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Coupled micromechanical analysis and life cycle assessment as an integrated tool for natural fibre composites development

Antoine Le Duigou*, Christophe Baley

University of South Brittany, LIMATB, C Huygens Research Center, Rue de Saint Maudé BP 92116, 56321 Lorient Cedex, France

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ABSTRACT

Nowadays, Eco-design is mainly carried out through Life Cycle Assessment (LCA) tool by companies in the post-production stage of parts to provide useful information for the next production. Although no methodology is currently in the pre-production step that could help companies generate cleaner parts and save time. Thus, the proposed work provides an innovative method that associates a micromechanical analysis, material index selection and LCA methodology. The method is applied to a flax fibre/polypropylene (PP) composite, being potential substitute of glass/PP composites in automotive applications. The studied 30% w/w flax fibre/PP composite is found to be 6% lighter than 30% glass/PP composites and to generate 10%–20% lower environmental burdens. Combining a micromechanical analysis, material index selection and LCA shows that: fibre content, Young's modulus, and aspect ratio have to be maximized to achieve a decrease of the environmental footprint of flax/PP biocomposites.

1. Introduction

The End-of-life vehicles directive imposes on car manufacturers to achieve recovery and recycling targets of 85% by average weight per vehicle deposited for appropriate treatment going up to 95% by 2015 (E.p.a.t. council, 2008). Thermoplastic composites such as glass-reinforced polypropylene (PP) are increasingly used in transportation and automotive applications due to their overall production rate, mechanical performance, lightness, chemical stability, and end-of-life recyclability.

Eco-design of car parts is increasingly being applied through the Life Cycle Assessment (LCA) tool following ISO 14044 frameworks (Ribeiro et al., 2007; Duflou et al., 2009). Such investigations reveals that the use phase is the most contributing step in the whole life cycle of a part, highlighting the major effect of lightweight design on the environmental burdens. Pietrini et al. (2007) show that the definition of the use step, whether static or transportation, is crucial prior designing the part design as it influences the overall environmental footprint.

Automotive industry is now heading towards a new path, consisting in introducing plant fibres instead of glass fibres as green reinforcing agent (Koronis et al., 2013; Zah et al., 2007; Alves et al., 2010). Their low density (around 1.5 against 2.5 for glass) associated with their high mechanical properties bring automotive manufacturers new opportunities for a lightweight design approach (Corbière-Nicollier et al., 2001; Farag, 2008; Joshi et al., 2004; Luz et al., 2010). For example, the production of flax fibres as reinforcing component brings lower environmental impacts than production of glass fibres (Le Duigou et al., 2011). Static applications of PLA/Flax biocomposites and PLA/Flax/Balsa bio-sandwich exhibit several environmental advantages compared to those of glass/polyester composites and sandwich counterparts (Le Duigou et al., 2012a; Le Duigou et al., 2012b). Moreover, plant fibre composites can be recycled (Le Duigou et al., 2008; Bourmaud and Baley, 2007) or composted providing that matrix resin is biodegradable. In addition, the mechanical properties of natural composites can be estimated accurately by micromechanical equations taking into account component properties, volume ratio, and their length-to-diameter aspect ratio (L/d).

A typical LCA is often carried out after part production, thus justifying the use and enabling possible improvements for the following production cycle. Examples can be found in the literature with the introduction of carbon (Duflou et al., 2009) or natural fibres (Alves et al., 2010) reinforced composites in automotives.

However, eco-design is basically defined as the integration of environmental parameters during the design step. Thus, an integrated LCA methodology during design and prior the production step should be considered to achieve a cleaner production. Some

* Corresponding author. Tel.: +33 2 97 87 45 86; fax: +33 2 97 8745 88.
E-mail address: antoine.le-duigou@univ-ubs.fr (A. Le Duigou).

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works (Miller et al., 2013; Giudice et al., 2005) have already been done in that way by coupling material selection in the life cycle process.

The present article aimed to go further on this issue by coupling a micromechanical model, a material index selection methodology and LCA. Thus cleaner production of flax fibre composites can be monitored by optimizing the composite mechanical parameters (e.g. fibre modulus, fibre fraction). The procedure is carried out on a flax/polypropylene composite in comparison to glass/PP composites for automotive applications.

2. Methodology

2.1. Goal and scope definition

The purpose of the present study is to develop a new methodology of LCA that associates a micromechanical analysis, index material selection such as the Ashby approach (Ashby, 1999), and LCA. The example used to apply this new methodology is that of under-engine panels manufactured with PP/glass or PP/flax. The assessment focuses on the PP/flax composite as it may be a good candidate for PP/glass substitution. However, just because materials are natural is no guarantee that they have a low environmental impact. Therefore, to avoid greenwashing, LCA following the ISO 14044 framework (ISO-14044, 2006) is used as a standard, objective, and reliable tool to carry out an eco-design properly.

2.2. Functional unit and determination of material flow

The specifications for under-engine panel are the protection of the bodies of the engine compartment from the external aggressions while supporting bending load during use phase.

Others specifications are the reduction of gas consumption with better aerodynamics and lower weight and the improvement of the noise level.

Thus, the functional unit considered in this study is the following: “an automotive flax fibre reinforced polypropylene part, manufactured by extrusion and injection moulding, with similar material index for a stiffness-limited panel with flexural loading as glass/polypropylene composite counterparts”.

Estimations of material flows are required as input for LCA calculations. First, the composite mechanical properties are estimated by using micromechanical models whose correlations with experimental values have been previously checked. Micromechanical models are used to estimate composite properties by using component properties, volume fraction, reinforcement geometry, and orientation. The input properties used in the micromechanical models are shown in Table 1.

The composite manufacturing steps are carried out by typical automotive processes such as extrusion and injection moulding. Such processes induce short fibre reinforcement with nearly random-in-plane orientation. The Halpin–Tsai equation (Equation. (1) and Equation. (2)) is first used to estimate the longitudinal Young's modulus E_L and the transverse Young's modulus E_T for a ply reinforced by short unidirectional fibres (Halpin and Kardos, 1976).

$$\frac{M}{M_m} = \frac{1+\xi\cdot\eta\cdot V_f}{1-\eta\cdot V_f} \quad (1)$$

where

$$\eta = \frac{\frac{M_f}{M_m}-1}{\frac{M_f}{M_m}+\xi} \quad (2)$$

where $M = E_L$ or E_T, $M_f = E_{fL}$ or E_{fT} and m, f, L, T correspond to matrix, fibre, longitudinal and transverse. V_f is the fibre volume fraction and ξ the form factor. For the longitudinal modulus $\xi = (2L/d)$, where (L/d) is the fibre aspect ratio (reinforcement length, L, divided by its diameter, d). For the transverse modulus (E_T), satisfactory results have been obtained with $\xi = 2$ (Gibson, 1994).

Then, the Young's modulus of a ply reinforced by randomly dispersed fibres is given by the following Equation (3) (Gibson, 1994):

$$E_{mat} = \frac{3}{8}E_L + \frac{5}{8}E_T \quad (3)$$

where E_L is the longitudinal Young's modulus and E_T the transverse Young's modulus of the unidirectional ply. These approaches have already been used to estimate the Young's modulus of extruded and injected flax/PP, flax/PLLA biocomposites or hemp/PP composites with good agreement with the experimental values (Le Duigou et al., 2008; Ausias et al., 2013).

Once the Young's modulus is estimated, material index determination is carried out by using the Ashby method (Ashby, 1999). A stiffness-limited panel (with flexural loading) and a light part are required. Hence, $I = E^{1/3}/\rho$ criterion is used to discriminate the glass/PP and flax/PP composites.

Weight variation and thus the material flow induced by substitution of the glass/PP automotive part by flax/PP is estimated with Equation (4) (Pietrini et al., 2007).

$$\text{Weight variation} = \left[\left(I_{PP/Glass}\big/I_{PP/Flax}\right)-1\right]\cdot 100 \quad (4)$$

With $I_{PP/glass}$ and $I_{PP/Flax}$ the material index respectively for PP/glass and PP/Flax composites. Table 2 shows the results for the composite Young's modulus (calculated), the material index, and the weight change for a 30% w/w fibre-reinforced composite. This fibre content is assumed as it is widely used in automotive applications for common parts (Rachini et al., 2012). For a similar fibre-weight ratio, the Young's modulus of both composites is very close. However, the density of glass fibre composites is higher, hence the material index and the weight change (−5.6%) will be favourable to flax/PP composites.

The weight change is taken into account in the LCA calculation by multiplying the weight change by that of the automotive part to be produced (700 g for the actual glass/PP part). Therefore, the part manufactured with a flax//PP composite will weigh 661 g, which corresponds to the material flow. Secondary weight reductions (e.g. lighter motor of the weight of the Body-In-White (BIW) is lower) is not taken into account here.

Table 1
Mechanical properties used for micromechanical modelling.

Material	Density	Longitudinal Young's modulus (GPa)	Transverse Young's modulus (GPa)	Aspect ratio after injection moulding with PP (L/d)	Ref.
PP	0.9	1.7 ± 0.03	1.7 ± 0.03	X	(Le Duigou et al., 2012b)- From producer
Glass	2.5	70.3 ± 5.8	70.3 ± 5.8	40 ± 20	(Le Duigou et al., 2012b; Ashby, 1999)
Flax	1.5	54.1 ± 15.1	7.0 ± 2.0	15 ± 7	(Le Duigou et al., 2012a; ISO-14044, 2006; Halpin and Kardos, 1976)