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Fretting fatigue stress analysis in heterogeneous material using direct numerical simulations in solid mechanics

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ABSTRACT

In this paper, we present the first numerical analysis upon the effect of heterogeneity on the stresses in fretting fatigue problems. We analyze the stress distribution in heterogeneous material under fretting fatigue loading condition based on Direct Numerical Simulations (DNS) in solid mechanics. The heterogeneity is introduced to the fretting fatigue specimen using two models based on micro-voids, namely a single hole cell model and a four hole cell model. From this study, it is found that the effect of heterogeneity is more significant in shear stress than in normal stress due to more complex loading after applying the fatigue cycle. Moreover, the numerical results indicate that the peak shear stress is shifted from the interface in case of homogeneous material, to the micro-voids in case of heterogeneous material.

1. Introduction

Fretting fatigue is a complex mechanical failure phenomenon, in which two contact surfaces undergo a small relative oscillatory motion due to time variable loading, i.e. cyclic or random. It is commonly recognized that fretting causes a substantial reduction in fatigue life [1,2]. Several methods to quantify fretting fatigue damage are available as it often leads to catastrophic failure in clamped components with relatively small displacement amplitudes [3]. Several factors such as coefficient of friction (COF), normal contact stress, slip amplitude, cyclic axial stress, and interface stress distribution can affect the fretting fatigue behaviour of a material [4–6]. Investigation of the effects of these variables on the macroscopic mechanical response, more importantly at the interface of a contact problem is necessary especially in the case of heterogeneous material.

Heterogeneous or multi-phase materials, with enhanced properties in contrast to the respective constituents, have been the subject of ever increasing interest to civil, mechanical and aerospace industries in the recent few years [7–10]. Material heterogeneity has a compelling effect on its macroscopic behaviour as the various phenomena occurring at the macroscopic level originate from the mechanics of the underlying microstructure. Observed macroscopic behaviour largely depends upon the size, shape, spatial distribution and properties of the microstructural constituents and their interfaces, which sometimes interact in complex manner. The microstructural morphology and properties may also evolve under macroscopic thermal and mechanical loadings. Consequently, these microstructural influences are of great importance in production approaches and the life performance of the material and products made thereof. The existence of the inherent micro-voids may affect the mechanical properties of the material significantly [11]. By increasing loading, nucleation and growth of these micro-voids take place and lead to micro-cracks that may propagated until eventual rupture. Therefore, for an accurate FE simulation, inherent micro-voids in heterogeneous material should be considered [12]. Regarding simulations in contact problems, an attempt has been made to study the effect of micro-inclusions in contact loading [13] and a solution was presented to solve the problem of a rigid indenter sliding with friction on a half plane containing a near-surface imperfection in the form of a circular void or rigid inclusion [14]. Although in these previous studies, heterogeneity was considered under contact loading, no attempt has been made in the literature for fretting fatigue problems.

Fretting fatigue damage occurs when components in contact are subjected to fluctuating loads and relatively small displacements simultaneously. Since combination of several parameters related to the macroscopic mechanical response of a material leads to fretting fatigue failure, an acceptable level of understanding of the macroscopic fretting fatigue behaviour of heterogeneous material is mandatory for the efficient design of engineering structures in civil, mechanical and

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aerospace industries. Thus, it is essential to develop a quantitative link between the macro variables and its microstructural counterpart. Although the task can be achieved by performing an experimental study, it seems to be seldom practical from the time and cost point of view due to large number of fretting fatigue variables as well as due to the difficulty in accurately measuring few variables. Alternatively, DNS assimilating full microstructural details accompanied by a mesh discretization of sufficient resolution can be performed. However, most of the numerical studies in the literature on fretting problems [15–20] have considered only the case of homogenous materials, while no study can be found on heterogeneous materials. In DNS of turbulence modelling in fluid mechanics, the microstructure is modelled directly in a macroscale structure [21–23]. Recently, DNS has been applied to solid mechanics, where microscale and macroscale models have been combined in a single simulation [24–26]. Bishop et al. [24] has used DNS in solid mechanics to investigate the macroscale response of polycrystalline microstructures and performed 100 direct numerical simulations in which polycrystalline microstructures are embedded in a macroscale model. An investigation for quantifying macroscale effects of microstructure and material model-form error using in DNS in solid mechanics has been recently conducted [25]. Furthermore, the application of DNS to the micro or meso mechanics of porous piezoelectric materials has been recently reported [26].

In this paper, a study with the objective to evaluate the fretting fatigue stress behaviour of a heterogeneous material by direct numerical simulations (DNS) is presented for the first time. It also includes a brief description about the fretting fatigue contact problem, analytical solution along with the details of DNS, results and conclusions.

2. Analytical solution for homogenous materials

Analogous to any contact problem, contact stresses play a crucial role in the fretting fatigue problem. Hertz plane (2D) contact model, cylinder-flat contact in elastic body, can be used to calculate the normal stress distribution at the contact interface [1,2]:

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

where $p(x)$ represents the normal stress distribution, p_0 is the maximum normal contact stress and a is the semi contact width. In the contact model, where l is thickness, P is the normal load applied on the indenter, ν is Poisson's ratio, $R_1$and R_2 are the radii of contact surface of indenter and specimen, E_1 and E_2 are the moduli of elasticity of indenter and specimen, respectively, the maximum normal contact stress can be calculated as follows:

$$p_0 = \frac{2P}{\pi a l} \tag{2}$$

$$a^2 = \frac{2PA}{\pi k l} \tag{3}$$

where A and k are constants given by:

$$A = 2\left(\frac{1-\nu_1^2}{E_1}+\frac{1-\nu_1^2}{E_2}\right) \tag{4}$$

$$k = \frac{1}{R_1}+\frac{1}{R_2} \tag{5}$$

An example of normal stress distribution along the contact interface in the fretting fatigue specimen is shown in Fig. 1.

Cattaneo [27] and Mindlin [28] extended the Hertz' original theory to cover the application of tangential loads and the presence of friction at the interface respectively. The Coloumb friction model was employed:

$$q(x) = \mu p(x) \tag{6}$$

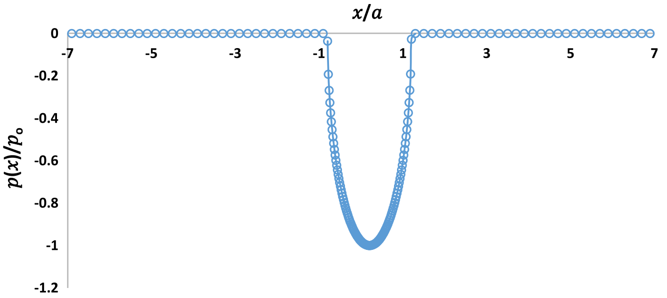

Fig. 1. Normal stress distribution along the contact surface.

where $q(x)$ is the shear traction at point x and μ is the coefficient of friction. In this case, the Coloumb friction law is applied on a local basis, i.e. if the shear traction at any point is less than the critical value $\mu p(x)$, no relative displacement occurs. However, if the Coloumb limit is reached at any point along the surface, the shear traction at this point is essentially the pressure scaled by μ, i.e.:

$$q'(x) = -\mu p_0\sqrt{1-\left(\frac{x}{a}\right)^2} \tag{7}$$

If the global Coloumb friction limit is not exceeded, a central stick region of width 2c will exist, where c can be calculated from:

$$\frac{c}{a} = \sqrt{1-\frac{Q}{\mu P}} \tag{8}$$

A shear traction in the region $-c < x < c$ is given by:

$$q''(x) = -\mu\frac{c}{a}p_0\sqrt{1-\left(\frac{x}{c}\right)^2} \tag{9}$$

The effect of the bulk stress is to create an eccentricity to the Mindlin Cattaneo shear traction distribution:

$$q''(x) = -\mu\frac{c}{a}p_0\sqrt{1-\left[\frac{x-e}{c}\right]^2} \tag{10}$$

where $e = \frac{\sigma_{axial}a}{4\mu p_0}$. Please note that the distribution $q''(x)$ is a corrective distribution that must be added to the full sliding distribution $q'(x)$ at the stick zone ($|x+e| < c$).

The shear traction at the stick zone is given by superposition of $q'(x)$ and $q''(x)$, i.e.

$$q(x) = -\mu p_0\sqrt{1-\left(\frac{x}{a}\right)^2}+\mu\frac{c}{a}p_0\sqrt{1-\left[\frac{x-e}{c}\right]^2} \tag{11}$$

An example of shear stress distribution along the contact interface using this analytical solution is depicted in Fig. 2.

3. Direct numerical simulations of fretting fatigue

The objective of this section is to evaluate the fretting fatigue stress behaviour of a heterogeneous material. We propose to use DNS in solid

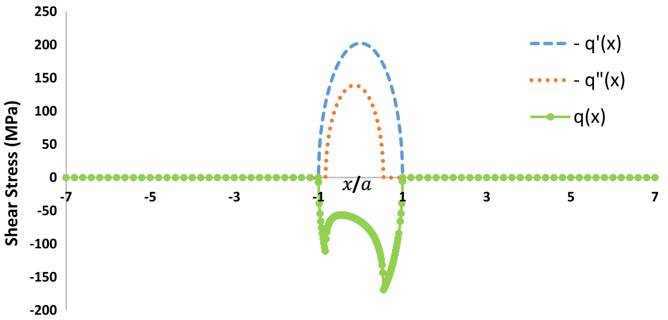

Fig. 2. Shear stress distribution along the contact surface.