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Buckling analysis of a reinforced sandwich column using the Bloch wave theory

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ABSTRACT

This paper deals with sandwich structures whose core layer is made of a homogeneous foam periodically strengthened by orthogonal reinforcements. Beside traditional sandwiches which generally display satisfactory specific flexural properties but fatally insubstantial stiffnesses in the through-thickness direction, 3D reinforced sandwich materials provide optimal out-of-plane mechanical properties. Despite this, buckling remains one of the major failure modes of such structures and, compared to the case of traditional sandwiches, both global and local buckling phenomena are more complicated in presence of transverse reinforcements. Indeed, in most cases, the modal deformed shapes involve simultaneously the skins and the reinforcements in an intricate way. The main feature of these buckling modes is periodicity, but the typical wave length appears to be generally different from the characteristic length between reinforcements. However, it is possible to investigate such periodic modes on a simple unit cell by using the so-called Bloch wave theory. In this work, an efficient procedure is defined so as to deal with the buckling behavior of a sandwich column with periodic orthogonal reinforcements. First, a numerical method is implemented in the framework of the commercial software Abaqus. The evaluation of the critical strains is performed on a unit cell: an initial average compressive strain is enforced, then natural frequencies are computed and the critical strains are deduced by extrapolation of the previous eigenvalues. A Python program is developed so as to automate these successive calculation steps and a Fortran program is also needed (within Abaqus) in order to cope with the two real and imaginary problems to be solved due to the Bloch-periodic conditions. Furthermore, an exact analytical solution of this problem is obtained in the particular case of a reinforced sandwich with no foam core (for simplicity purposes). The analytical and numerical solutions obtained with a unit cell model are finally compared to the results of numerical computations performed on a complete beam with an arbitrary number of cells, for validation purposes. The critical strains/displacements are found to be in very good agreement and the buckling modes rebuilt from the real and imaginary components of the unit cell modal solutions perfectly coincide with the buckling modes of the complete beam obtained through a linearized buckling analysis.

1. Introduction

Sandwich composites are plate-like structures which traditionally consist of two thin and stiff skin layers separated by a thicker and softer core layer. The core material is often a homogeneous and isotropic foam, which provides the extreme lightweight property of the sandwich. Conversely, the skins and their distance to the middle surface of the composite contribute to the tensile properties and particularly to the flexural rigidity. The resulting composite material thus combines both lightweight and strong mechanical properties and, thanks to this interesting compromise, sandwich structures are increasingly used in aerospace, marine or transportation industries, among others. However, such classical sandwiches show two main weaknesses. The first one concerns the out-of-plane behavior (in through-thickness compression and transverse shear), directly related to the low mechanical properties of the homogeneous soft core material. In order to improve the load carrying capacity in the thickness direction without being detrimental to lightness, the low density core layer may be usually strengthened, using transverse fibrous reinforcements or replacing the foam core by a thin-walled core layer (with a honeycomb or corrugated structure, for instance). Unfortunately, the presence of thin or slender reinforcements adds up to that of thin faces and makes the sandwich material even more sensitive to buckling which turns out to be the major remaining weakness of such composite structures (apart from delamination).

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As a matter of fact, due to their geometric and material configuration, sandwich structures are prone to collapse when submitted to compressive loadings. The buckling analysis of sandwich structures is therefore an important issue for dimensioning purposes and so it has been widely studied in the past decades (see [1] and [2] as two of the first leading references in this field). On one hand, when dealing with classical sandwiches, one usually distinguishes two types of geometric instabilities, namely the global buckling of the sandwich structure under overall compression and the so-called wrinkling (or local buckling) of the faces, which may appear insofar as they undergo compressive stresses (when the sandwich structure is submitted to axial compression or pure or simple bending, for instance). If the global buckling of a sandwich material can be easily viewed as the classical buckling of a homogeneous structure (as soon as the equivalent properties have been properly derived), the local buckling analysis requires the use of advanced models. If the earliest contributions rely on uncoupled formulations, where the global and local buckling analyses are treated separately, many authors have tried to achieve unified models capable of describing both global and local modes (both symmetric/hourglass and antisymmetric/snaking) in the particular case of a sandwich column under axial compression (Benson and Mayers [3] have been the first to suggest a unified approach to solve the overall buckling and wrinkling problems simultaneously). Among them, a hybrid beam/2D model (with no kinematic assumption in the core layer) was recently developed by Douville and Le Grognec [4] which was first able to derive closed-form expressions of both buckling and wrinkling critical values of sandwich beam-columns (accounting for all mode types) with a very good accuracy, compared to the numerous simplified models in earlier literature (see also [4] for a comprehensive review of analytical or numerical models for the buckling analysis of sandwich beam-columns/plates under various loading conditions, using different simplified kinematic assumptions).

On the other hand, a compressive loading in the thickness direction of a 3D reinforced sandwich will also fatally lead to an instability phenomenon. This response can be seen as the buckling of reinforcements inside the homogeneous core material, if any. Among others, López Jímenez and Triantafyllidis [5] investigated the buckling behavior of rectangular and hexagonal honeycomb structures under transverse compression, possibly combined with transverse shear. In the context of stitched sandwich structures under transverse compression and out-of-plane shear, the buckling of reinforcements (which can be considered as slender beams) is governed by Euler's theory, as soon as the core material is neglected (see [6], for instance). However, in practice, despite its comparatively low modulus, the presence of the core material cannot be ignored and the classical Euler critical values are no more valid (the core material generally displays a stabilizing effect). Several analytical solutions have thus been proposed in the literature to better estimate the critical loading for such a micro-buckling problem, where simplified strain states are supposed in the core material which is sometimes even replaced by spring distributions [7] (see [8] for a more comprehensive review on this subject). Recently, one of the authors [8] analyzed the buckling behavior of similar composites, namely Napco® reinforced sandwiches (whose manufacturing is based on transverse needling, see Fig. 1), under through-thickness compression. Exact closed-form solutions were derived using a similar hybrid beam/2D (unit cell) model as in [4] (where the skins are replaced here by the reinforcements and without any simplification regarding the deformation field in the core material). The prevailing mode was proved to be the so-called shear mode (see Fig. 2), as long as the volume fraction of reinforcements is sufficiently high, as shown in [9].

Considering now reinforced sandwiches, but under in-plane loading (such as axial compression), most complicated solutions may arise since both faces and reinforcements are supposed to interact in the buckling response. Such sandwich structures are also likely to buckle in a localized as well as in a global way, depending on the geometric and material parameters, but the new modes (and therefore the new critical values) cannot be obtained by a simple combination of the original buckling modes involving either the skins or the reinforcements (see Fig. 3 for an illustration of global and local modes of classical or reinforced sandwiches). Such a problem has thus been far less investigated in the literature. Let us mention Wang and Abdalla [10] who examined the global and local buckling behavior of grid-stiffened composite panels (like sandwiches with only one skin) and Combescure et al. [11] who analyzed the post-bifurcation and stability of an hexagonal honeycomb under equi-biaxial compression, among few others.

The present paper deals again with a sandwich material manufactured with polymeric foam core reinforced thanks to the Napco® technology. Here, this work specially investigates the axial compression behavior of sandwich columns in a 2D context. Based on the previous study dealing with through-thickness compression, a unit cell model is still preferred for obvious efficiency purposes. Two differences occur nonetheless between the two problems. Firstly, for the through-thickness compression analysis, the skins were not included in the model, since they did not deform during the corresponding buckling response, whereas the unit cell model here naturally includes both reinforcements and skins. Secondly, periodic boundary conditions were simply applied on the edges of the unit cell, since the wave length of the periodic buckling modes was strictly the length of the unit cell. Here, as seen in Fig. 3, the modes are supposedly periodic but with an arbitrary wave length. An appropriate technique for the identification of such periodic modes using a single unit cell turns out to be the Bloch wave theory. In the sequel, a numerical procedure devoted to the buckling analysis of reinforced sandwich columns under axial compression is first described. It consists of three successive calculation steps, namely (i) the compression of the unit cell with an arbitrary strain, (ii) the evaluation of the natural frequencies and corresponding modes under the so-called Bloch-periodic boundary conditions and (iii) the estimation of the critical strain by means of extrapolation. The presence of complex boundary conditions (with real and imaginary parts) requires the use of a specific Fortran program within the framework of the commercial software Abaqus and a Python program is also implemented so as to automate all the numerical procedure. In the particular case of a reinforced sandwich where the foam core has been removed, analytical solutions are also obtained from a general bifurcation analysis involving the same Bloch-periodic complex conditions. Numerical computations (linearized buckling analyses) on complete reinforced sandwich columns (displaying several cells) are finally performed for validation purposes.

2. Numerical analysis of the buckling behavior of reinforced sandwich columns

2.1. Problem definition

In this study, the objective is to solve numerically (and also analytically) the buckling behavior of a Napco® sandwich under axial compression. The Napco® technology is a manufacturing process of 3D sandwich composites based on transverse needle punching. Among the existing methods, such as tufting, Z-pinning and stitching [12], the patented Napco® technology allows one to produce tailored sandwich structures in a continuous way, while preserving a high production efficiency and a relatively low cost. It consists in strengthening the foam core of a sandwich structure by adding orthogonal (or inclined) through-thickness reinforcements, but it differs from other technologies by the fact that the fibrous reinforcements here come from the skin material, so that the facing fabrics (mats) and the foam core make up a monolithic whole (see Fig. 4).

The core layer is classically made up of a linearly elastic isotropic closed cell polyurethane foam. The skins are also elastic and are supposed to be isotropic, with equivalent Young's modulus E_s and Poisson's ratio ν_s.