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A unified formulation for the biaxial local and global buckling analysis of sandwich panels

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ABSTRACT

Sandwich structures are increasingly employed in many practical applications thanks to their interesting compromise between lightweight and high mechanical properties. However, due to some specific geometric and material features, such structures are subject to global as well as local buckling phenomena, which lead to collapse in most cases. The buckling analysis of sandwich panels is therefore an important issue for their mechanical design. In this respect, this paper is devoted to the theoretical study of the elastic local/global buckling of rectangular sandwich plates under uniaxial or biaxial compression(-tension). Only classical sandwich materials are considered with homogeneous and isotropic core/skin layers. In the present formulation, a Love–Kirchhoff plate model is used to represent the thin skins, whereas the relatively thick core is modeled as a 3D continuous solid. Furthermore, the proposed approach is based on the elastic bifurcation theory in a general 3D framework, and leads to closed-form analytical expressions of the critical loadings and the corresponding bifurcation modes. The accuracy of the derived formulae is checked for both local and global modes by comparison with the results of finite element computations. Parametric analyses are finally performed, investigating primarily the influence of the aspect ratio of the plate and the ratio of the compressive (or tensile) loadings between both directions on the first buckling mode type and the associated minimum critical value.

1. Introduction

Sandwich structures traditionally consist of two thin skin layers separated by a thicker and softer core layer. The resulting composite material combines both lightweight and high flexural stiffness. Thanks to this interesting compromise, such sandwich composites are increasingly used in aerospace, marine or transportation industries, among others. In return, sandwich structures are unfortunately prone to collapse easily when submitted to compressive loadings. Owing to their geometric and material configurations, the buckling phenomena involved in their failure behavior may be both local and global. While the global buckling of a sandwich panel is quite similar to that of a homogeneous structure, the local buckling (also called wrinkling) mainly involves the skin layers and may be either antisymmetric (the top skin buckles in phase with the bottom one) or symmetric (the top skin buckles out of phase with the bottom one).

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. The earliest contributions (see [1–4], for instance) rely on the so-called uncoupled formulations, where the global and local (antisymmetric and/or symmetric) buckling analyses are treated separately. Such modeling approaches generally predict the global buckling behavior very well but often show some limitations and prove inaccurate in the estimation of the wrinkling loads. In order to overcome these drawbacks, some authors have more recently developed the so-called coupled theories, considering global buckling modes as particular antisymmetric modes (with reduced half-wave numbers). Benson and Mayers [5] have been particularly the first to develop a unified theory for predicting the global buckling and both antisymmetric and symmetric wrinkling of sandwich plates. Such models allow one to deal with local and global modes in a unified way and thus analyze the possible interactions between both types of modes.

Until now, most of the available theoretical investigations concern the buckling problem of uniaxially loaded sandwich columns (see [6] for a detailed review of the literature on the buckling analysis of sandwich beam-columns). For such a geometry, using either the uncoupled or coupled approaches mentioned above, several analytical or semi-analytical solutions have been derived, thanks to appropriate kinematic assumptions. While the Euler–Bernoulli hypotheses are consistently employed for the description of the skin layers in most of the existing analytical models, various approximate theories are proposed for the core layer. When dealing now with sandwich plates under uniaxial or biaxial compression (often encountered in practical applications), the buckling problem turns out to be far more

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complicated to formulate and it has been rarely handled so far. Even with similar kinematics (namely when the faces are represented by a Love–Kirchhoff plate model), the few existing models are partially or totally based on the use of numerical methods and, at most, only solution procedures are presented and no closed-form solutions are provided. Some of the major works in this field are summarized in the sequel.

Following Benson–Mayers theory, Hadi and Matthews [7] derived a general semi-analytical approach in order to analyze the overall buckling and face sheet wrinkling phenomena in anisotropic sandwich panels. Their general approach is based on energy methods and the core is assumed to be anti-plane (the longitudinal stiffness is neglected). Pandit et al. [8] studied the buckling behavior of laminated sandwich plates using an improved higher-order zig-zag theory in the context of the finite element method. In their plate model, the in-plane displacements are supposed to be cubic along the thickness direction throughout all the layers, while the transverse displacement in the core is assumed to vary quadratically. More recently, Magnucka-Blandzi [9] presented a semi-analytical model for the buckling analysis of simply supported rectangular sandwich plates under in-plane compression (the plates are made of isotropic skins and a porous-cellular metal foam core). The system of differential equations resulting from the principle of stationarity of the total potential energy is here only approximately solved. Finally, Kheirikhah et al. [10] proposed a mathematical formulation with similar kinematic assumptions as in [8], also based on the principle of stationary total potential energy, so as to study the biaxial buckling of rectangular sandwich plates made of orthotropic core and laminated face sheets. In all these studies, the results provided by the corresponding contributions generally seem to be in good agreement with full numerical computations. However, to the best knowledge of the authors, none of the previous models provides any explicit formulae for the critical loadings and modes of sandwich panels under uniaxial/biaxial compression.

The objective of this paper is therefore to present a new unified formulation for the buckling analysis of biaxially loaded sandwich plates. This formulation has already been introduced by one of the authors in an earlier work in the context of sandwich beam-columns [6]. Unlike most other models, no simplifying assumption is made in the core kinematics. Such an “exact” buckling analysis has already been performed once, in the 2D case of sandwich beams for various stress/strain formulations, but again, no explicit solutions were derived [11]. Here, the present formulation leads to closed-form analytical expressions, suitable for both global buckling and face sheet wrinkling of classical sandwich plates (with homogeneous foam core) under uniaxial or biaxial loading. To this end, a general 3D elastic bifurcation analysis is first achieved, leading up to analytical solutions for both antisymmetric and symmetric mode types. The obtained formulae are first confronted to finite element numerical calculations (linearized buckling analyses) performed for validation purposes. Then, the influence of some geometric, material and loading parameters on the buckling response is discussed.

2. Theoretical formulation

The sandwich structure involved in this study is a rectangular plate of length L and width l (see Fig. 1 for the definition of the associated coordinate system). The two skin layers are supposed to be identical with thickness $2h_s$. They are separated by a foam core layer of thickness $2h_c$. Both constituent materials are supposed to be linearly elastic and isotropic, defined by Young's moduli E_s and E_c and Poisson's ratios ν_s and ν_c, related to the skin and core materials, respectively.

Considering the geometric features of each layer, one can suggest the following set of kinematic assumptions:

- The two skin layers are sufficiently thin that transverse shear effects can be neglected. This allows one to represent their structural behavior using a Love–Kirchhoff plate model.
- The much thicker core layer should be modeled by a 3D continuous body without any particular assumption regarding the deformation field in order to describe the buckling response of the sandwich structure in a more accurate and realistic way than most other models in the literature.

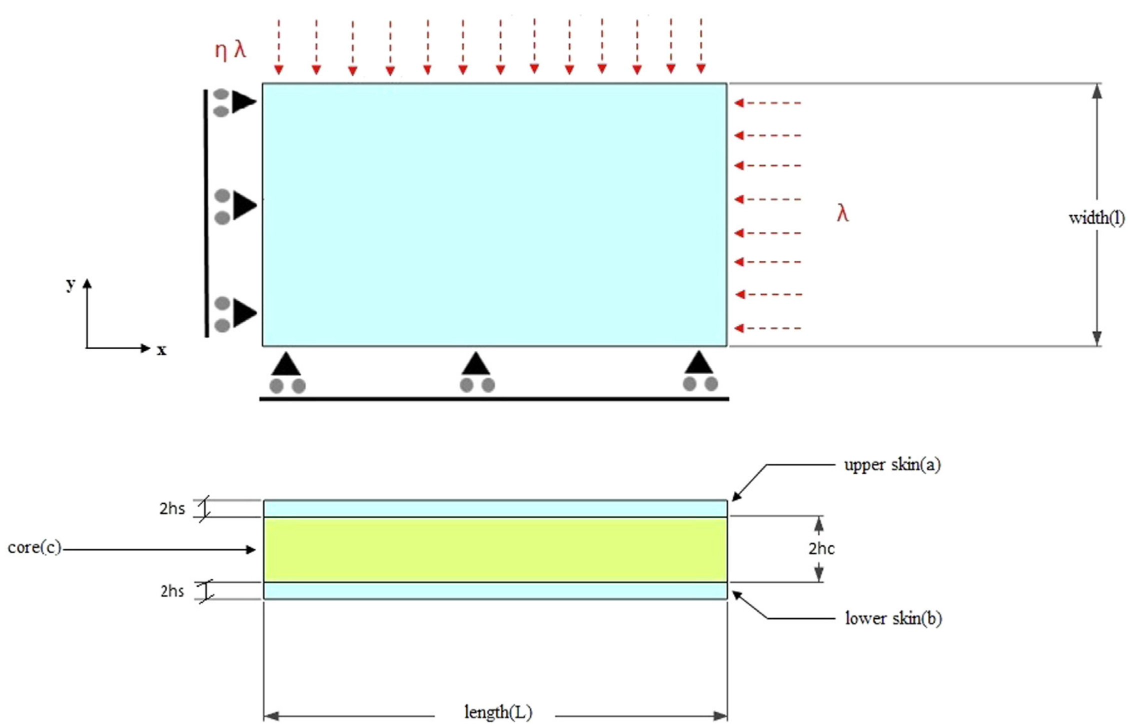

Fig. 1. Sandwich plate under biaxial loading.