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Vibro-acoustic optimisation of Wood Plastic Composite systems

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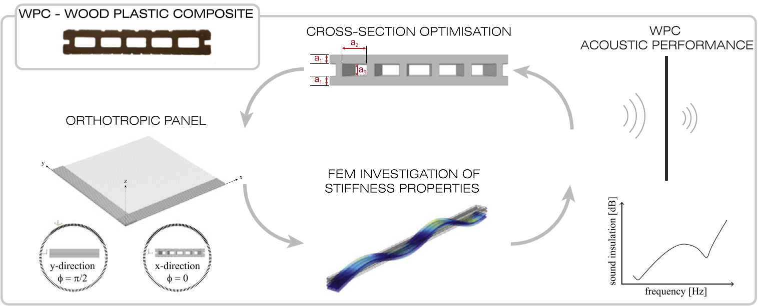
HIGHLIGHTS

- A numerical approach to characterise WPC sandwich structures is proposed.
- An optimisation method to improve the WPC plates' acoustic performance is provided.
- Orthotropic WPC plates are modelled by using frequency-depended elastic properties.
- An elliptic interpolation is used to approximate the orthotropic bending stiffness.
- An empirical equation to evaluate the bending stiffness frequency-decay is derived.

GRAPHICAL ABSTRACT



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ABSTRACT

"Wood Plastic Composite" or WPC is becoming increasingly popular in outdoor applications because of the advantage of a better durability in wet environments compared to natural wood. The possibility of using WPC as a sound barrier, or as façade cladding, is investigated in this paper. The sound transmission loss (TL) of an orthotropic WPC panel, obtained by coupling together several boards, is computed by means of the transfer matrix method. The plate is modelled as a thin orthotropic layer, described by frequency dependent elastic properties. A numerical procedure, based on a finite element simulation, is proposed in order to determine the stiffness properties along the principle direction of the panel. The reliability of this approach is verified by comparing the numerical results with the experimental stiffness measured on a WPC beam. The orthotropic behaviour is approximated by an elliptic interpolation of the flexural stiffness along the two principle directions, based on a simplified assumption which considers the in-plane shear modulus proportional to the orthotropic elastic moduli. The model based within the transfer matrix method framework is validated with the experimental transmission loss measured on a WPC panel in a reverberant room. Finally, the possibility of increasing the acoustic performance of WPC structures by optimising their cross-section is investigated.

1. Introduction

Besides widely accepted benefits of environmental friendliness, natural-fibre-filled polymers are interesting materials due to their convenient balance of mechanical properties and cost. Natural fibres, in fact, are relatively cheap, as they originate from local agricultural or industrial waste. Although traditional reinforcement, like glass fibres, impart higher stiffness and strength, the mechanical properties of natural-fibre-filled plastics are usually adequate. Among natural fibres, wood flour is one of the most widely used filler, mainly because of its wider availability. The resulting material

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is often termed “Wood Plastic Composite” or WPC and is becoming increasingly popular as a wood substitute. The WPC market share has expanded in the last twenty years by an average annual growth around 3.0% [1,2] and the trend is still increasing. The main advantage with respect to natural wood is outdoor durability, also in a wet environment, which allows applications like external flooring, decking, fences, and near-water structures such as piers. WPC boards can be processed with standard woodworking procedures, e.g. sawing and drilling, but at the same time they can be extruded like a standard plastics profile, thereby allowing engineering-optimized sections that are usually not obtainable with natural wood. The main research activities concerning WPC that are available in the scientific literature aim at improving the mechanical properties of the material, i.e. strength and stiffness, usually by acting on the WPC composition [3]. The main factors that are considered are the presence and quantity of additives, e.g. the coupling agents, and the amount, quality and geometrical properties of the wood fibres in the formulation. It is normally found that the optimum properties are obtained using a wood fibre filling level of about 50 wt%, the fibres possessing an aspect ratio of 10 or higher and using an amount of coupling agent around 4 wt% [4,5]. Mechanical properties may also be improved by using polypropylene as the matrix [6,7], which on the other hand has the drawback of a more difficult processing and characterization [8].

In this article we explore the possibility of using WPC boards as a sound barrier or a façade cladding system, which are relatively new fields of application. To the best of our knowledge, there are very few studies that are concerned with the acoustic performance of such structures. The acoustic performance of wood-polymer composites has been previously investigated, however, research so far has been mainly focused on sound absorption of composite foams [9] and different sustainable composites [10,11], rather then on sound insulation provided by this kind of materials. Zhao et al. [12] investigated the normal incidence sound insulation of wood-rubber composite panels by using a four-microphone measurement technique. In order to simulate the sound transmission loss (TL) of an orthotropic WPC panel, which is constructed by binding together several boards, the transfer matrix method (TMM) is used [13], although to implement this method it is necessary to know the stiffness characteristics of the investigated element. The material dynamic elastic modulus is firstly derived by means of a standard procedure. The apparent frequency-dependent flexural stiffness of a WPC extruded board is then determined numerically and verified with experimental data. By means of frequency-dependent stiffness properties the dynamic response of complex structures, such as sandwich beams or WPC boards, can be approximated with good accuracy using low-order theories [14]. Furthermore, in order to describe the orthotropic behaviour of the WPC board, the stiffness characteristics should be determined along both principle directions [15]. To this purpose, a numerical approach based on Finite Element (FE) simulations, is presented and validated with numerical results.

In the present paper a noise barrier has been constructed by coupling together several WPC boards. The sound insulation provided by this panel has been tested in a reverberation room coupled with a semi-anechoic chamber. This method allows a much more accurate measurement with respect to the impedance tube method, as it considers a diffuse incident sound field, and more realistic boundary conditions. The experimental transmission loss is used to validate the numerical model based on the TMM framework. Finally, thanks to the possibility of easily varying the profile cross-section by changing the extrusion die, an optimized shape of the cross section has also been simulated by numerical computation using the methods described in Section 4.

2. Material and methods

The material used in this investigation was a commercial WPC board manufactured by Iperwood srl (Ferrara, Italy). This material is a high density polyethylene (HDPE) filled with 50 wt% of wood fibres from pine sawdust.

In order to investigate the vibro-acoustic behaviour of WPC elements it is necessary to dynamically characterise both the material’s properties and the dynamic response of the entire system. Acoustically excited structures exhibit very small deflections. Thus, according to the small strain assumption, WPC can be assumed as a linear viscoelastic material, characterised by a complex elastic modulus taking into account the energy dissipation due to viscous damping. Moreover, the dynamic response of elements with complex structural geometries can be approximated by means of low-order theories, using frequency dependent elastic properties.

2.1. Material characterisation

The “Oberst beam” is a classical method to dynamically characterise the elastic and damping properties of viscoelastic materials. The methodology, described in the ASTME756 standard [16], is based on the analysis of the Frequency Response Function (FRF) measured on a clamped-free homogeneous bar. The element should be excited by an electromagnetic transducer, in order not to interfere with its response. Unfortunately, WPC is not a ferromagnetic material and it was necessary to excite the bar mechanically in a different way. An alternative setup to apply Oberst’s technique was proposed by Wojtowicki et al. [17]. It was compared to other experimental techniques to determine the elastic and damping properties in Ref. [18], showing that, with contacting piezoelectric transducers, it is necessary to perform a large number of measurements in order to experimental dispersion and obtain more accurate results, especially at low frequencies where the resulting loss factor is usually highly fluctuating and characterised by significant variability. A homogeneous WPC bar was excited by using an impact hammer equipped with a force transducer, as shown in Fig. 1. It is possible to determine the elastic modulus of the homogeneous elastic material from the resonance frequencies of the bar, evaluated from the measured FRF, as [16]:

$$E = \frac{12\rho l^4 f_n^2}{h^2 C_n^2}, \tag{1}$$

where ρ is the material density, l is the bar’s length and h its thickness, f_n is the resonant frequency of mode n, while C_n represents a coefficient of the clamped-free beam associated with mode n, given in the E756 ASTM standard [16] and reported in Table 1. In order to verify the reliability of the results, the dynamic elastic modulus was compared with the static Young’s modulus.

Static Young’s modulus was determined with the three-points bending method according to the ASTMD790 standard, using an INSTRON 4467 dynamometer equipped with a 500 N full scale load cell. Four specimens in the form of 23 mm × 4.5 mm rectangular cross section bars cut along the longitudinal extrusion direction were loaded in the central section of a 80 mm span at room temperature. Since the Young’s modulus had to be compared with the stiffness coming from measurements performed at high loading frequencies, the highest allowable cross-head speed was used, i.e. 200 mm/min. Following the three-points bending method, the stress σ could be obtained by

$$\sigma = \frac{3}{2}\frac{FL}{bh^2}, \tag{2}$$

while the strain ε can be obtained by