1800 mm and a maximum force of 515 kN was recorded. After this successful test, 112 meters of guiding beams were produced using a steel mould with an RTM injection process. The beams have been installed in Delfzijl in October 2019.

7.3 Crane mats

On building sites crane mats are used to obtain a stable work area on which heavy cranes and other machinery can operate. Generally crane mats are composed

Figure 13.
Crane mats in use at a building site [3].

of beams of tropical hard wood. The choice for this material is based on the requirements on strength, wear resistance and durability. The crane mats depicted in **Figure 13** have outer dimensions of 1 x 5 m and are composed of five azobé beams with dimensions 200 x 200 x 5000 mm that are assembled using five steel bars.

In cooperation with Welex (manufacturer of crane mats, based in The Netherlands), a crane mat was made from EoL thermoset composite beams. RTM-infusion was used for the production of the beams. In the mould first a glass injection mat (900 g/m^2), 2 layers of quadraxial glass reinforcement (1200 g/m^2) and 10 layers of UD glass reinforcement (840 g/m^2) were applied after which the core was built up from flakes of EoL composite in combination with fire-dried sand (1–2 mm grain). The five holes of 30 mm diameter for the assembly of the crane mat were created in the beams using tubular inserts. The crane mat was tested under various severe operating conditions. After the filling of the core with resin, the reinforcement layers from the bottom were folded over the top before closing the mould and starting the injection process. The EoL composite crane mat performed very well, showing good resistance to wear by vehicles and was easy to clean, see **Figure 14**.

Figure 14.
Crane mat made of EoL composite tested in practice [3].

Figure 15.
Dinzer bridge with deck profiles of re-used composite: Installation and final result [15].

7.4 Bridge deck profiles

In a project to renew the Dinzer bridge over a canal in Friesland (The Netherlands) deck profiles were applied made from re-used EoL thermoset composite. It was one of the requirements that the profiles should resemble the original hard wood profiles by their cross-sectional dimensions (thickness 95 mm, width 245 mm) and were able to withstand heavy traffic loading.

The profiles were designed with an outside layer of virgin glass fibre reinforced polyester and a core from re-used EoL thermoset composite flakes embedded in polyester resin. Before starting production, prototypes of the profiles were mechanically tested in order to verify the mechanical loading capacity. These tests were successful and showed that the beams fulfilled the requirements for Dutch infra structural design [15]. The required profiles were produced using a resin casting method in a steel mould.

The profiles were successfully mounted on the new bridge structure of the Dinzer bridge and give off the appearance of a traditional deck with wood deck profiles, see **Figure 15**. The big advantage of these profiles made of re-used composite is that the expected service life is much longer and maintenance is lower.

8. Design rules

In general, for building applications in Europe the Eurocode is used. There is, however, no specific Eurocode dedicated to composites. In The Netherlands a specific recommendation for design with composites is available [16] but only for composites made from virgin materials. Nevertheless, the general methodology from the Eurocode can be followed irrespective of the origin of the raw materials from which it is built. This is described in the European standard EN 1990 [17]. In this standard, in Annex D (Design assisted by testing) it is described in what manner material properties can be determined using a test programme.

Based on extensive testing of EoL thermoset composites [18] to date the following conclusions can be made for the design with these materials made with re-used EoL thermoset composites:

- Design for long-term loading (creep) and fatigue should be avoided for parts solely consisting of re-used EoL composites in a product. For these load types continuous virgin fibre reinforcement must be incorporated into the product to ensure resistance to creep and fatigue.

- For design on stiffness and strength (with exclusion of creep and fatigue) design formulas can be used [16], with the conversion factor set to 0.9. It is required that re-used EoL composite is compatible with the virgin resin in which it is embedded (e.g. good adhesion) and that the virgin resin is resistant to the user conditions of the new product and is properly cured.

9. Business case

A business case consists of several components that determine whether or not it is attractive for industry. Most critical factor is economic profitability. Can products be sold for a price that is attractive for the market and leaves a profit for the manufacturing company? There is also an increasing demand for products that are sustainable, this aspect must also be taken into account as non-sustainable products could be excluded in the future. In the Netherlands from 2023 the policy of the government is to purchase only sustainable products.

Product sustainability can be achieved by using raw materials with a low carbon footprint, for example: recycled or re-used materials. The use of materials with a low carbon footprint alone is not enough to ensure sustainability. The energy needed for production and the CO_2 production that is related to the production of the new product must also be included.

The economical profitability of structural re-use of EoL thermoset composites for retaining walls was considered. During the production of the infra-structural demonstrators it had become apparent that manual production was too costly for economic profitability. Trials were carried out with our industry partners using the automated production technique of pultrusion, with a very positive outcome. Following that success, the pultrusion company Krafton in The Netherlands installed a compounder to mix re-used EoL composite flakes with resin and injects this into the core of pultrusion profiles. This is an efficient continuous production process that involves very little labour.

A financial tool was developed to analyse the profitability of a factory that produces these profiles with a pultrusion-based continuous process at a production speed of 15 m/hour [18]. Costs for the production are based on raw material costs, energy consumption, labour costs, depreciation of machinery, rent of production

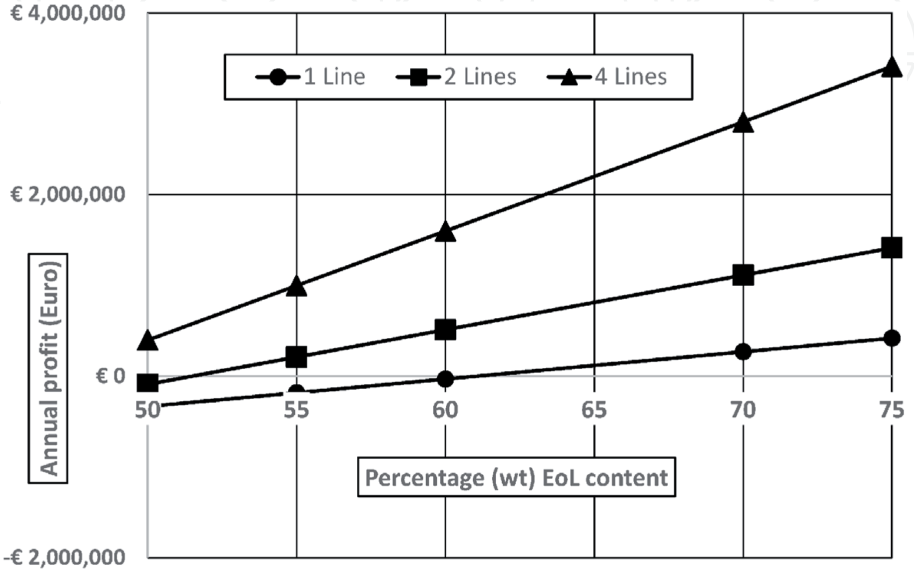

Figure 16.
Annual profit for a model production plant for profiles with EoL composite core [3].

space and overhead. Based on price discussions with local councils and water municipalities in The Netherlands, a factor of 1.3 was applied to the sales price of identical profiles made of tropical hard wood (azobé).

A factor of 1.3 means that a product made of re-used EoL thermoset composite can be sold for a 30% higher price than the traditional tropical hard wood profile. This higher sales price was found acceptable by the water municipalities based on the longer life span in wet conditions and the circular characteristics of the product.

Variables in the tool are the weight percentage of EoL material in the profile and the number of production lines. **Figure 16** shows the annual profit of the model factory as a function of weight percentage of EoL material in pultruded profiles, for production facilities with 1, 2 and 4 production lines respectively.

From the analysis it can be seen that already with one production line the facility becomes profitable when the content of EoL material in the profiles reaches at least 62% by weight. With more production lines the profitability becomes higher as the number of persons working in the pilot plant weighs heavily within the calculation. From the trials by the industry partners using a pultrusion set-up it was found that an EoL content of 70% by weight is possible in the profile under consideration.

For the same profile also the CO_2 footprint was analysed. For this, the ECO-Calculator of EuCIA was used [19]. This tool evaluates the CO_2 footprint of composite products 'from cradle to gate', which means it considers the effect of the raw materials used and the production process. Using this tool the CO_2 emission per kg of product was calculated for two percentages of EoL composite material content (50 wt% and 70 wt%, respectively). Moreover, the CO_2 emission per meter profile was analysed when the profile with the same mechanical performance was made using only virgin raw materials, either as a profile made with an RTM-process with a PET-foam core or as a hollow profile with shear webs inside made with a pultrusion process. Cross-sections of the four profiles are presented in **Figure 17**.

The results of the analysis is given in the graph in **Figure 18**. Obviously the amount of CO_2 for the production of a meter profile is strongly related to the percentage of re-used EoL thermoset composite used. This is mainly connected to the amount of virgin resin that is used to embed the EoL composite flakes. Comparing virgin based profiles with EoL composite material containing profiles, the carbon footprint of the latter becomes advantageous when the amount of re-used EoL thermoset composite is at least 70 wt% or higher.

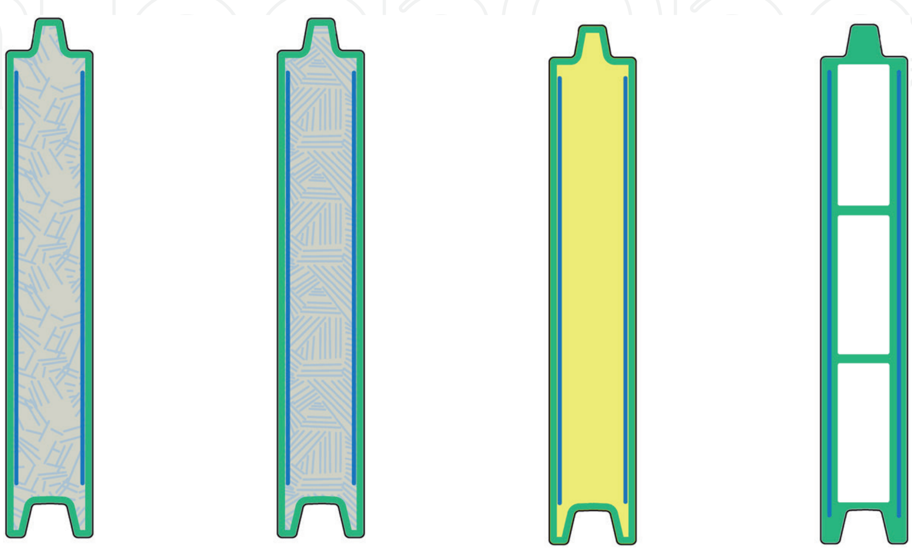

Figure 17.
Profile types with identical mechanical performance analysed for their CO_2 – footprint. From left to right: 50% EoL, 70% EoL, virgin RTM, virgin pultrusion.

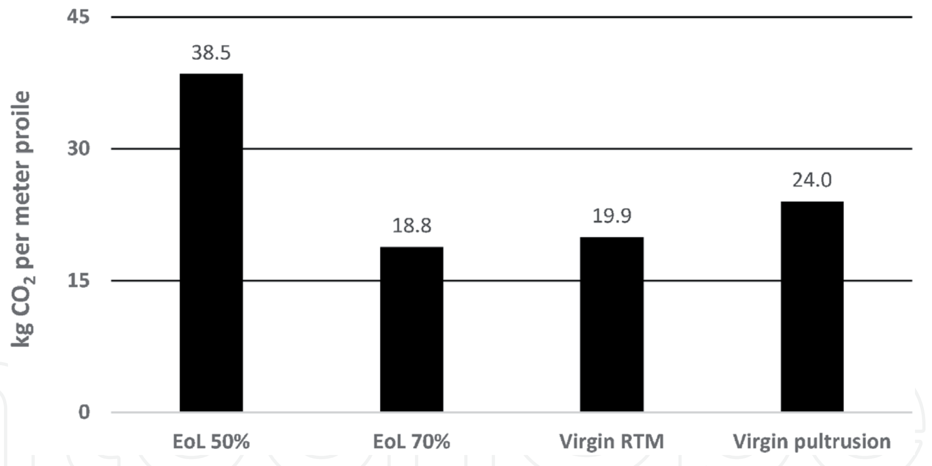

Figure 18.
Graph of CO_2 footprint per meter profile for different profile build up [3].

10. Conclusions

The methodology of structural re-use of EoL thermoset composites as developed by Windesheim and partners offers the possibility of industrial re-use of previously non-recyclable thermoset composites. From the various infrastructural demonstrators it could be concluded that strong, robust and water resistant products can be made. A set of design rules was developed according to the Eurocode to evaluate structural behaviour of products made with re-used EoL thermoset composites. It was shown that industrial processing of these materials can be achieved using a pultrusion type process. The lower labour costs of such a process and the high percentages of EoL-content in the new products can lead to an automated production and a profitable sales of products. It was found that the percentage of EoL material in the new product is the key parameter for both profitability and low CO_2 emission overall.

Author details

Albert Ten Busschen
Windesheim University of Applied Sciences, Zwolle, The Netherlands

*Address all correspondence to: a.ten.busschen@windesheim.nl

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