Nonlinear Fracture Dynamics of Double Cantilever Beam Sandwich Specimens

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Abstract. A virtual testing of double cantilever beam interlaminar fracture toughness sandwich specimens under different types of dynamic loads and loading rates is considered. The nonlinear dynamic response of those sandwich specimens being fractured during the test is numerically examined using the two-dimensional finite element model within the ABAQUS™ code. The interaction integral method is exploited to extract the dynamic stress intensity factor. Cohesive elements allocated along the face/core interface are used to simulate the dynamic fracturing of the specimens.

Introduction

The interfacial debonding between the core and the face sheets poses a threat to the structural integrity of a whole sandwich construction. As a result, fracture mechanics methods, which are able to validate sandwich composites in terms of damage tolerance and possible failure should be used. In this respect, interlaminar fracture toughness specimens supply necessary information regarding the fracture resistance. A commonly used experimental method for studying the mode I interlaminar fracture is a double cantilever beam (DCB) sandwich specimen. Then, the fracture parameters such as stress intensity factors (SIFs) or strain energy release rate (ERR) controlling the fracture process are inferred. The understanding of the dynamic behaviour of fracture is required for a complete assessment of the interlaminar strength. Thus, a great deal of attention should be given to dynamic DCB tests. The aim of this research is to develop an accurate and efficient finite element model of the DCB sandwich specimen for predictions of a nonlinear dynamics and strength of sandwich material in virtual fracture testing.

Formulation of the model

A dynamic framework of the finite element method (FEM) with cohesive elements is used in the present work. By assuming infinitesimal deformations, neglecting body forces, but accounting for cohesive and contact forces for a 2-D body occupying a space V and containing crack at a surface $\partial V_c = \partial V_c^+ \cup \partial V_c^-$, and with prescribed displacements $\bar{\mathbf{u}}$ at a boundary ∂V_u and given traction $\bar{\mathbf{t}}$ at ∂V_t, the principle of virtual work can be stated as [1]:

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

for all kinematically admissible displacement fields $\delta\mathbf{u}$. Herein, ρ is the density of material; $\boldsymbol{\sigma}$ is the Cauchy stress associated with a displacement field $\mathbf{u}$, and $\ddot{\mathbf{u}}$ stands for an acceleration field. $\boldsymbol{\Delta}$ is the displacement jump across ∂V_c^+ and ∂V_c^-, along which the cohesive traction $\mathbf{T} = \boldsymbol{\sigma}\cdot\mathbf{n}_c$ directed by the normal $\mathbf{n}_c$ acts in accordance with a bilinear traction separation law (TSL), given for each fracture mode $(i = I, II)$ in the form [2]:

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

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. The damage initiates based on the quadratic stress criterion, whereas the damage propagates if the Benzeggagh-Kenane fracture criterion is met. Also in (1), $\mathbf{t}_N = t_N\mathbf{n}_c$ and $\mathbf{t}_T$ are normal and tangential components of the contact traction, which are interrelated with appropriate normal g_N and tangential $\mathbf{g}_T$ gap functions [3]. In terms of these functions, the impenetrability and friction constraints are stated in the form of Karush–Kuhn–Tucker conditions as follows:

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

respectively. In the case of the Coulomb friction model, $\tau_{crit} = \mu t_N$, where μ is the coefficient of friction.
In the context of the FEM, at time instant t Eq. (1) is transformed to the discrete system of equations as follows:

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

where $\{U\}$ are nodal displacements; $\{R_{int}\}$, $\{R_{ext}\}$, $\{R_{coh}\}$ and $\{R_{cont}\}$ are nodal internal, external, cohesive and contact forces, respectively; $[M]$ is the mass matrix. Either central difference explicit or Hilber-Hughes-Taylor implicit time-stepping schemes available in ABAQUS are used for solving (4).
The components of the SIF $(i = I, II)$ are evaluated using the interaction integral method as follows:

$$K_i = \frac{H}{2K_i^{aux}} \left(\lim_{\Gamma \to 0} \int_{\mathcal{C}+\mathcal{C}_+ + \Gamma + \mathcal{C}_-} \mathbf{m} \cdot \left\{ \boldsymbol{\sigma} : (\boldsymbol{\varepsilon})_i^{aux} \mathbf{I} - \boldsymbol{\sigma} \cdot \left(\frac{\partial \mathbf{u}}{\partial x_1} \right)_i^{aux} - (\boldsymbol{\sigma})_i^{aux} \frac{\partial \mathbf{u}}{\partial x_1} \right\} \cdot \mathbf{q} d\Gamma \right), \tag{5}$$

where $H = (2\cosh^2 \pi\epsilon)/(1/\bar{E}_1 + 1/\bar{E}_2)$ with $\bar{E}_k = E_k$ 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; (*aux*) stands for auxiliary factors known from the asymptotic Williams solutions; $\mathbf{q}$ is a weighting function within the region enclosed by a contour $\mathcal{C} \cup \Gamma \cup \mathcal{C}_+ \cup \mathcal{C}_-$; $\mathbf{m}$ is the outward normal. The line integral in (5) is computed based on the domain integral formulation.

Numerical Results

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 near the crack-tip region.
The effect of impulsive loading on the transient dynamic SIF of the DCB with stationary debonding is demonstrated in Figure 1. One can see that the DSIFs exceed their static counterparts for all cases and the form of impulse remarkably affects their time histories. A significant mode II component is generated due to this loading.

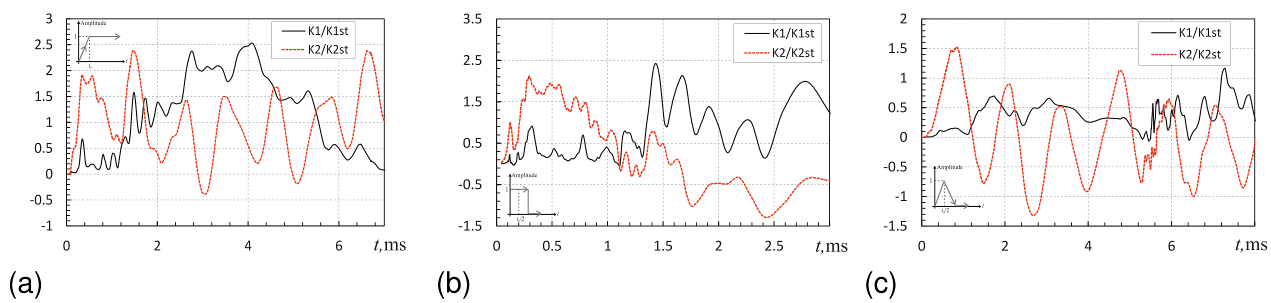

Figure 1: Dynamic SIFs with a ramp time $t_0 = 1$ ms due to: (a) step loading; (b) rectangular pulse; (c) triangular pulse.

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

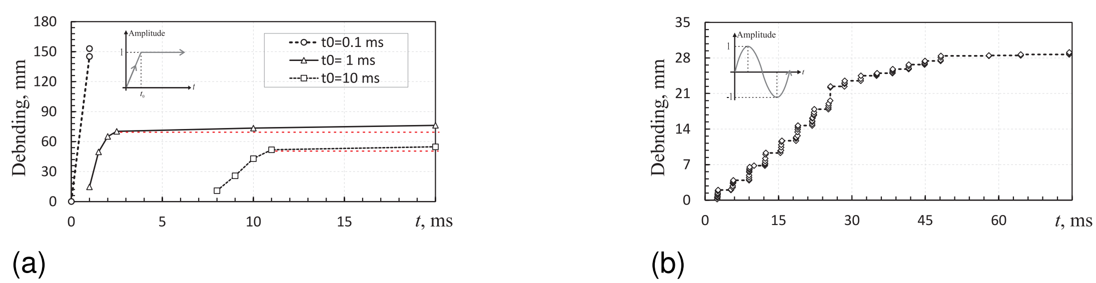

Figure 2: Debonding propagation versus time under: (a) impulsive step loading; (b) harmonic loading.

Conclusions

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.

References

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