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Natural fibre selection for composite eco-design

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ABSTRACT

Natural fibre composites (NFC) are gaining interest in manufacturing because they address some of the environmental problems of traditional composites: use of non-renewable resources, and large impacts related to their production and disposal. Since natural fibres are not yet optimized for composite production, it is crucial to identify the most appropriate applications, and determine the optimal fibre/matrix ratio. A methodology is proposed for early-stage decisions support on selection of bio-composite materials. Results help identify the application with the largest reduction in environmental burden and show that the fibre/matrix combination with the lowest environmental burden also has the best mechanical properties.

1. Introduction

Composites offer high mechanical stiffness at low material density. This combination of properties makes them attractive for use in lightweight constructions. When used in a dynamic application (e.g. in a car), the weight reduction offered by composite materials may allow considerable fuel savings. On the other side, the production and disposal of conventional composites based on glass or carbon fibre is related with considerable environmental and human health challenges [1]: the fibre production process is energy intensive, while the heterogeneity of composite materials creates problems with their disposal.

Use of plant fibres in composites can help overcome some of these difficulties. They can be produced from a renewable and almost carbon neutral feedstock, the energy consumption for their production is moderate and their disposal causes fewer environmental issues, since the fibre are biodegradable or when incinerated they can produce energy [2]. However, the use of natural fibres (NF) for composite production has not yet been optimized to achieve the highest mechanical properties and to identify the best applications.

Life Cycle Assessment (LCA) is the tool of choice for assessment of the environmental performance of a product or service. Previous LCA studies of natural fibre composites (NFC) are limited. Comparative studies have been based on mass-to-mass comparisons ignoring differences in stiffness between the compared materials [3]. Alternatively, they have resorted to use of simplified micromechanical models for calculating the mechanical properties of the composites [4], not suitable to represent the behaviour of natural fibre composites due to their special characteristics compared to synthetic fibre composites, as pointed out in [5]. An important problem related to use of NF is the typically higher porosity and the lower maximum obtainable fibre volume content of the resulting composites compared to the use of man-made fibres [5].

In addition, LCAs of various products based on NFC indicate that the type and context of the application of NFCs influences the outcome of the comparison with conventional fibres.

In order to evaluate such materials properly, an adequate framework is needed, which accounts for all those issues and is generalizable to assess all composite type.

This paper proposes an assessment framework that addresses these shortcomings. It caters to the needs of Life Cycle Engineering (LCE) by taking into account specific (mechanical) properties of the material as well as the application context of the material in order to develop a more relevant life cycle inventory (LCI) for comparison of composites.

2. Methodology

The proposed methodology has three steps and combines: a micromechanical model developed to be representative also for NFC [5], the Ashby methodology [6] for the functional comparison of composites in different structural applications, and LCA for the assessment of the environmental impact across a multitude of impact indicators. Fig. 1 shows the graphical representation of theproposed framework. The individual modules provide the input needed for the succeeding module. Outputs from the proposed methodology are the environmental impact profiles of the different material scenarios. With this new approach, it is possible to evaluate different materials and applications in a unified framework, not relying on case based comparisons. The methodology allows for a comparative early stage material screening with obvious eco-design

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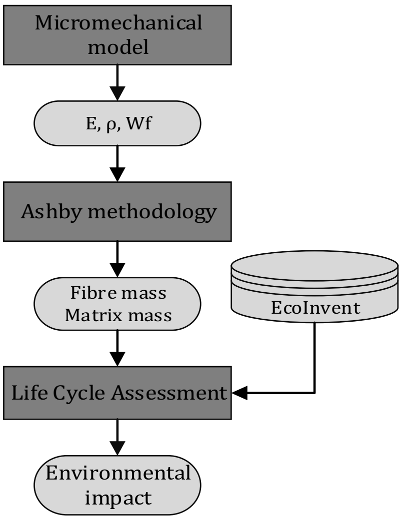

Fig. 1. The proposed method (E is the elastic modulus, ρ the density and Wf the fibre weight fraction of the composite).

application perspectives, or else identifying the application where a selected material can have the lowest environmental impacts.

2.1. Material properties

Composite properties depend on the specific properties and mixing ratio of fibre and matrix materials.

To predict the composite properties, we used the micromechanical model developed by Madsen et al. [5], which takes into account the effect of the porosity on the final composite properties and allows calculating the mechanical properties and the density of the composite as a function of the fibre weight fraction.

Porosity is known to affect the properties of the composite and for synthetic fibres (e.g. glass fibres); a large pool of knowledge has been accumulated on how to diminish the porosity part when producing composites [7]. For NFs, the porosity is related to a number of known factors including the luminal cavities in the plant fibre, the heterogeneous shape of the fibre and the surface chemistry between fibre and matrix [8].

The model predicts two cases of composite volumetric interactions, at low and high fibre fraction. Those are separated by a transition fibre weight fraction, at which the combination of a high fibre volume fraction, low porosity and a high composite density is optimal, resulting in the highest mechanical properties achievable. Detailed explanation of the method is available from [5].

Once the fibre and matrix parameters and the fibre weight fraction have been decided, the model calculates density and elastic modulus of the resulting composite. The model can also be used to calculate the optimal fibre weight fraction (Wf_{trans}) which under the specific operating conditions results in the best achievable mechanical properties.

2.2. Type of structural application

The second module evaluates the material performance in different applications using the Ashby methodology [6]. This methodology is widely employed for material selection, allowing for calculation of the masses of alternative materials needed to achieve equal mechanical performances.

The Ashby methodology calculates a performance index (Ashby's index) for each considered application, based on the material properties and the design constraints. The mass of a material needed to fulfil the design requirements will be proportional to the calculated Ashby index.

Inputs for the Ashby index calculation, are the mechanical properties and density of the composite obtained from the micromechanical model. Outputs of this module are the Ashby indices representative for the different applications considered. Subsequently, when the mass of the reference scenario has been defined, it is possible to estimate the mass of material needed to fulfil the same design requirements.

2.3. Environmental performance/impact

LCA is used to assess the environmental performance of the resulting composite material. LCA is the most generally accepted method for quantification of the environmental impacts related to a product or a system [9]. It estimates the potential impacts arising during the whole life cycle of a product, from the extraction of the resources (cradle) to the final disposal of the product (grave), considering a broad range of environmental impact categories, and is hence not only focusing on climate change. LCA is an iterative process composed of 4 phases:

- Goal and scope definition
- Inventory data collection
- Impact assessment
- Interpretation

Input for the LCA module are the material amounts required for each composite scenario which are used to scale the inventory to represent the specific material scenario.

3. Application of the method

The presented method was applied in a comparison of the environmental performance of glass fibre reinforced plastic composite (GFRP) and flax fibre reinforced composites (FFRP).

3.1. Goal and scope definition

The purpose of the study is to compare the use of FFRP and GFRP in different structural applications and at different fibre weight fractions. The fibre materials evaluated in this study are: flax fibres, one of the most commonly used natural fibres on the market [10], and glass fibres, representing the dominating conventional fibrous reinforcement solution. The fibres are combined with a thermoplastic polypropylene matrix. Polypropylene is the most frequently used thermoplastic reinforcement, holding almost 70% of the European market for thermoplastic matrix materials [11]. The material properties used as input for the micromechanical model are presented in Table 1. Composite structures are produced via thermoforming processes. The focus of the study is on indoor furniture applications, where stiffness is the dominant design constraint, and UV light and/or high moisture exposure [12] are unlikely to compromise the durability of the composite.

Table 1
Input parameter for the micromechanical model.

Parameter	Unit	FFRP	GFRP
Fibre elastic modulus	GPa	50	72
Matrix elastic modulus	GPa	2	2
Fibre density	g/cm^3	1.5	2.7
Matrix density	g/cm^3	0.9	0.9
Fibre porosity constant	[–]	0.1	0
Maximum fibre volume fraction	[–]	0.35	0.50
Fibre orientation factor	[–]	0.38	0.38

3.2. Functional unit

Following the ILCD guidelines for LCA, a comparison of materials can only be conducted when the same function or service is provided [13]. The functional unit in this study is: "To provide the equivalent mechanical stiffness performance of 1 kg of GFC in different mechanical applications".