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Experimental and numerical studies of bolted joints subjected to axial excitation

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A B S T R A C T

The dynamic behaviour of bolted joints subjected to axial excitation is investigated using experimental and numerical methods. Firstly, the amount of reduction in clamp force is found by experiments. In addition, the damage of threads is analysed using scanning electron microscope (SEM) and Energy Dispersive X-ray (EDX). Secondly, by changing the tightening torque, the amplitude of the axial excitation, and coating lubricant (MoS_2) on the threads, their effects on both the clamp load loss and the damage of threads are determined in experiments. It is found that the clamp force decreases rapidly in the early stage because of the cyclic plastic deformation, and then slowly because of fretting wear in the later stage. With the increase of the tightening torque and the decrease of the amplitude of the axial excitation, the clamp load loss decreases and the damage of threads becomes slight. The lubrication (MoS_2) of bolt threads is useful to reduce bolt loosening and damage of threads.

A three-dimensional finite element model used to simulate the bolted joint under axial excitation is created using ABAQUS, through which the frictional stress, slip amplitude and frictional work per unit area along two specified paths on the first thread are studied. It is found that the FE results agree with the experimental observations very well.

1. Introduction

Bolted joints have found wide-spread use in many machines and structures. As basic fastening pieces, they have direct influences on the safety and reliability of a structural system. Assemblies which utilise bolted joints often work in vibratory environments. Most of past studies are focused on energy dissipation and damping of bolted joints [1–3], parameter uncertainties [4–6], failure and fatigue of structural joints [7–9], and loosening mechanisms [10–12].

When viewed from how the load is applied, bolted joints are subjected to four different types of loads: axial tensile load, transverse or shear load, torsional load, and prying load. Such vibratory loading conditions can lead to vibration-induced bolt loosening which can result in increased maintenance and/or failure. The loosening mechanism for an axial tension-loaded joint has been studied extensively in the literature. In general, there are two basic views of the loosening mechanism: (1) microslip occurs both on the screw thread and on the bearing surface; (2) fastener elongation is beyond its elastic limit.

Vibration will increase loosening through wear and hammering. After a sufficient amount of friction force is lost, the nut actually starts to back off and the clamp load is completely lost [6]. Goodier et al. [13] seem to have been the first to study the loosening mechanism for a bolt under axial load. They pointed out that an increase in load caused a bolt thread to move radially inward and a nut thread radially outward. This action results in a radial microslip between the contact threads. Based on static equilibrium conditions, this theory predicted a loosening twisting during loading and a tightening twisting during unloading, with a loosening twisting per cycle. Hosokawa et al. [14] reported that during the loading and unloading process, relative microslippage occurred radially both on the screw thread surface and on the bearing surface due to Poisson's ratio effect. Izumi et al. [15] analysed the detailed loosening behaviour of bolt and nut under axial tension load using a three-dimensional finite element method. Sakai [16] investigated the self-loosening mechanism based on the strength of materials. Experiments and analyses by Basava et al. [17] and Hess et al. [18] with thread fasteners loaded by gravity and subjected to axial harmonic vibration revealed that thread components can twist with or

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against gravity in the presence of vibration. It was shown that the direction of twist depended on initial preload, the frequency and amplitude of the vibratory input, the component mass and material, and thread fit and friction. The physical explanation for this observed behaviour concerns the nonlinear dynamic interaction of vibration and friction, and the resulting patterns of repeated sliding, sticking, and separation between the thread components.

The torque–tension relationship for a thread fastener is highly sensitive to friction variation between the turning surfaces at the head/nut interface and between male and female threads [19,20]. In some cases, the fastener's tensile stress may exceed its yield strength due to decrease of the coefficients of friction [21]. Karamiş et al. [22] used theoretical and experimental methods to study the friction behaviour of bolted joints. It was shown that the surface roughness of the joint members and joined materials had an important effect on self-loosening of the joint. When a bolted joint is put in service, it may be subjected to an external separating load, which will increase the fastener tension and simultaneously reduce the clamped load [23]. In a recent study, Nassar et al. [24] investigated the nonlinear behaviour of a bolted joint under cyclic separating tensile load using experimental and the finite element methods. The effects of the level and location of the separating load on the variation in clamp load and bolt tension were studied. Yang et al. [25] investigated the effects of separating load level, thread friction coefficient, and bolt preload level on the variations of the clamp load and bolt tension using experimental, analytical and the finite element methods.

Aluminium alloy is widely used to reduce the weight of machines and structures. However, its low strength causes bolt loosening or joint fatigue failure in bolted connections. A thread insert is used to improve the mechanical properties of female threads made of aluminium alloy.

In this paper, an extensive experimental study is conducted for investigating the behaviour of bolted joints (coated with a lubricant of MoS_2), made of aluminium alloy and equipped with a thread insert, subjected to axial excitation. The effects of the excitation level, the tightening torque and the lubrication (MoS_2) of bolt threads on the clamp load loss and the damage of threads are studied. Additionally, the levels of the clamp load loss and the damage of threads are investigated, while the bolted joints are subjected to longer-term excitation. The frictional stress, slip amplitude and frictional work per unit area along two specified paths on the first thread is analysed using the finite element method.

2. Experimental method

The joint tested in the experimental investigation is shown in Fig. 1. Two bolt testing fixtures made of high strength steel are clamped with a bolt and a nut. One fixture is fixed at one end and an axial excitation is applied at the end of the other fixture. The bolts used in the experiments are made of low-carbon steel (A283D, ASTM A283/A283M-03) and coated with zinc to protect them from rust. The thickness of coating is about 5 μm. The washer and the square nut are made of aluminium alloy (7050-T7451, ASTM B209-04). A thread insert, which is made of stainless steel (316L, ASTM A580/A580M—2008), is used to improve the engagement between the threads of the bolt and the female threads of the square nut. Between the bottom bolt testing fixture and the nut, a load cell is used to measure the clamp force. In order to protect the load cell from fretting wear, a thin washer made of aluminium alloy is placed in between the load cell and the bolt testing fixture.

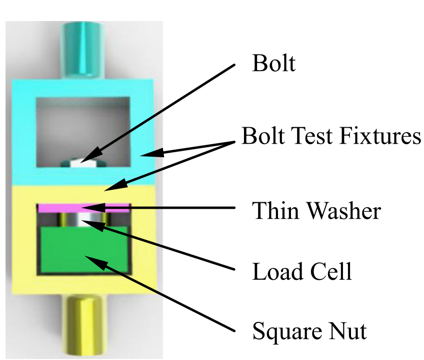

Fig. 1. Experimental setup.

In the experiments, five levels of tightening torque, M_0, are used. They are 30 Nm, 35 Nm, 40 Nm, 45 Nm, and 50 Nm. The axial excitation, denoted as F_e, is the controlling parameter. The amplitude of the axial excitation, F_e, will be referred to as A_F. A number of A_F values are used, and they range from 7.5 kN to 12.25 kN. Furthermore, the frequency of the axial excitation is 30 Hz. A lubricant is used to study its effect on bolt loosening. It is made from lithium soap of a hydroxy fatty acid, antioxidant and molybdenum disulphide (MoS_2). The procedure of application is as follows: 1) a thin layer of MoS_2 grease is applied on the thread surface of the bolt and the surface of the upper fixture which is in contact with the bolt head; 2) the joint is assembled and the tightening torque is applied. The test conducted for each experimental condition is repeated for four separate times. All the experiments are conducted in air at room temperature. The axial excitation, the stroke (the displacement of the bolt testing fixture), and the clamping force are measured for every loading cycle continuously throughout an experiment. The morphologies of wear scar are examined using a scanning electron microscope (SEM, JOELJEM-6610LV), and chemical compositions of damage zone are analysed by Energy Dispersive X-ray (EDX, OXFORDX-MAX50 INCA-250).

3. Distribution of preload

Tightening a bolt to a torque value is the most popular means of controlling the preload provided by a threaded fastener. However, it is experimentally observed that the preload is not a constant value when the same tightening torque is applied on nominally identical bolted joints under the same condition. Therefore, a tightening torque of 30 Nm is applied on each of 45 bolted joints tested, and the distribution of preload is shown in Fig. 2. About 50% of these joints have achieved preload in the range of 13.5 kN ~ 14.5 kN. This is one reason why many bolts joints work correctly but some get loose under the same condition.

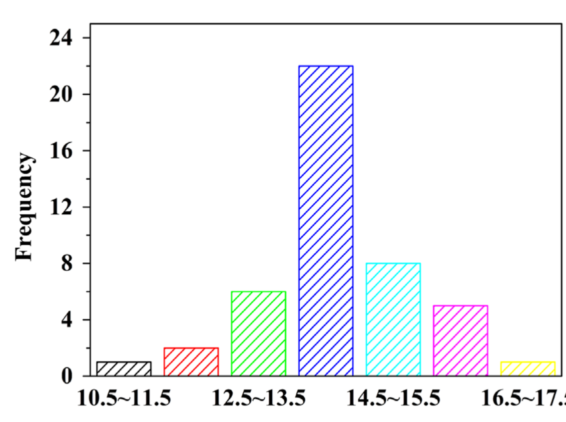

Fig. 2. The distribution of preload (M_0 = 30 Nm).