International Journal of Fatigue 32 (2010) 72–81

Contents lists available at ScienceDirect

International Journal of Fatigue

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

Bearing damage evolution of a pinned joint in CFRP laminates under repeated tensile loading

Satoshi Seike [a,1], Yoshihiro Takao [b,*], Wen-Xue Wang [b], Terutake Matsubara [b]

[a] *Kyushu University, Department of Aeronautics and Astronautics, 6-1 Kasuga Park, Kasuga, Fukuoka 816-8580, Japan*
[b] *RIAM, Kyushu University, 6-1 Kasuga Koen, Kasuga, Fukuoka 816-8580, Japan*

ARTICLE INFO

Article history:
Available online 15 February 2009

Keywords:
Fatigue
Pin joint
CFRP
Critical damage
Critical condition

ABSTRACT

A mechanical pinned joint in the CFRP laminates such as $[0/\pm45/90]_{3S}$, $[90/\pm45/0]_{3S}$, $[0/\pm45/90]_{2S}$ and $[90/\pm45/0]_{2S}$ is loaded statically and cyclically to finally obtain the critical condition for fatigue. It is derived that in the static loading, the critical damage that yields shear matrix crack is kink and the critical condition to the final failure is the appearance of kink in every inner 0° layer and that in the fatigue loading within the moderate load, the critical damage that yields shear matrix crack is almost always kink-like damage along the collapse front and at high load it is rather kink. Next, the non-elastic elongation of a joint at the maximum load subtracted by the one at 10th cycle is focused on and its capability is figured out for various stacking sequences. The critical value U_{NE,F^*} for the elongation rate change to the final fatigue failure is around 50–65 μm in the present material. The critical condition to the final fatigue failure and corresponding to U_{NE,F^*} is roughly the appearance of mostly kink-like damage in every inner 0° layer.

1. Introduction

Carbon fiber reinforced plastics (CFRP) that have high specific strength and stiffness have been widely used as secondary structures and will be used more and more as primary structures of various sized aircrafts. Structures usually need joints and a mechanically fastened joint in CFRP laminates is necessary due to its advantages in inspection, replacement and reliability, even though it has disadvantage in stress concentration. There are three main macroscopic failure modes [1–6] of a mechanical joint as shown in Fig. 1. In the present study the bearing mode is focused on, since it has high strength and toughness, and the mechanical joint is designed to make it occur.

Hart-Smith [7] discussed the geometrical condition for bearing failure mode and requested both W/D and E/D to be more than five, where W, D and E denote the specimen width, hole diameter, and distance between end edge and hole center, respectively. The failure mechanism of a joint was also investigated under static loading. It is quite complicated since there are many design parameters such as stacking sequence, geometry, number of pins, material and torque force of washers [8–10]. There are two main approaches to solve this complicated problem. One is a numerical simulation [11] and the other is a microscopic investigation of damage evolution [4,10,12]. Wang et al. [4] reported the bearing failure of a pinned joint and attributed it to matrix crack, delamination, fiber kink, and other factors. Camanho and Matthews [10] conducted bolted joint tests and examined the damage evolution in tension, shear-out, and bearing modes. Furthermore, Hirano et al. [12] reported the bearing failure mechanism of a pinned joint for both $[0/\pm45/90]_{3S}$ and $[90/\pm45/0]_{3S}$ CFRP laminates and arrived at the conclusion that a critical damage to the final failure was kink.

Fatigue tests of a bolted joint in composite laminates were performed by Smith and Pascoe [13]. It was presented that bolt torque was an important parameter and the damage was small when the clamping force of a bolt was large. There are few studies on the failure mechanism of fatigue. Recently the damage morphology of a pinned joint in CFRP laminates was focused on and its difference between static and fatigue loading cases was studied [14], and damage evolution was discussed in detail [15], which are mentioned briefly in the following section.

In this study tensile cyclic load is applied to a mechanical pinned joint to derive the critical condition to the final failure and effects of parameters such as the maximum load and number of stacked plies are also studied. In the tensile test the stroke speed is constant and the maximum load is a dependable guide to the critical condition, while the maximum load is constant in fatigue and the stroke speed change becomes an alternatives. Thus, the displacement of a pin joint is measured precisely by a laser displacement meter with accuracy of up to 1 μm, the non-elastic elongation of a pin joint hole is obtained, and the elongation rate change is used to discuss the critical condition in fatigue, which is a key item of the present paper.

---

[*] Corresponding author. Tel.: +81 92 583 7756; fax: +81 92 583 7760.
E-mail address: ytakao@riam.kyushu-u.ac.jp (Y. Takao).
[1] Present address: Composite Materials Research Laboratories, Ehime-plant, Toray Industries Inc., Japan.

0142-1123/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijfatigue.2009.02.010

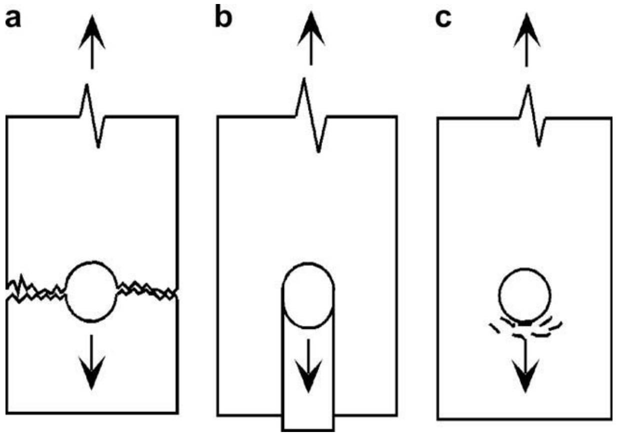

Fig. 1. Failure modes of a mechanical joint.

It is noted here before closing this section why a pinned joint without clamping torque is studied. A bolted joint with clamping torque should be investigated for the practical and useful technical information, and the future final goal is to discover the identity and difference in failure mechanisms of a bolted joint between under static and fatigue loading. However, the clamping torque of a bolted joint causes frictional shear stress, which is supposed to complicate the failure mechanism and conceal the intrinsic difference between fatigue and static failure. Thus, a simple joint without clamping torque is admirably adapted here.

2. Overviews of damage analysis of a pinned joint with a full-circular-hole [14–16]

2.1. Static tests [14,16]

Failure mechanism of the static case was clarified by using a new monitoring technique developed by Hirano et al. [12], who performed comprehensive study with a half-circular-hole specimen under static loading condition. However, there is the difference from the mechanical point of view between half and full-circular-hole specimen, since the latter has a ligament part to support the axial load and the former does not. Thus, microscopic damages of a full-circular-hole joint were studied for both $[0/\pm45/90]_{3s}$ and $[90/\pm45/0]_{3s}$ CFRP laminates. Schematic figures and photographs of $[0/\pm45/90]_{3s}$ are shown in Fig. 2a and b, respectively, where C, D, K, KC and M denote collapse, delamination, kink, kink-like damage along the collapse front and shear matrix crack, respectively. It was confirmed that (1) in the 0° layers the in-plain bending damage called as collapse here appears at various loads and collapse has small direct relation to the final damages (2) at $0.95P_{UTS}$ collapse and delamination exist (3) at P_{max} kink appears at most of inner 0° layers and the end of kink yields frequent delaminations and few shear matrix cracks and (4) at the final stage shear matrix cracks from kink appear and develop together with the development of delaminations. It was concluded that kink is the critical damage and its appearance at almost all inner 0° layers becomes the critical condition to the final failure. At $0.95P_{UTS}$ and P_{max} the kink-like damage explained in the next section is sometimes observed at the front of a developed collapse in the inner 0° layers near the surface. Here, P_{UTS}, P_{max} and the final stage mean the average strength of P_{max}, practically the maximum load [12] of the tested specimen and the stage where the load is decreased after P_{max}, respectively.

The definition of collapse and kink used in this paper is noted here. Collapse is defined here as bucking failure of fibers of 0° layers at the loaded surface edge that bears not only the compressive force but also the transverse force originated from the frictional shear force between pin and hole surface. This in-plain friction leads to the in-plain bending moment. The surface 0° layer suffers from the out-of-plain bending moment due to the small bending deformation of a pin. On the other hand, kink is defined ideally as the buckling failure of the 0° layers under pure compression away from the contact surface edge and thus accompanies the intact or nearly intact zone between (mostly collapsed) contact surface and itself. That is, the ideal kink is characterized by the intact zone.

Several damages such as C, K and KC are observed in a single layer. At the top of each schematic figure and following cross

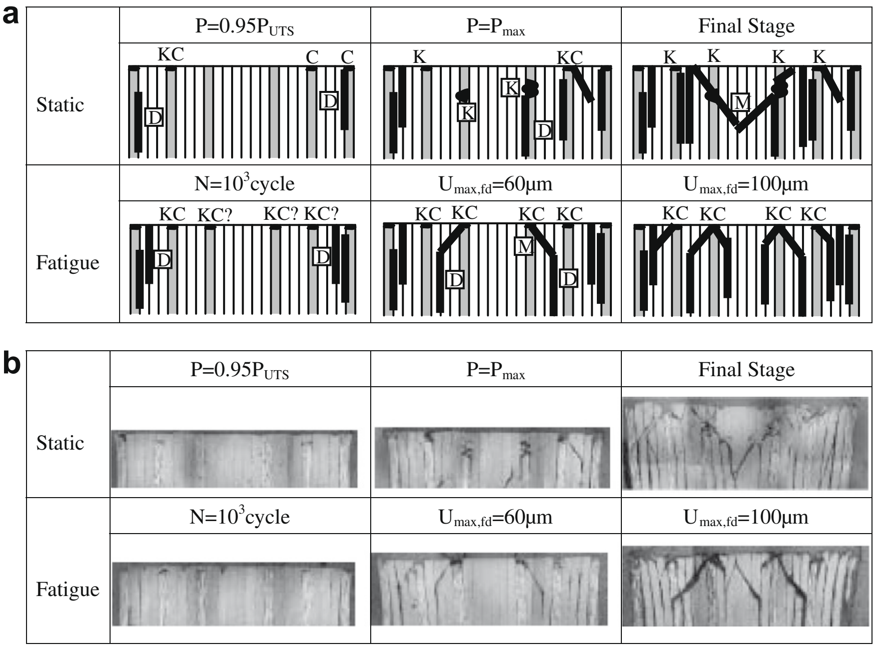

Fig. 2. The difference of damage evolution between static and fatigue conditions in 3S0: (a) schematics and (b) photographs.