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A probabilistic model for strength analysis of composite double-lap single-bolt joints

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ABSTRACT

A probabilistic model involving the randomness of basic design parameters was presented to predict the probabilistic strength of a typical composite double-lap single-bolt joint. In the probabilistic model, statistical models of the random parameters including geometrical dimensions, fiber orientation angles and material properties were constructed. In addition, a parametric failure prediction model employing a modified characteristic curve method was established. Static tensile tests of fifteen composite double-lap single-bolt joints made of T800 carbon/epoxy composites were carried out. The probabilistic failure load of the joint obtained from the proposed model is in good consistency with that from the experiments, which verifies the effectiveness and accuracy of the proposed model. Meanwhile, it shows that the proposed model is not sensitive to the probability distribution type of random variables, although the probability distribution type of random variables slightly influences the statistical parameters of the probabilistic failure load. Furthermore, a relationship between the failure probability and the tensile load is determined, and longitudinal compressive strength X_C, ply thickness t_{ply} and longitudinal elastic modulus E_{11} of T800 unidirectional lamina are the key factors affecting the probabilistic failure load and reliability of the joint remarkably.

1. Introduction

Carbon fiber reinforced plastics (CFRPs) have been increasingly utilized in aircraft structures due to their high stiffness/strength-to-weight ratio and unique designability, etc. Numerous composite bolted joints are applied to aircraft structures to connect different composite parts and transfer high loads. However, bolted joints are generally weak parts of composite structures because the drilling process causes potential damage in composites and results in remarkable stress concentration around the fastener hole. Moreover, many uncertain design parameters from the material to structure level, such as severely scattered material properties, stochastic geometric dimensions, and misaligned fiber orientation angles, etc., lead to considerable mechanical property uncertainty of bolted joints, which further imperils the safety and reliability of composite structures. Generally, to solve this problem, a large safety factor is introduced in traditional deterministic designs of composite bolted joints, which significantly diminishes the weight lose superiority of advanced composites. Thus, systematic investigations on the probabilistic design and analysis of composite bolted joints are really necessary to exert the potential of composites and achieve high reliability composite structures.

Up to now, numerous studies have been performed to quantify uncertainty in mechanical properties of composite laminates [1,2]. They focused on the probabilistic strength predictions [3–5], reliability analysis method modifications and comparisons [6–11], reliability based safety factors [12–15], reliability based design optimizations (RBDOs) [16–21] and new proposed techniques for improving computational efficiency [22–27]. Considering the specificity of hole laminates, a few researchers have endeavored to investigate the probabilistic strength of composite pin-loaded laminates with normal distribution assumptions on several design parameters, by combining a progressive damage method with statistical analysis techniques. Based on a 2D progressive damage model (PDM), Li et al. [28] employed a point estimate method and Edgeworth series to evaluate the probabilistic bearing strength of pin-loaded laminates with random material properties, and a maximum entropy method was recommended to replace the Edgeworth series because it can avoid the pitfall encountered in Edgeworth expansions [29]. In later research, Subset Simulation was applied to perform a more efficient probabilistic analysis of a

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pin-loaded laminate involving random material properties as well as fiber orientation angles [30]. Similarly, Nakayama et al. [31] combined a 2D PDM with a response surface method based Monte Carlo simulation (MCS) to predict the probabilistic strength of a pin-loaded laminate in terms of a random hole diameter and longitudinal compressive strength. Lately, they utilized two 3D PDMs to predict the probabilistic knee point strength of a pin-loaded laminate with random transverse modulus, longitudinal and transverse compressive strengths [32]. It is worthwhile noting that an effective PDM of a composite structure should be validated by a series of experiments and a progressive damage analysis consumes dramatic time and computational cost, especially for complicated composite structures. Moreover, for composite structures, uncertainties of design parameters are various, which requires more thorough discussion to accurately predict the probabilistic strength of composite structures.

The existed investigations are still limited to simple structures such as laminates and pin-loaded laminates, and it is lack of reports on the complicated bolted joints, which is a bottleneck for the safety and integrity of composite structures. In this paper, a probabilistic model was presented to predict the probabilistic strength of a composite double-lap single-bolt joint by combining MCS with a parametric failure prediction model, in which a modified characteristic curve method [33] instead of a PDM was adopted to dramatically reduce the computational cost and additional validation experiments. Basic design parameters including geometrical dimensions, fiber orientation angles and material properties were regarded as random variables and corresponding statistical models were established. Static tensile tests of fifteen joint specimens were performed to obtain the ultimate failure loads of the joint, which further provides validation for the proposed model. Furthermore, reliability and sensitivity analyses were performed to determine the failure probability of the joint as well as key influence parameters of the failure probability.

2. Specimens and experiments

In order to conduct an experimental investigation on probabilistic strength of a typical composite double-lap single-bolt joint and further provide validation for the probabilistic model, fifteen specimens were manufactured and static tensile tests were performed to obtain their failure loads.

2.1. Specimen description

A typical composite double-lap single-bolt joint as depicted in Fig. 1 was designed and fifteen specimens were manufactured. Composite laminates of the specimens were made of T800 carbon/epoxy prepreg with the stacking sequence of $[\theta_3/\theta_1/\theta_4/\theta_1/\theta_2/\theta_1/\theta_3/\theta_1/\theta_4/\theta_1]_s$. The nominal geometrical dimensions and fiber

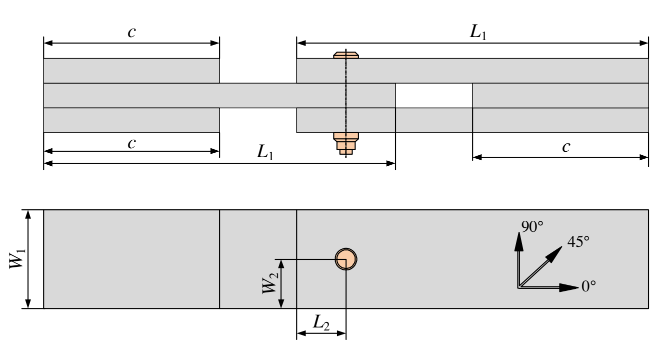

Fig. 1. Schematic diagram of the specimens.

orientation angles are presented in Table 1, where D denotes the hole diameter of the laminates and t_{ply} represents the thickness of a unidirectional lamina. The length c of the doublers is 75 mm. A protruding head bolt HST12-6-7 and a high locking collar HST1078-6 both fabricated with titanium alloy were employed to join the laminates. The nominal diameter of the bolt is 4.76 mm. An assembly tightening torque of 5.0 N·m was applied.

2.2. Experimental procedures and results

Static tensile tests of fifteen specimens were performed according to ASTM D 5961 [34] utilizing a testing machine Instron-8803. A tensile load was applied to the specimens by moving the lower grip holder at a loading rate of 1 mm/min and remaining the upper grip holder still. The tensile load was continuously increased until the ultimate failure of the specimens occurred. The load-displacement (P-δ) curves of the specimens were automatically recorded by computers as represented in Fig. 2, where the peak values of the curves were deemed to be the ultimate failure loads of the specimens [34]. Table 2 further lists the ultimate failure loads of all the joints, where the mean and standard deviation of the ultimate failure loads are 21.01 kN and 0.85 kN respectively. The minimum and maximum values of the ultimate failure loads are 19.00 kN and 22.34 kN respectively.

3. Probabilistic model

A probabilistic model accounting for random geometrical dimensions, fiber orientation angles and material properties was developed to predict the probabilistic failure load of the composite double-lap single-bolt joint. In the probabilistic model, a group of statistical models was used to describe probability distribution of random design parameters. To study the effects of the probabilistic distribution type of random design parameters on the probabilistic failure load of the joint, four groups of statistical models of random design parameters were constructed by combining different probabilistic distribution types. Simultaneously, a modified characteristic curve method combined with a parametric finite element model (FEM) was employed to predict the failure load of the joint. Furthermore, a flowchart was provided to describe the implementation process of the proposed model.

3.1. Statistical models of random design parameters

For the double-lap single-bolt joint in this paper, the randomness of the geometrical dimensions, fiber orientation angles and material properties, which have significant influences on uncertain failure of composite bolted joints, were focused on and corresponding statistical models were established.

Table 3 lists statistics of geometrical dimensions and fiber orientation angles of composite laminates. The width W_1, end distance L_2, edge distance W_2, hole diameter D as well as ply thickness t_{ply} are assumed to follow a normal distribution. The means and standard deviations of each random variable are assumed according to the nominal values as well as ASTM D 5961 and 3σ principle, respectively. Moreover, fiber orientation angles are presumed to be normal distributed with a standard deviation of 0.9 [35–37]. Concerning the fastener, only the bolt diameter is considered to be random, which is always consistent with the hole diameter of composite laminates to remain a perfect fitting state. It should be noted that all geometrical dimensions and fiber orientation angles in Table 3 are mutually independent.

As regards the material properties, the micro-level and macro-level based methods are widely utilized to obtain their statistics. The former combines a selected micro-mechanical model with