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CRACK TUNNELING IN LAMINATES

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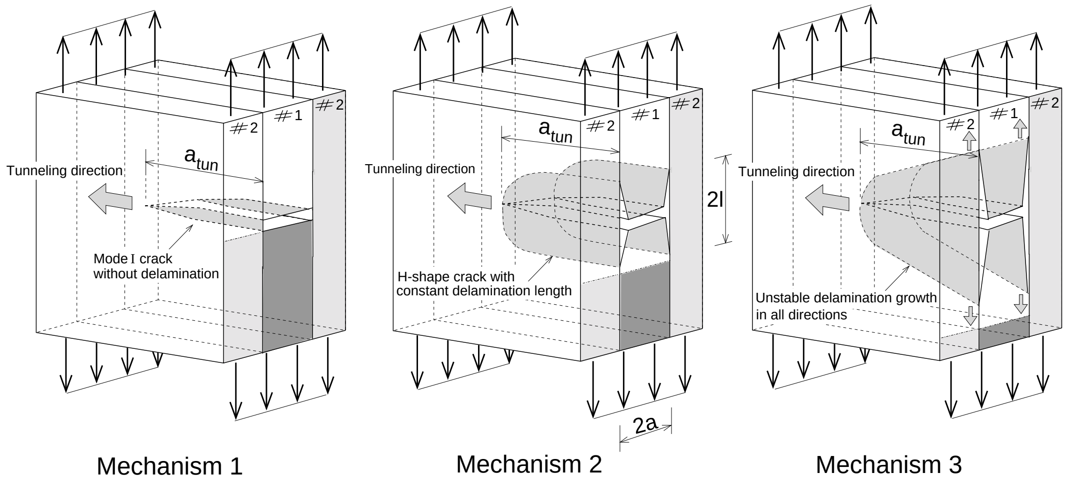
Summary Steady-state tunneling and plane-strain delamination of an H-shape crack are examined for elastic, isotropic multi-layers. Both tunneling and delamination are analysed by employing linear elastic fracture mechanics within a 2D finite element framework. Failure maps are produced to reveal the sensitivity of cracking path to the relative toughness of layer and interface, and to the stiffness mismatch of layers. A comparison with experimental values taken from the literature shows that the model results are useful in the determination of the residual strength and the fatigue crack growth rate in elastic multilayers.

FAILURE MECHANISMS

The current study considers possible crack propagation paths for alternating layers of two dissimilar but isotropic elastic, brittle solids, designated as materials ’1’ and ’2’ in Figure 1. The initiation/nucleation phase of cracking is neglected, and it is assumed that the crack has grown from a large pre-existing flaw in the mid-layer (material 1) and is driven by a *remote tensile stress*. The competition is addressed for: (i) tunneling of a mode I crack in the mid-layer with delamination absent (*mechanism 1*), (ii) tunneling of an H-shape crack with constant delamination length (*mechanism 2*), and (iii) unstable delamination in all directions (*mechanism 3*). It is assumed that the penetration toughness of the layers of material 2 is sufficiently high for the initial mode I crack in the material 1 layer not to penetrate them; this is commonly the case for the fibre-metal laminates such as ARALL and GLARE (aluminium sheets alternately stacked with aramid fibre layers and glass fibre layers, respectively). The assumption of elastic isotropy may be an acceptable simplification for multi-directional fibrous laminates when the elastic mismatch between fibres and matrix is moderate.



Mechanism 1 Mechanism 2 Mechanism 3

Figure 1. Three possible failure mechanisms for a laminate of two dissimilar, isotropic materials. *Mechanism 1* : Tunneling of a mode I crack without delamination. *Mechanism 2* : Tunneling of an H-shape crack with constant delamination length. *Mechanism 3* : Unstable delamination growth in all directions.

Both plane-strain delamination of an H-shape crack and steady state tunneling of an H-shape crack are investigated by 2D finite element analyses. Although tunneling is a 3D phenomenon, the remote stress for steady-state tunneling can be computed from a plane-strain elasticity solution for an H-shape crack: the difference in strain energy upstream and downstream of the tunneling crack front is equated to the delamination work and, for simplicity, the delamination toughness is taken to be independent of the mode-mix, see Hutchinson and Suo (1992).

RESULTS

One of the cracked configurations analysed is a 5/4 lay-up (5 layers of material 1 alternately stacked with 4 layers of material 2) where the specific fracture scenarios plotted in Figure 1 occur in the mid-layer. The numerical results have been reduced to failure mechanism maps, such as Figure 2a, in which the minimum remote tunneling stress in the layer of material 1, $\sigma_{tun,min}$ is plotted against the toughness ratio G_{dc}/G_{Ic} for selected stiffness mismatches $\bar{E}_2/\bar{E}_1$. Here, G_{dc} is the delamination toughness, G_{Ic} is the toughness related to mode I cracking in the layer of material 1 and $\bar{E}_i$ is the plane-strain Youngs modulus in layer $i \in \{1, 2\}$. The three failure modes plotted in Figure 1 are displayed with

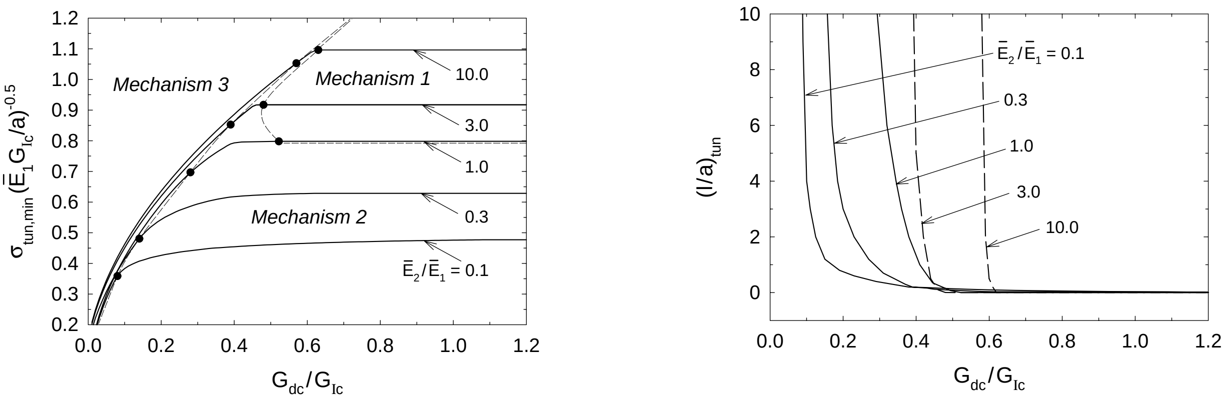


Figure 2. Cracking in the centre layer of the 5/4 lay-up. *LEFT:* Minimum tunneling stress $\sigma_{tun,min}$ versus fracture toughness ratio G_{dc}/G_{Ic}. Dashed lines indicate the zones corresponding to the three failure mechanisms in Figure 1. *RIGHT:* Delamination length $(l/a)_{tun}$ versus fracture toughness ratio G_{dc}/G_{Ic}.

the location of their boundaries indicated by dashed lines. For each curve of tunneling stress versus toughness ratio the transition from one mechanism to another is indicated by a black dot. The corresponding values for the delamination length at tunneling are depicted in Figure 2b, where l and a are the semi-length and the semi-width of the H-shape crack (*Mechanism 2*) depicted in Figure 1. Figure 2 can be used to estimate the (critical) tunneling stress $\sigma_{tun,min}$ and the delamination l/a for assumed values of G_{dc}/G_{Ic} and $\bar{E}_2/\bar{E}_1$. More details about the model, as well as the results for other cracked configurations, can be found in Suiker and Fleck (2004a).

A comparison with experimental results taken from the literature shows that the present study provides a useful tool for the prediction of the residual strength of laminates (Suiker and Fleck, 2004a). Also, combining the results with Paris law provides excellent predictions for the steady-state fatigue crack growth rate in ARALL and GLARE laminates (Suiker and Fleck, 2004b), see Figure 3.

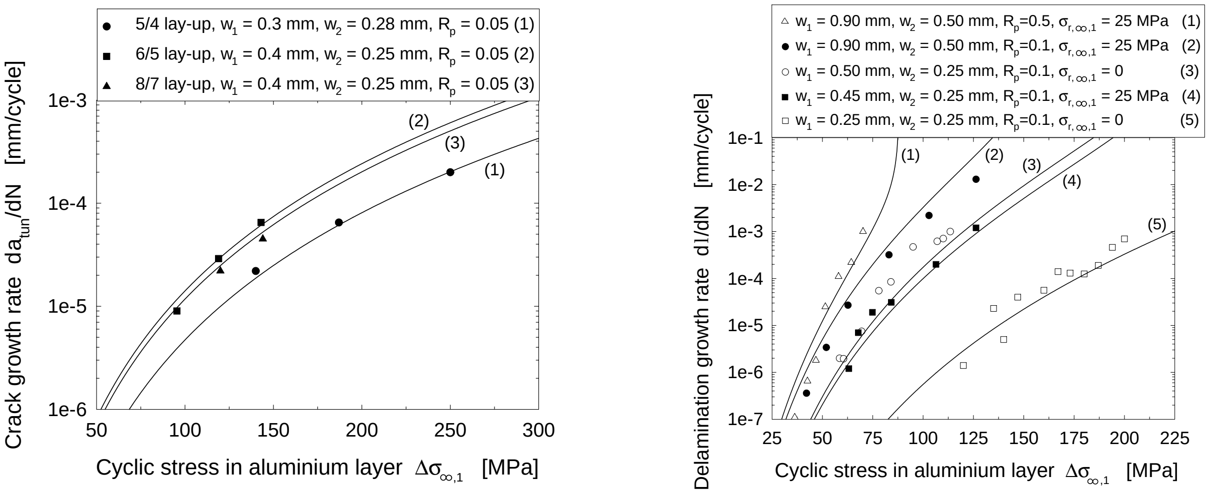


Figure 3. Fatigue crack growth rate in laminates, model (*solid lines*) and experiments (*symbols*). *LEFT:* Tunneling crack growth rate da_{tun}/dN versus remote cyclic stress in aluminium layer $\Delta\sigma_{\infty,1}$ (material 1 layer) for various centre cracked GLARE specimens. *RIGHT:* Delamination growth rate dl/dN versus versus remote cyclic stress in aluminium layer $\Delta\sigma_{\infty,1}$ (material 1 layer) for ARALL 2/1 lay-ups under various conditions. The parameters w_1 and w_2 are widths of the material 1 and 2 layers, respectively, R_p is the load ratio and $\sigma_{r,\infty,1}$ is the remote residual stress in the aluminium layer (material 1 layer). The experimental values for ARALL have been taken from Marissen (1988), and for GLARE have been taken from Takamatsu *et al.* (1999) and Shim *et al.* (2003).

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