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Partial slip contact modeling of heterogeneous elasto-plastic materials

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ABSTRACT

In this study, a semi-analytic solution is developed for heterogeneous elasto-plastic materials under partial slip contact, and the effects of a single inhomogeneity embedded in the matrix material are investigated. The stick and slip areas are determined by an iterative conjugate gradient method with the assistance of the discrete convolution and fast Fourier transform algorithm. The inhomogeneities within a material are homogenized as homogeneous inclusions with properly determined eigenstrains based on the equivalent inclusion method, and the surface displacements induced by these eigenstrains along with those caused by the shear tractions are then introduced into the gap between the contact bodies to update surface geometry. The accumulative plastic deformation is iteratively obtained by a procedure involving a plasticity loop and an incremental loading process. The model takes into account the interactions among the contact bodies, the embedded inhomogeneities and the plastic zones, thus leading to an accurate solution of the surface pressure distributions, tangential tractions, plastic zones and subsurface stress fields. This solution is of great importance for the analysis of frictional heterogeneous contact coupling the normal and tangential behaviors in the elastic-plastic regime.

1. Introduction

When two surfaces in contact are subjected to a tangential force, their relative motion is impeded by friction. Surface strains on the counterpart surfaces are not in a harmonic distribution as long as the static contacts involved. Local micro-slip would take place at certain regions where the shear traction reaches the shear stress limit determined by the localized Amonton's law of friction. Within these regions the points attached to the two surfaces gradually depart from each other owing to the difference in displacement; stick phenomenon takes place elsewhere within the contact area, and the contact points always stay together due to the same displacement they undergo [1,2]. The partial slip contact could be widely found in engineering practices and would cause fretting wear of components or even lead to surface failures [3–5].

Partial slip contact has been extensively explored for the past decades [6–10]. Most works were based upon the assumption of homogeneous materials and heterogeneous effects are not considered in their solutions. However, materials are naturally inhomogeneous at a small enough scale, consisting of inhomogeneities, such as inclusions and voids. They not only affect the mechanical and physical properties of materials at local and global scales [11] but also accelerate their wear and fatigue damage [12].

The inhomogeneities and their interactions within materials have been intensively studied [13–25]. Embedded inhomogeneities may contain eigenstrains, which refer to as non-elastic strains, such as thermal expansion, plastic strains or misfit strains. Recently, Zhou et al. [26–28] formulated the eigenstrains into a set of simultaneous constitutive equations based on Eshelby's equivalent inclusion method (EIM) [29] and obtained a solution for multiple interacting inhomogeneities of arbitrary shape embedded in an infinite space or a half space. Similar numerical techniques were employed by Nelias and others [30–33] to study the microscopic response of subsurface inhomogeneities. Zhou and Wei [34] developed a semi-analytic solution for multiple inhomogeneities and cracks by means of distributed dislocation technique [35]. Dong and Zhou [36–38] and Dong et al. [39,40] investigated the effects of subsurface inhomogeneities and cracks on the lubricated contact. A comprehensive survey of recent related works was provided by Zhou et al. [41].

Plastic behaviors play a significant role in the reliability of contact bodies, and the analysis of these behaviors would provide assistance to the interfacial design improvement [42–47]. Fotiu and Nemat-Nasser [48] built a universal algorithm for the integration of the elastic-plastic constitutive equations, and their scheme turned out to be unconditionally stable and accurate. A fast semi-analytical method was developed by Jacq et al. [49], and the return mapping algorithm

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was introduced into the solution by Boucly et al. [50] and others [51–58] to improve the efficiency and accuracy. Amuzuga et al. [59] recently developed a model to investigate the mutual interactions among inhomogeneities and their surrounding plastic zones, however the stick-slip effects caused by the surface friction were not considered in this model.

This study aims to model partial slip contact for elasto-plastic materials with inhomogeneities. The approach developed takes into account the interactions among the contact bodies, the embedded inhomogeneities and plastic zone. The solution of pressure distribution, tangential tractions, plastic zone and subsurface stress fields would provide foundations for the reliability analysis of heterogeneous materials, in particular their wear and fatigue analyses.

2. Model formulation and solution method

2.1. Problem description and solution approach

In this study, we aim to investigate the effects of a single inhomogeneity embedded within a half space; it should be noted that the model is also capable of solving problems concerning multiple inhomogeneities of arbitrary shapes. The present solution is based on the model developed by Chen el al. [53] for layered materials under elasto-plastic contact, which has been well validated by the finite element method and experimental results from previous studies. Consider the contact system of a sphere $(E_1, \ \nu_1)$ with a half space $(E_2, \ \nu_2)$, as shown in Fig. 1. The radius of the sphere is R and the static friction coefficient is μ_f. The origin of the Cartesian coordinate system is at the initial contact point. The half space contains n arbitrarily-shaped subdomains Ω_ψ ($\psi = 1, \ 2, \ ... \ , \ l$), each of which has material constants different from the matrix.

In order to formulate the governing equations, the domain under the contact surfaces is discretized into $N_x \times N_y \times N_z$ cubic elements of the same size $2\Delta_x \times 2\Delta_y \times 2\Delta_z$ and each element is indexed by a sequence of three integers (α, β, γ) with $0 \le \alpha \le N_x - 1, \ 0 \le \beta \le N_y - 1, \ 0 \le \gamma \le N_z - 1$, while the contact surface is composed of $N_x \times N_y$ square patches of $2\Delta_x \times 2\Delta_y$.

The ball indenter is compressed onto the half space by a normal load W, and tangential loads F_x and F_y are applied on the surface parallel to the $x - y$ plane. The contact interaction results in normal pressure p and shear tractions q^x and q^y in the interface. The relative surface displacements at patch (α, β) could be obtained by

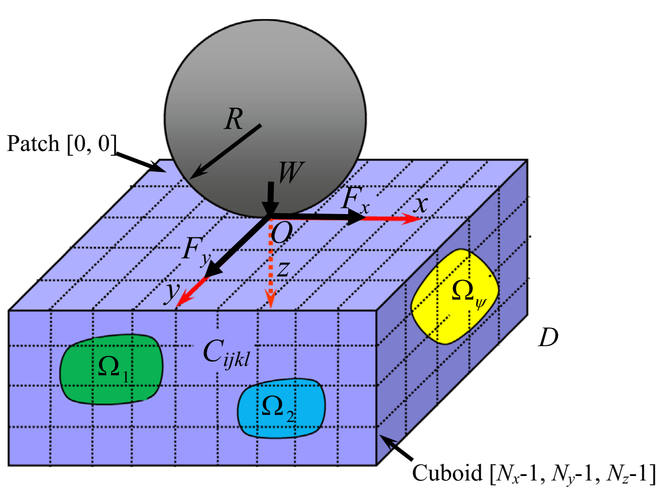

Fig. 1. Partial slip contact of a sphere with a half space with inhomogeneities.

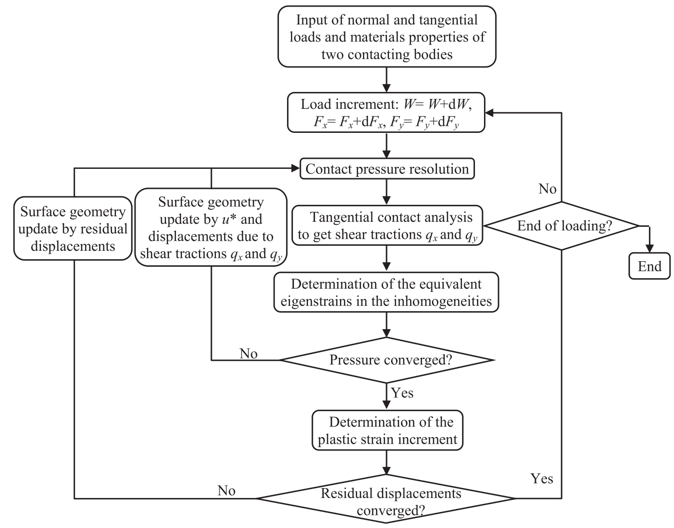

Fig. 2. Flowchart of the numerical procedure.

Table 1
Material parameters and contact conditions for plastic contact validation.

Parameter	Value
Normal load, W (N)	800
Loading steps	10
Tangential modulus for linear hardening law	E_T = 0.0, 0.5 and 0.8E_2
Sphere radius, R (mm)	20
Young's modulus for the sphere, E_1 (GPa)	$+\infty$
Young's modulus for the half space, E_2 (GPa)	100
Poisson's ratio for half space, ν	0.3
Yield stress, σ_y (MPa)	600
Maximum Hertzian contact pressure, p_0 (MPa)	1671.92
Hertzian contact radius, a_0 (mm)	0.4780

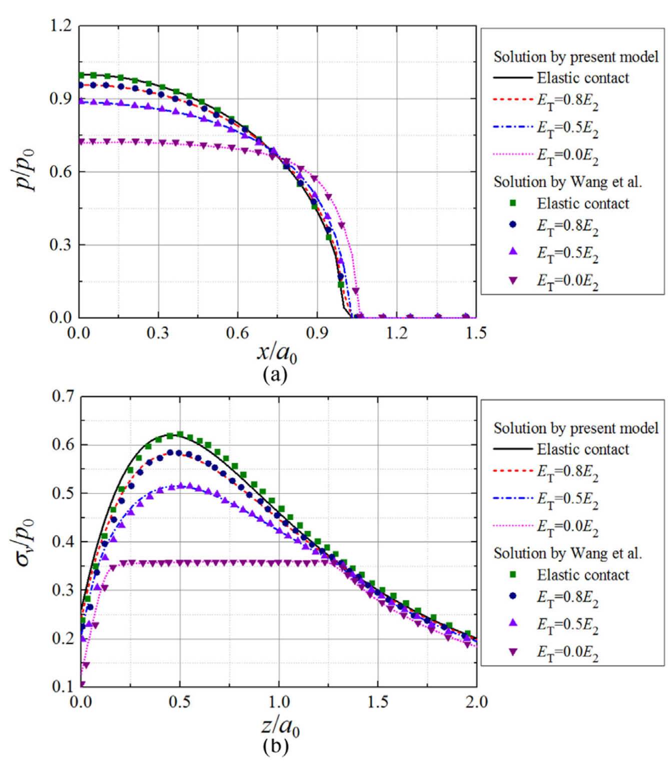

Fig. 3. (a) Dimensionless pressure p/p_0 along x-axis and (b) von Mises stress σ_v/p_0 for plastic contact.