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RESPONSE PREDICTIONS FOR FRICTION PENDULUM BEARINGS CONSIDERING THE DEPENDENCE OF FRICTION ON AXIAL PRESSURE, TEMPERATURE AND VELOCITY

Manish Kumar[1], Andrew Whittaker[2,3], and Michael Constantinou[2]

[1] Graduate student, Dept. of Civil, Structural and Environmental Engineering, University at Buffalo, Buffalo, NY (mkumar3@buffalo.edu)
[2] Professor, Dept. of Civil, Structural and Environmental Engineering, University at Buffalo, Buffalo, NY
[3] Director, Multidisciplinary Center for Earthquake Engineering Research (MCEER)

ABSTRACT

The global force-displacement relationship for the Friction Pendulum™ (FP) bearings is well understood for given material and geometrical properties. The coefficient of sliding friction, which influences the isolator response, is dependent on sliding velocity, temperature and pressure, and changes over the course of an earthquake as energy is dissipated at the sliding surface, producing changes in force-deformation behavior of the sliding. This paper presents the results of a numerical study considering the axial pressure, temperature and velocity dependence of the coefficient of friction. Relationships between the coefficient of sliding friction and pressure, temperature and velocity, based on limited test data, are presented. Response-history analyses are performed on FP bearings with friction behavior described using different models that consider or ignore the dependence of the coefficient of friction on velocity, temperature and pressure.

INTRODUCTION

Friction Pendulum™ (FP) bearings are commonly used devices for the seismic isolation of structures. These bearings in their single concave configuration comprise a spherical sliding surface of polished stainless steel and an articulated slider coated with a PTFE-type composite material. Figure 1 shows a section through an FP bearing.

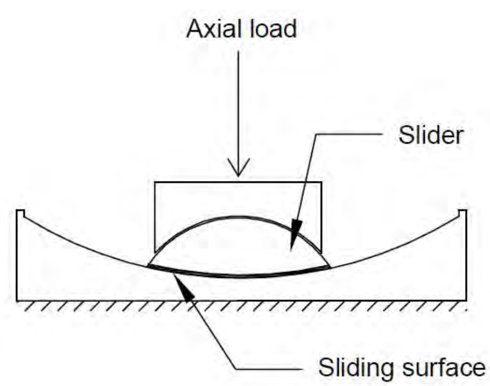


Figure 1: A section through a Friction Pendulum™ (FP) bearing

The lateral force-displacement relationship of an FP bearing is completely defined by the coefficient of friction between the slider and the sliding surface, the axial load on the bearing, and the effective radius of curvature of the sliding surface. The effective radius of curvature depends on the radius of curvature of the sliding surface and the location of the geometrical center of the articulated slider. Figure 2 shows the lateral force-displacement relationship of an FP bearing with fixed values of the coefficient of friction, axial load and the effective radius of curvature. The relationship is characterized by the characteristic strength *Q*, the product of the coefficient of friction and the instantaneous axial load, and the post-yield stiffness *K*, the ratio of the instantaneous axial load and the effective radius of curvature. The yield displacement is about 1 mm (Constantinou *et al.* 2007).

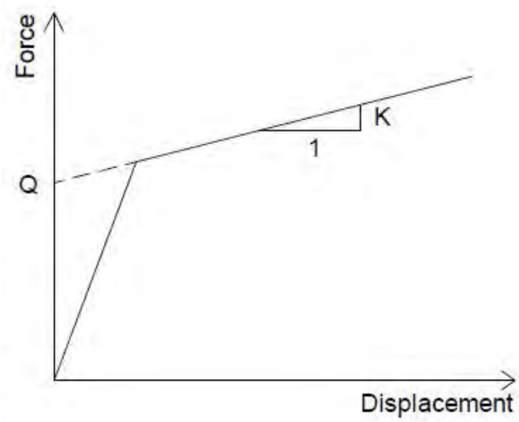


Figure 2: Lateral force-displacement relation of an FP bearing

The axial load on the bearing changes during the course of an earthquake due to the ground motion in the vertical direction and the frame action in the superstructure. Consequently, *Q* and *K* change continuously during an earthquake. The characteristic strength also changes as the coefficient of sliding friction updates with the velocity of sliding, axial pressure on the bearing and the temperature at the sliding surface. A brief introduction on the dependence of friction on velocity, pressure and temperature is presented below. A detailed discussion is presented in Constantinou *et al.* (2007).

The velocity dependence of friction is a result of the viscous nature of the PTFE-type composite material used as the coating material of the slider. The coefficient of friction increases to a constant value with a small increase in the velocity of sliding. A relationship describing the dependence of the coefficient of the velocity was proposed by Constantinou *et al.* (1990), which has been incorporated in some of the commercially available software programs such as SAP2000 (SAP 2013).

The coefficient of friction decreases asymptotically with an increase in the axial pressure. Mokha *et al.* (1996) present experimental data on the coefficient of sliding friction between different PTFE-type composite materials and polished stainless steel surface, at different levels of axial pressure measured at a low and a high velocity of sliding. To the best of authors' knowledge, there is only one software program 3D-BASIS-ME (Tsopelas *et al.* 1994) that has incorporated this pressure dependence of friction.

There is limited experimental data available on the temperature dependence of friction. However, it is believed that the coefficient decreases with increase in the temperature at the interface asymptotically to a value, which is about half of that at room temperature.

This paper defines the dependence of the coefficient of friction on velocity, pressure, and temperature, based on the information available in the literature. Five friction models are considered to study the aforementioned dependence. A single FP bearing with different levels of static axial load and different friction models is subjected to thirty ground motions. The results of the response-history analyses are presented.

DEPENDENCE OF FRICTION ON PRESSURE, TEMPERATURE, AND VELOCITY

A reference coefficient of friction μ_{ref} is considered, which is measured at a reference axial pressure, p_o, and at a high velocity of sliding. The initial temperature at the sliding surface, T_o, is 20˚C. To consider the effect of pressure, temperature or velocity, μ_{ref} is multiplied by factors given by following equations.

$$k_v = 1 - 0.5e^{-100v} \tag{1}$$

$$k_p = 0.70^{(p-p_o)/50} \tag{2}$$

$$k_T = 0.79 \times \left(0.70^{T/50} + 0.40\right) \tag{3}$$

where v, p and T are the velocity of sliding, the axial pressure and the temperature at the sliding surface, respectively, and k_v, k_p and k_T are the factors accounting for the effect of velocity, pressure and temperature on the coefficient of friction, respectively. The units of v, p and T are m/s, MPa and Celsius, respectively. All other parameters are defined previously.

This paragraph briefly describes the basis for the factors k_v, k_p and k_T. An equation to define the velocity dependence of friction was proposed by Constantinou *et al*. (1990). The factor k_v is obtained from the equation after making an assumption that the coefficient of friction measured at a small velocity of sliding is half of that at a high velocity of sliding, at all levels of axial pressure. Note that only high-velocity coefficient of friction changes with the axial pressure. The relationship for the pressure dependence of high-velocity coefficient of friction (and the factor k_p) was obtained by fitting a curve on the experimental data presented in Mokha *et al*. (1996) in the range of values of axial pressure FP bearings are normally subjected to. There is limited data to establish an accurate relationship between the coefficient of friction and temperature. It is assumed, based on the information presented in Constantinou *et al*. (2007), that at a high temperature the coefficient of friction decreases asymptotically to a value about half of that at room temperature. The value of the factor k_T, defined using Equation (3), is 1.0 at 20˚C which decreases asymptotically to 0.5 at 200˚C.

The method to compute temperature at a given point on the sliding interface is described in Constantinou *et al*. (2007) and is summarized here. The temperature at the sliding surface depends on the prior heating of the surface and its decay with time, and the instantaneous heat flux. The temperature rise ΔT at time t is calculated using the following expression.

$$\Delta T(x,t) = \frac{\sqrt{D}}{k\sqrt{\pi}} \int q(t-\tau) e^{\left(\frac{-x^2}{4D\tau}\right)} \frac{d\tau}{\sqrt{\tau}} \tag{4}$$

where x is the depth measured from the sliding surface, D is the thermal diffusivity of steel, k is the thermal conductivity of steel and q is heat flux. The instantaneous heat flux at the point is the product of the instantaneous values of coefficient of friction, axial pressure and the velocity of sliding, if the point falls within the square with its area equal to the contact area at the sliding surface, its geometrical center coinciding with the instantaneous geometrical center of the contact area and its sides oriented either parallel or perpendicular to the line joining the point and the instantaneous geometrical center of the square, and zero otherwise. The temperature at the point on the sliding surface is calculated as the sum of the initial temperature, T_o, and the temperature rise, ΔT. For this study, the temperature at the center of the sliding surface was used to compute the factor k_T using Equation (3).

GROUND MOTIONS

Thirty ground motions scaled to match the geomean spectra with an annual frequency of exceedance of 10^{-4} for the site of a nuclear power plant at Diablo Canyon were considered. The length of the ground motion records was 40 s with the acceleration ordinates defined at intervals of 0.01 s. The procedure for selecting and scaling the ground motions is presented in Huang *et al.* (2009). Figure 3 shows the response spectra of the ground motions in the three orthogonal directions.

Figure 4 shows the duration of strong shaking for the thirty ground motions estimated using the approach suggested by Trifunac and Brady (1975). The duration of strong shaking is the greater of the values computed in the two horizontal directions. Of the thirty ground motions considered, the minimum duration of strong shaking is for ground motion number 20 (6.6 s) and the maximum duration is for ground motion number 29 (28.2 s).

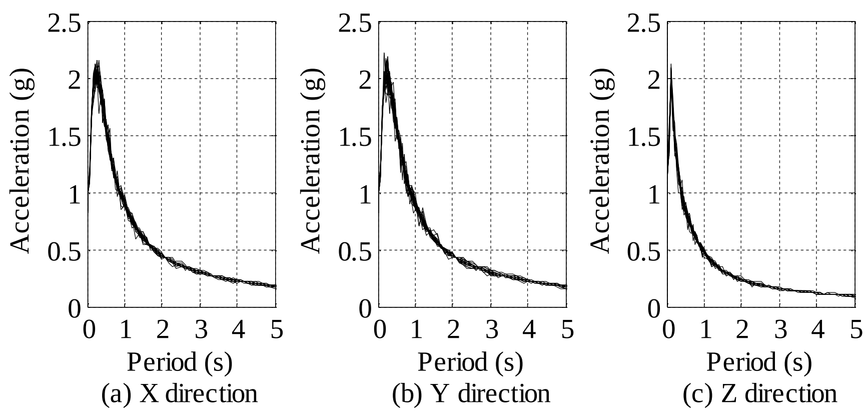


Figure 3: Response spectra of the ground motions

MODELING AND ANALYSIS SCHEME

A model of an FP bearing to incorporate the effects of velocity, axial pressure and temperature at the sliding interface on the coefficient of friction should be able to update the coefficient of friction at every step of the analysis. The open-source software program OpenSees (OpenSees, 2012) is suitable for the task. An element *flatSliderBearing* available in OpenSees simulates the behavior of a flat slider. The source code for the element was modified so that the new element would update the coefficient of friction at every step of analysis. In addition, expressions for the shearing force in the two horizontal directions and the lateral stiffness matrix were modified to include the effect of the curvature of the FP bearing. The vertical motion due to the curvature of the bearing was ignored. The axial force was set equal to zero in the event of uplift.

An FP bearing with a sliding period of oscillation 3 s was analyzed. Two values of reference axial pressure were considered: 10 MPa and 50 MPa. In practice, a reference coefficient of friction is achieved by combining static axial pressure and a PTFE-type composite material. Two bearings, one with a static axial pressure of 10 MPa and another with the pressure of 50 MPa, are considered, with the reference coefficient of friction set equal to 0.06 (this would be achieved with different composites). For each bearing, the pressure dependence of friction is described by two curves, obtained using Equation (2). The radius of the area of contact at the sliding surface was 200 mm. The entire mass associated with the static axial load was considered to be active in the three orthogonal directions. The bearings were subjected to thirty ground motions, each with three components. Analyses were performed with friction described by the five models of Table 1.

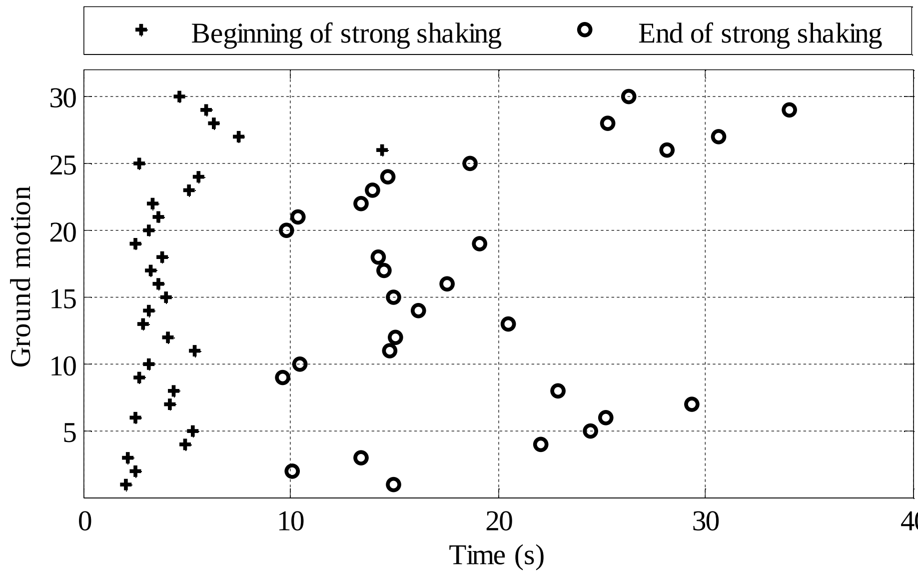


Figure 4: Duration of strong shaking for the ground motions

Table 1: Friction models considered for the study

	Friction model	Notation
Model 1	Coulomb	$\mu =$ Coulomb
Model 2	Pressure dependent	$\mu = f(p)$
Model 3	Temperature dependent	$\mu = f(T)$
Model 4	Velocity dependent	$\mu = f(v)$
Model 5	Pressure, temperature and velocity dependent	$\mu = f(p, T, v)$

RESULTS

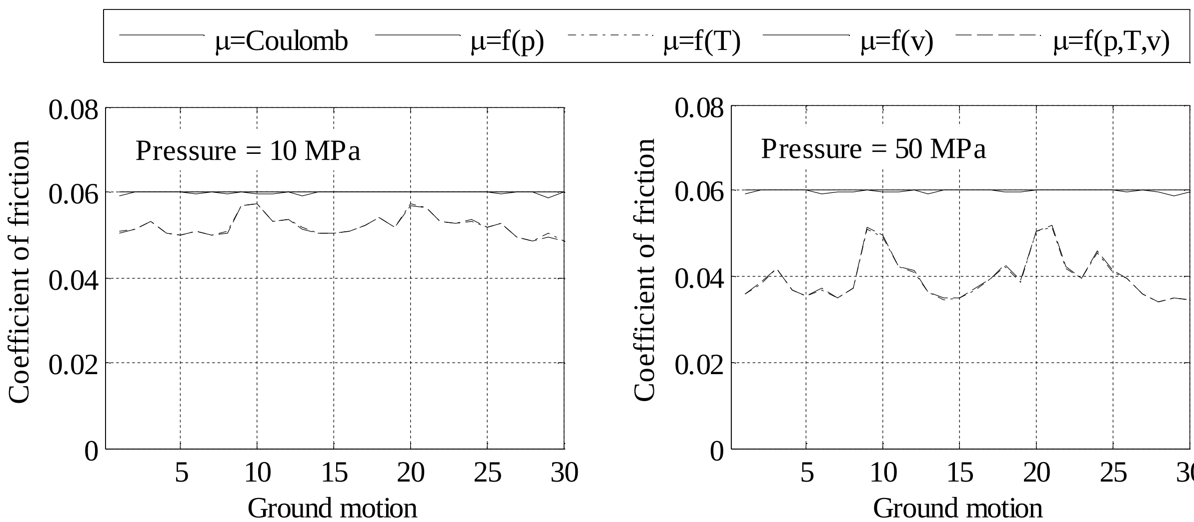
The FP bearings with all combinations of static axial pressure (10 MPa and 50 MPa) and friction models (see Table 1) were subjected to the thirty ground motions of Figure 3. The results of the response-history analyses are presented below.

Average Value of Coefficient of Friction

Panel (a) of Figure 5 presents the averaged values of the coefficients of friction for each ground motion calculated over the duration of strong shaking (see Figure 4) for the FP bearings with a static axial pressure of 10 MPa. It can be seen that the responses can be categorized into two groups depending on whether the friction behavior includes the effects of temperature or not. For example, for the bearing subjected to ground motion number 29, the average values of the coefficient of friction are 0.060, 0.060 and 0.059 if the friction is Coulomb type (Model 1), pressure dependent (Model 2) and velocity dependent (Model 4), respectively, whereas the values are 0.050 and 0.050, respectively, if the friction is assumed to vary only with temperature (Model 3) and is assumed to vary with pressure, temperature, and velocity (Model 5).

Panel (b) of Figure 5 shows the averaged values of the coefficient of friction for bearings with a static axial pressure of 50 MPa. The consideration of the temperature dependence of the coefficient of friction is more pronounced in this case compared to the bearing with the static axial pressure of 10 MPa. For the bearing subjected to ground motion number 29, the average values of the coefficient of friction over the duration of strong shaking are 0.06, 0.06 and 0.059, when the friction behavior is described by Model 1, Model 2 and Model 4, respectively, which do not include the effect of temperature on friction, and 0.035 for the remaining two models.

For the bearing with static axial pressure of 10 MPa subjected to ground motion number 29, the coefficient of friction averaged over the duration of strong shaking is 17% smaller when the temperature dependence of friction is considered in the analysis. The percentage difference is 42% for the bearing with a static axial pressure of 50 MPa. Averaged across all the ground motions, the values of percentage difference are 13% and 35% for the bearings with static axial pressure of 10 MPa and 50 MPa, respectively.



(a) Static axial pressure 10 MPa

(b) Static axial pressure 50 MPa

Figure 5: Averaged values of the coefficient of friction over the duration of strong shaking

Force-displacement Response

As discussed in the previous section, temperature affects the coefficient of friction much more than instantaneous axial pressure and velocity of sliding. The effect of the reduction in the coefficient of friction due to the increase in temperature at the sliding interface is a reduction in the characteristic strength Q (see Figure 2). As a result, the displacement demand on the bearing increases. Panel (a) of Figure 6 shows the force-displacement response of the bearing in a horizontal direction subjected to ground motion number 30. The static axial pressure on the bearing was 10 MPa with its friction behavior described by Coulomb friction. Panel (c) of the figure shows the response when temperature dependence of friction is incorporated in the analysis. The maximum displacement for the two cases is 230 mm and

310 mm, respectively. Similarly, panels (b) and (d) of the figure show the response corresponding to the Coulomb friction and temperature-dependent friction models, respectively, for the bearing with a static axial pressure of 50 MPa subjected to ground motion number 30. The maximum displacement in the horizontal direction is 230 mm when Coulomb friction is considered, which increases by 93% to 440 mm when the temperature dependence of friction is incorporated in the analysis. The temperature effects are expectedly more pronounced when the static axial pressure on the bearing is higher, as the heat generated on the sliding surface is directly proportional to the axial pressure. On the other hand, the difference between the maximum and minimum force ordinates for a given level of displacement is smaller for panel (c) compared to panel (a), and for panel (d) compared to panel (b), because of the reduction in the coefficient of friction associated with the increase in temperature.

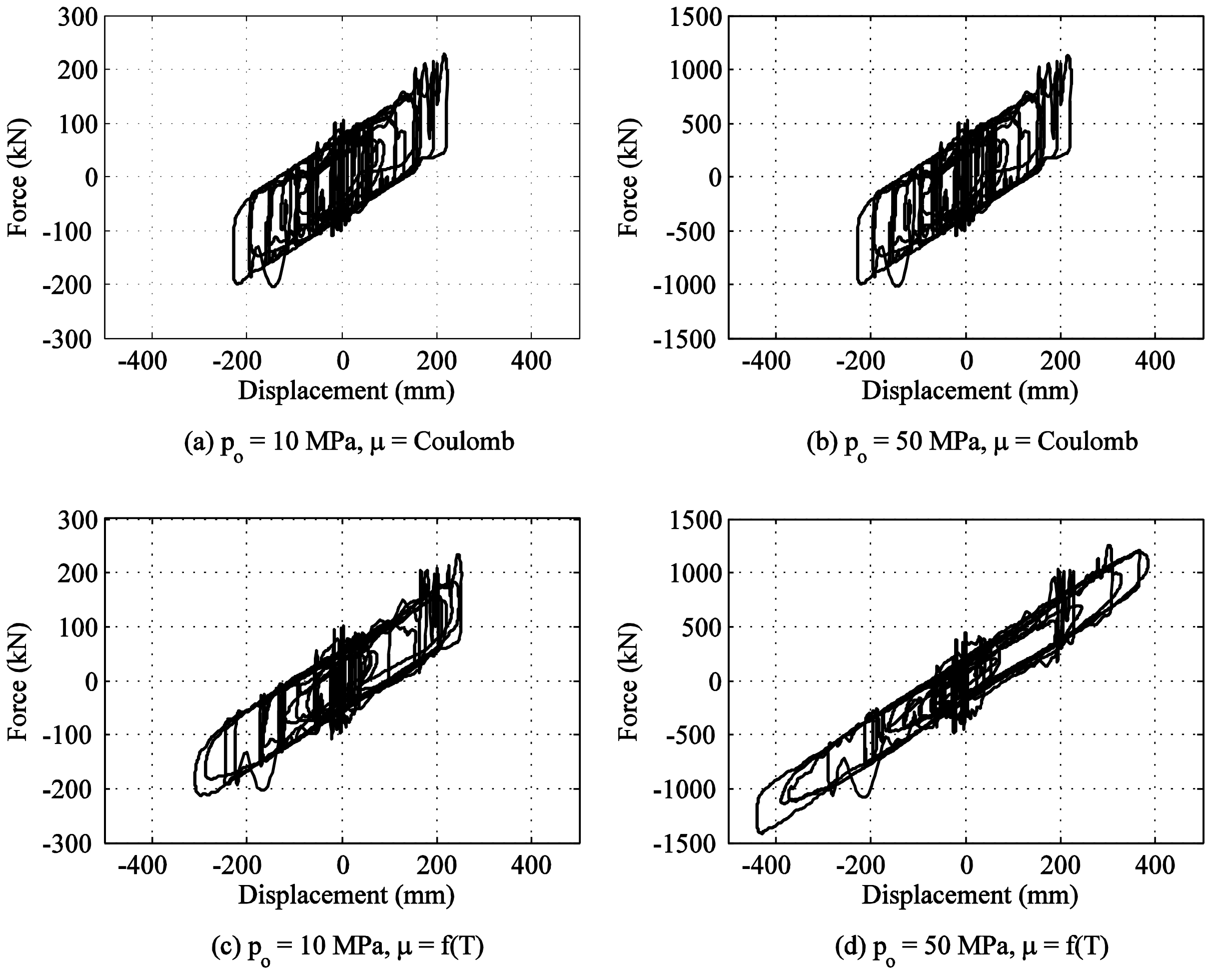


Figure 6: Force-displacement response of an FP bearing with different levels of static axial pressure and friction models

Distribution of Displacement Demand

Panel (a) of Figure 7 show the 16th, 50th, 84th and 99th percentiles of the displacement demand assuming a lognormal distribution of the responses obtained from the analyses of an FP bearing with the static axial pressure of 10 MPa subjected to the thirty sets of ground motions. Panel (b) of the figure shows the distribution of displacement demand for bearings with the static axial pressure of 50 MPa. As seen in panel (a), the percentiles do not differ considerably with the different definitions of friction for the bearing with a static axial pressure of 10 MPa. Conversely, panel (b) shows significant effect of the temperature dependence of friction for the higher value of static axial pressure, where the median displacement demand is underestimated by about 120 mm (or 20%), if the dependence is ignored. The effect reduces at higher percentiles. At the 99th percentile, the displacement demand is underestimated by only 40 mm (or 5%) if the dependence of friction on temperature is ignored. Consistent with the observations made previously, incorporating the pressure and velocity dependence of the coefficient of friction in an analysis does not significantly affect the distribution of displacement demand.

Distribution of Maximum Temperature

Figure 8 shows the 16th, 50th, 84th and 99th percentiles of the maximum temperature response at the sliding surface of the bearings subjected to the thirty ground motions, assuming a lognormal distribution of the temperature response. Panel (a) of the figure presents the results for the bearing with a static axial pressure of 10 MPa. The median temperature is slightly overestimated if the temperature dependence of friction is ignored in the analysis: 90˚C if the temperature dependence is ignored and 80˚C if the dependence is considered. The overestimation is greater for higher percentiles: the 99th percentile temperatures are 140˚C and 115˚C when the friction model ignores the temperature effects and when it does not, respectively.

For the FP bearing with a static axial pressure of 50 MPa, the maximum temperature at the sliding surface of the FP bearing is substantially overestimated if the temperature dependence of the coefficient of friction is ignored in the analysis, as shown in the panel (b) of Figure 8. The median estimate of the temperature response is 365˚C when the dependence was ignored and 230˚C when the dependence was considered. The 99th percentile values are 650˚C and 300˚C, respectively. It should be noted that the higher percentile estimates of maximum temperature response are associated with lower percentile estimates of displacement demand, and vice-versa.

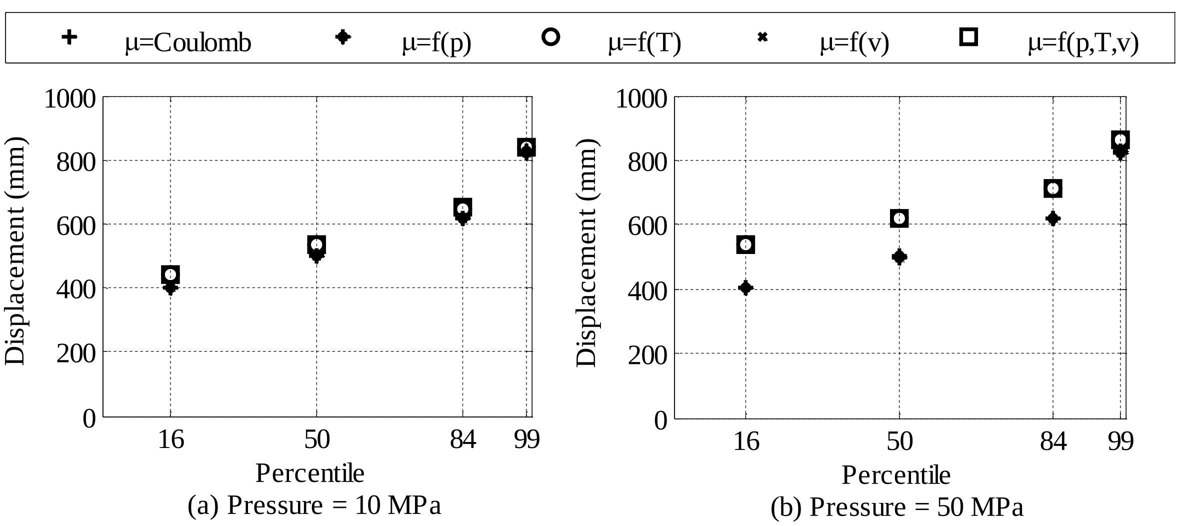


Figure 7: 16th, 50th, 84th and 99th percentile values of displacement demand on the FP bearing with different levels of static axial pressure subjected to 30 ground motions

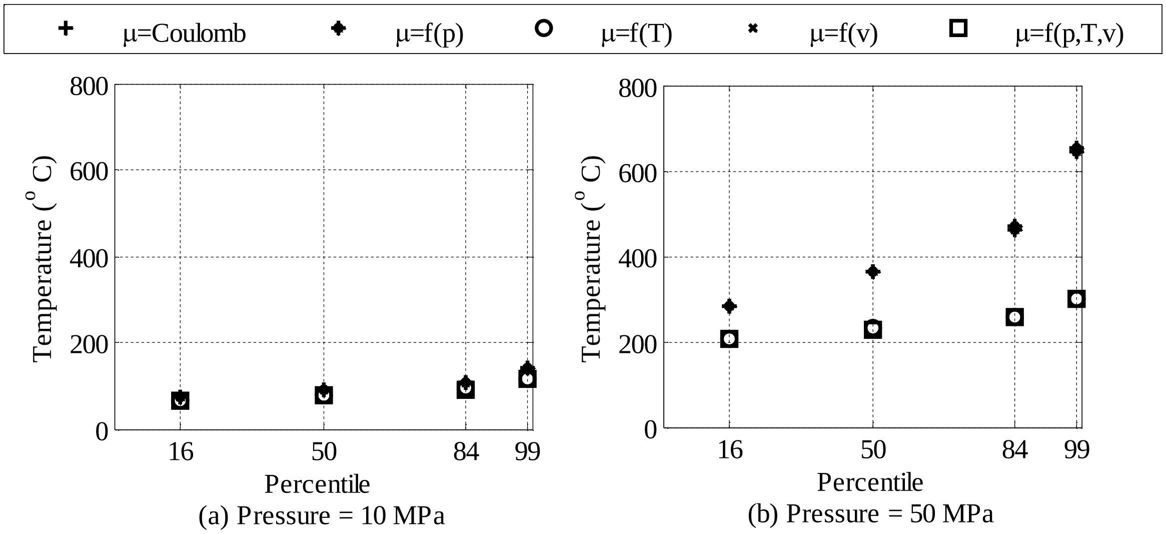


Figure 8: 16th, 50th, 84th and 99th percentile values of the maximum temperature on the sliding surface of the FP bearing with different levels of static axial pressure subjected to 30 ground motions

SUMMARY AND CONCLUSIONS

The frictional behavior of an FP bearing was described using five different friction models to study the effects of axial pressure, velocity of sliding and the temperature at the sliding surface on the coefficient of friction. The relationships between the coefficient of friction and pressure, velocity, and temperature were based on results of past experimental studies. Response-history analyses were performed on FP bearings with a period of oscillation 3 s and two levels of static axial pressure (10 MPa and 50 MPa). The reference coefficient of friction measured at respective values of static axial pressure (10 MPa or 50 MPa), at an ambient temperature of 20˚C and at a high velocity of sliding was set equal to 0.06.

The estimates of responses are most significantly influenced by the temperature-dependence of the coefficient of friction. Variations in the coefficient of friction due to sliding velocity and axial pressure over the course of an earthquake do not change the response significantly. The magnitude of the variation in the coefficient of friction was greater with higher static axial pressure. Averaged over all the thirty ground motions, the values of the coefficient of friction averaged over the duration of strong shaking were 13% and 35% smaller for the bearings with the static axial pressure 10 MPa and 50 MPa, respectively, when the temperature dependence of friction was incorporated into the analysis compared to when the dependence was ignored.

The median displacements were underestimated by 40 mm and 120 mm for the bearings with static axial pressure of 10 MPa and 50 MPa, respectively, when the temperature effects were not incorporated into the analysis. The magnitude of the underestimation at the 99th percentile level was 15 mm and 30 mm, namely, the higher percentile estimates of displacement were not significantly influenced by the choice of friction model.

The maximum temperature at the sliding surface response was overestimated when the temperature dependence of friction was not incorporated in the analysis. The overestimation in the median (99th percentile) maximum temperature was 10˚C (30˚C) and 135˚C (350˚C) for the bearings with static axial pressure of 10 MPa and 50 MPa, respectively. The magnitude of the overestimation of the maximum temperature increased for higher percentiles if the temperature dependence of friction was ignored. The choice of friction model does not considerably influence the higher percentile displacement demand and the lower percentile maximum temperature at the sliding surface response estimates, which is expected as the maximum temperature on the sliding surface is small (and so are the changes in the coefficient of friction) when the displacement demand on the bearing is high.

The conclusions from the study are summarized in this paragraph. Heating at the sliding surface affects the coefficient of friction most significantly during the course of an earthquake. The effects of instantaneous values of pressure and velocity on friction are negligible on the displacement demand and maximum temperature at the sliding surface responses. Median displacement demand on the bearing is significantly underestimated, especially at higher axial pressure, if the temperature effects are ignored. The magnitude of underestimation is small at higher percentile estimates. The maximum temperature at the surface response is overestimated when the temperature effects are not considered, and the magnitude of overestimation increases at higher percentiles. These conclusions are based on the analyses performed on FP bearings with one combination of period of oscillation and reference coefficient of friction subjected to one set of ground motions. The results and conclusions for bearings with different properties subjected to ground motions representing hazard at different locations are presented in Kumar *et al.* (2013).

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