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Comparative impact assessment for flax fibre versus conventional glass fibre reinforced composites: Are bio-based reinforcement materials the way to go?

Joost R. Duflou (1)[a,*], Deng Yelin[a], Karel Van Acker[b], Wim Dewulf (2)[a]

[a] Department of Mechanical Engineering, KU Leuven, Belgium
[b] Department of Metallurgy and Materials Engineering, KU Leuven, Belgium

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ABSTRACT

In many applications the use of composite materials can offer significant weight reduction opportunities, which can have a positive influence on the life cycle impact of a component or system primarily through energy saving effects in the use phase. The impact associated with the production and end-of-life (EOL) phases, however, forms a possible counter indication for systematic replacement of conventional structures by composite solutions.

Bio-composites are considered a promising strategy to limit production and EOL impact. In this paper a comparative LCA study is presented for flax fibre reinforced composites based on PP on the one hand, and functionally equivalent glass fibre reinforced PP composites on the other. The analysis results and conclusions derived from a comparative attributional LCA study are summarised in this paper.

1. Introduction

As part of the general trend towards increased energy efficiency of transportation systems, mass reduction is an important design objective. Offering good strength and stiffness properties for a relatively low component weight, composite materials offer clear advantages in this context. However, the high production impact of the composing materials and the poor recyclability pose major problems in terms of environmental impact when the state-of-the-art for conventional composites, such as carbon or glass fibre reinforced epoxy, is considered [1].

As part of the efforts to overcome these deficiencies, the use of renewable materials in composites is intensively investigated. Plant fibre reinforced polymer composites (PFRPs) have recently received substantial attention due to their potential for replacing conventional fibre reinforced polymer composites, specifically glass fibre reinforced polymer composites (GFRPs). It is forecasted that by 2020 fibres derived from bio-based sources will represent up to 28% of the total market of reinforcement materials [2]. Flax fibre is the most widely used plant fibre for polymer reinforcement due to its exceptional mechanical properties [3]. The wide availability, low cost, low density, high specific properties and the eco-friendly image of flax fibres have portrayed them as prospective substitutes for the traditional composite reinforcements, specifically E-glass [2]. Moreover, flax fibre is a combustible resource leaving no slag after incineration.

* Corresponding author. Tel.: +32 16 322845.
E-mail address: joost.duflou@mech.kuleuven.be (J.R. Duflou).

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The results of a wide literature study with respect to the mechanical properties achievable with different flax FRPs are summarised in Fig. 1. In this figure different categories are distinguished according to the nature of the polymer matrix, the structure of the flax fibre reinforcement and the applied manufacturing method.

While currently over 95% of PFRPs produced in the EU are used for non-structural automotive components [2], the properties

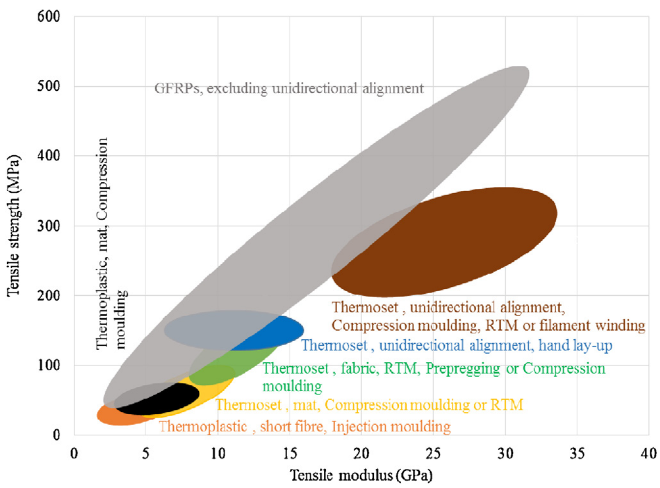

Fig. 1. Mechanical properties for different categories of flax FRPs compared to GFRPs.

summarised in Fig. 1 support the envisaged structural applications of flax FRPs that are more recently being developed. In this context the question can be raised whether the substitution of GFRPs by PFRPs in general, and by flax FRPs in specific, would be an environmentally benign decision. In order to answer this question a systematic comparative LCA study has been conducted as summarised in this article.

2. LCA modelling approach

2.1. Goal and scope definition

The goal of this LCA study is to compare flax FRPs to conventional GFRPs in a cradle to grave approach. Within the scope of this paper this research question is limited to injection and compression moulding as the predominantly used production techniques for PFRP composite materials in Europe [4]. This limits the considered polymer categories to thermoplastics. Being the dominant thermoplastic matrix material, covering approximately 70% of the current European PFRP market [4], polypropylene (PP) was chosen to represent this category.

Bio-based matrix materials are not considered here mainly due to their high production cost and current negligible industrial penetration, as well as the uncertainties concerning their technical performance, e.g. due to their high water absorptivity and low melting point or decomposition temperature [2].

The geographical boundary for this study was set to be within Europe since the European automotive industry is currently the strongest promoter for the application of plant FRPs. With France being the dominant producer of flax fibres in Europe, flax cultivation and fibre processing in France are modelled to represent the general situation in Europe.

Two categories of applications were distinguished for the use phase: dynamic 'transport system' applications, in which a change in mass typically induces a change in energy consumption rate of the system; and static applications characterised by insignificant energy consumption in the use phase. In this analysis, the use application in a transport system will be the main focus since static systems can be regarded as a special case thereof with a negligible environmental impact in the use phase.

Incineration with energy recovery is a logical scenario for composite disposal. Coproduction of heat and power (CHP) was selected as the mainstream technology in this context.

The ReCiPe midpoint (H) method was used to quantify the impacts, using Ecoinvent 2.2 as primary data source.

As will be explained in the next paragraphs, the systematic use of material specific mass indicators for functionally equivalent structures and the derived Life cycle Environmental Indicator (LEI), allow comparing the performance of different materials without need for detailed dimensional specifications for the considered structures. In order to assure an exact functional unit, the type of transport system in which the component is to be used and the functional lifetime of the system expressed as a total travel distance however have to be specified. For this study the chosen transport system is a gasoline car with an expected total travel distance over the entire lifetime of 200,000 km.

2.2. Functional equivalence modelling

To maintain functional equivalence in this comparative study, the Ashby method [5] was followed, assuring equal structural properties for the design alternatives. Two widely used criteria for equivalent performance in structural components are equal stiffness and strength. The material mass indices outlined by Ashby are summarised in Table 1. These mass indices, consisting of only material intrinsic properties (density ρ and E or σ (for tension: tensile modulus and strength; for bending: bending modulus and strength)) can be used to quantify the relative weight of a design for a material under specified load conditions.

Table 1
Material mass indices (MI_{mass}) proportional to design weight.

Shape	Load	Variable	Mass index equal stiffness	Mass index equal strength
Strut	Tension	Section area	ρ/E	ρ/σ
Beam	Bending	Beam height	$\sqrt{\rho/E}$	$\rho/\sigma^{2/3}$
Panel	Bending	Panel thickness	$\sqrt[3]{\rho/E}$	$\rho/\sqrt{\sigma}$

The recently developed modified generalised rule-of-mixture (ROM) model [2] provides formulas to calculate the tensile modulus and strength of PFRPs in function of the mechanical properties of the fibre and matrix materials, the respective volume fractions and a series of coefficients taking into account the nature and orientation of the fibre reinforcement. Since no pragmatic theoretical model for the bending modulus/strength could be identified, the tensile modulus and strength were used as proxies for the bending properties in this analysis. Rodríguez et al. [6] measured the bending and tensile moduli for various natural fibre reinforced polymer composites. Their results show that the deviations between the respective bending moduli and tensile moduli are within 10%. For the bending strength a correction factor of 1.5 was applied to the tensile strength in accordance with the findings in [6].

2.3. Use phase modelling

The fuel-mass correlation in transportation systems can be presented by the following equation [7]:

$$FC = FRC \times M + B \tag{1}$$

where FC is the fuel consumption (l/km); FRC stands for the fuel consumption reduction coefficient (FRC) (expressed in l/(km kg)) determined by the rolling, gradient, and acceleration resistance; M is the vehicle mass (kg); and B is a constant representing the parasitic loss (l/km), which is strongly related to the aerodynamic design.

Since the parasitic losses cannot be influenced by the component mass M_c, the fuel consumption attributed to the component FC_c should be solely mass-induced and can be formulated as

$$FC_c = FRC \times M_c \tag{2}$$

2.4. LCA model at component level

The impact that can be attributed to the composite component in the different life cycle phases can be expressed as

$$EI_i^{Prod} = \frac{\sum_{j=matrix,\, fibre} M_j \times (eEI_{i,j}^P + eEI_i^F}{\eta_{proc}} \tag{3}$$

$$EI_i^{Use} = FRC \times M_{FRP} \times D \times eEI_{WtW,i} \tag{4}$$

$$EI_i^{EoL} = -\eta_{net} \times \left[\sum\nolimits_j 0.97 \times \frac{M_j}{\eta_{proc}} \times LHV_j\right] \times eEI_i^{prim} + \frac{M_{FRP}}{\eta_{proc}} \times eEI_i^{comb} \tag{5}$$

where $EI_i^{Prod,\ Use,\ or\ EoL}$ equals the environmental impact in impact category i during the respective life cycle stages; M_j is the mass of the matrix or fibres in the product; η_{proc} is the process efficiency; eEI_{ij}^P is the environmental impact in category i for the primary production per kg material j; eEI_i^F is the environmental impact in category i in composite fabrication per kg material input; M_{FRP} stands for the mass of the FRP component; D (km) represents the expected travel distance over the entire lifetime of the specific transport system; $eEI_{WtW,i}$ is the unit impact for category i per litre of fuel from well-to-wheel; eEI_i^{Prim} is the unit impact in category i for the substituted energy source per MJ; and eEI_i^{Comb} stands for the unit process impact for category i for incineration.