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Damage analysis for an elastic-plastic body in cylindrical contact with a rigid plane

Bo Zhao [a, b], Fei Shen [b], Yi Cui [c], Youbai Xie [a], Kun Zhou [b, *]

[a] State Key Laboratory of Mechanical System and Vibration, Shanghai Jiao Tong University, 800 Dongchuan Road, Minhang District, Shanghai, 200240, China
[b] School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[c] Key Laboratory for Power Machinery and Engineering of Ministry of Education, Shanghai Jiao Tong University, 800 Dongchuan Road, Minhang District, Shanghai, 200240, China

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ABSTRACT

The fatigue failure can be explained by the accumulation of damage. By coupling the fatigue damage evolution with the elastic-plastic constitutive model, a numerical approach based on the continuum damage mechanics is proposed to conduct the fatigue damage analysis of the material under cyclic loadings. The elastic-plastic behavior of the material with nonlinear kinematic hardening effects and the damage induced by both cyclic stress and accumulated plastic strain are taken into account. The proposed approach is adopted to an asperity in cylindrical contact with a rigid flat under normal cyclic loading, which can be considered as a fundamental simplification of the contact between two rough surfaces. Finally, the fatigue macro-crack initiation and the evolution of load-carrying capacity of the asperity are predicted.

1. Introduction

The fixed joints, such as the bolted joints, play key roles in the overall static and dynamic characteristics of mechanical systems under static and dynamic loading. The experiments have shown that joints contribute much to the stiffness and damping in assemblies [1]. However, fretting fatigue damage easily occurs in contacting components and thus affects their proper function while they are subjected to fluctuated loading and relatively small movement [2]. On the microscopic scale, engineering surfaces are rough; primarily the asperities on the conjunction surfaces are in contact, which determines the stiffness of joints [3]. Therefore, it is very important to understand the damage mechanism of contacting asperities so as to predict the endurance and effectiveness of mechanical systems.

A single asperity contact pair with a rigid flat is generally considered as a fundamental simplification of the contact between rough surfaces [4]. In the past decades, many investigations on the asperity contact have been reported. Hertz [5] first conducted the elastic contact simulation without friction and adhesive. Greenwood and Williamson [6] applied the Hertz model to each asperity contact and developed the so-called GW contact model between complex surfaces. Then, by extending the GW model to the elastic-plastic contact, other scholars proposed several statistical elastic-plastic contact models [7,8].

Based on the finite element (FE) method, Kogut et al. [9] developed an elastic-plastic frictionless contact model (KE model) for a deformable sphere supporting a rigid flat. Jackson and Green [10] proposed the variations of the contact area and reaction force during the loading process. Shankar et al. [11] investigated the contact behavior of the material with different yield strengths and tangent moduli. With the aim of simulating granular materials using particle methods, Olsson and Larsson [12] presented a unified method for calculating the contact area and force between two dissimilar elastic-plastic spheres.

Besides the loading process considered above, the unloading process is equally important and should be also considered [13–15]. Etsion et al. [16] investigated the unloading performance of an elastic-plastic spherical contact. Kadin et al. [17] considered the adhesion behavior in the unloading process. Then, according to the work of Chang et al. [18], Kogut and Etsion [19] investigated the performance of sliding contact between a sphere and a plane. The fast Fourier transform (FFT) method was also introduced to investigate the problems of contact between the sphere and plane [20–22]. Zhou et al. [23,24] developed semi-analytic models with the FFT method to solve the problems of three-dimensional arbitrarily shaped inclusions in an isotropic half space. By breaking up the inhomogeneous inclusions into small cuboidal elements, Zhou et al. [25,26] also developed a general solution for multiple 3D arbitrarily-shaped inhomogeneous inclusions near surfaces under contact

* Corresponding author.
E-mail address: kzhou@ntu.edu.sg (K. Zhou).

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loading. Based on the conjugate gradient technique, Polonsky [27] numerically investigated rough contact problems. Ghaednia et al. [28] proposed a new expression for the permanent deformation after the impact of a rod with a flat surface during both loading and unloading processes. Then, they studied the frictionless contact behavior of an elasto-plastic sphere with an elasto-plastic flat [29].

In order to investigate the friction contact which widely exists in dry contact [30,31], Brizmer et al. [32,33] investigated the influence of the stick on the elastic-plastic spherical contact. Zait et al. [34] investigated the influences of the stick on the unloading behaviors of the sphere contact between dissimilar materials. Mulvihill et al. [3] presented a sliding friction model for both cylindrical and spherical elastic-plastic contacting asperities. Based on the slip line theory, Jackson et al. [35] investigated the relationship between the average pressure and the yield strength in the case of a rigid sphere indenting a frictionless perfectly-plastic half-space. Zhou et al. [36–38] modeled line and point elasto-hydrodynamic lubrication contacts between a rigid body and a heterogeneous half-space with inclusions beneath its surface.

For many materials, the strain-hardening behavior is obvious during deformation. Olsson and Larsson [39] investigated the contact between elastic–plastic adhesive bodies obeying the power hardening law. Lan et al. [40] studied the influences of the elastic-plastic properties on the hardness of the material. Zhao et al. [41] developed an FE model for a frictionless sphere in contact with a power-law hardening elastic-plastic property. Then, Zhao et al. [42] investigated the loading and unloading performances of a power-law hardening spherical contact under stick contact condition. Considering frictional, oblique contact and strain hardening effects, Brake et al. [43] developed a new formulation for frictional elastic–plastic contact between two surfaces.

However, the above investigations have mostly focused on the initial performances of the asperity contact and neglected the performance degradation over time. In fact, the asperities on the contacting surfaces may experience repetitive interaction and suffer from fatigue damage, which can easily initiate a crack and significantly reduce the fatigue life of the components as well as the connection stiffness [44]. Recently, the failure of asperity has been studied by several scholars. Beheshti et al. [45] explained the wear mechanisms by asperity fatigue. Based on linear-elastic fracture mechanics, Xu [46] investigated the crack process of a two-dimensional asperity under normal contact. However, the studies on the fatigue damage-induced crack initiation and mechanical performance degradation of the asperity have been rarely reported.

Therefore, this work is concerned with the fatigue macro-crack initiation and the performance degradation of a cylindrical asperity in contact with a rigid flat under normal cyclic loadings. By coupling with the elastic-plastic constitutive model, a continuum damage mechanics (CDM)-based approach is introduced to derive the evolutions of stress, strain and damage of the material. The nonlinear kinematic hardening of the material is considered, and the damage evolution induced by both cyclic stress and accumulated plastic strain is calculated. The contact between a cylindrical asperity and a rigid flat under the normal cyclic loading is modeled. The macro-crack initiation and the evolutions of mechanical performances of the asperity, as well as their dependencies on the cyclic loadings, are discussed and presented.

2. Continuum damage mechanics (CDM) model

Fatigue damage can be considered as a progressive degradation of the material due to irreversible changes occurring in material microstructures. The initiation of macro-cracks will take place once the damage accumulates to a critical level. By coupling the mechanical behavior law and the CDM theory, a damage-coupled elastic-plastic constitutive model is developed to predict the damage and hardening behaviors of the material.

2.1. Damage-coupled elastic-plastic constitutive model

In the theory of CDM, a damage variable D is often introduced to estimate the deterioration of material caused by fatigue loadings. Fig. 1 illustrates a representative volume element (RVE) [47–50] to describe the damage of the material. The damage variable is a quantification of the surface density of micro-cracks, voids and cavities lying on an elemental cross-sectional plane. The mechanical measurement of the local damage relative to the direction $\vec{n}$ is defined as

$$\boldsymbol{D}_n = \frac{S_D}{S}, \tag{1}$$

where S denotes the total section area of RVE, and S_D the total damaged area. By assuming the isotropic damage evolution for the material, the damage tensor $\boldsymbol{D}$ is reduced to a scalar defined as

$$D = \frac{S - S_R}{S}, \tag{2}$$

where S_R is the effective area of resistance, and can be expressed as $S_R = S - S_D$.

Over the total section of RVE, the total load P is resisted by the effective stress $\tilde{\sigma}$ which can be identified as

$$\tilde{\sigma} = \frac{P}{S_R} = \frac{P}{(1-D)S} = \frac{\sigma}{1-D} = E\varepsilon^e, \tag{3}$$

where ε^e and σ are the strain and stress of the damaged material, respectively. Alternatively, the damaged material property can be expressed as

$$\sigma = E(1-D)\varepsilon^e = \tilde{E}\varepsilon^e, \tag{4}$$

where E and $\tilde{E}$ are the elastic moduli of the initial and the damaged material, respectively. The Poisson's ratio remains unchanged in the damaged material [51]. The damage scalar can be rewritten as

$$D = 1 - \frac{\tilde{E}}{E}. \tag{5}$$

In engineering, damage measurement can be achieved by using the reduction of the elastic modulus.

The J_2 flow model is employed in this study to simulate the elastic-plastic behavior. By combining the Mises yield criterion with the CDM theory, the Mises yield surface function F can be defined as

$$F = \sigma_{eq} - Q, \tag{6}$$

where σ_{eq} is the equivalent stress and defined as

$$\sigma_{eq} = \left[\frac{3}{2}\left(\frac{\mathbf{S}}{1-D} - \boldsymbol{\alpha}\right) : \left(\frac{\mathbf{S}}{1-D} - \boldsymbol{\alpha}\right)\right]^{1/2}, \tag{7}$$

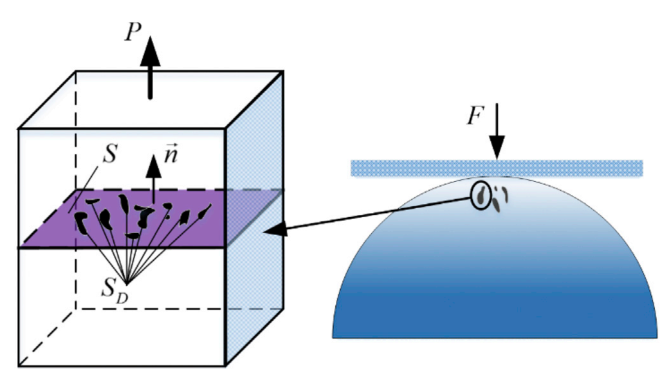

Fig. 1. Representative volume element.