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Multiaxial fatigue life prediction of composite bolted joint under constant amplitude cycle loading

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ABSTRACT

In this paper, a fatigue model of composite is established to predict multiaxial fatigue life of composite bolted joint under constant amplitude cycle loading. Firstly, finite element model is adopted to investigate stress state of composite bolted joint under constant amplitude cycle loading. Secondly, Tsai–Hill criterion is used to calculate equivalent stress of joint. At last, modified S–N fatigue life curve fitted by unidirectional laminate S–N curve which takes ply angle and stress ratio into consideration is adopted to determine fatigue life of composite. Calculation results of equivalent stress model show excellent agreement with experiments of composite bolted joint.

1. Introduction

Fiber reinforced composite materials widely used in structural engineering components demand connecting with other components, where failure exists earliest. Particularly composite bolted joint where stress concentrate and strength reduction are made by hole in composite laminate will play an important role in structure safe and reliability. So many researchers [1,2] have investigated failure of composite bolted joint under monotonic tensile load. Effects of geometric parameters, ply sequence and bolt torque on failure of joint are studied.

Compared with static mechanical properties of composite, fatigue of composite just has been studied in the past few decades. The behavior of composite materials under uniaxial constant amplitude cyclic stress states has been extensively studied for the purpose of developing methodologies for safe fatigue assessments. Miner linear damage accumulation rule [3] is a most common fatigue life prediction method [4–6]. Damage variable D is used to determine fatigue life of composite in this model. Some researchers modify the linear Miner's rules to nonlinear rules including: Marco–Starkey rule [7], Owen and Howe rule [8] and Bond and Farrow rule [9]. Residual strength model is another common approach used to calculate fatigue life of composite which is based on the assumption that the residual strength is a monotonically decreasing function of the cycles applied, including: Broutman and Sahu model [10], Reifsnider model [11,12], Schaff and Davidson model [13,14] and Hahn and Kim model [15,16].

Most researchers treat composite fatigue as uniaxial stress or the plane stress state which could not represent actual stress state of composite. Composite structure is often under mutiaxial stress state [17] caused by anisotropy of composite and contact between different structure components. Few researchers investigate multiaxial fatigue of composite. Kawai [18] uses Tsai–Hill static failure criterion and constant fatigue life (CFL) diagrams calculate fatigue life of unidirectional carbon/epoxy laminates, and his fatigue model can predict composite fatigue life with any stress ratio and any fiber orientation. Mahadevan [19] introduces characteristic plane to investigate multiaxial fatigue of isotropic and anisotropic materials. The effect of the mean normal stress is also included in his model and calculation results of fatigue life of unidirectional and multidirectional composite laminate show excellent agreement with experiments. Naik [20] presents an analytical model based on minimum strength model and fiber failure criterion to study fatigue of laminated composites with a circular hole. Analytical predictions are compared with the experimental results for uniaxial and multiaxial fatigue loading cases. Lessard [21,22] presents a generalized residual material property degradation model to study fatigue of composite by experimental and numerical method. Kawai [23,24] introduces effective stress to study fatigue of composite under and room and high temperature. In his model, effective stress is treated as plane stress state and experimental results match the numerical results well.

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In practice, composite laminates are often bolted with other components, which result in stress concentration and varying stress ratios at different points, especially if material or geometric nonlinearities are involved. However, fatigue tests under at wide range of stress ratios are time consuming and expensive. It is not suitable that multiaxial stress is simplified as plane stress or uniaxial stress state which could not reflect effect of shear stress on fatigue of composite. Therefore it is important to establish a model to consider fatigue damage due to arbitrary stress ratio and three-dimensional stress state without having to perform excessive amounts of test. In this paper, equivalent stress fatigue life prediction model is established for composite bolted joint under constant amplitude loading. In proposed model, firstly, 3D FE model is adopted to analyze stress state of composite bolted joint under single cycle loading. Secondly, tensile or compressive failure mode is determined by stress state, and a non-dimensional equivalent stress based on three-dimensional Tsai–Hill criterion is calculated. At last, normalized equivalent stress S–N curves are fitted by S–N curves of unidirectional laminates which take ply angle and equivalent stress ratio into consideration. Results of proposed model show excellent agreement with fatigue experiments of composite bolted joint. In the last two procedures, all the calculations are carried out by Matlab program written by authors.

2. Fatigue life model

To predict fatigue life of composite bolted joint under multiaxial stress state, a non-dimensional equivalent stress fatigue model is established based on modified Tsai–Hill criterion, which will be explained in the next two parts in detail. The whole calculation process is shown in Fig. 1.

As shown in Fig. 1, fatigue life calculation of composite bolted joint is carried out by FE model, firstly. Stress distribution of composite bolted joint under single cycle loading with specific stress ratio (R) is obtained from FE model. According to FE results, critical element under tensile or compressive state is determined which represents the fatigue life of composite laminate. And then, equivalent stress of the critical element is calculated based on modified Tsai–Hill criterion. Fatigue life of composite laminate is determined by modified normalized S–N curves, which will be explained in section 2.2 in detail.

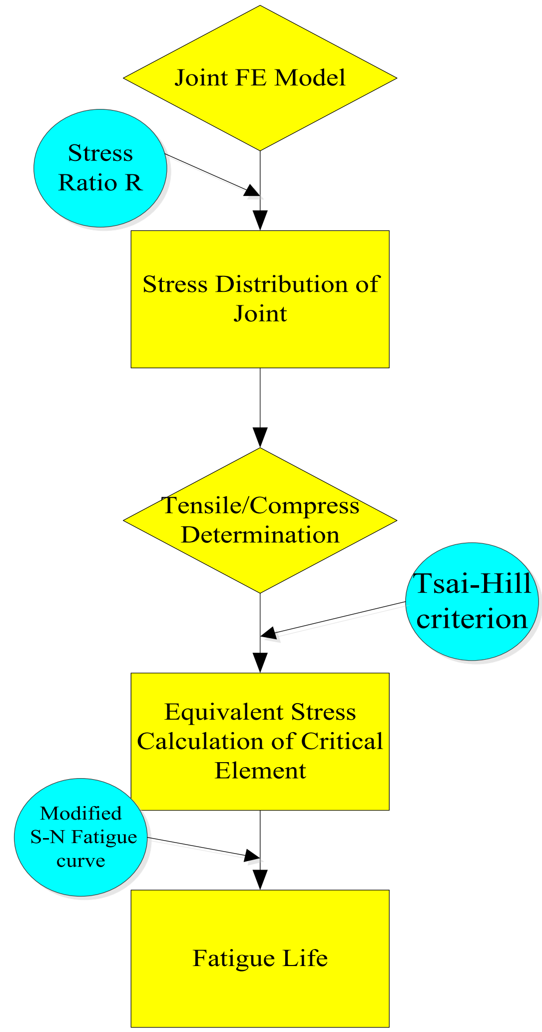

Fig. 1. Algorithm of fatigue life assessment of equivalent stress model.

2.1. Equivalent stress

It is known that some parts of composite laminates are under tensile stress state and other parts are under compressive stress sate when composite bolted joints are subjected to monotonic tensile load. When composite bolted joints are under constant amplitude cycle loading, most researchers treat composite laminate as simple tensile or compressive cycle loading, which could not represent real multiaxial stress state and fatigue mode. So in this section, equivalent stress is introduced to solve this problem. Regardless of stress state of composite laminate, damage variable D can be calculated by failure criterion. In other words, when composite laminate under any kind of cycle loadings, stress components can be derived from FE result, damage variable can be calculated by failure criterion which is determined by stress state and strength of laminate. In this paper, three-dimensional Tsai–Hill is chosen to calculate damage of laminate under cycle loading, and the damage variable is called as equivalent stress which will be used in fatigue life prediction in section 2.2.

Non-dimensional equivalent stress is defined on the basis of the modified Tsai–Hill static failure criterion. For the case of three-dimensional stress, it is expressed as:

$$\sigma^* = \sqrt{\frac{\sigma_{11}^2}{X^2} + \frac{\sigma_{22}^2}{Y^2} + \frac{\sigma_{33}^2}{Y^2} - \frac{\sigma_{11}\sigma_{22}}{X^2} - \frac{\sigma_{11}\sigma_{33}}{X^2} - \left(\frac{2}{Y^2} - \frac{1}{X^2}\right)\sigma_{22}\sigma_{33} + \frac{\tau_{12}^2}{S_{12}^2} + \frac{\tau_{13}^2}{S_{13}^2} + \frac{\tau_{23}^2}{S_{23}^2}} \quad (1)$$

In Eq. (1), σ_{11} is lamina stress in longitudinal direction, σ_{22} and σ_{33} are lamina stresses in transverse direction, τ_{12}, τ_{13}, τ_{23} are lamina shear stresses in plane, and all these stresses can be gotten from FE model. X, Y and S are strength of laminate according to the tensile, compressive and shear state. Three-dimensional stress is introduced to calculation of equivalent stress, so multiaxial stress is simplified as uniaxial stress, and uniaxial S–N curves could be used in the fatigue life prediction of composite.