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Coupled, multiple cracking systems in multilayered composite materials

Yang, Qingda, qdayng@miami.edu, University of Miami

ABSTRACT

Multidirectional composite laminates have been increasingly used as primary load-bearing structures in many applications such as aircraft frames, wings, and turbine or wind-mill blades, owing to their excellent weight-to-strength ratios, better environmental resistance, and much improved long-term durability. Such high-performance polymer matrix composites typically consist of dozens of unidirectional plies of ~0.1 mm thick and aligned in different directions. However, because of the highly heterogeneous nature of such materials, they exhibit very complex progressive damage processes which are dominated by the nucleation, propagation, merging, bifurcation of many different systems of small cracks (intraply cracks, delaminations, microbuckle induced kinking, etc) before they eventually grow to a sufficiently large damage zone of structural criticality. In the past, this complex problem has been addressed by various continuum damage mechanics models, which are of phenomenological nature and merely consider the load-bearing loss of the damaged materials, but with no explicit representation of these crack systems. More recently, the need to address such subcritical cracks has been increasingly appreciated because their evolution represents a significant portion of the structural life and they can facilitate many unexpected early structure failure upon changing of loading or environmental conditions. However, up to date there still lack effective analytical or numerical methods that can faithful predict the evolution of such cracking systems, let along to quantify their effects on structural criticality. The difficulties arise from multiple fronts: (i) a lack of adequate understanding of the damage process zones associated with different types of small cracks; (ii) the in situ critical stress or strain conditions responsible for crack nucleation and propagation; (iii) numerical or analytical platforms that can account for the arbitrary nucleation and propagation of multiple cracks in a way that is consistent to the material failure/damaging descriptions. In this presentation, I shall first review the much improved understandings of how such composite materials fail at subply (microscopic) level under in situ loading, which was enabled only recently by the microscopic computer tomography, X-ray technology. The improved understanding thus allows us to construct realistic material failure descriptions based on the in situ stresses–displacement relations (as appose to the classic global laminar stress–strain relations). I shall then introduce a newly developed numerical platform named augmented finite element method (A-FEM), which can explicitly embed microscopic material failure descriptions (as cohesive failure models) in any structural models. Thus, the formation and propagation of nonlinearly coupled multiple cracks can take place at any locations dictated by the in situ local stresses. We shall demonstrate with several complex laminate systems that the numerical performance of the A-FEM based platform is very effective in dealing with such problems with very high fidelity. More critically, the method can effectively link the evolution of the complex damage processes with structural performance, which represents a big step towards the quantification of subcritical crack growth to final structural criticality.