Composite Structures 196 (2018) 76–88

Contents lists available at ScienceDirect

Composite Structures

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

An experimental study on mechanical response of single-lap bolted CFRP composite interference-fit joints

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ARTICLE INFO

Keywords:
Composite joints
Mechanical response
Interference-fit size
Tightening torque
Stacking sequence

ABSTRACT

This paper reports an experimental study on mechanical response of single-lap bolted composite interference-fit joints in their entire life span. Particular focus was given to interface behavior, bearing response, strain distribution and out-of-plane deformation under varying multiple parameters including interference-fit percentage, tightening torque and stacking sequence. The 3D digital image correlation system was used to characterize development of strain concentration and deformation. Microscopy studies on coupled interface and bearing plane were conducted to understand the damage mechanism. It's found that the bolt-inserting can act as cold expansion which facilitates forming tightly coupled interface and prohibits inclination of bolt. The linear phase of stress-strain behavior is prolonged by tightening torque which inhibits delamination growth in bearing plane, induces friction force to balance external load and postpones bolt-to-hole bearing action. The strain around the hole goes through a switch from release of residual pressure on tensile side to squeezing on bearing side. During the switch the interface keeps tightly coupled without delay in load take-up. Strain concentration bands were observed in the joints with highly anisotropic laminates, whereas it is localized around bolt-hole in quasi-isotropic laminates. The joint structure possesses its own response characteristics which are beyond extrapolation from ply properties.

1. Introduction

As high performance carbon fiber reinforced polymer (CFRP) composites are increasingly utilized in airframe structures, the need for reliable and efficient load-carrying joints becomes imperative [1]. Commonly the airframe components are assembled by mechanically fastened joints [2], among which the interference-fit has been shown to improve the mechanical performance by alleviating the magnitude of local oscillatory stresses [3] and has been applied in metal materials for decades [4]. However, when the interference fit technology is used for the assembly of composites, the discrepancy of material properties in such joints would cause unexpected consequences. Owning to material brittleness, the CFRP composites in joint structures cannot redistribute local high stresses by yielding as ductile metals do [5]. The bolt-hole undermines the integrity of fibers [6] and causes potential weak spots in composites [7]. Furthermore, the material anisotropy complicates the stress behavior around the bolt-holes [8]. All these problems would cause premature failure to the joint structure and limit its safe and efficient application. In order to drive the maximum benefit of interference-fit joints in composites, a comprehensive understanding of their mechanical response is essential.

A number of studies have attempted to establish the knowledge base for application of composite bolted joints including specimen preparing, bolt installing, tightening and loading [9]. As for joint specimens preparing, the laminate fabricating, ply-orientation, specimen geometry and bolt-hole making are often the issues. Previous work shows that vacuum infusion processed GFRP joint samples promote better fatigue life improvement than hand lay-up specimens [10]. Stacking sequence [11,12] along with edge-distance to pin ratio (e/d) and width to pin ratio (w/d) [13,14] affects the failure mode and joint strength, whereas bearing strength was more sensitive to e/d than w/d ratio. The cold expansion process is an effective anti-fatigue manufacturing technology for metal joints, but it requires further investigation in composites [15].

The primary goal for the interference-fit joining is to achieve a uniformly distributed residual stresses around the bolt-hole with minimal scraping damage. An analytical solution based on Lekhniskii's complex potential theory was proposed to determine the stress and strain around the bolt-hole and the results agreed well with FE method when no damage is considered [8]. While by virtue of micro-scale fiber

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https://doi.org/10.1016/j.compstruct.2018.05.016
Received 8 December 2017; Received in revised form 30 March 2018; Accepted 2 May 2018
Available online 03 May 2018

Table 1
Elastic properties of employed materials.

Composite materials	E_1 (GPa)	E_2 (GPa)	G_{12} (GPa)	υ_{12}	X_t (MPa)	X_c (MPa)	Y_t (MPa)	Y_c (MPa)	S (MPa)
CFRP lamina	120.0	8.0	4.5	0.25	1803	1194	55.6	200.1	96.7
Metal materials	E (GPa)			υ	σ_b (MPa)		σ_s (MPa)		Δ (%)
Titanium (bolt and nut)	112			0.29	931		862		10
Steel (flat washer)	210			0.30	900		1200		10

damage induced by large interference-fit size, strains measured at peak points in the pin inserting test of Ti-alloy bolt on GFRP lap were 50% lower than that form numerical method [13]. The damage evolution of the hole during the inserting process in meso-scale and macro-scale has been modeled numerically with local representative volume elements (RVEs) [16] and user defined subroutine (USDFLD) together with Hashin failure criteria [17], respectively. By degradation of material properties it yielded similar failure modes as microscopy of the hole surface.

The main concern associated with composite joints is the bearing performance, which is often evaluated by bearing response tests [18]. The pin-loaded tests have been employed to estimate the bolt-to-hole fit type on bearing behavior, and it turned out that clearance-fit caused high compressive stress in the bearing area [19,20], whereas interference-fit can effectively reduce the peak circumferential stresses around the hole and improve bearing strength [21,22]. The nonlinear contact analysis in 3D FE model performed by Pradhan et al. [3] revealed that for each material combination in composite joints, there existed an optimal interference-fit percentage for best load carrying capability. In practical use, composite joints are often exerted with tightening torque to provide extra lateral support [2]. The tightening process was proved to help improve optimum bearing performance in double-lap, single-bolted joints [23,24] and achieve a more evenly distributed load in multi-bolt joints [25]. Besides, the clamping force induced by tightening torque also altered the mechanism and sequence of failure in bolted joints of composite laminates [26]. Recently, Giannopoulos et al. [27] summarized the recent progresses in the strength and damage tolerance characteristics of torque-tightened, bolted composite joints and their application aspects in airframe design, airworthiness certification requirements and current design airframe lifespan.

In addition, the effects of interference-fit size [28,29], applied stress ratio [28,30], and clamping torque [27,29] on fatigue performance of composite joints have been studied to provide necessary knowledge base for joint design. Currently the interference-fit titanium inserts are employed as a new repair solution of high joint efficiency for damaged holes [31], and the interference-fit sleeve bolts are also widely used for lightning strike protection [32].

While the previous studies related to interference fit concentrated on bolt inserting and loading separately, the damage characteristics of connecting interface and their effects on subsequent bearing behavior are rarely reported. Besides, pin-loaded or double-lap composite joints with clearance-fit under applied bolt torque were the focus in the majority of the former literatures, whereas most skin-structure are singlapped joints [20,33] and the out-of-plane deformation induced by eccentric load path haven't got enough attention. Moreover, the combined interactive mechanism of interference fit and tightening torque on complex strain and loading response remains inadequate.

These facts have led the authors to the focus of the current research, which involves a systematic experimental study on mechanical response of composite interference-fit joints in their life span. Particular attention was paid to the characteristics of connecting interface, bearing response, local strain distribution and out-of-plane deformation under various interference-fit percentages, tightening torques, stacking sequences and their combined or interactive effects. It is hoped the findings reported here will help to provide some guidance for design and application of the interference-fit joint in composites.

2. Experimental approach

2.1. Material and specimen preparation

The composite materials were manufactured by Guangwei Composites Co., Ltd., China using vacuum bag molding process. Unidirectional carbon fiber prepreg USN20000 with a thickness of 0.2 mm per ply was used as reinforcement, and unsaturated polyester resin 7901 was used as matrix. Three types of typical stacking sequences were designed, namely quasi-isotropic (QI) lay-up $[90/\pm45/0]_{2s}$, angle-ply (AP) $[\pm45]_{4s}$, and cross-ply (CP) $[0/90]_{4s}$. Note that all the laminates have a thickness of 3.2 mm with 16 plies. The volume fraction of carbon fibers was 56.3% and the mass fraction was 67%. The material properties of the lamina are presented in Table 1.

The geometric configurations of composite joints with protruding head (PH) and countersunk head (CH) bolts are shown in Fig. 1a and b, respectively. All joints were designed with the same w/d ratio of 6 and e/d ratio of 3 to ensure bearing failure according to Effect of the clearance and interference-fit on failure of the pin-loaded composites D5961 Standard [18]. The composite coupons were cut by water-jet dissector to ensure their identical geometry sizes. Steel plates were used as doublers on the specimens. The bolts and self-lock nuts were aerospace grade titanium alloy interference-fit fasteners supplied by Oriental Bluesky Titanium Technology Co., Ltd., China. Steel flat washers were employed to increase clamping region and to avoid surface wear on CFRP when exerting tightening torque. The properties of fasteners and washers are also given in Table 1.

2.2. Interference-fit size and tightening torque

In order to create interference-fit in composite specimens, the titanium alloy bolt with a standard size was installed into undersized holes. The interference-fit size (or percentage) is defined by:

$$I = \frac{D-d}{d} \times 100\% \tag{1}$$

where d is the bolt-hole diameter and D is the bolt shank diameter.

The nominal interference-fit sizes chosen for the research were 0.5%, 1.2% and 2.1%. Since the standard diameter of the bolts was 6.000 ± 0.010 mm, the corresponding bolt-holes in CFRP specimens were 5.970 mm, 5.929 mm, 5.877 mm in nominal diameter, respectively. The desired dimensions of bolt-holes were achieved by drilling and reaming operations to attain a precision of ± 0.004 mm. In order to achieve the designed interference-fit sizes, the diameters of bolts and holes were measured with digital micrometer and plug gage and then selectively fitted. That is, for each level of interference-fit size the bolts under the nominal size within the tolerance are selected to connect the corresponding holes under the nominal size, and it is the same with the bolts and holes above their nominal sizes. By means of selection, the three real interference-fit strips are 0.34%–0.67%, 0.96%–1.36% and 1.92%–2.26%, respectively.