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Investigation into the energy dissipation of a lap joint using the one-dimensional microslip friction model

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ABSTRACT

In this paper, the energy dissipation in a mechanical lap joint is studied using the one-dimensional microslip friction model by incorporating the effect of interface tangential contact stiffness. A non-uniform pressure distribution of exponent law at the interface is considered and the resulted distinct stick-slip transitions along the contact interface are presented. Expressions of the critical slip loads giving rise to stick-slip transitions along the contact interface are determined. The loading force–displacement curves for different pressure distribution laws and different interface tangential stiffness are obtained and compared with each other. The hysteresis curves of the oscillating tangential contact forces versus tangential displacements and the dissipated energy at the contact are determined. It is shown that a classical power-law behavior is predicted between the energy dissipation and the applied tangential force. However, the exponents of the power-law are not the theoretical cubic but vary with interface stiffness and pressure distributions. The obtained results suggest that the joint interface tangential stiffness and interfacial pressure distribution are reasons for the varying exponent values obtained in experimental work.

1. Introduction

Engineering structures are often built up by connecting structural components through joints. In joint assembled structures, the micro-slip motion taking place in local regions of the frictional joint interface provides dominant damping mechanism of the structure and thus plays an important role in the dynamic behavior of the system (Beards, 1992; Berger, 2002; Xiao et al., 2012). Micro-slip is defined as a small relative tangential displacement in a contacting area at an interface while the rest of the interface is not relatively displaced tangentially (Ouyang et al., 2006).

Significant effort has been expended in an attempt to develop predictive models for microslip motions along the frictional interface in the mechanical joints and to facilitate the associated energy dissipation. Discrete models of the friction interface are proposed by Iwan (1966, 1967) and are based on combinations of spring-frictional slider elements. In the Iwan models, the microslip motions are described through stick-slip behavior of a series of sliders. Segalman (2002) developed a four parameter Iwan model which can reproduces the qualitative and quantitative properties of the joint dynamics by using the results of energy dissipation and force–displacement relations from experiments. Song et al. (2004) developed an adjusted Iwan beam element (AIBE) based on a parallel-series Iwan model which can be used to capture experimentally observed profiles with proper identification of the model parameters.

Continuum models representing the microslip motion are generally based on the one-dimensional beam description of the friction damper. Menq et al. (1986) described a one-dimensional continuous microslip model, in which the friction element was modeled as an elastic beam and in contact with a rigid ground through an included shear layer in between. Based on the model developed by Menq et al. (1986), Csaba (1998) presented a microslip model with a quadratic pressure distribution at the friction interface with the shear layer removed for simplicity. Quinn and Segalman (2005) considered a similar model of an elastic beam on a frictional foundation and showed that for a general class of normal load distributions the resulting energy dissipation follows a power-law and is qualitatively similar to observed experimental findings. Cigeroglu et al. (2006) developed a dynamic one-dimensional microslip friction model by including the inertia of the damper. The distinct stick-slip transitions along the contact interface were studied for three types of normal load distributions. The similar one-dimensional models to describe the microslip

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motions along the frictional interface also have applications in other fields. For example, in fiber-reinforced composites involving partial pull-out (Mahesh et al., 2004) and in vibratory pile driving (Rausche, 2002; Loukidis et al., 2008).

The energy dissipation in the joints is commonly characterized by the relation between the dependence of energy dissipation and amplitude of applied force. Different theoretical works, focused on the effect of mechanical joint on the damping capability of the assembled structures, remark that the energy dissipated in the microslip regime is proportional to the cube of applied tangential force for uniform pressure distribution along the interface (Goodman and Klumpp, 1956; Goodman, 1959; Metherell and Diller, 1968; Chen and Deng, 2005; Allara, 2009), and exhibits a power series starting from the third order of the magnitude of loading for un-uniform pressure distributions (Song et al., 2005). If the normal traction varies as exponent power law α, the frictional dissipation per cycle scales with the forcing amplitude to a power of $(3+2\alpha)/(1+\alpha)$ (Quinn and Segalman, 2005). Experimental results confirm the power-law relationship between energy dissipation and magnitude of tangential load. However, the exponent of the power-law relation obtained from experimental data is not unanimously the theoretical value 3 but ranges from 2.0 to 3.33 (Klint, 1962; Ungar, 1964, 1973; Kragelsky et al., 1982; Smallwood et al., 2000; Hartwigsen et al., 2004). It is noted that the interface tangential contact stiffness is ignored in these previous studies in identifying the dissipation mechanisms and explaining the difference between theoretical result and experimental results.

The purpose of this work is to evaluate the effect of interface tangential stiffness and pressure distribution laws on the energy dissipation at bolted joints and to explain for the experimental results. To include the interface tangential stiffness into the dynamics and the energy dissipation in the joint, a one-dimensional microslip friction model is employed. In the microslip friction model, the friction damper is modeled as an elastic beam in contact with a rigid ground and connected to a spring at the left end. A shear layer with elastic stiffness, which permits elastic deformation of the beam before the occurrence of slip, is inserted between the beam and the ground to incorporate the effect of interface tangential stiffness. A non-uniform pressure distribution of exponent law is considered and the resulted distinct stick-slip transitions along the contact interface are studied. The hysteresis curves of the oscillating tangential contact forces versus tangential displacements and the dissipated energy at the contact are presented. The power-law behavior between the energy dissipation and the applied tangential force is predicted. The exponents of the power-law are further determined for different interface tangential stiffness and interfacial pressure distribution and the varying exponent values obtained in experimental work is recovered.

2. Description of the studied model

A shear lap joint under a longitudinal force is considered, as shown in Fig. 1. The micro-slip motion at the frictional interface, with the length of contact region being $2L$, is induced by a

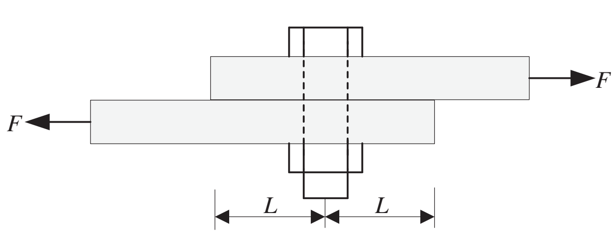

Fig. 1. Sketch diagram of a lap joint under a tangential force.

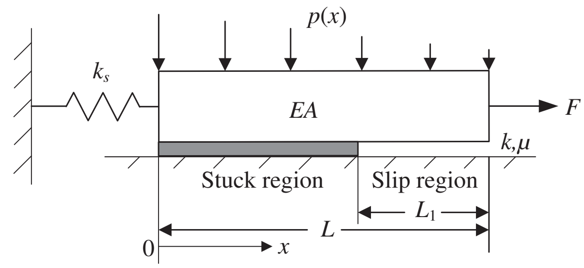

Fig. 2. The one-dimensional microslip friction model.

tangential force F. The dynamic model to examine the microslip motion is shown in Fig. 2. In this model, only the right half of the joint is considered. A one-dimensional rectangular beam with a constant cross-sectional area A and a uniform Young's modulus E, is excited by the tangential force F. The length of the beam is L. The frictional interface is modeled using the microslip friction model developed by Menq et al. (1986). A shear layer with per unit length stiffness k, which permits elastic deformation of the beam before the occurrence of slip, is inserted between the beam and the ground, and obeys the Coulomb friction law with a constant friction coefficient, μ, throughout the length of the beam. A non-uniform normal load, $p(x)$, is distributed along the beam length and is assumed to be directly transmitted to the shear layer. To allow for the possibility of strain hardening in the frictional element after the entire shear layer has slipped, the beam is connected to the ground from the left end with a spring, k_s (Menq et al., 1986; Cigeroglu et al., 2006).

Assuming the pressure variation along the beam length has the expression as

$$p(x) = p_0\left(1-\frac{1}{2}\left(\frac{x}{L}\right)^{\alpha}\right) \tag{1}$$

where p_0 is the pressure amplitude, α is a non-negative coefficient representing different pressure laws, i.e. $\alpha \geq 0$. A uniform pressure distribution is introduced when $\alpha = 0$ and a non-uniform pressure corresponds to $\alpha > 0$. Fig. 3 shows the plots of pressure distributions for different α values with $p_0 = 1$. The pressure at the interface has a maximum at the left end, i.e. $x = 0$ and decreases along the length of the beam. It is noted that the similar power law pressure

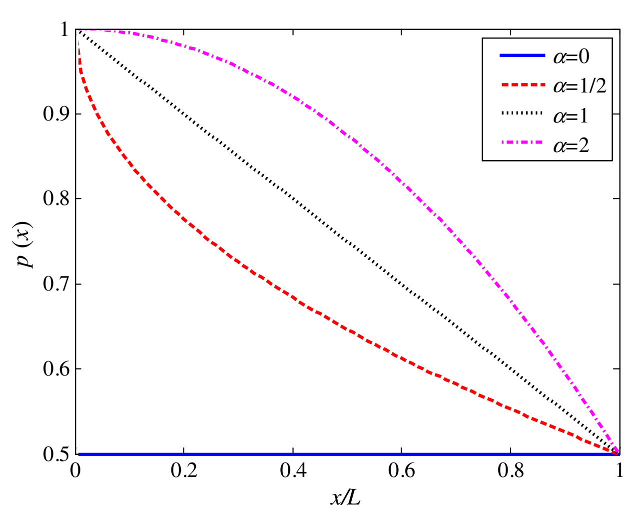

Fig. 3. Different pressure distribution functions along the friction interface.