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A theoretical 4-stage shear model for single-lap torqued bolted-joint with clearances

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Abstract:

In this paper, a theoretical 4-stage shear model for a single-lap torqued bolted-joint with clearance is proposed. The deformation mechanism of the bolted-joint indicates that the contact status is the key factor for the nonlinearity of the load-displacement curve. On the basis of the contact status, the expression of this model and its parameters are proposed. Compared with the previous Tri-linear model, this model is improved on three aspects. First, the 1st stage of the model has been improved by using the partial slip theory. Second, an additional 2nd stage is considered for taking into account the asynchronous slip of the interfaces between components and between bolt head and component. Third, the 4th stage of this model is derived from the elastic foundation beam model and the Cai-Shan Liu's approximate contact model. Moreover, the 4-stage shear model is validated by 3-D detailed FE-models. The results show that the 4-stage model can correctly describe the shear behavior, especially the nonlinearity of the load-displacement curve in the 1st stage and the 4th stage. In addition, the effects of clearance and bolt length on the joint stiffness in each stage are presented.

Keywords: Composites; Bolted joints; Clearance; Preload; Analytical model.

1. Introduction

In industry and transportation, mechanical bolted-joints are widely applied in many structures assembled by composite components, which ensures the load transfer from one component to another. However, pin load transferred by bolt associates with a high stress concentration, which would lead to an easy failure of the bolt and its surrounding region. Therefore, under the shear loading, the estimation of pin load is critical to the security of the entire structure, which is usually studied by experiments, theoretical spring-based method [1-3] and finite element method (FEM) [4-6], respectively. The experiment has high authenticity and reliability, yet it has limited applications in the initial design due to the large consumption of time and money [7-9]. The theoretical spring-based method simplifies the components and bolts as a series of spring-mass structure and has a very high computational efficiency. Nonetheless, the spring-based method needs an accurate joint constitutive model and is limited to one-dimensional problem. Taken into account the preload on the bolt and the contacts between the components, the FEM can reliably simulate the behavior of bolted-joint with 3-D detailed finite element model (FE-model), but it is very expensive in both modelling and computing. For better computational efficiency, recently a reduced-element was developed to substitute the 3-D detailed bolt FE-model [10-13], which also requires an accurate joint constitutive model.

The bolted-joint structure contains numerous contact interfaces between bolt head and component, between bolt shank and bolt hole and between components, separately. The various contact statuses of these interfaces with respect to the external load make the shear behavior of the bolted-joint very complicated. The joint constitutive model was developed from a simple linear model to multilinear model. Originally, considering the contact interface between the bolt shank and bolt hole, Tate and Rosenfeld (1946) [14,15] simplified the bolt as a linear spring. They deduced a semi-empirical expression of joint stiffness for double-lap joint with isotropic materials. In their semi-empirical expression, the joint stiffness was associated with the shear and bending of bolt shank and the bearing of bolt shank and components. This semi-empirical expression was modified by Nelson et al (1983) [16] for single-lap joint with anisotropic materials. For the convenience of assembly, the clearance is usually designed between bolt shank and bolt hole, which will delay the increase of external load. The external load will be transmitted only after the clearance is taken up. McCarthy et al (2006) [16] proposed a Bilinear joint model considering the effects of bolt-hole clearance. This Bilinear model contains two stages. The first zero load stage corresponds to the elimination process of the clearance; the second linear stage corresponds to the load transmission process. Moreover, to account for the bolt-torque, McCarthy et al (2011) developed a Tri-linear joint model[17]. In the first Initial Quasi-linear stage, both the interface between components and the interface between component and bolt head firmly stick together because of the preload of bolt-torque. The external load is mainly transmitted by the static friction of the interface between components. In the second Transition stage, both the interface between components and the interface between component and bolt head completely slip, the clearance starts to be eliminated. The load would equal to the critical friction force. After the clearance is

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