The Role of Dynamics in Face sheet/Core Interface Debonding of Sandwich Panels

Vyacheslav N. Burlayenko*, Svetlana D. Dimitrova†
*Department of Applied Mathematics, National Technical University 'KhPI', Kharkiv, Ukraine
†Department of Higher Mathematics, National Technical University 'KhPI', Kharkiv, Ukraine

Summary. The current research addresses the study of debonding the face sheet from the core in a sandwich structure in dynamic regime by means of the use of a cohesive zone model accounting for contact and friction nonlinear effects. The finite element method within the ABAQUS environment is used for modeling and simulations of the dynamic debonding propagation problem. By numerical examples, the influence of different parameters, such as the adhesive properties in terms of the interface strength and toughness and the type of traction separation law and types and rates of the imposed loading, in relation to the double cantilever beam test are estimated. The obtained results demonstrate the relevance of both the adhesive properties and loading conditions, the changes of which may notably modify the stress state near the interface crack tip and the debonding evolution in the sandwich specimen in dynamics.

Introduction

The use of lightweight sandwich composites as primary structural components has been considered as one of the means for designing structures with increasing stiffness and strength at minimal increasing in their weight. However, sandwich structures are very susceptible to debonding of the face sheet from the core. Dynamic loading is relevant for many applications of sandwich structures. In dynamics, the debonding growth and eventual structural failure may happen even at a load level significantly lower than the predetermined critical one [1]. Therefore, sandwich composites to be safely exploited should be developed to withstand the debonding propagation at a certain level of dynamic loading.
In the present study, the cohesive element formulation is used to model the debonding behaviour along the face sheet/core interface of sandwich panels in dynamic regimes. First, the finite element formulation is outlined and the constitutive relationships for the cohesive element are introduced. Finally, the numerical calculations related to the finite element model of the double cantilever sandwich beam (DCB) test are carried out and the results are discussed in details.

Formulation and method of solution

A dynamic framework of the finite element method (FEM) combined with cohesive zone approach is considered. By assuming infinitesimal deformations, neglecting body forces, but accounting for cohesive and contact forces for a body occupying a space V and containing crack modeled by cohesive elements at the surface $\partial V_c = \partial V_c^+ \cup \partial V_c^-$, the principle of virtual work states as follows [2]:

$$\int_{V\setminus\partial V_c} (\boldsymbol{\sigma} : \nabla\delta\mathbf{u} + \rho\ddot{\mathbf{u}}\cdot\delta\mathbf{u})\, dV + \int_{\partial V_c} \mathbf{T}\cdot\delta\boldsymbol{\Delta} dA + \int_{\partial V_c} (t_N \delta g_N + \mathbf{t}_T\cdot\delta\mathbf{g}_T)\, dA - \int_{\partial V_t} \bar{\mathbf{t}}\cdot\delta\mathbf{u} dA = 0 \qquad (1)$$

for all kinematically admissible displacement fields $\delta\mathbf{u}$ and given displacements $\bar{\mathbf{u}}$ at a boundary ∂V_u and a traction vector $\bar{\mathbf{t}}$ at ∂V_t. Herein, ρ is the density of material; $\boldsymbol{\sigma}$ is the Cauchy stress tensor associated with a displacement field $\mathbf{u}$, and $\ddot{\mathbf{u}}$ stands for an acceleration field; $\boldsymbol{\Delta}$ is the displacement jump across and $\mathbf{T} = \boldsymbol{\sigma}\cdot\mathbf{n}_c$ are cohesive forces along ∂V_c oriented by the normal $\mathbf{n}_c$; $\mathbf{t}_N = t_N\mathbf{n}_c$ and $\mathbf{t}_T$ are normal and tangential components of the contact traction which are interrelated with normal g_N and tangential $\mathbf{g}_T$ gap functions [3]. It is assumed that a bilinear traction separation law (TSL) governs the fracture behaviour. The TSL has the following form for each fracture mode $(i = I, II, III)$ [4]:

$$T = \begin{cases} k_i\Delta_i, & \Delta_i \le \Delta_i^0 \\ (1-D_i)k_i\Delta_i, & \Delta_i^0 \le \Delta_i \le \Delta_i^f \\ 0, & \Delta_i \ge \Delta_i^f, \end{cases} \qquad (2)$$

where $D_i = \left(\Delta_i^f(\Delta_i - \Delta_i^0)\right) / \left(\Delta_i(\Delta_i^f - \Delta_i^0)\right)$ is a damage variable. Herewith, damage initiates based on the quadratic stress criterion, whereas the damage evolves when the Benzeggagh-Kenane fracture criterion is met.
The impenetrability and friction constraints are stated in the form of Karush–Kuhn–Tucker conditions as follows:

$$t_N \le 0, \quad g_N \ge 0, \quad t_N g_N = 0 \quad \text{and} \quad \|\mathbf{t}_T\| \le \tau_{crit}, \quad \|\mathbf{g}_T\| \ge 0, \quad (\|\mathbf{t}_T\| - \tau_{crit})\,\|\mathbf{g}_T\| = 0 \qquad (3)$$

In the case of the Coulomb friction model, $\tau_{crit} = \mu t_N$, where μ is the coefficient of friction.
Following the FEM framework, the discrete system of dynamic equations of motion at time t takes the form:

$$[M]\{\ddot{U}\}_t + \{R_{int}\}_t + \{R_{coh}\}_t + \{R_{cont}\}_t = \{R_{ext}\}_t\,, \qquad (4)$$

where $\{U\}$, $\{R_{int}\}$, $\{R_{ext}\}$, $\{R_{coh}\}$ and $\{R_{cont}\}$ are the vectors attributed to the nodal displacements, and the nodal internal, external, cohesive and contact forces, respectively; $[M]$ is the mass matrix. The system (4) is solved using either central difference explicit or Hilber-Hughes-Taylor implicit time-stepping schemes available in ABAQUS [5].

To estimate the stress state close to the crack tip appeared along the surface ∂V_c, the interaction integral method is used to calculate the components of stress intensity factors as follows:

$$K_i = \frac{H}{2K_i^{aux}} J_{int}^i, \quad \text{where} \quad H = (2\cosh^2 \pi\epsilon)/(1/\bar{E}_1 + 1/\bar{E}_2), \tag{5}$$

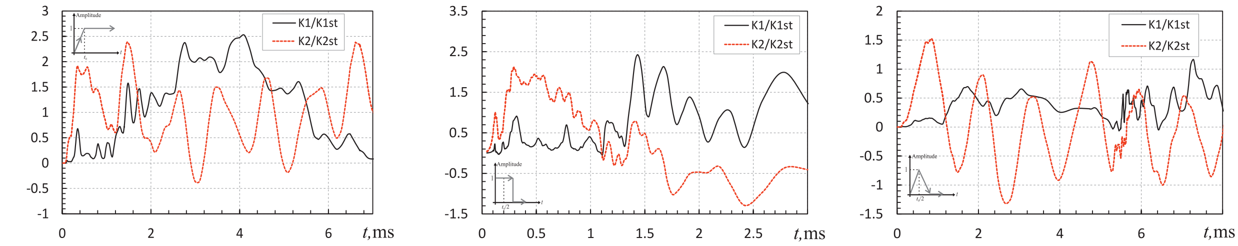
where (*aux*) stands for auxiliary factors known from the asymptotic Williams type' solutions of the corresponding material system; $\bar{E}_k = E_k$ for in plane stress and $\bar{E}_k = E_k/(1-\nu_k)$ for in plane strain, $k = 1, 2$; and ϵ is the bi-material oscillation index. Herewith, the interaction integral is defined as

$$J_{int}^i = \lim_{\Gamma\to 0} \int_{\mathcal{C}+\mathcal{C}_+ + \Gamma + \mathcal{C}_-} \mathbf{m} \cdot \left\{ \boldsymbol{\sigma} : (\boldsymbol{\varepsilon})_i^{aux} \mathbf{I} - \boldsymbol{\sigma} \cdot \left(\frac{\partial \mathbf{u}}{\partial x_1} \right)_i^{aux} - (\boldsymbol{\sigma})_i^{aux} \frac{\partial \mathbf{u}}{\partial x_1} \right\} \cdot \mathbf{q} d\Gamma, \tag{6}$$

where $\mathbf{q}$ is a weighting function within the region enclosed by a contour $\mathcal{C} \cup \Gamma \cup \mathcal{C}_+ \cup \mathcal{C}_-$; $\mathbf{q} = \mathbf{q}_1$ on Γ and $\mathbf{q} = 0$ on $\mathcal{C}$; $\mathbf{m}$ is the outward normal. The line integral (6) is computed based on the domain integral formulation [6].

Results and conclusions

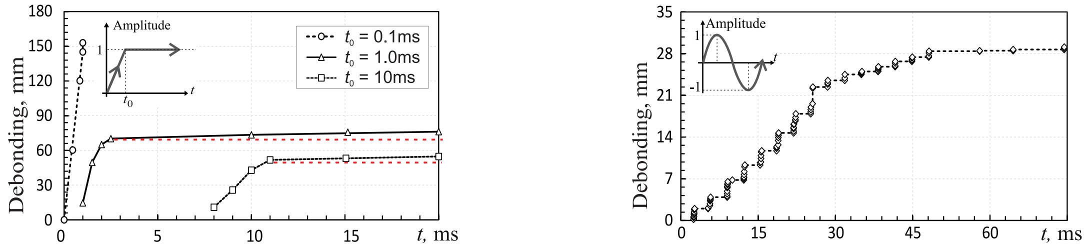
A 2-D finite element model of the DCB specimen is developed using eight-node reduced integration plane strain finite elements (`CPE8R`) available in ABAQUS. The mesh contained a refinement around the crack-tip.
The effect of impulsive loading on the transient dynamic SIFs of the DCB with stationary debonding is demonstrated in Figure 1. One can see that the DSIFs exceed their static counterparts for all the cases of loading. Also, the forms of impulse remarkably affect the time histories of the DSIFs. Herewith, unlike the stationary loading, the transient loads generate a high enough value of the mode II component.



(a) (b) (c)

Figure 1: Dynamic SIFs with a ramp time $t_0 = 1$ ms due to: (a) step loading; (b) rectangular pulse; (c) triangular pulse.

Four-node cohesive elements (`COH2D4`) satisfying the TSL (2) were inserted into the finite element mesh of the DCB model to simulate fracture of the specimens under dynamic loading. The debonding growth under impulse loads of different durations and the harmonic load at a ceratin driving frequency is shown in Figure 2.



(a) (b)

Figure 2: Debonding propagation versus time under: (a) impulsive step loading; (b) harmonic loading

The calculations revealed that there is a large dynamic effect in the DCB test, primarily due to stress waves from both the loading and crack face contact. Such waves interact with the crack tip and strongly affect the fracture parameters and the debonging behaviour of the DCB sandwich specimen.

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