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Finite element analysis of fretting contact for dissimilar and nonhomogeneous materials

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Abstract

Fretting problem arises in the case of relatively small sliding motion between contacting surfaces leading to reduction in fatigue life of these parts significantly. The purpose of this study is to investigate the effects of fretting on the contact region in a cylindrical on flat contact configuration. In order to identify fretting contact, a finite element (FE) model was constructed by using commercial finite element package ABAQUS™. Fretting contact is studied under two types of loading: tangential loading of the pad and axial bulk stress loading of the specimen. The numerical calculated stresses are compared with Mindlin analytical solution and Nowell and Hills analytical solution (which includes the effect of bulk stress). In order to get a better estimate of fretting in real type structures such as bolted joints and lug type structures, dissimilar materials in the contact region are then studied. For dissimilar materials, in the light of the conducted numerical analysis, Mindlin solution does not give reliable results in terms of shear traction distribution when compared to FE results. Finally, the effect of non-homogeneity in materials is investigated by addition of circular voids.

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Keywords: fretting; fatigue; finite element modeling; contact modeling; friction

1. Introduction

When relative small sliding takes in place between two contacting surfaces, failure due to fretting can occur. This situation is observed in different kinds of parts, such as bolted joints and lug attachments of aircraft and helicopters. Waterhouse (1992) reported that bolted and riveted structures which are subjected to fluctuating loads are possible sources of fretting fatigue failures. Fatigue life of these parts may be significantly reduced due to fretting. To observe the effect of the fretting in the contact region, numerous work in literature can be found with both analytical and finite

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element (FE) methods. Hertz (1881) developed an analytical approach (Hertzian contact theory) to investigate the pressure distribution in the frictionless contact region between two elastic materials. Later, Mindlin and Deresiewicz (1953) further developed Hertz contact theory by adding the effect of tangential loading and corresponding friction at the contact interface. Mindlin theory gives the shear traction distribution at the contact interface in addition to the stick and slip regions in the contact region. However, this theory cannot simulate the bulk stress effect in calculations of the shear traction distribution. This effect is considered by Hills and Nowell (1986) where they modified the Mindlin theory to investigate the bulk stress effect in the contact region in terms of shear traction distribution. Furthermore, Nowell (1980) showed that Mindlin theory for shear traction calculations is only valid for contact between elastically similar materials. Finite element analysis has an opportunity to identify and compare different situations by taking the geometrical non-linearity into account in the contact region for various loading conditions and geometries. Numerous studies were carried out to model fretting contact by using finite element methods in the literature. For example, Ruiz et al. (1984) and Stower et al. (1985) simulated fretting contact using FEA. Lee and Mall (2003) reported the effect of dissimilar materials on fretting fatigue behavior of Ti-6Al-4V. Giner et al. (2008) used extended finite element method to numerically calculate crack propagation in the contact region. Kim et al. (2011) simulated fretting fatigue using both 2D and 3D finite element analysis and compared the results. In this study, we investigate the effect of friction coefficient and material dissimilarity on the stress distribution. In addition, the effect of tangential loading of the pad vs. applied axial bulk stress on the specimen to generate a shear traction on the contact region is investigated. Finally, material non-homogeneity in cylindrical on flat fretting contact configuration is investigated by introduction of holes near the contact region.

2. Theoretical Background

A brief description of the theories, which are necessary to verify finite elment results from this work are reported in this section. Hertzian contact theory is used to calculate the contact pressure and to determine the contact area between the two different elastic bodies without friction (Fig. 1). This theory is only valid when the effective radius of curvature is extremely greater than the semi contact width.

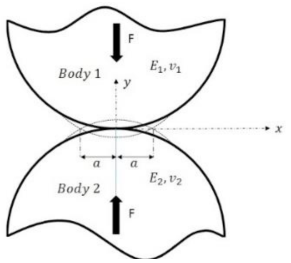


Figure 1 Representative view of Hertzian contact

According to Hertzian theory, when a normal load is applied to two cylindrical bodies in contact, a rectangular contact area forms between the two bodies under deformation with a pressure distribution. This contact pressure becomes maximum at the center of the contact region and becomes zero at the edges of contact as,

$$p(x) = -\frac{2F}{\pi a l}\sqrt{a^2 - x^2} \tag{1}$$

where *p(x)* is the contact pressure, *F* is the normal load, *l* is the thickness, and *a* is the semi-contact width given by,

$$a = \sqrt{\frac{2F}{\pi}\left(\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2}\right)\left(\frac{1}{R_1} + \frac{1}{R_2}\right)} \tag{2}$$

where E_i, ν_i, R_i are the elastic modulus, Poisson's ratio and radius of the top and bottom surfaces for $i=1,2$.

Mindlin and Dereiswicz (1953) further developed the Hertz theory to include the effect of the tangential load which takes into account the effect of friction coefficient. They divided the contact region into two regions consisting of stick and slip regions (Fig. 2). Part of the contact region where there is no relative displacement between the pad and the specimen is called the stick region and the other part where there is relative displacement is called the slip region (Nicholas, 2006).

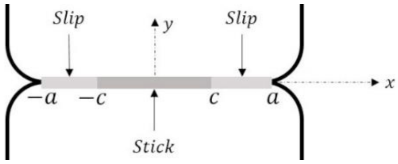


Figure 2 Representative view of the stick slip relation in the contact region

The shear traction distribution, $q(x)$, is calculated by,

$$q(x)=\begin{cases} -fp_{\max}\sqrt{1-(x/a)^2} & c\le|x|\le a \\ -fp_{\max}\left[\sqrt{1-(x/a)^2}-2\dfrac{c}{a}\sqrt{1-(x/c)^2}\right] & |x|<c \end{cases} \tag{3}$$

where f is the friction coefficient and c is the length of the stick region given by,

$$\frac{c}{a}=\sqrt{1-\frac{Q}{2fF}} \tag{4}$$

However, Hills and Nowell (1993) showed that when the shear loading is generated by an axial bulk stress applied to one component, the stick region is shifted by the eccentricity value e which causes a change in the shear traction distribution given by the following equation,

$$q(x)=\begin{cases} -fp_{\max}\sqrt{1-(x/a)^2} & c\le|x|\le a \\ -fp_{\max}\left[\sqrt{1-(x/a)^2}-2\dfrac{c}{a}\sqrt{1-\left(\dfrac{x+e}{c}\right)^2}\right] & |x+e|<c \end{cases} \tag{5}$$

3. Finite Element Modelling

In order to simulate the cylinder on flat contact configuration in the case of fretting contact a finite element model is generated using ABAQUS™. Half of the specimen is modelled due to symmetry conditions in the y-direction and the vertical movement along the bottom symmetry axis is restricted. Two loading cases are generated by loading points and boundary conditions: loading case 1) tangential loading of the pad, and loading case 2) bulk axial loading of the bottom specimen. For both cases, a specimen with length $L=40$ *mm*, width $w=5mm$ and thickness t=4mm was used (Hojjati-Talemi, 2014). The radius of the pad, R, was chosen as 10mm. In the first case, where the tangential load Q is applied to the pad, the horizontal movement of specimen along its side surfaces is constrained (Fig. 3a). In the second case, where a uniform axial stress is applied to the right boundary, the cylinder pad is restricted in the horizontal direction along its side surfaces and is free to move in the vertical direction (Fig. 3b). The loading is applied to the model in two steps. In the first step normal load applied and kept constant in the next step where a tangential load is applied. The loading conditions are given in the Table 1.

Table 1. The loading conditions of fretting fatigue contact. (Hojjati-Talemi et al. 2014)

	Step 1	Step 2
Normal Load [N]	543	543
Axial stress[MPa]	0	100
Reaction stress[MPa]	0	92.2

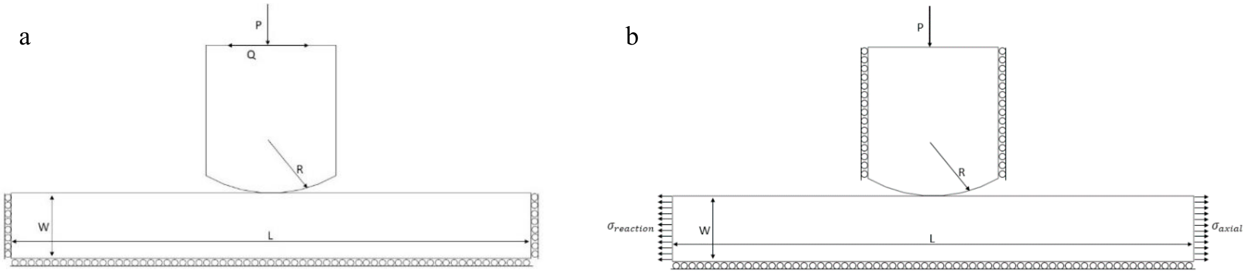


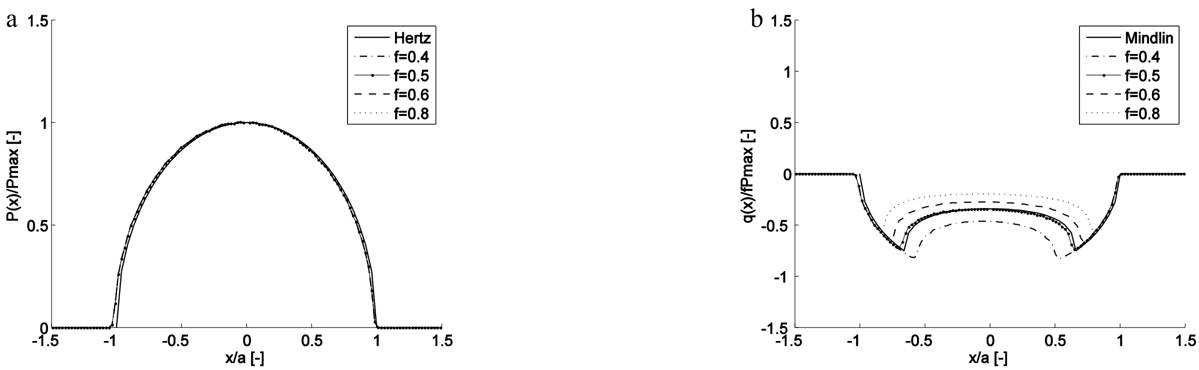
Figure 3 Geometric and loading conditions of (a) Fretting contact (b) Fretting fatigue contact

A 2D quadrilateral, 4-node, plane strain, reduced integration element (CPE4R) was used in the model. The mesh size at the contact area was selected as 5 μm by 5μm.The contact between the pad and the specimen was described by utilizing master slave algorithm in ABAQUS. The simulation of the Coulomb friction model was achieved by using Lagrange Multiplier formulation for the tangential behavior and Augmented Lagrange Algorithm for the normal behavior. Multi-Point Constraint (MPC) was used at the top of the pad in model in order to prevent pad from rotating because of the applied loads. The material of the specimen and pad was selected as Al2024 T3. In addition, the bimaterial was studied by changing the pad material to Steel 410. The modulus of elasticity is 72.1 GPa and the Poisson's ratio is 0.33 for Al2024 T3 and modulus of elasticity is 210 GPa and Poisson's ratio is 0.33 for Steel 410.

4. Results and Discussion

4.1. Loading case 1: Fretting Contact Under Tangential Pad Loading

In this section, the stresses and relative displacement in the specimen in the contact region is presented for the case of tangential loading of the pad. In addition, the effect of friction coefficient value and material dissimilarity between the pad and the specimen is discussed. The role of the friction coefficient on the contact region is examined in terms of contact pressure, shear traction distribution, tangential stress magnitudes and relative slip values.



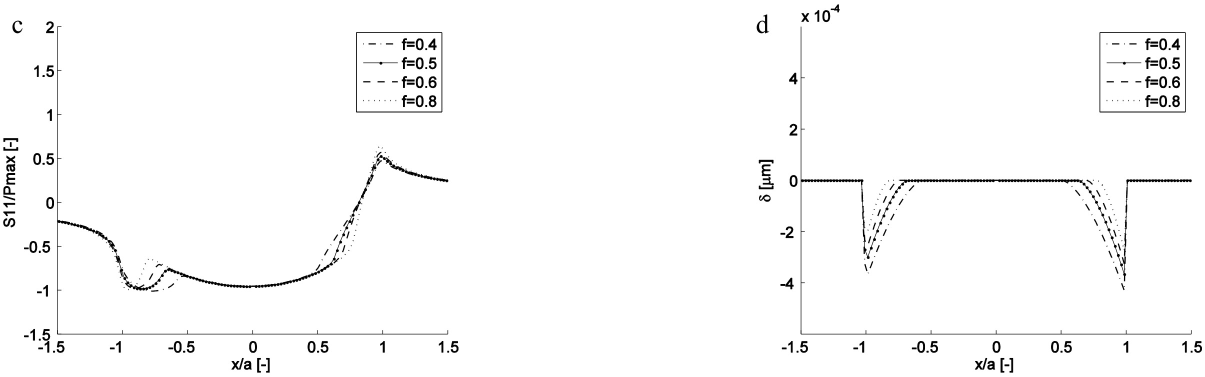


Figure 4 Variation of (a) Nomalized contact pressure distribution (b) frictional shear stress (c) normalized tangential stress (d) relative slip amplitude along the contact surface between the pad and the specimen.

For the same materials, the values of the friction coefficient are taken as 0.4, 0.5, 0.6 and 0.8 in the FE model. According to Hertzian contact theory, contact pressure does not depend on the friction coefficient which can be verified by finite element analysis (Fig. 4a). Contrary to contact pressure, shear traction depends on friction coefficient as shown in Fig. 4b where the stick region is found to increase with increase the friction coefficient *f*. The boundary of the stick-slip regions is given by a sudden decrease in the shear stress. For *f=0.5*, a good agreement is obtained with Mindlin solution. The stick region increases and contact area remains the same which can be seen in Fig. 4d. Tangential normal stress, used to predict the location of crack initiation, is plotted in Fig. 4c. Ruiz et. al. (1984) claimed that the location of crack initiation is at the point of maximum of tangential stress. However, the maximum value of tangential stress is found to be independent of *f* (Fig. 4c). Although tangential stress gives information about the

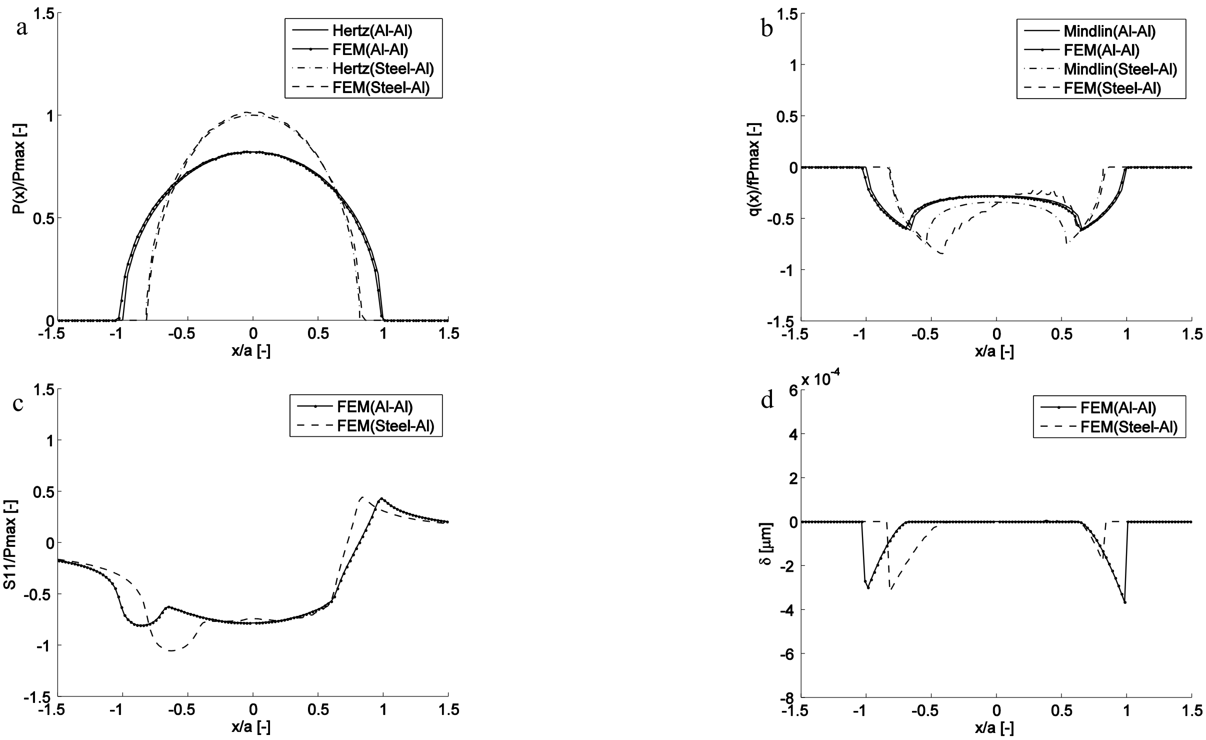


Figure 5 Variation of (a) Nomalized contact pressure distribution (b) frictional shear stress (c) normalized tangential stress (d) relative slip amplitude along the contact surface between the pad and the specimen.

location of initial crack, in order to get a better location estimation, tangential stress and relative slip should be combined. However, the value of the relative slip decreases when *f* is increased which can be seen in the Fig.4d.

The previous analyses were carried out for similar materials. However, especially in aerospace industry there exist many dissimilar materials in contact. To examine the effect of dissimilar materials on the fretting contact region Al2024 T3 and Steel 410 pad materials were used. The results are compared with Hertz and Mindlin solutions. Hertz solution is capable of calculating the exact pressure distribution in the contact region. When a steel pad is used the maximum value of contact region increases, total contact region decreases (Fig 5a). However, according to finite element results, Mindlin solution seems unsuccessful in capturing the shear traction distribution on the contact region for dissimilar materials (Fig 5b). The absolute maximum value of tangential stress for dissimilar materials is greater than that for similar materials as seen in Fig. 5c and the location of maximum tangential stress also moves closer to the center of the contact region. Stick regions are nearly symmetrical with respect to the center of contact region when similar materials are in contact. For dissimilar materials, stick regions shift in the opposite direction to the applied tangential load and the relative slip amplitude decreases (Fig.5d).

4.2. Loading Case 2: Fretting Contact Under Bulk Axial Stress

For comparison purposes with Case 1, the bulk axial stress magnitude applied is such that the tangential load created is equal to the tangential load directly applied to the pad in the previous section. It was shown that pressure distribution does not depend on tangential load, therefore, for both cases the similar contact pressure distribution were observed (Fig. 6a). However, eccentricity of the shear stress distribution was observed in the stick region shown in Fig. 6b. Even though the shape of the tangential stress distribution nearly remains same, it was observed that the tangential stress curve shifted upward which implies increase in maximum tangential stress (Fig. 6c). Compared to loading case 1, the relative slip amplitude decreases in the leading edge of the contact region and increases at the trailing edge (Fig 6d).

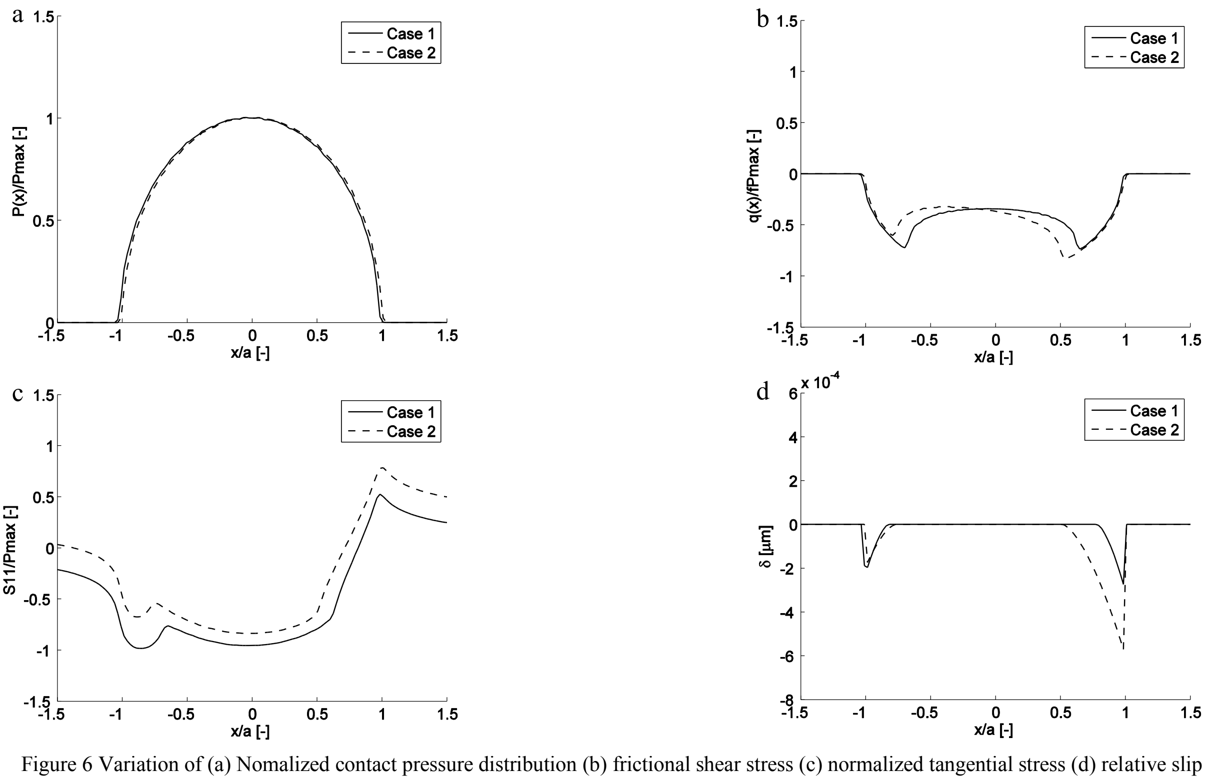


Figure 6 Variation of (a) Nomalized contact pressure distribution (b) frictional shear stress (c) normalized tangential stress (d) relative slip amplitude along the contact surface between the pad and the specimen.

In engineering applications, it is hard to use a perfectly homogeneous materials and voids may exist in real materials. Murakami and Endo (1994) stated the importance of those voids in engineering alloys in terms of fatigue crack formation. To observe the effect of a void, a circular hole was generated under the center of contact surface for loading case 2. The distance of center of circular void to the contact surface was taken to be equal to the diameter of the circular hole. Finite element analyses were conducted for two different hole radii of 0.1, 0.2 and 0.3 mm. The geometries and the von Mises stress distribution for hole radii of 0.1 and 0.3 are shown in Fig. 7a and 7b, respectively. A larger hole had the effect of redistributing the stress and alleviating the stresses in the contract region.

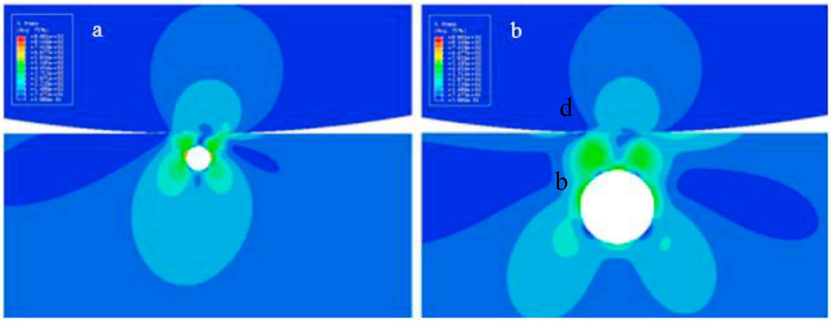


Figure 7 Von Mises stress contours (a) hole radius is equal to 0.1 (b) hole radius is equal to 0.3

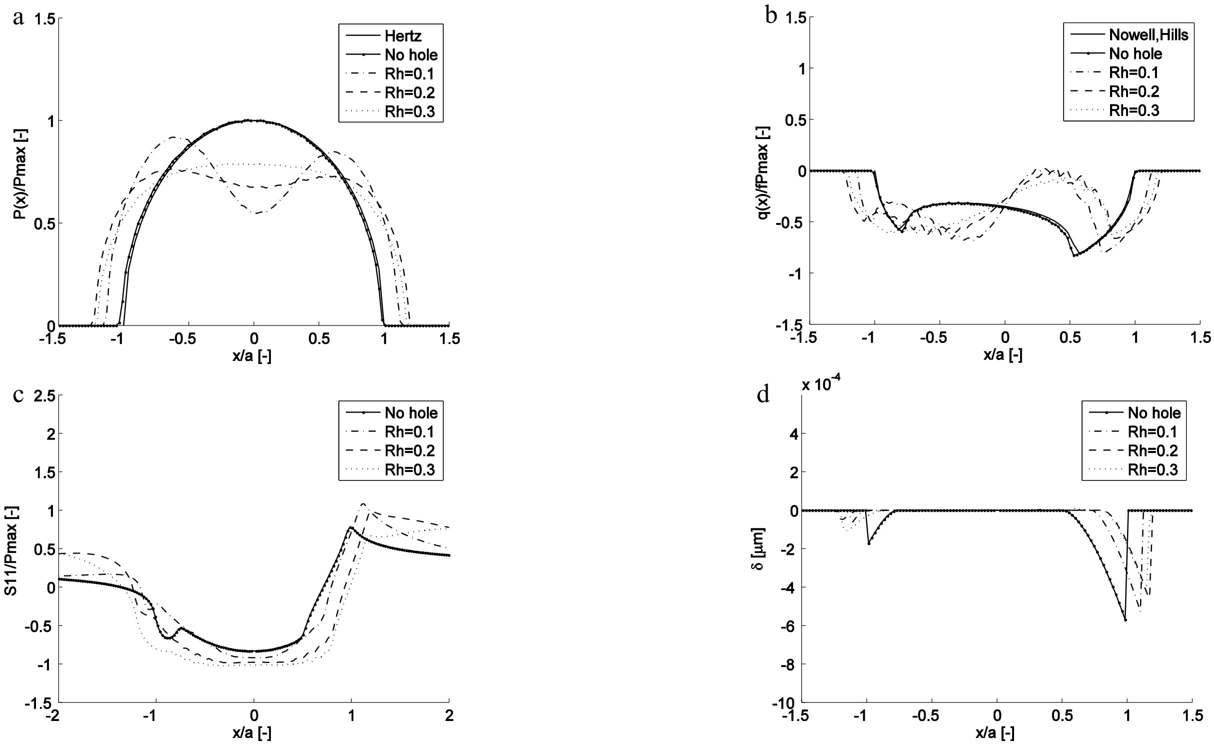


Figure 8 Nomalized contact pressure distribution (b) frictional shear stress (c) normalized tangential stress (d) relative slip amplitude along the contact surface between the pad and the specimen.

As shown in Fig. 8a, the maximum value of contact pressure decreases while the contact region grows with hole size. In addition, the contact pressure was found to gradually decreases at the center of contact region as the hole size increased (Fig. 8a). The absolute maximum value of shear traction distribution also decreases with a larger hole size as can be observed in Fig. 8b. In contrast, the maximum tangential stress tends to increase when a hole is inserted in the specimen (Fig 8c). Relative slip amplitude also decreases when a hole is inserted (Fig. 8d).

5. Conclusions

In this work, fretting contact conditions between a cylindrical pad and a flat specimen are examined using finite element analysis. The effect of friction coefficient, material dissimilarity, tangential loading case, and holes in the specimen on the stresses and the relative slip of the contact surfaces were investigated. In summary,

- Tangential load applied to the pad represented is used to observe the effect of friction coefficient and to compare similar and dissimilar materials. It was concluded that if the friction coefficient increases, then the stick region increases. A good agreement was found to exist with the theories.
- For dissimilar materials, although Hertz contact theory is capable of producing similar results with finite element analysis in terms of contact pressure, Mindlin solution is not aligned with the finite element results for shear traction distribution.
- Axial stress produces eccentricity in shear traction distribution which implies eccentricity in stick region as also stated by Hills and Nowell.
- Inserting a hole in a specimen near the contact surface decreases the maximum contact pressure and extends the stick contact region and reduces the relative slip amplitude.

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