analysis. In the pre-damage analysis, the proper constitutive model of lamina is a key tool to describe the real behavior of each layer within the laminate under loading. In the previous study, it is assumed that the fiber and matrix perform as elastic-plastic behavior[8] and the in-plane shear behaves nonlinear with a constant shear parameter[17]. In this study, it is proposed that the in-plane shear behaves nonlinearly with a variable shear parameter. The difference between these two distinct types of shear parameter is investigated in this literature. In the past, the Tsai-Wu failure criterion[14] is the most common criterion used to determine the damage onset of individual layer. However, Zhu and Sankar[20] and Lin and Hu[21] suggested that the combination of both the Tsai-Wu criterion and the maximum stress criterion, which is called the mixed criterion, was a much better criterion for damage determining of lamina. Thus, in this paper the mixed criterion is employed to determine the damage onset of individual layer within the laminate under loading. For the post-damage analysis, a degrading mode for matrix and brittle modes for fiber and in-plane shear are proposed to simulate the post damage behaviors of individual lamina.

In this paper, a proposed nonlinear analysis model included various post damage modes is introduced first. Second, a material constitutive model considering the nonlinear in-plane shear behavior with variable shear parameter and the elastic-plastic behavior of fiber and matrix is developed. Third, various failure criteria and post damage modes are reviewed, and a mixed failure criterion and the post-damage modes are proposed. Fourth, the laminate governing equations are built up to describe the incremental force-strain relations of the composite laminates. Then, the ABAQUS finite element program[22] is used to carry out numerical analyses for laminates with various configurations and various off-axis loads. Finally, numerical results predicted by the proposed nonlinear analysis model are tested against the experimental data of Petit and Waddoups[5] and compared with those predicted by other failure criteria and post damage modes.

2. Nonlinear Analysis Model

2.1 Proposed stress-strain curves and post damage model

For a single lamina subjected to tensile loading, the stress-strain curves of the proposed nonlinear analysis model are shown in Figs. 2a and 2c. It is assumed that the material response can be represented by bilinear stress-strain curves in the principal material directions, i.e. 1 direction (fiber direction) and 2 direction (transverse direction), of the lamina. Let X_{yt} and X_{ut} be the yield strength and the ultimate strength of the lamina for tension in 1 direction, Y_{yt} and Y_{ut} be the yield strength and the ultimate strength of the lamina for tension in 2 direction. For the elastic regions, i.e. $\sigma_1 \le X_{yt}$ and $\sigma_2 \le Y_{yt}$, the elastic moduli are denoted by E_{iie} $(i = 1, 2)$. For the plastic regions, i.e. $X_{yt} \le \sigma_1 \le X_{ut}$ and $Y_{yt} \le \sigma_2 \le Y_{ut}$, the elastic moduli are denoted by E_{iip} $(i = 1, 2)$. For a lamina subjected to compressive loading, the stress-strain curves are shown in Fig. 2b and 2d. It is obvious that X_{yc} and X_{uc} are the yield strength and the ultimate strength of the lamina for compression in 1 direction and that Y_{yc} and Y_{uc} are the yield strength and the ultimate strength of the lamina for compression in 2 direction. Let S be the ultimate in-plane shear strength. It is assumed that the in-plane shear in 1-2 direction can be modeled by a nonlinear stress-strain curve as shown in Fig. 2e.

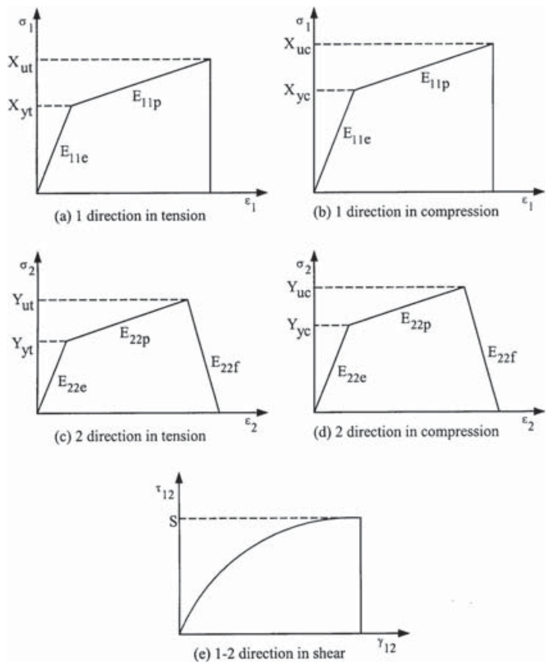

Figure 2 Stress-strain curves of the proposed nonlinear failure model

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