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A new nonlinear model for studying a sandwich panel with thin composite faces and elastic–plastic core

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ABSTRACT

In this paper elastic–plastic behavior of a sandwich beam with a transversely flexible core and thin faces is investigated. The elastic–plastic behavior of the core is described by a bilinear constitutive relation of the shear stress. The governing equations for linear and nonlinear regions are derived using higher order sandwich panel theory. The governing equations are solved by finite element method based on the Galerkin weighted residual method. Since the limits of the plastic regions spread through the solution, an iterative procedure is employed to obtain reliable results. Three different boundary conditions including simply supported, clamped and three point bending configurations are studied. The results are compared with the available results in literatures and a good agreement can be seen. The results reveal that as the bilinear ratio decreases the maximum of the shear stress decreases and the plastic region extends. Comparing different boundary conditions shows that by increasing the constraint of the edges, the maximum of shear stress decreases. In addition, the plastic regions spreads by decreasing bilinear ratio and the maximum growth is belonged to clamped configuration.

1. Introduction

In recent years, sandwich structures are widely used in various applications such as aerospace, marine and automobile industries. These structures consist of two thin stiff metallic or composite face sheets separated by a thick soft or stiff core. This configuration enhances stiffness and strength of the structure without a significant increase in weight. In this regard, there are many works have done by researchers devoted the sandwich structures. Carrera et al. [1] have investigated the accuracy of theories proposed for the sandwich and multilayered composite structures. Noor et al. [2] reviewed more than 800 papers on sandwich and multilayered composite structure models. In many applications the sandwich structures are made by foam cores. Lightweight and flexibility of foam cores makes them appropriate for these structures. Conceptually the face sheets carry the bending load of the entire structure and transverse shear one is sustained by the core. The stress–strain behavior of foam cores consists of three stages: first part is a linear elastic behavior up to a yield point, then a nearly constant stress line is called plateau and finally a rapid increase in stress is called densification part. The plateau is due to yielding or buckling of the foam cells and the densification is occurred due to crushing of cell structure and the foam is densified. The two last stages are plastic and permanent deformations. In many works the behavior of the sandwich structure is analyzed by considering only the linear elastic manner for the core and the faces, however, the core shear yielding could not be neglected in many applications. In many practical cases the applied load, such as impact loading on vehicles or dynamic loading of waves on marine applications. Thus, in order to predict accurate stress and displacement responses of the core under a given loading and with a certain boundary conditions, elastic–plastic behavior of the core is considered in the present study. The core behavior is usually described by a bilinear constitutive relation, as shown in Fig. 1. Gibson and Ashbi [3] studied the structure of cellular solids such as foams and their mechanical, thermal and other properties as well as the behavior of foam cores and their constitutive relation. Zhu et al. [4] studied the mechanical behavior of open-cell foams experimentally and proposed a stress–strain relation and nonlinear geometrical relations. Also, the dependency of material type and its density on the shape of the stress–strain curve was described. Mercado and Sikarskie [5] investigated a sandwich panel by considering bilinear behavior of core shear stress. The core is assumed incompressible due to considering classical sandwich beam theory. According to experimental results, the bilinear

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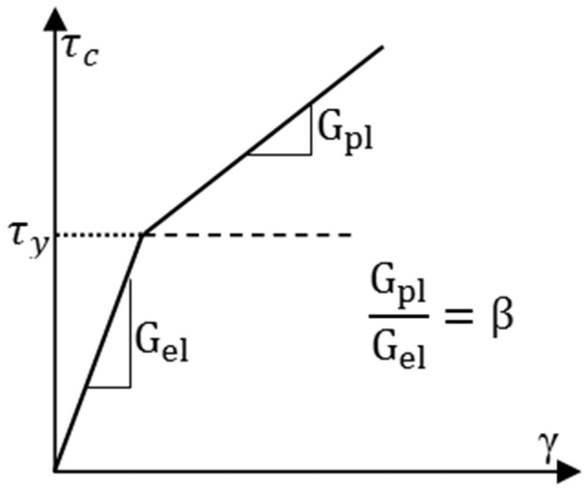

Fig. 1. Bilinear behavior of the core shear stress.

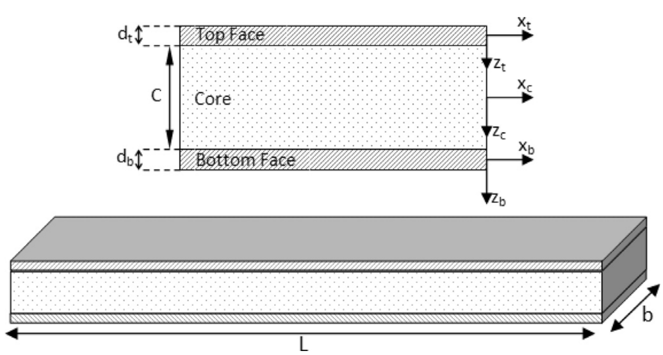

Fig. 2. Geometry and the coordinate systems of the sandwich beam.

Table 1
Geometrical and mechanical properties of sandwich beam [20].

Geometrical		Mechanical	
Beam Length	**130 mm**	**Young Modulus of Faces**	**E_1=48.9 Gpa** **E_2=E_3=5.5 Gpa**
Beam Width	**30 mm**	**Shear Modulus of Faces**	**G_{12}= G_{13}=5.5 Gpa** **G_{23}=5 Gpa**
Core Thickness	**10 mm**	**Young Modulus of Core**	**0.116 Gpa**
Top Face Thickness	**2.7 mm**	**Shear Modulus of Core**	**0.02885 Gpa**
Bottom Face Thickness	**2.7 mm**	**Core Yielding Shear Stress**	**0.073 Gpa**

constitutive relation is a good approximation to predict the material behavior of the cores in small strain analyses. Liu et al. [6] investigated the elastic–plastic dynamic response of a fully backed sandwich plate under localized impulse load. They modeled the core as an elastic-perfectly plastic foundation. It was shown that a large portion of impulsive energy could be absorbed by plastic deformation of the core and the face sheets. Frostig et al. [7] studied the response of a sandwich panel by considering a bilinear constitutive relation for both transverse shear and normal stresses of the core in three-point bending configuration. The governing equations are formulated based on the high order sandwich panel theory that had been developed by Frostig et al. [8]. The higher order sandwich panel theory (HSAPT) considered a second order and a third order distribution through the thickness for the vertical and longitudinal displacements of the core, respectively. Many studies used HSAPT for various problems and it was shown that this theory predicts the behavior of sandwich structures with an appropriate agreement with 3D elasticity solution and experimental results. Frosting et al. studied many static and dynamic problems such as bending [9,10] free vibration [11–14], buckling [15–17] and etc. using this theory. Sokolinsky et al. [18] studied a sandwich beam experimentally and compared with HSAPT results and show that the results of the theory are in excellent agreements with experimental results. Swanson [19] examined high order theory for some sandwich plate problems and mentioned the importance of stress concentration in the face sheets and the core revealed from this theory. Jedari Salami et al. [20]studied response of a sandwich panel with bilinear constitutive behavior for shear stress of a core based on the improved extended high order sandwich panel theory. In this theory the face sheets are analyzed based on the first order shear deformation theory that hitherto is not applied in the conventional extended high order sandwich panel theory. Besides, the two-dimensional (2D) elasticity is used for the core. In the present paper, the nonlinear material behavior of a sandwich beam with composite face sheets and a transversely flexible core is investigated. Three different boundary conditions are considered to study the effects of boundary conditions on the elastic–plastic response of the core based on creation and development of the plastic regions. The governing equations for both elastic and plastic regions and appropriate boundary conditions are derived using the high order sandwich panel theory. The faces are assumed linear elastic and the vertical normal stress constitutive law and distribution of the vertical displacement of the core are not affected by nonlinear constitutive relation of the core shear stress. An appropriate finite element procedure is employed to solve the governing equations of both elastic and elastic–plastic regions. The continuity of variables at the interface of elastic and plastic regions has been considered and guaranteed through FEM procedure.

2. Mathematical formulation

In the high order sandwich panel theory presented in [7], governing equations and appropriate boundary conditions derived via variational principle of potential energy minimization:

$$\delta(U + V) = 0 \tag{1}$$

where U and V are internal potential energy and external energy, respectively. In this theory the axial normal stress of the core is neglected compared to those for the face sheets. So the first variation of internal potential energy in terms of stresses and strains of the core and the face sheets reads:

$$\delta U = \int_{V_t} \sigma_{xx}^t \delta\varepsilon_{xx}^t dV_t + \int_{V_b} \sigma_{xx}^b \delta\varepsilon_{xx}^b dV_b + \int_{V_c} (\tau_{xz}\delta\gamma_{xz} + \sigma_{zz}\delta\varepsilon_{zz}) dV_c \tag{2}$$

where σ_{ii} and ε_{ii} are normal stress and strain of the core and the face sheets, and τ_c and γ_c are shear stress and strain of the core. Symbols t and b mean top and bottom face sheets. The first variation of the external energy equals:

$$\delta V = -\int_0^l (q_t\delta w_t + q_b\delta w_b + n_t\delta u_t + n_b\delta u_b + m_t\delta w_{t,x} + m_b\delta w_{b,x})dx - \sum_{j=1}^{NC}\int_0^l \begin{bmatrix} (P_{tj}\delta w_t + P_{bj}\delta w_b + N_{tj}\delta u_t + N_{bj}\delta u_b + M_{tj}\delta w_{t,x} \\ +M_{bj}\delta w_{b,x})\delta_d(x - x_j) \end{bmatrix} dx \tag{3}$$

where q_i, n_i and m_i are distributed vertical, horizontal and bending moments of external loads at the face sheets; P_i, N_i and M_i are external concentrated vertical, horizontal and bending moments