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A new finite element model for low-velocity impact analysis of sandwich beams subjected to multiple projectiles

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ABSTRACT

In this paper, a new finite element formulation is presented for high-order impact analysis of sandwich beams with any boundary conditions subjected to simultaneous multiple small projectiles. The contact of the projectiles may occur on arbitrary places on both faces of the beam. Hamilton's principle is used for driving the governing partial differential equations of motion. The effect of each projectile is modeled by a one degree of freedom spring-mass system with variable stiffness by assuming the Hertzian contact law. The appropriate elemental matrices are derived for a sandwich beam element that carrying four sprung masses on both face sheets. Based on the presented formulation, an FE code is developed using the Newmark method with direct iteration process. The various cases are used to validate the predictions of the presented higher order theory and FE formulation shows good agreement with available results in the open literature and exact solution. Furthermore, numerical examples are presented to investigate effects of various parameters on the response of the structure.

1. Introduction

Sandwich panels have historically been known as primary members with excellent stiffness-to-weight and strength-to-weight ratios where are used in various industries such as aerospace, naval, transportation and civil structural. The wide range and importance of these applications stress on the analysis of these structures subjected to various loading conditions by using the accurate model.

In the simplest simulation, the deformation of sandwich structures with honeycomb cores has been modeled by the incompressible core hypothesis [1–6]. This model was known by name of classical theory which was used in the first times by Di Taranto [1] and Mead and Marcus [2] for the analysis of sandwich beams. Mead [3] compared and assessed several models which used for the free vibration analysis of sandwich beams. The basic assumption of the classical model consists of the Bernoulli–Euler beam theory and the linear shear deformations for the faces sheets and the core, respectively. This model was interested in many researchers. The impact over sandwich systems was first analyzed by Lee et al., [4]. In their study, an anti-plane sandwich theory was used, and the transient contact force and central deflection history were analyzed. Tsai et al. [5] also conducted a study about the impact analysis of a linear sandwich system based on the classical model. Recently, Khalili et al. [6] presented the free vibration of sandwich beam carrying sprung masses using classical theory.

The higher order theory models the cross-sectional warping through a cubic axial strain and considers the variation of transverse displacement across the thickness through a linearly varying transverse normal strain and incorporates transverse shear strain where varies cubically across the cross-section. This model is investigated by Frostig and Baruch [7] for the analysis of sandwich structures with polymer foam materials. The various model were presented by the researchers where had different in type of dynamic deformation or the mechanical behavior of the core, etc.

Among them, Sokolinsky et al. [8] and Bekuit et al. [9] simulated the responses of sandwich structures with foam core by using of finite element method. Bekuit et al. [9] investigated a quasi-2D finite element where considered the axial stiffness of the core. Regarding to the experimental results as benchmark, the high-order theory is supremacy model in comparison with the classical types where made assess by Mead and Markus [2]. The high-order theory was used for predicting the responses of sandwich beams subjected to low velocity impact loading by Yang and Qiao [10]. In this research work, three models (A, B and C) are compared where the basic different of them were related to dynamic deformation of the core. The horizontal vibration and rotatory inertia of face sheets and the weight of core were removed in the (A) model. The superiority of (B) in comparison with (A) was related to considering the dynamic effect of core with a linear interpolation of

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Nomenclature

A_t, A_c, A_b vertical area of layers
A^j jth constant index
b width of the element
B^j jth constant index
E_t, E_c, E_b Young's modulus of layers
F_{it}, F_{ib} contact forces
$\mathbf{f}$ global force vector
$\mathbf{f_e}$ elemental force vector
G_c shear's modulus of core
h_t, h_c, h_b thickness of layers
i counter for natural numbers
i $\sqrt{-1}$
j counter for natural numbers
$\mathbf{K}$ global stiffness matrix
$\mathbf{K_e}$ elemental stiffness matrix
k_{it}, k_{ib} stiffness constants of springs
l length of an element
L length of the beam
$\mathbf{M}$ global mass matrix
$\mathbf{M_e}$ elemental mass matrix
M_b, M_t bending moment of face sheets
M_{ib}, M_{it} nodal bending moments
m_{it}, m_{ib} masses of sprung masses
P_b, P_t axial force of face sheets
P_{ib}, P_{it} nodal axial forces
Q_{it}, Q_{ib} external forces on masses
t time
T kinetic energy
$\mathbf{u}$ global displacement vector
$\mathbf{u_e}$ elemental displacement vector
$u_b, \quad u_t u_{ct}, \quad u_{cb}\}$ axial displacement of layers
$u_{ib}, \quad u_{it} u_{ict}, \quad u_{icb}\}$ nodal axial displacements
U strain energy
V_b, V_c, V_t shear force of layers
V_{ib}, V_{ic}, V_{it}
nodal shear forces
$\bar{V}_b, \ \bar{V}_c, \ \bar{V}_t$ volume of layers
v_{it}, v_{ib} velocity of masses
w_b, w_c, w_t
vertical displacement of layers
w_{ib}, w_{ic}, w_{it} nodal vertical displacements
x member axis
X axial direction
y member axis
y_{it}, y_{ib} displacement of masses
Y vertical direction
Z width direction
γ_{xy} shear strain
δ first variation operator
ε_x normal strain
θ_b, θ_t rotation displacement of faces
θ_{ib}, θ_{it} nodal rotation displacements
ν_{it}, ν_{ib} Poisson ratio of masses
ρ_t, ρ_t, ρ_b density of layers
σ_x normal stress
τ_{xy} shear stress
ω natural frequency
$(\dot{\ })$ $\frac{d}{dt}$
$(\ddot{\ })$ $\frac{d^2}{dt^2}$
$(')$ $\frac{d}{dx}$
$('')$ $\frac{d^2}{dx^2}$
$(''')$ $\frac{d^3}{dx^3}$

the top face sheet and the bottom face sheet vertical accelerations. In (C) model, the dynamic effects of each layer are assumed with a linear function for horizontal and vertical directions. The validity of the models in the impact response predictions of simply supported boundary condition was demonstrated by comparing with FEM solutions of LS-DYNA.

Apetre et al. [11] investigated the low-velocity impact analysis of a sandwich beam with functionally graded core such that the density, and hence its stiffness, vary through the thickness. The effect of one projectile on the simply supported sandwich beam was considered and the quasi-static approximation was used to solve the governing equations.

Tagarielli et al. [12] presented the experimental results for the dynamic response of glass fiber–vinylester composite sandwich beams by impacting the beam at mid-span with metal foam projectiles. High-speed photography was used to measure the transient transverse deflection of the beams and to record the dynamic modes of deformation and failure. Qiao and Yang [13] investigated the impact analysis of an as-manufactured FRP honeycomb sandwich system with sinusoidal core geometry in the plane and extending vertically between face laminates. Qiao and Yang [13] demonstrated the accuracy and capability of the higher order impact sandwich beam theory in analysis, design applications and optimization of efficient FRP honeycomb composite sandwich structures for impact protection and mitigation. Ivañez et al. analyzed the dynamic responses sandwich beams considering failures of core and face sheets by developing a 3D finite-element model and dynamic three points bending tests [14]. Qin and Wang [15] investigated the dynamic large deflection response of fully clamped metal foam core sandwich beam struck by a low-velocity heavy mass. Analytical solution and 'bounds' of dynamic solutions, finite element analysis, quasi-static and numerical solutions were derived and compared with numerical results. Wang et al. [16] analyzed the structural response of dynamically loaded monolithic and sandwich beams made of aluminum skins with different cores by loading the end-clamped beams at mid-span with metal foam projectiles. Laser displacement transducer was used to measure the permanent transverse deflection of the back face mid-point of the beams. Recently, Damanpack et al. [17] investigated active control of geometrically nonlinear transient responses sandwich beams subjected to the various blast loads using piezoelectric patches. As revealed in presented literature review, all previous studies are restricted to analysis of sandwich structures subjected to single projectile on one of the face sheets.

In this study, the high-order impact analysis of sandwich beams subjected to multiple projectiles on both face sheets is carried out using the new finite element formulation. Implementation of the Hamilton's principle leads to the governing partial differential equations of motion for the system. Neglecting the vibration of the projectile and using the Hertzian contact law, the effect of each projectile modeled by a one degree of freedom spring-mass system with variable stiffness with structural response. After applying the effect of each projectile on face sheets and using the finite element formulation, the elemental matrices are derived. The presented finite element results are validated using results of static, free vibration and dynamic results of sandwich beams in the open literatures. Finally, some numerical examples are presented to evaluate the effects of various parameters such as number of projectiles, contact positions and boundary conditions on the contact forces generated on the sandwich beams.