DAMAGE AND FAILURE IN FIBER-REINFORCED LAMINATES

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Summary Using continuum damage mechanics approach the paper develops a methodology to analyze damage initiation and progression in fiber-reinforced composite laminates impact loaded by a slow moving impactor, and uses it to analyze deformations of a laminate.

Damage in composites, which often is undetectable, includes matrix cracking, fiber breakage, fiber/matrix debonding, and delamination/sliding of two adjoining layers or interfaces. Even when the damage does not cause catastrophic failure, it significantly reduces structural stiffness. A possibility is to assume that damage initiates at a point when the state of deformation and/or stress there lies on a damage envelope defined in terms of the equivalent stress, or the equivalent strain, or their combination. The moduli are degraded due to the damage evolved till they become zero, and the material point then is taken to have failed completely. A challenge in using this continuum damage mechanics (CDM) approach is the postulation of damage evolution laws, the determination of energy dissipated in each failure mode, and computing results subsequent to the failure of one or more material points.

In [1] we developed a CDM approach using an internal variable for each damage mode except delamination, and found the energy dissipated during impact loading of a laminate. The damage evolution laws were derived from the test data. The delamination between adjoining layers was modeled by the nodal release technique, and the matrix and the fibers were modeled as Hookean materials. Here we model the matrix by a pressure-dependent Drucker-Prager yield criterion, fibers as a Hookean material, and homogenize elasto-plastic material properties of the composite using a micromechanics approach [2]. We analyze damage initiation, damage progression, and failure during 3-dimensional deformations of a composite laminate impacted by a rigid sphere, and compare computed results with the published experimental findings. We assume damage initiates when one of Hashin's failure criteria is satisfied, and model its evolution by an empirical relation. The transient problem is solved by the finite element method (FEM) using 8-node brick elements with 1-point integration rule, hour-glass control and the explicit conditionally stable central-difference algorithm for integrating the coupled ordinary differential equations obtained from the Galerkin formulation of the problem. A user defined subroutine has been developed and implemented in the commercial FE software ABAQUS. From strains supplied by the software it uses values of material parameters of the constituents to find average stresses in an FE, and checks if Hashin's failure criteria are satisfied. If applicable, the subroutine evaluates irreversible damage developed, computes resulting stresses, and provides them back to ABAQUS. The delamination between plies is simulated by using the cohesive zone model.

The above-described technique is used to study transient deformations of a square n-ply composite laminate resting on a square steel plate having a circular hole at its center as shown in Fig. 1. We assume that initial displacements and velocities of the laminate particles are zero, all bounding surfaces, except for points on the contact surfaces, are traction free. Points on the contact surface conform to the shape of either the impactor or the supporting plate. Here the influence of stacking sequence is examined by studying the impact problem for the $[0]_{16}$, $[-45/\ 0/\ 45/\ 90]_{2S}$ and $[0\ /90]_{4S}$ laminates.

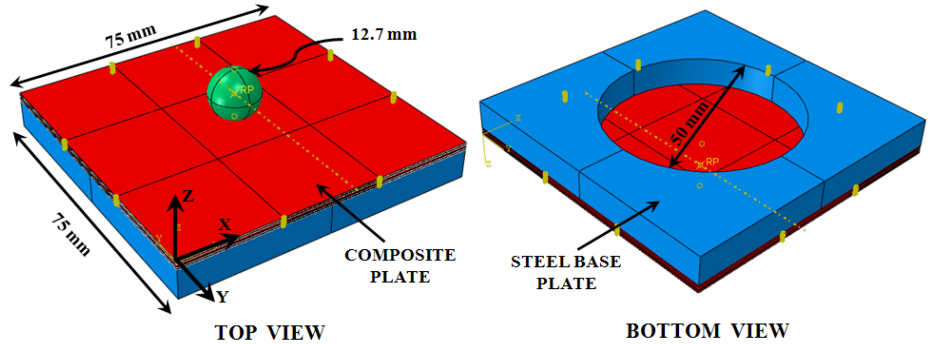

Fig. 1: Schematic sketch of the problem studied; the impactor is shown in green, the composite laminate in red and the supporting steel plate in blue color.

The time histories of the contact force for the three stacking sequences plotted in Fig. 2 reveal that the initial rate of increase of the contact force before the damage threshold load for the $[0]_{16}$ stacking sequence is much less than that for the other two stacking sequences. In terms of either the damage threshold or the peak contact load the stacking sequence $[-45/\ 0/\ 45/\ 90]_{2S}$ offers a better impact resistance than that offered by the other two stacking sequences. Some other results are included in [3].

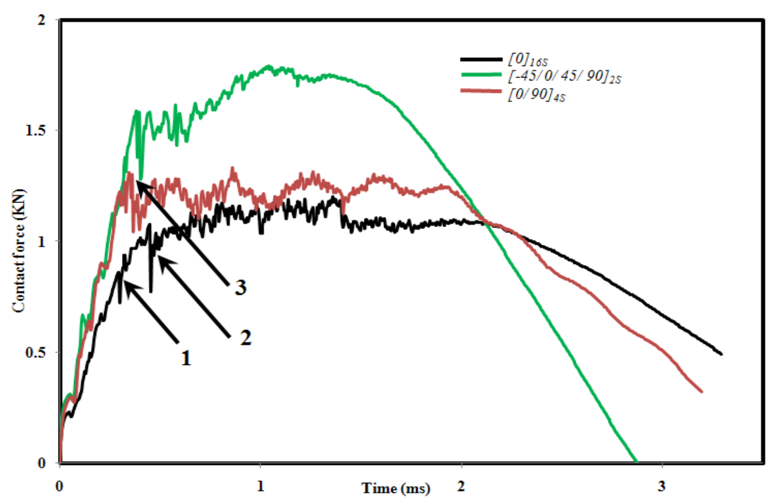

Fig. 2: Comparison of contact force time histories for three laminate stacking sequences

References:

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[3]. R. C. Batra, G. Gopinath and J. Q. Zheng, Damage and Failure in Low Energy Impact of Fiber-Reinforced Polymeric Composite Laminates, *Composite Structures*, **94**, 540-547, 2012.