Progressive damage analysis and failure load of ceramic matrix composite hollow-shaft

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Abstract—Composite damage is one of important reasons for the destruction of engineering structures; therefore the research target is a typical engineering component – hollow shaft. Firstly, based on the continuum damage mechanics, a stiffness degradation method is proposed to simulate the progressive damage process of ceramic matrix composite hollow-shaft. Afterwards, program development using solid finite element method in ANSYS, the simulative load–displacement curves and tensile failure load of the hollow-shaft are achieved. Finally, Qualitative and quantitative analysis by computer calculation and experimental results, successfully predict the structure failure modes and bearing capacity under axial load. This work proves that the correctness and feasibility of this progressive damage analysis method for ceramic matrix composite hollow-shaft, and further deepen the understanding of damage development.

1. INTRODUCTION
The number of engineering applications using composites in the aerospace industry has exploded in the past [1]. The damage development is one of the important reasons to cause the structure failure. Progressive failure analysis has been proved to be an excellent approach to acquire the damage initiation and accumulation of composite structures, which are the research focus. Lots of research on composite failure problems has been studied [2,3].An important factor to the failure evolution of ceramic matrix composite is stiffness degradation, which can be considered as the macroscopic representation of the micro crack propagation [4].

The finite element analysis is a useful method for the methodologies of progressive failure analysis of composite structure [5][6]. In this study, a progressive damage model is established to investigate the non-linear stress–strain relation by combined continuum damage mechanics with the finite element analysis method; afterwards, the progressive failure process of hollow-shaft is numerically simulated; finally, the calculation precision of computational investigation based on the experimental results is shown.

2. PROGRESSIVE DAMAGE ANALYSIS METHOD
The progressive damage model is established based on continuum damage mechanics (CDM) and the solid finite element analysis method. The research emphasis of progressive failure model is failure initiation criteria and numerical simulation of damage evolution. Various theories and failure criteria have been proposed to predict the damage initiation [7][8][9]. Particularly, Tsai-Wu can’t predict the
failure mode of material, but this criterion is suitable for complicated structures considering the interaction of stress or strain. Linde[10], Zhao[11] and Engelsta[12] achieved good simulation effect using Tsai-Wu failure criterion. Present, there are three types of methods to derive damage evolution equation, which are the experimental (or experience) method[13][14], irreversible thermodynamics[15] and equivalent displacement method[16]. Different forms of equations are obtained, including linear, polynomial and exponential form. Among them, exponential damage evolution law conforms to continuous fiber ceramic matrix composites in engineering practice, because of the speed of damage in initial time faster than later period.

This work is based on Tsai-Wu failure criteria:

$$\varphi = F_i \sigma_i + F_{ij} \sigma_i \sigma_j, i, j = 1,..., 6$$  \hspace{1cm} (1)

When $\varphi \geq 1$, Damage occurs.

The damage variables $d_i$ employ exponential equation [17], Related to the stress of response point.

$$d_i = \begin{cases} 
0, & \varphi_i \leq \varphi_{i0} \\
1-e^{(\ln R)\frac{(\varphi_i-\varphi_{i0})}{\sigma_{i0}}}, & \varphi_i > \varphi_{i0}
\end{cases}, i = 1...6$$  \hspace{1cm} (2)

Where R is equal to 0.01, as residual stiffness coefficient, indicating the lower limit of stiffness degradation coefficient; m is equal to 0.8, as stiffness degradation curve shape factor. $\varphi_i$ are intensity factor of each direction in the Tsai-Wu failure criteria; $\varphi_{i0}$ is stress intensity factor of each direction, when the initial failure.

3. PROGRESSIVE DAMAGE ANALYSIS BASED ON THE NUMERICAL AND EXPERIMENTAL INVESTIGATION

In the work, the hollow shaft structural material is used continuous fiber ceramic composites(C/SiC). The geometric structure form shown in figure.1, Total length is about 180 mm, and examination structure length is 90 mm. Figure.2 shows axial load by pin using the step by step loading method. 8 node SOLID185 units are adopted to establish the finite element model (figure.3).

Under axial load, numerical simulation of the progressive damage is shown in figure.4 (red shows damage location); Structural failure forms obtained from three repetitive axial experiments are showed in figure.5 to figure.7. Comparison and analysis of results, the structural damage location is similar.
Figure 2. The experimental load of hollow-shaft

Figure 3. The finite element model of hollow-shaft

Figure 4. Damage simulation of the hollow shaft (damage showed the red)

Figure 5. Experimental destruction -1#
The simulation of axial load–displacement curve (Figure 8) and the final failure load is compared with experimental results (Figure 9). Because of limited experimental conditions, only the comparison of structural ultimate bearing is showed in Table 1. The relative errors can reach the order of 20% magnitude. Meanwhile, in similarly experimental conditions, the relative differences of experimental ultimate load are is larger. Research for the reason, may be the dispersion of material performance, and experimental conditions are not exactly the same.
TABLE 1. COMPARISON BETWEEN EXPERIMENTAL LOADS AND PREDICTED VALUE

| Cracking load | Experimental loads/kN | Predicted value/kN | Fractional error |
|---------------|-----------------------|-------------------|-----------------|
| 1#            | 25.23                 | 22.541            | -10.66          |
| 2#            | 25.68                 |                   | -12.22          |
| 3#            | 29.24                 |                   | -22.91          |

4. CONCLUSION

This manuscript provided a progressive damage model to predict the failure of ceramic matrix composite structure combining continuum damage mechanics with the finite element analysis method, which included the Tsai-Wu failure criteria and exponential damage equation related to stress. The damage form and failure load of the ceramic matrix composite hollow-shaft under axial load were achieved, based on the progressive damage analysis model. Through the contrast of numerical simulation and experimental results, the fractional errors of structural ultimate bearing are achieved. Finally, this work provides a progressive understanding of the damage propagation behaviors of ceramic matrix composite structure.

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