Progressive Failure Analysis of Fiber Reinforced Composite Plates using Continuum Damage Mechanics and Phase Field

Fiber reinforced composites exhibit failure in different modes (fiber rupture in fiber tension, fiber kinking/micro-buckling in fiber compression, matrix cracking in transverse to fiber tension, matrix crushing/shearing in transverse to fiber compression, and delamination). The macroscopic effect of the progressive failure in different failure modes can be captured phenomenologically using Continuum Damage Mechanics (CDM). Continuum damage models can be derived based on phenomenological observations from experiments or using principle of maximum dissipation by employing first and second law of thermodynamics. Damage models can also be categorized into failure mode dependent and failure mode independent damage models. Damage evolution equations can be present in both differential form and analytical form. While differential form can be derived based on laws of thermodynamics, analytical form of equations takes less computational time. An alternate path for progressive failure analysis is Phase Field Method (PFM). PFM approximates sharp crack interface using a diffuse band modeled by crack surface density functional dependent on phase field variable.

Based on the detailed literature review, it is found that failure mode dependent damage models with thermodynamic consistency, generalized coupling vectors and damage model parameters characterized based on all experimental uniaxial/shear stress-strain curves are not available. \Additionally, an efficient layerwise phase field framework utilizing two dimensional theory for displacement field and phase field to capture both in-plane and through thickness crack propagation in composite plates subjected to transverse loading is also not available in the literature. Therefore, the main contributions of this thesis are: development of coupled failure mode dependent damage model for generalized plane stress conditions (MLTGPS model), 3D thermodynamically consistent damage model with damage evolution equations derived based on principle of maximum dissipation (MLTTCM model) and post-peak response, and 3D damage model with analytical expressions of evolution equations and generalized coupling vectors ($Dam-pro$ model). The damage model parameters of all the damage models are characterized using all uniaxial/shear experimental stress-strain curves and blind predictions of the calibrated models are validated against experimental data for laminated composites under three dimensional state of stress. Also, a layerwise phase field framework is developed with quadratic variation of phase field variable in thickness direction in each layer to capture fiber orientation dependent crack propagation in each lamina of the composite laminate.

The governing equations involving continuum damage mechanics and phase field method are solved using in-house developed finite element codes based on the Newton–Raphson method. The developed failure mode dependent damage models predict different damage in tension and compression consistent with strength properties of fiber reinforced composite materials. The blindly predicted failure loads by the calibrated MLTTCM and $Dam-pro$ damage models are in close agreement with experimental results for notched laminated composite panels available in the literature with different central hole diameters. Blind predictions of the damage model with

post peak response are in excellent agreement with in-house conducted experiments on laminated and sandwich composite panels subjected to uniaxial compression and three point bending, respectively. The layerwise phase field framework predicts crack paths and failure loads close to experimental observations and other numerical models in the literature for composite laminae with a central hole and different fiber angles subjected to uniaxial extension.