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Localized buckling in sandwich struts with inhomogeneous deformations in both face plates

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ABSTRACT

A nonlinear analytical model for investigating localized interactive buckling in simply supported thin-face plate sandwich struts with weak cores is extended to account for local deformations in both face plates, which have been observed in experiments and finite element simulations. The original model is based on potential energy principles with large displacement assumptions. It assumes Timoshenko shear deformable theory for the core and approximates the overall mode as a half-sine wave along the length of the strut while the local face plate displacements are initially unknown and are found as solutions of the governing equations. The extended model is able to capture measurable local face plate displacements in the less compressed face plate, beyond the secondary bifurcation which leads to localized interactive buckling, for the case where overall buckling is critical. Moreover, the allowance of local displacements in both face plates allows the extended model to predict the post-buckling behavior better in cases where local buckling is critical. The results from this model compare very well with nonlinear finite element simulations with respect to both the equilibrium paths and panel deformations.

1. Introduction

Sandwich construction is well-known in many engineering disciplines as a versatile structural solution with a favorable combination of low weight and high bending stiffness [1]. Such structures usually comprise two stiff thin plates separated by a soft compliant core. By positioning the stiff plates away from one another increases the bending rigidity of the sandwich structure, while the compliant core is able to resist shear stresses. This optimized configuration, however, is prone to instability phenomena such as overall buckling and wrinkling. These phenomena are triggered at certain critical loads with sandwich structures buckling either globally (effectively as an Euler strut) or locally in each face plate in a symmetric (hourglass) or antisymmetric (snake-like) fashion, as shown in Fig. 1 [2,3]. Moreover these types of instability might interact leading to localized buckling [4,5], or bring about damage in terms of face–core delamination [6,7], both of which can destabilize the structural component violently. Since imperfections can have an erosive effect on the critical load carrying capacity of the sandwich strut [8], it is very important for these effects to be accounted for when modeling these components properly.

Critical loads for overall buckling and wrinkling (local buckling) in sandwich panels have been reported in the classical texts of Allen [9] and Plantema [10]. Fazio et al. [11] and Drysdale et al. [12] reported on different models for various loadings on sandwich structures. Frostig and co-workers [13,14] provided elasticity solutions for different structural configurations while analytical and numerical models for overall buckling and wrinkling have been studied extensively [15–19], including multiscale techniques by Yu et al. [20]. Léotoing et al. [21] investigated the geometrically nonlinear interaction between overall and local buckling modes, which were first successfully captured analytically by Hunt and Wadee [4] using a variational formulation based on the potential energy method and Timoshenko bending theory. Further work by Wadee and co-workers included the extension of the interactive buckling model for orthotropic cores [22], higher order shear deformable theories [5], beam-columns [23] and functionally graded cores [24]. The development of using novel materials in sandwich construction such as metal foams for the core and high strength composites for the face plates has led to renewed interest in investigating the stability of such structures with metal foam cores [25,26] and for composite reinforced sandwich structures [27].

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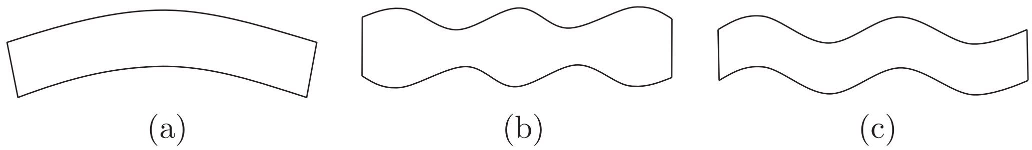

Fig. 1. The three principal buckling modes of sandwich strut. (a) Overall or global buckling; (b) symmetric or the hourglass mode of local face plate buckling; (c) antisymmetric or the snake mode of local face plate buckling.

Mode interaction and localization in sandwich structures is a very important phenomenon since it can dominate the post-critical response, regardless of the initiating mode [8]. This work seeks to extend the fundamental model for interactive buckling developed by Hunt and Wadee [4] which considers localization that occurs solely at the more compressed face of the sandwich strut. More recently, Wadee and Bai [28] successfully modeled interactive buckling between minor axis buckling of an I-section strut, using a similar modeling technique. Although this is a different problem, the aim herein is to present an analytical model that investigates and accounts for local deformations on both face plates during post-buckling. Specifically for the case where overall buckling occurs first, it has been observed both experimentally [29] and in FE simulations [5] (see Fig. 2) that smaller amplitude local deformations begin to appear practically immediately after the secondary bifurcation when local buckling within the other face plate has been triggered. The current work aims to capture these responses and study their effects on the post-buckling response of different sandwich configurations. The results from this model are compared with the results obtained from Hunt and Wadee [4] as well as FE simulations performed in the commercial finite element software ANSYS [30]. Further considerations and extensions of the model are subsequently discussed.

2. Analytical formulation

2.1. Definitions, geometry and kinematics

In the current work, the original Hunt and Wadee model [4]—hereinafter termed the '1998 model'—is modified to allow local deformations within both face plates. The dimensions of the sandwich strut and the coordinate system are shown in Fig. 3. The model assumes isotropic face plates with Young's modulus E and Poisson's ratio ν as well as an isotropic core material with Young's modulus E_c and Poisson's ratio ν_c. Loading is applied axially by a compressive force P acting at the mid-section, through rigid end plates to ensure equal load transfer to the face plates.

The purely compressive displacement prior to buckling is represented by ΔL, while overall (Euler-type) buckling is decomposed into sway and tilt components, $W(x)$ and $\theta(x)$ (see Fig. 4). These components are represented by predetermined trigonometric functions with dimensionless amplitudes q_s and q_t respectively as:

$$W(x) = q_s L \sin\frac{\pi x}{L}, \quad \theta(x) = q_t \pi \cos\frac{\pi x}{L}, \tag{1}$$

since it is well known that the solution for the overall buckling mode of a simply supported strut can be best approximated by a half-sine wave and the total shear effect is determined by the difference of sway and tilt. The amplitudes q_s and q_t, as well as Δ enter the model as generalized coordinates, which are computed during the solution process. The new model retains the Timoshenko beam theory assumption for the core material under which shear strains are allowed to develop within the core, which are essential for including the interaction between the two buckling modes of different length scales [5]. For the range of application of this model (weak, isotropic core and stiff thin face plates) Timoshenko shear deformable theory for the core suffices and offers a sufficiently good approximation of the kinematics of the overall mode. Furthermore, along with the contributions of the sway and tilt components for overall buckling to the displacement of the strut, both face plates are allowed to form local deformations. Hence, for the top face plate $w_t(x)$ is defined as the displacement of the buckled face plate perpendicular to the unbuckled face, and $u_t(x)$ is defined as the displacement parallel to the unbuckled face. The corresponding displacements for the bottom face plate are defined as $w_b(x)$ and $u_b(x)$. These functions of x have no predetermined form and are sought as solutions from the minimization of the total potential energy functional formulated in a later subsection. To ensure continuity of the displacements within the core, the top and bottom interactive mode displacements are taken to vary linearly with y, as:

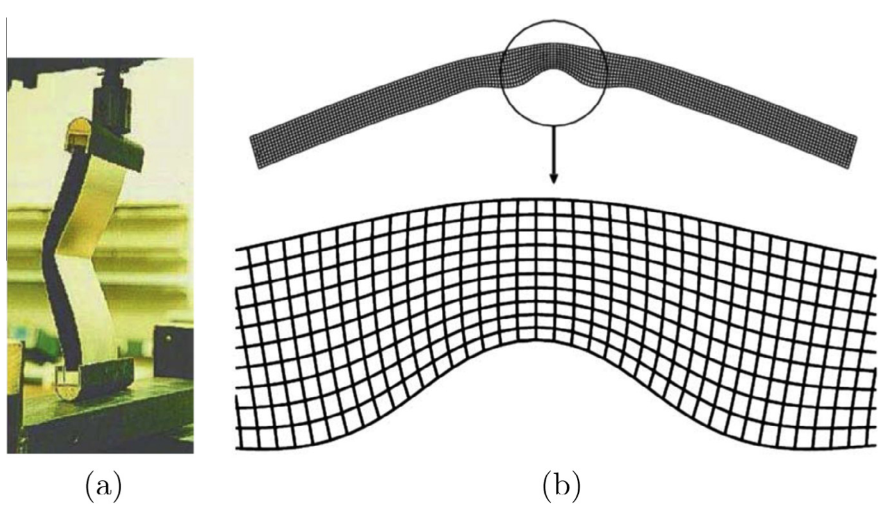

Fig. 2. Interactive localized buckling exhibited in the more compressed face plate and local deformations within the less compressed face plate as exhibited in (a) experimental work [29] and (b) FE simulations performed in ABAQUS [5].