Composite Structures 108 (2014) 915–923

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

A progressive damage analysis based characteristic length method for multi-bolt composite joints

Jianyu Zhang [a,*], Fengrui Liu [a], Libin Zhao [b], Yuli Chen [a], Binjun Fei [a]

[a] Institute of Solid Mechanics, Beihang University, Beijing 100191, PR China
[b] School of Astronautics, Beihang University, Beijing 100191, PR China

ARTICLE INFO

Article history:
Available online 25 October 2013

Keywords:
Progressive damage model
Characteristic lengths
Multi-bolt joints
Strength prediction

ABSTRACT

A progressive damage analysis based characteristic length method (PDA-based CLM) with only unidirectional layer properties required is proposed to predict the failure of composite multi-bolt joints. This method absorbs the convenience of the CLM on predicting failure of multi-bolt joints and introduces the PDA to obtain the characteristic lengths, which avoids time-consuming and expensive characteristic length tests. Meanwhile, only two simple and universal structures, an open-hole laminate and a single-bolt joint, instead of complex multi-bolt joints, are conducted by the PDA, which provides positive advantages for prediction accuracies and escapes from unbearable time consumption due to large amount of numerical iterations. Two progressive damage models (PDMs) which are composed by in situ strength, Hashin or modified Yamada–Sun criterion and Camanho's degradation rules are recommended. Static tensile tests of multi-bolt joints were also carried out. Although the final failure load errors of multi-bolt joints predicted by the method proposed are over-conservative, further schematically designed error transfer analysis discloses the errors are mainly caused by the CLM itself. In fact, the errors induced by the numerical characteristic lengths are no more than 4%, which suggests a good prospect of the proposed method in engineering.

1. Introduction

Advanced carbon fiber reinforced composites have broad application prospects in aerospace and navigation fields due to their high strength-to-weight ratio and high stiffness-to-weight ratio. For most composite structures composed by different parts, especially for primary structures, mechanical joints are really necessary because they are able to be dismantled and detected conveniently and have capacity of carrying and transferring high loads. However, mechanical joints are usually weak points in structures and thus their failure predictions have drawn significant attention of many researchers [1–5]. Studies show that the failure behaviors of mechanical joints can be affected by many design parameters, such as the geometric dimensions and stacking sequence, which leave expansive design space for joints but meanwhile enormously increase experimental cost. Therefore, an efficient numerical approach on failure predictions of mechanical joints is highly required in structural analyses and designs.

Characteristic length methods (CLMs) [6,7], such as characteristic curve method [7], characteristic point method (CPM) [6,8,9], and corresponding modified method [10–13], are of widespread use for failure analyses of mechanical joints in industry. The core of these methods is the characteristic length, which is first proposed for open-hole laminates by Whitney and Nuismer [6] as a kind of material properties determined by experiments. To predict bearing failure of joints, Chang et al. [7] proposed a concept of compressive characteristic length, which could be obtained by tensile tests of pin loaded laminates. However, in further researches, Chang et al. [14] found that the characteristic lengths changed with the hole-diameter D, the ratio of width-to-hole-diameter (W/D) and the stacking sequence. Moreover, Kweon et al. [13] indicated that W/D had a higher impact on tensile characteristic length and the ratio of edge-to-hole-diameter (E/D) had a greater influence on compressive characteristic length. Similar effects were found by Nuismer and Labor [15,16] and Pipes et al. [17]. Consequently, characteristic length is considered as a function of the parameters D, W/D, E/D and stacking sequence. Thus, due to the dependence of the characteristic lengths on the geometric characteristics and the stacking sequence, expensive and time-consuming characteristic length tests are required for the design and failure prediction of multi-bolt joints, which extremely limits the increasing applications of CLMs in engineering, especially for the initial stage of design, during which no abundant test data are accumulated.

In order to save cost and improve efficiency, Kweon et al. [13] redefined the characteristic lengths with the concept of average

* Corresponding author. Tel.: +86(0)10 82338663; fax: +86(0)10 82339228.
E-mail address: jyzhang@buaa.edu.cn (J. Zhang).

0263-8223/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruct.2013.10.026

stress and further proposed a new method to determine the new characteristic lengths without tests. Different from Kweon's idea, in this work, a numerical method to determine the characteristic lengths with only unidirectional layer properties is presented by using the progressive damage method.

Progressive damage method is effective to predict failure loads and modes of different composite structures with only available unidirectional layer properties. For different geometric configurations, load levels, constraint conditions, and material systems, etc., a suitable progressive damage model (PDM) is required to be established and verified. Once it is established, the PDM can be used to predict the failure of similar structures with various geometric dimensions and stacking sequences, which is an overwhelming advantage and can greatly spread the application of progressive damage method. Recently, many PDMs have been developed for failure predictions of mechanical joints. For example, Chang et al. [18,19], Tan [20] and McCarthy et al. [21] developed various acceptable PDMs for open-hole laminates. Shokrieh et al. [22], Tserpes et al. [23,24], Dano et al. [25], Camanho et al. [26] and Hühne et al. [27] modified PDMs for single-bolt joints with different failure criteria and material degradation rules. The PDMs show good capability to provide the damage onset and propagation and forecast accurate failure strength and failure modes for the open-hole laminate and single-bolt joint.

In this work, in considering of advantages and disadvantages of both the CLMs and progressive damage method, a PDA-based CLM is proposed to predict the failure of composite multi-bolt joints, in which PDA instead of static experiments of the open-hole laminate and single-bolt joint are carried out to determine the characteristic lengths, and the convenient and simple CPM is adopted to predict the failure of multi-bolt joint. It performs the PDA of simple and universal unloaded- and loaded-hole laminates instead of complex multi-bolt joints, which can not only provide a universal strategy for characteristic length determination obviating expensive and time-consuming experiments, but also significantly reduce the calculation scale and computation time. Different factors, including material strength parameters, failure criteria and material degradation rules, are combined to establish suitable PDMs for the open-hole laminate and single-bolt joint. Meanwhile, characteristic length tests are performed to validate the PDMs. Furthermore, the ultimate failure loads and failure modes of two- and four-bolt joints predicted by the proposed method as well as the conventional test-based CPM are compared with the experimental outcomes. The PDA-induced error for characteristic length calculations and its influences on the failure prediction of multi-bolt joints are discussed.

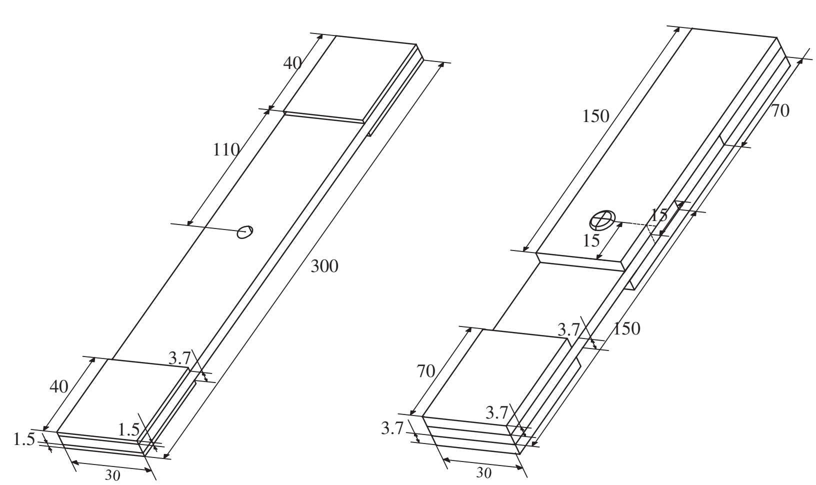
2. PDMs for the open-hole laminate and single-bolt joint

2.1. Key factors for PDMs

Various PDMs combined by different failure criteria, material degradation rules and strength parameters have been established to adapt for different composite structural problems [18–28]. Thus, in this work, some commonly used failure criteria, material degradation rules and different strength parameters are briefly surveyed, compared and analyzed to obtain suitable PDMs for the open-hole laminate and single-bolt joint.

The failure criterion is one of the most important factors in PDMs. It attracts enormous attention and provokes a world-wide failure competition [30]. According to researches, no failure criterion can perfectly predict all of the failure mechanism of arbitrary structures, and more often one failure criterion is just suitable for a certain structure with specific failure mechanisms. Two types of failure criteria, Hashin type failure criteria [21,23,25,26] and the Yamada–Sun failure criterion [12,13,18,19,28], are widely used in the failure analysis of composite bolted joints. The former include Hashin failure criterion [29] and various Hashin failure criteria, which are deemed to be amongst the best approaches by many researchers (Camanho et al. [26], McCarthy et al. [21], Tserpes et al. [23] and Dano et al. [25], etc.), due to their prominent capabilities to detect failure and distinguish failure modes in the context of elastic damage mechanics [31]. Yamada–Sun failure criterion [28] is another popular criterion to predict the composite bolted joints. Meanwhile it is the most commonly used one in CLMs [12,13]. A modified Yamada–Sun criterion with satisfied predictions was developed and implemented in the PDM presented by Chang et al. [18,19]. In this work the Hashin failure criterion [29] and modified Yamada–Sun failure criterion [19] are adopted and discussed.

Material degradation model is another focus of PDMs. Considering different failure modes in composite structures, Chang et al. [18,19] first presented varied degradation rules for different failure modes, in which additional shape parameters were required but difficult to be obtained. Based on Chang's degradation rules, Shokrieh [22] and Tserpes et al. [23,24] adopted complete degradation model, which directly reduced the corresponding stiffness to be zero. However, Camanho et al. [26] proposed a series of



(a) Open-hole laminate (b) Single-bolt joint

Fig. 1. Configurations and dimensions of characteristic length specimens (Unit: mm).