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On the fully coupled partial slip contact problems of orthotropic materials loaded by flat and cylindrical indenters

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ABSTRACT

Fully coupled partial slip contact problems for orthotropic materials are considered in this paper. The problem is formulated by virtue of the Fourier transform method. The governing singular integral equations are solved numerically for both flat and cylindrical stamps under the plane strain conditions. An extensive parametric study is carried out to investigate the effect of material orthotropy parameter as well as the coefficient of friction on the contact stresses and the stress intensity factors. It is found that the coefficient of friction and the orthotropic material parameters have a great effect on the stress intensity and the in-plane contact stresses as well as stick and slip zones. Especially, the shearing ratio parameter has a pronounced effect on the stress distribution of cylindrical punches which is important from the crack initiation and fretting wear point of view. The results obtained from this study can be used as benchmark results in the design of contacting parts with orthotropic material properties.

1. Introduction

Partial slip contact problems are of great interest to the tribologist since the surface crack propagation can start from stationary connections under cyclic loads which is the first stage of the fretting contact (Hills, 1994). In partial slip problems, there is no tangential load between the contacting bodies. However, if this load exist then the partial slip problem converts to a fretting contact problem which may subsequently cause fretting wear and ultimately surface failure of the components (Gallego et al., 2006; Gallego and Nelias, 2007; Gallego et al., 2010). This is the subsequent stage of the fretting contact where damage can nucleate from the slip zones in the form of fatigue crack. Fretting fatigue has been one of the main root cause of fatigue failures in railway, aerospace and nuclear industries (Nowell et al., 2006). Especially the three most important wear mechanisms seen in almost all turbine engines are reported to be standard wear, galling and fretting (Calcaterra and Naboulsi, 2005). In fact, according to the USA national high cycle fatigue (HCF) program, it has been reported that, around one in six of all in-service mishaps attributed to HCF in United States Air Force (USAF), engine hardware can be linked to fretting-induced damage (McVeigh et al., 1999). Fiber-reinforced composites that can be considered as orthotropic materials is another application area of this study where the main goal is to demonstrate that the orthotropic material properties may significantly modify the contact stress distribution within the contacting bodies and subsequently the slip and shear distributions at the interface. Therefore, it is important to find the correct stress state in the critical regions of the contacting bodies susceptible to the fatigue crack propagation. In a review paper by Hills and Nowell (2014), studies in fretting fatigue can be split into three broad categories namely: mathematical analysis of the fretting process, role of the fretting in crack nucleation and the contact stresses. In this paper, the last category will be studied.

The partial slip contact problem involving Hertzian contact was first studied by Cattaneao (1938) and later by Mindlin (1949) where his interest was on the axisymmetric contact problems. Contact problems under the cyclic tangential loading for isotropic materials have been studied in the open literature (Spence, 1973; Nowell et al., 1988; Hanson and Keer, 1989; Ciavarella, 1998; Ciavarella and Hills, 1999; Wang et al., 2010). Also, this type of contact problem has been extensively discussed for homogeneous materials (Ciavarella, 1998; Ciavarella and Hills, 1999; Hanson and Keer, 1989; Nowell et al., 1988; Spence, 1973; Wang et al., 2010).

However, limited literatures consider the partial slip and fretting contact of anisotropic and/or non-homogeneous materials. Regarding the transversely isotropic piezoelectric materials, Su et al. (2015) solved the two-dimensional fretting contact of a homo-

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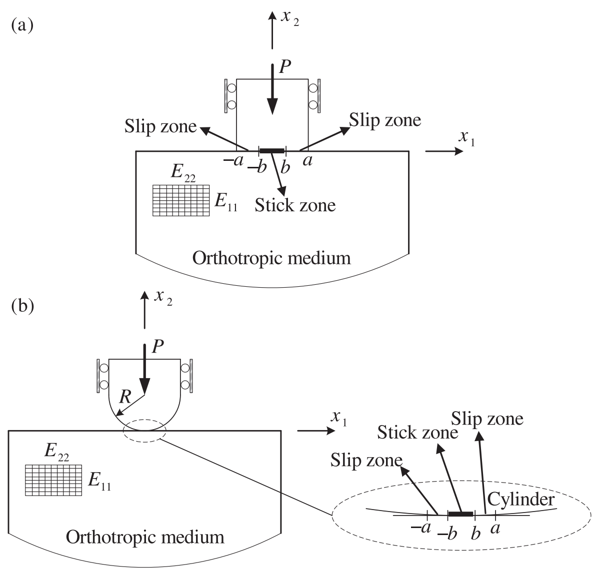

Fig. 1. Geometry of the partial slip contact problem between (a) flat or (b) circular punch and an orthotropic half-plane.

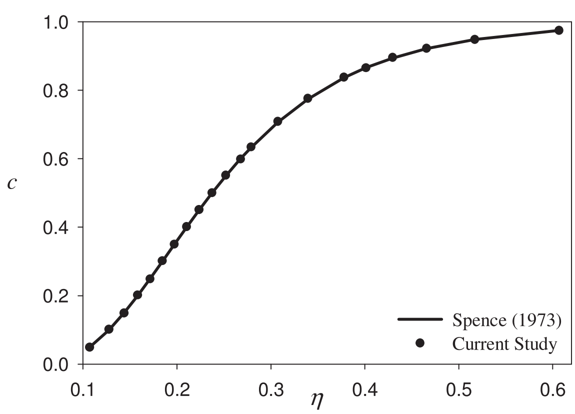

Fig. 2. Variation of the stick zone length versus the coefficient of friction for the case of flat punch and the isotropic half-plane. The solid lines stand for Spence (1973) and the symbols present the results of current study ($\delta = 1, \kappa = 1, \nu = 3/7, \nu_0 = 0.3$).

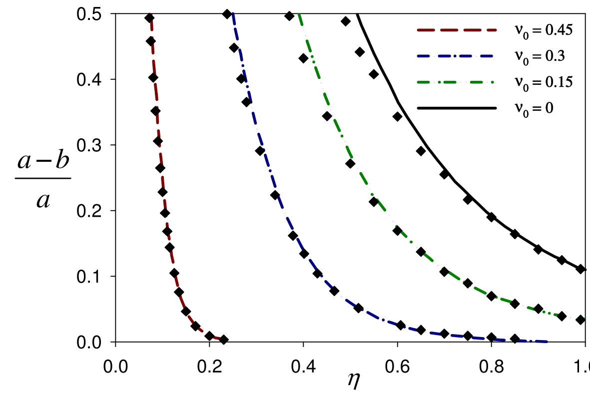

Fig. 3. Variation of the slip zone length, $a - b$, versus the coefficient of friction for various values of Poisson's ratio for the case of flat punch and the isotropic half-plane. The solid lines stand for Adams (2016) and the symbols present the results of current study ($\delta = 1, \kappa = 1$).

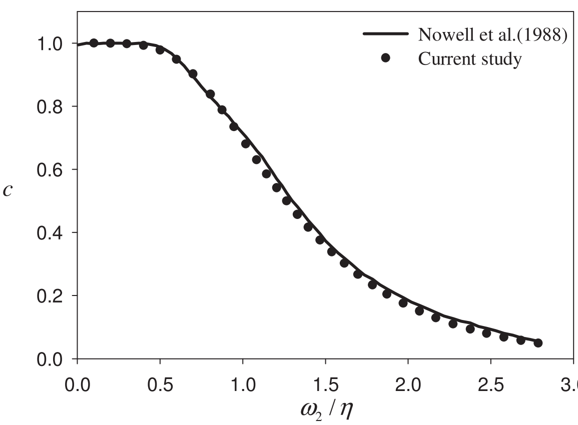

Fig. 4. Variation of the stick zone length versus the parameter ω_2/η for the case of cylindrical punch and isotropic half-plane. The solid lines stand for Nowell et al. (1988) and the symbols present the results of current study ($\delta = 1, \kappa = 1$). (Uncoupled solution).

geneous transversely isotropic piezoelectric half-plane loaded by a rigid insulating cylindrical punch. Regarding the Functionally Graded Materials (FGMs), Ke and Wang (2010) solved the fretting contact problem between two dissimilar elastic bodies coated with functionally graded layers. A fully coupled partial slip contact problem of a graded half-plane was studied by Elloumi et al. (2010). Note that, FGMs generally exhibit orthotropic behavior as a result of their oriented microstructure. This behavior is a consequence of the processing technique. For example, plasma sprayed coatings have a lamellar microstructure with weak cleavage planes parallel to the boundary (Sampath et al., 1995; Sevostianov and Kachanov, 2001). On the other hand, coatings processed by the electron beam physical vapor deposition (EB-PVD) technique have a columnar structure with weak cleavage planes perpendicular the free surface (Kaysser and Ilschner, 1995; Schulz and Schmücker, 2000). It is noteworthy to mention that FGMs processed by EB-PVD technique increase the life of turbine components by a factor of two due to their columnar structure (Wolfe and Singh, 1998). Also, the fiber-reinforced composites with a variable fiber volume fraction can be considered as orthotropic functionally graded materials (Benatta et al., 2008). Regarding the Functionally Graded Piezoelectric Materials (FGPMs), Su et al. (2016a) solved the axisymmetric partial slip contact problem for an FGPM-coated half-space indented by a rigid conducting spherical punch. Su et al. (2016b) also solved the two dimensional fretting contact problem of an FGPM layered half-plane loaded by a rigid conducting cylindrical punch where an exponential variation in thickness direction is used for the elastic properties of FGPMs.

The contact mechanics of anisotropic materials has been studied from several aspects. Dahan and Zarka (1977) provided an analytical solution to the elastic contact problem between a sphere and a transversely isotropic semi-infinite medium by means of the Hankel transform. Bakirtaş (1984) solved the normal contact problem of an orthotropic graded half-space in the light of Fourier transform. The partial slip contact problem of a stressed orthotropic medium indented by a rigid flat punch was considered by Bjarnehed (1991). His study mainly focuses on the effect of transverse uniaxial stress on the contact tractions and stick zone length. Lin et al. (1991) employed the displacement potential formulation to extract the interior stress field corresponding to the point load and the square load of a transversely isotropic medium. Ovaert (1993) found a solution for the ellipsoidal indentation of a transversely isotropic material and subsequently simulated the solid lubricant thin film behavior under the contact loading. An FEM based numerical algorithm was given by Varadi et al. (1998) to study the contact problem between a steel ball and