Composite Structures 132 (2015) 1–11

Contents lists available at ScienceDirect

Composite Structures

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

Design-oriented strength of mechanical joints in composite laminate structures and reliability-based design factor

Masahiro Nakayama [a,*], Nobuhide Uda [a,1], Kousei Ono [a,1], Shin-ichi Takeda [b], Tetsuya Morimoto [b]

[a] Department of Aeronautics and Astronautics, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan
[b] Japan Aerospace Exploration Agency, 6-13-1 Osawa, Mitaka-shi, Tokyo 181-0015, Japan

ARTICLE INFO

Article history:
Available online 2 May 2015

Keywords:
Composite material
Mechanical joint
Design
Strength
Bearing test

ABSTRACT

Mechanical joints may act as bottlenecks in the design process of composite structures. Fitting factors need to be multiplied with the applied load condition to assure reliability. For more efficient design, this paper proposes a brand-new design-oriented strength: knee point strength for the mechanical joints in composite laminates. The knee point strength is derived from the stiffness change rate for the bearing stress–strain behavior in a bearing test. The strength can be correlated with the internal bearing damage; this is verified by micrography about the bearing test specimen and finite element analysis. The probabilistic design and analysis method was applied to acquire the reliability-based fitting factor. An approach combining finite element damage analysis and a stochastic technique was adopted to analyze the probabilistic properties for the design-oriented strength of the bolted joints in CFRP laminates. The probabilistic and deterministic designs were compared and discussed. Then a proper value of the fitting factor was proposed.

1. Introduction

Applications of advanced composite materials such as carbon-fiber-reinforced plastics (CFRPs) are expanding in not only the aerospace industry but also other industries because of their high specific strength and stiffness, good fatigue resistance, etc. However, composite materials generally have more scattering properties than conventional metallic materials. Therefore, the "design tolerance," which is the material strength used in structural design processes, is reduced. The tolerances for composite materials need to be set low because of the large variation in their strength properties. In addition, there is much less experience with using composites as structural materials than with metals. Therefore, structural designs that use composite materials tend to be conservative.

One example of conservative structural elements is mechanical joints. Composite-made joints have often been the subjects of many studies both experimentally and analytically [1–9]. In actual applications, mechanical joints are commonly used to assemble structural components; they are necessary because they allow re-access to internal structures and easy replacement of damaged components. They can be critical to strength assessment of the structure because of the stress concentrations their opening holes induce. ASTM standard D 5961 [10] defines the bearing strengths under high loads, which corresponds to the ultimate load state. The testing standard does not define the strengths under relatively low applied loads, which correspond to the limit load state.

The "fitting factor" is a design factor with regard to airworthiness [11]; it is multiplied with external loads separately from the safety factor. The fitting factor is greater than or equal to 1.15 [11]. However, the value for joints in CFRP laminate structures should be higher than 1.15 because of the previously noted uncertainty and lack of empirical knowledge. Therefore, more reasonable definitions for the design strength and a suitable design factor are desirable for efficient design of mechanical joints in CFRP structures.

This paper proposes a brand-new design-oriented strength for mechanical joints in composite laminates and a reasonable design factor for the joints. Two approaches are adopted. Knee point strength F_{KP} is a design-oriented strength based on an experimental approach. The strength is acquired by focusing on stiffness reduction during bearing behavior, which is unfavorable for actual structures. Former researches about the bearing strength [2,12,13] seem that they focus on nonlinearity of bearing load-displacement relationship. Our research related the nonlinearity, especially in the early steps in the bearing curve, to internal damages in the

* Corresponding author. Tel./fax: +81 92 802 3036.
E-mail address: mshrnkym@kyudai.jp (M. Nakayama).
[1] Tel./fax: +81 92 802 3036.

http://dx.doi.org/10.1016/j.compstruct.2015.04.044
0263-8223/

bearing-loaded specimens. We developed a method to identify the starting point of the stiffness reduction, which would be used as a criterion for the limit stress, defined as the stress generated in the composite joint when a limit load is applied to the structure [14].

This study utilized micrography and damage propagation analysis by finite element method to reveal the relationship between the internal bearing damage and the stiffness reduction.

The second analytical approach sets the fitting factor based on the reliability of the joint. To obtain greater efficiency in the design of structures made from composites, attempts have been made to introduce a probabilistic or reliability-based design method [15–17]; this is generally called the probabilistic design and analysis (PDA) method. This method optimizes structures on the basis of their probability of failure or reliability; it should be able to avoid too conservative designs and more fully utilize the good mechanical properties of composite materials. Damage propagation analysis using the finite element model to calculate F_{KP} was combined with the Monte Carlo method to estimate the stochastic properties of the design strength. Allowable stresses by probabilistic and deterministic designs were compared, and the probabilistic one was translated into the form of fitting factor. The PDA method can be used for providing reasonable fitting factors for composite structures.

2. Experimental

2.1. Bearing test

The bearing test is a standard method for evaluating the properties of composite joints. Fig. 1 shows a simplified image of the test and a photograph of an actual system. The CFRP specimen had a fastener hole, and a bearing load was applied through the fastener. Extensometers were equipped on both edges of the specimen to measure relative displacements between the specimen and testing jig. In this study, Toray T800S/3900-2B [18,19] prepreg was used to fabricate the laminates. The composite laminate

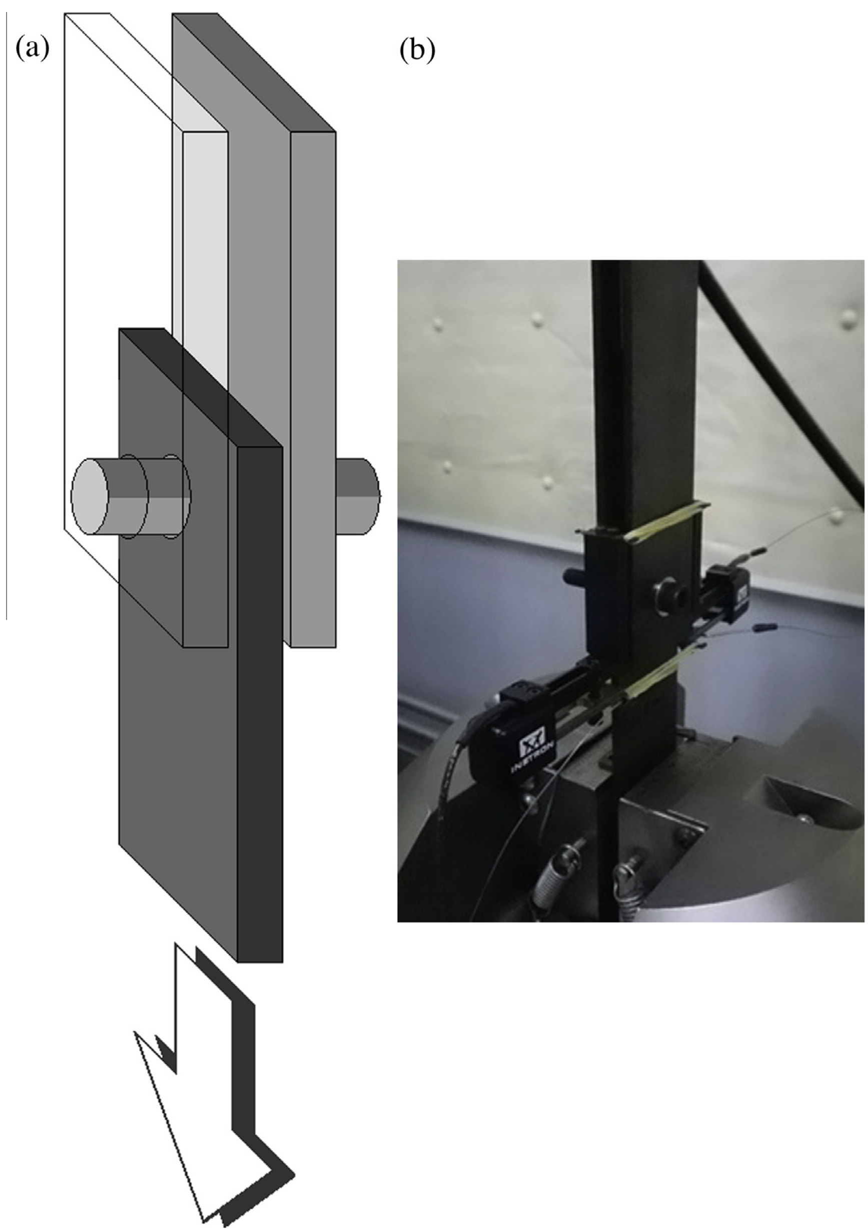

Fig. 1. Schematic and actual photograph for the bearing test. (a) Schematic for bearing test. (b) Actual photograph.