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An equivalent material formulation for sinusoidal corrugated cores of structural sandwich panels

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ABSTRACT

Metal sandwich panels with corrugated cores are an appealing industrial solution as structural components thanks to their high stiffness-to-mass ratio. Nevertheless, using detailed finite element models for numerical computation of their properties leads to large models and long solution time, especially for acoustic simulations. Therefore, reduction of the complex shaped core to an equivalent homogenous material is commonly used.

In this paper, an innovative aluminum sandwich panel with sinusoidal corrugated core is investigated. The properties of the equivalent material are determined both analytically and numerically for the chosen Reissner–Mindlin orthotropic representation. The two derived models are compared in a comprehensive parametric study to validate the computationally much cheaper analytical formulation. Moreover, a validation of the equivalent models is done based on the bending stiffness per unit width of the sandwich panel. Finally, the acoustic behavior of the structure is investigated comparing the reduced layered model with the fully detailed 3D model.

1. Introduction

Metal sandwich panels are becoming increasingly important as multi-functional components in many industrial areas. One of the main characteristics is their high stiffness-to-mass ratio, especially under bending conditions. This property strongly depends on the two faces, but other properties – acoustic, thermal, etc. – are governed by the core. Therefore, interest in innovative cores is justified by the effort the industry is making to create multi-functional components that integrate good performances in different fields. For this reason, several core types are already commercially available, such as foams, honeycomb, cellular metals, etc. Among all sandwich panels, corrugated core structures are an interesting alternative that is being increasingly used in the transportation industry. For these panels there are different core shapes, such as truss-type corrugations (i.e. triangular), trapezoidal cores or circular shape [1–3]. In this paper, aluminum sandwich panels with sinusoidal corrugated cores are investigated, as shown in Fig. 1.

The main field of application of these innovative aluminum structures is the transportation sector, e.g. in the automotive industry, where energy conservation, lightweight construction and recycling are critical requirements. Also marine interior applications are common, since these panels provide good structural performance with small thicknesses and they can also be easily supplied in semi-finished components. Finally, rail vehicles are using this kind of structures, due to their high stiffness to weight ratio and good fire insulation properties. Typical railway applications for these panels are inner floors since they are able to withstand high loads, both point and distributed [4,5].

In order to simultaneously meet different functional requirements of panels, the industry is increasingly using multidisciplinary optimization techniques on both component and system levels. The methods to derive objective and constraint functions in optimization are typically based on Finite Element (FE) method. However, to accurately represent the sinusoidal cores, FE models need a very large number of elements, causing the optimization solving time to be penalizing even for relatively simple models. For this reason, homogenization techniques are used to reduce the complex core to an equivalent homogeneous material, allowing to represent the sandwich panel as a layered medium.

In the literature several authors studied the behavior of sandwich structures, see Mackerle [6] for a deep bibliographic study up to 2001. In particular, regarding homogenization techniques, honeycomb cores have been extensively investigated [7–9] even with particular sinusoidal-shaped cells [10–13]. Moreover, increasing importance is given to lightweight cellular cores [14,15]. Moving to corrugated cores, the literature shows a

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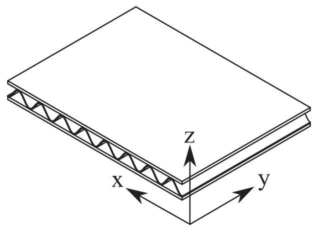

Fig. 1. Aluminum sandwich panel with corrugated core with global system of reference.

particular focus on triangular and trapezoidal shaped core panels [16–21] – with the two fundamental NASA reports by Libove and Hubka [1] and by Ko [3] – or circular shaped corrugations [16,20,22,23]. An interesting study on the influence of slightly different geometries on the equivalent properties is given in [24]. Nevertheless, homogenization techniques applied to panels with sinusoidal corrugated cores are limited to cardboard panels, which have been studied in a few works with both FE [25–27] and analytical techniques. The main drawback of the latter techniques for cardboard is that they are based on limiting assumptions, such as the Baum's approximation [28] for the in-plane shear modulus in [29–31] which is not feasible for a metallic panel since it is based on measurements only on cardboard, or the Kirchhoff–Love representation of the core [32,33], which excludes the out-of-plane properties of the core. The only Reissner–Mindlin representation of a sinusoidal corrugated plate found in literature is given by Liew in [34] as an extension of the work of Briassoulis [32], but there the out-of-plane properties are approximated as for a trapezoidal core. On the other hand, Nordstrand [2] and Isaksson [29] gave an estimation of transverse parameters which will be compared to present results.

In view of the use of the equivalent model for the determination of noise reduction capabilities, the equivalent out-of-plane properties are crucial. Therefore in the present work, an orthotropic representation for a Reissner–Mindlin formulation of the equivalent core is proposed, based on the geometric characteristics of the sinusoidal corrugation. The present approach makes use of an energetic approach to compute the main parameters. Differences from previous works are explained in the text and the main results from the previously mentioned authors are included in comparative parametric studies to show the greater accuracy of the proposed analytical formulation assuming FE-derived parameters as the reference. Therefore, a FE-based technique to determine equivalent properties is also developed.

The orthotropic homogeneous material obtained is then included in a layered FE model together with the two faces: the coupling between the core and the faces is done by using the classical lamination theory, i.e. perfect bonding between layers.

Finally, the equivalent layered models are validated by comparing their static and acoustic behavior to those of a fully detailed 3D structure. In particular, the bending stiffness per unit width and the transmission loss spectrum are included in the validation.

One advantage of modeling the panel with the equivalent layer for the core is that parametric studies with respect to the core geometry becomes straightforward enabling optimization of the panel. Moreover, the results of the research will also allow the inclusion of panels, and specifically lightweight and engineered panels, within vehicle concept models, which currently are mainly based on beam-like structures [35–37].

The paper is organized as follows. In Sections 2 and 3 respectively, the analytical and FE-based formulations to determine equivalent parameters are illustrated. A parametric comparison of the two formulations is shown in Section 4, and the analytical representation is validated in Section 5, based on the complete panel bending stiffness, i.e. including the skins. Finally, in Section 6, the sound transmission of the equivalent model is compared to that of a complete 3D representation.

2. Analytical formulation

In this section, the parameters needed to properly represent the equivalent orthotropic core material are derived. Seven parameters are needed to represent the orthotropic material for isoparametric two-dimensional shell elements. Particular attention is given to the shear stiffnesses, as these properties are critical for the sound transmission, investigated in Section 6. The reference system used in this paper is shown in Fig. 1, where the *x-axis* corresponds to the machine-direction (MD), whereas the direction of the *y-axis* is denoted cross-direction (CD) and that perpendicular to the panel is the *Z*-direction (ZD).

The constituent material is chosen as for commercial panels, i.e. standard aluminum with properties listed in Table 1.

2.1. Transverse shear modulus G_{xz}

The first parameter of the equivalent material is the transverse shear modulus in the *xz-plane*. The authors that have studied this out-of-plane property are Isaksson [29] and Nordstrand [2]. Both the authors divide the core in infinitesimal layers and if the former computes the parameter based on their strain energy, the latter computes their deformations. On the contrary, in this paper, the parameter is analytically derived using an energetic method [38] over the unit periodic cell as described in the following. Moreover, the effect of shear stresses in the core lamina is also included. Comparison of results will be shown in Section 4.

Consider half a period of the sinusoidal corrugated sheet represented by its centre line, having thickness t_c and unitary width in *y-direction*, $b = 1$. The origin of the reference system is set in correspondence of the lowest point and there the structure is clamped (Fig. 2).

To determine the equivalent shear modulus, the horizontal displacement δ_H of the upper end due to a horizontal force H has to be determined. In addition, a dummy moment M_0 and vertical force V are applied to include proper BCs corresponding to pure shear deformation, i.e. vertical displacement and rotation of the free edge are not allowed (see Fig. 3).

The centre line of the sinusoidal shape can be described by:

$$f(x) = \left(h - h\cos\frac{\pi x}{p}\right) \tag{1}$$

where h is the amplitude and p is the half-period of the sine. The inner forces at a generic point x, as illustrated in Fig. 2, are:

$$M = H\left(h - h\cos\frac{\pi x}{p}\right) + Vx - M_0 \tag{2}$$

$$N = H\cos\varphi - V\sin\varphi \tag{3}$$

$$T = H\sin\varphi + V\cos\varphi \tag{4}$$

where φ is the angle between the tangent to $f(x)$ and the *x-axis*. The partial derivatives of the inner forces with respect to the applied loads can be computed as:

Table 1
Aluminum properties used.

Young's modulus (MPa)	Poisson's ratio (ad.)	Density (kg/m^3)
71000	0.33	2700