Composite Structures 187 (2018) 18–26

Contents lists available at ScienceDirect

Composite Structures

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

An enhanced spring-mass model for stiffness prediction in single-lap composite joints with considering assembly gap and gap shimming

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ARTICLE INFO

Keywords:
Spring-mass model
Joint stiffness
Assembly gap
Gap shimming

ABSTRACT

An enhanced spring-mass stiffness model was proposed, which was based on the supposition that the transverse shear stress under preload satisfies conical and spherical envelope, to predict the stiffness of the single-lap single-bolt composite joint with considering assembly gap and gap shimming. The validation experiments were conducted for different configurations. It shows that the analytical results were all in good agreement with the experimental results. Meanwhile, experimentally validated finite element model was used as an assistant validation in consideration of convenience and cost saving. The presented analytical model was then used for parameter studies, including gap size, gap radius and shim thickness. The major conclusions are: 1) as gap size increases 0.1 mm, the shear stiffness decreases about 1.1%; 2) the shear stiffness quickly becomes zero when the gap radius exceeds the boundary of the highly stressed portion; 3) shim thickness has much greater influence on the bolt stiffness than on the shear stiffness.

1. Introduction

The spring-mass method has been developed by many researchers to predict the composite joint stiffness, which shows good cost-effectivity and convenience. It was firstly proposed by Tate et al. [1] to study isotropic joints, which has been modified by Nelson et al. [2] to account for the single-lap orthotropic composite joints. After that, McCarthy et al. introduced the bolt-hole clearance [3] and shear stiffness of the joints under highly preload [4] into the spring-mass model. To describe the secondary bending stiffness for single-lap joints, Nelson et al. [2] proposed an experimental formula with coefficient β, which has been widely used [3–6], while Olmedo et al. [7,8] proposed an enhanced method based on the classic beam theory, which considers geometrical parameters, material properties, load path eccentricity, and stacking sequence. Meanwhile, an improved spring-mass method that combined the spring-mass method and finite element (FE) method was proposed by Xiang et al. [9], which was more time efficient than traditional spring-mass model. However, the existing spring-mass method has not been extended to the stiffness prediction for the composite joints with considering assembly gap or gap shimming.

The assembly gap is a big issue during the assembly process because the shape distortion problems of the composite parts are hard to be settled so far [10–13]. The assembly gap has an influence on load transfer and assembly-induced-stress, even assembly-induced-damages [14–16]. Therefore, gap shimming methods are common used in aerospace industries to compensate the gap between the composite assembly parts [17,18].

Experiments and numerical method are major methods to investigate the stiffness of the joints with shimming materials currently. Hühne et al. [19] investigated the effect of the shim thickness on the behavior of the single-lap single-bolt composite joints by both experiments and numerical method. And it was reported that the joint stiffness decreases as the shim thickness increases. In Liu's studies [20,21], effects of the liquid shim and substrates stiffness on multi-bolt single-lap composite-titanium joints were evaluated mainly by numerical method. The results showed that the maximum load, joint stiffness and design load of the joints decrease as the shim thickness increases; furthermore, it was mentioned that the shim layer significantly generates lower effect on the stiffness of the joint as the substrates become stiffer. The single-lap joints considering the shimming materials were also studied by Dhote et al. [22]. It was stated that the secondary bending effect was magnified by the shim layer because the shim layer increased the geometric eccentricity of the load path and induced a higher magnitude of bolt tilting. Similar results were also reported in literature

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https://doi.org/10.1016/j.compstruct.2017.12.041
Received 9 May 2017; Received in revised form 27 November 2017; Accepted 15 December 2017
Available online 16 December 2017

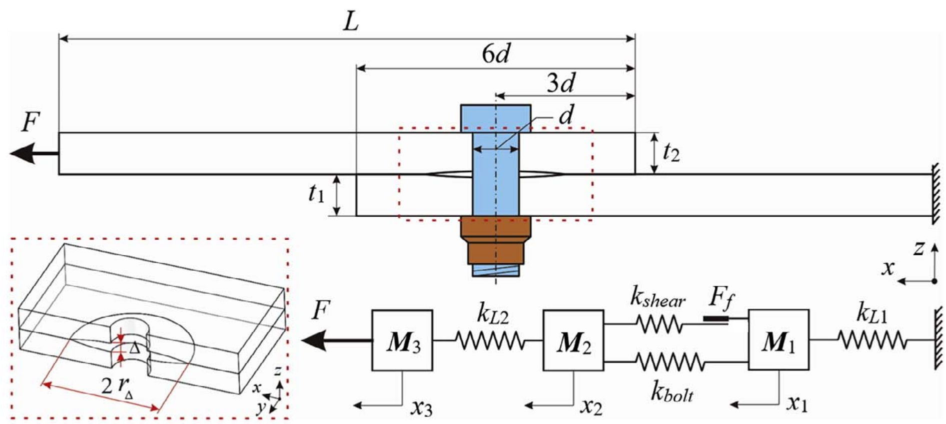

Fig. 1. Specimen of shimming joint and its spring-mass system model.

[23], in which an experimental study for single-lap single-bolt hybrid joint was conducted with considering the machined assembly gap. And the results showed that the specimen with solid shim gained a little better joint stiffness than that with liquid shim. However, for composite joint stiffness prediction with considering assembly gap or gap shimming, both experimental and numerical methods are cost expensive.

In this paper, an enhanced spring-mass model, which was an extension of Olmedo's model [7,8] considering the assembly gap and gap shimming, was proposed to predict the joint stiffness including shear stiffness [4] and bolt stiffness. The basic assembly gap shape was assumed as a circular ring. For arbitrary assembly gap shape, an equivalent method was proposed. Meanwhile, corresponding experiments and FE method were used to validate the present analytical model (AM). Finally, parameter studies were conducted to investigate the assembly gap size, gap radius and shim thickness.

2. Analytical model for joint stiffness

The single-lap single-bolt composite joint in Fig. 1, whose geometry sizes were set according to the ASTM D5961 [24], was utilized to investigate the effect of the assembly interface conditions on the joint stiffness. Taking the assembly gap with circular ring shape as an example, geometry of the assembly gap, including gap size Δ and gap radius r_Δ, was illustrated in the enlarged view in Fig. 1.

The specimen without assembly gap, named non-gap joint, was prepared according to the ASTM D5961 [24]. Whilst that with assembly gap (or shimming material), named gap joint (or shimming joint), was just modified at overlap region of the laminates.

In Fig. 1, F is the applied load; M_1 and M_3 are the masses of the lower and upper laminates, respectively, M_2 is the mass of the bolt; k_{L1} and k_{L2} represent the stiffness of the lower and upper laminates; k_{shear} is the shear stiffness of the laminates corresponding to the slope of the first linear region, while k_{bolt} is the bolt stiffness corresponding to the slope of the second linear region; $x_i (i = 1,2,3)$ represents the displacement along the loading direction for corresponding masses. The masses can only move in the x-direction, which leads to the dynamic equation as Eq. (1). Where $\mathbf{M}$, $\mathbf{K}$ are the matrices of the masses and stiffness, and $\ddot{\mathbf{x}}$, $\vec{\mathbf{x}}$, $\mathbf{F}$ are the vectors of the accelerations, nodes displacements, and applied loads.

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{K}\vec{\mathbf{x}} = \mathbf{F} \tag{1}$$

For quasi-static in-plane loading, the accelerations can be neglected so that Eq. (1) can be expressed as the following equation [4,7,8]:

$$\mathbf{K}\vec{\mathbf{x}} = \mathbf{F} \tag{2}$$

As illustrated in Fig. 2, there are three regions for typical load-displacement response of the highly torqued single-lap composite bolted joints before damage occurs, which are friction region, transition region and load take-up region [4,7,8]. The friction region, which is mainly

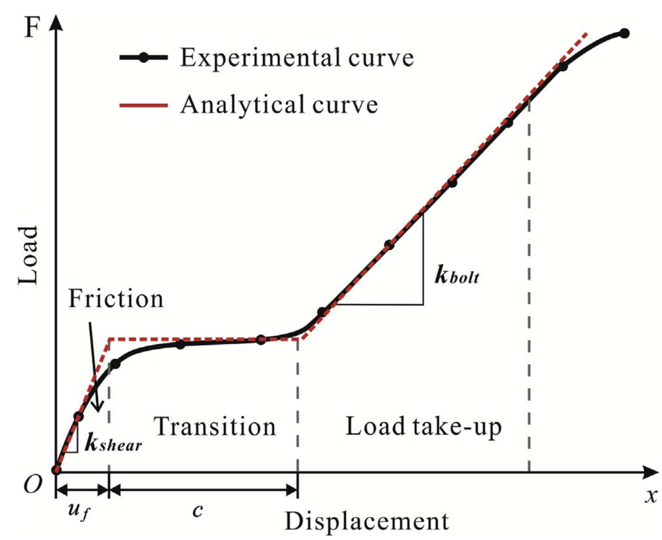

Fig. 2. Typical load-displacement response of the highly torqued single-lap composite bolted joints [7].

produced by friction force between the laminates, is determined by the shear stiffness k_{shear} and the friction force . The transition region is approximately equal to the bolt-hole clearance c [4], where displacement arises without any increase in load. After the transition region, it comes to the load take-up region, the bolt shank begins to contact the laminates and load can be transmitted by the bolt, which is mainly influenced by the bolt stiffness k_{bolt}.

At friction region, the linear equation is expressed by Eq. (3),

$$\begin{bmatrix} k_{L1} + k_{shear} & -k_{shear} & 0 \\ -k_{shear} & k_{shear} + k_{L2} & -k_{L2} \\ 0 & -k_{L2} & k_{L2} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ F \end{bmatrix} \tag{3}$$

the laminate stiffness k_{Li} can be calculated by Eq. (4) [4],

$$k_{Li} = \frac{E_{Li} \cdot W_i \cdot t_i}{p_i - d/2} \quad (i = 1,2) \tag{4}$$

where E_{Li} means the equivalent elasticity modulus in the longitudinal direction determined by composite laminate theory; W_i and t_i are width and thickness of the laminate, respectively; p_i is the distance between the hole center and the plate free end where load is applied; and d is hole diameter.

The shear stiffness k_{shear}, as the slope of the friction region, is the function of the shear stiffness of the laminates in series k_{sh-i} [7].

$$k_{shear} = \left[\frac{1}{k_{sh-1}} + \frac{1}{k_{sh-2}}\right]^{-1} \tag{5}$$