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Wave and rupture propagation at frictional bimaterial sliding interfaces: From local to global dynamics, from stick-slip to continuous sliding

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ABSTRACT

This paper presents the results obtained from a 2D non linear finite element analysis under large transformations of the onset and evolution of sliding between two dissimilar isotropic elastic bodies separated by a frictional interface.

The aim of this work is to investigate the time evolution of the global behaviour of the system, and relating it to the local phenomena occurring at the interface. Results from the numerical parameter space study show how the system parameters affect local dynamics. Consequently, local dynamics affect the macroscopic frictional behaviour of the system and excite the system dynamic response. The evolution of the tangential force changes from stick-slip like behaviour to continuous sliding as a function of local phenomena.

1. Introduction

Dry frictional sliding along an interface between two deformable solids is an old but always relevant issue in mechanics. In addition to classical experiments, numerical analysis of dry contacts in sliding state has been a major topic in recent literature that has been enriched over the past three decades by several articles (see [1] and reference therein) reporting several approaches at different scales. While recent literature has dealt with either established sliding contacts or rupture (an initially sticking zone of the frictional interface that becomes in sliding state) propagation in static contact interfaces, the initiation of the sliding process and its relationship with local phenomena have rarely been investigated (see for example [2–5]). During sliding initiation, rupture is triggered at the zones of the interface where, initially, the local tangential contact stress reaches the critical value imposed by the friction law. These events, being confined local slips, will be referred to in the following as micro-slips. Conversely, the slip will be referred to as macro-slip when it involves a large part of the interface. This classification recalls the terms "slip" and "sliding" used in [2]; however, it should be pointed out that in this paper micro-slip means a more restricted slip zone (in line with the concept of single nucleated rupture. Each micro-slip behaves as a single nucleated rupture ([6] and reference therein) and radiates different types of waves along the interface and inside the bodies (longitudinal waves, shear waves, surface waves). The macro-slip activates waves of greater magnitude that reach the boundaries of the mechanical system, where they are reflected, triggering the global dynamics of the system and exciting so-called friction-induced vibrations [7,8]. Inversely, the interaction between the waves (direct and reflected/stationary) affects the evolution of the slip along the interface in a sort of closed loop, setting up coupling between local and global dynamics. This relationship between local processes at the interface and global dynamics of the system has not been investigated in depth in the literature and only a limited number of papers have specifically focused on this problem (see for example [9–12]).

In this context the purpose of the present paper is to analyze the onset and evolution of sliding, investigate how local dynamics occur at the interface, and determine how the relative precursors acting as distributed ruptures at the contact interface affect macroscopic sliding between the two bodies in contact. Understanding micro-slip and macro-slip mechanisms will allow artificially modification of the macroscopic frictional behaviour and limit wave propagation and local stress oscillations. This is a necessary step in reducing friction induced vibrations and their damaging effects.

Frequently in mechanical systems involving sliding friction, the two parts in contact are made of different materials. It is very intriguing that the fact of changing from similar to dissimilar

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materials makes the physics of the phenomena at the interface more complex due to the so-called bimaterial effect [13–15]. A large number of the studies devoted to dissimilar materials belong to the field of geophysics due to the fact that many faults where earthquakes originate bring different types of rock into contact [15,16]. In addition even if the rupture nucleates between two homogeneous media, the rupture front may switch to possible bimaterial interfaces parallel to the first one [17]. Regarding material contrasts up to the highest value for which the generalized Rayleigh (GR) wave exists [18,19], it has been shown in the literature that the in-plane slip (mode II) along the frictional interface causes dynamic changes of normal contact stress [14,15]. More precisely, for subsonic propagation, i.e., a velocity of propagation less than the shear wave speed, this phenomenon creates dynamic dilatation directly ahead of the rupture tip that propagates in the slip direction of the more compliant solid, and dynamic compression right ahead the rupture tip in the opposite direction [20]. In this contest a self-healing slip pulse can propagate (in the slip direction of the more compliant solid) at the GR wave velocity [14,16]. On the contrary, in the case of supershear or intersonic rupture propagation, i.e., a propagation velocity above the shear wave speed, the bimaterial effects are reversed [21].

As demonstrated in [13,19] the dynamic changes in normal contact stress increase with the propagation distance due to the continual transfer of energy to shorter wavelengths (Adams instability). This could result in ill-posedness of the problem and grid size dependence [22]. To investigate this problem, different types of simulations have been carried out with ([22,23]) and without regularised contact laws, in "a balanced way", as suggested by Ben-Zion [15]. This allows obtaining features common to the behaviours of the system and probably of the behaviour of the real underlying physical phenomenon, avoiding the elimination of essential features that the regularization of the contact law might cause.

The paper is organized as follows: Section 2 presents the formulation of the explicit dynamic finite element code (PLASTD) used to perform the simulations; the numerical model and the relative assumptions are also described. In Section 3 wave propagation during sliding initiation is investigated. In Section 4 a parameter space analysis is carried out to asses the influence of different parameters: frictional law, damping coefficient, friction coefficient, normal force, etc. The results are finally summarized in Section 5.

2. Simulation details

2.1. Finite element formulation and contact law

The explicit dynamic finite element code PLASTD (in 2D) is used to simulate the behaviour of the system (Fig. 1) during frictional contact. This software [24] is designed for large transformations and non-linear contact behaviour and applies a forward Lagrange multiplier method for the contact between deformable bodies [25]. For the dynamic study, the formulation is discretized spatially by using the finite element method and discretized temporally by using an explicit Newmark scheme named the β_2 method. The contact algorithm uses slave nodes (situated on the $P^{(1)}$ contact surface in Fig. 1) and target surfaces (on the $P^{(2)}$ contact surface) described by a four node quadrilateral element with a 2×2 Gauss quadrature rule. The elementary target segments are described by two nodes and approximated by bicubic splines [26]. The forward Lagrange multiplier method is formulated by equations of motion at time ($t^i = i\Delta t$) with the

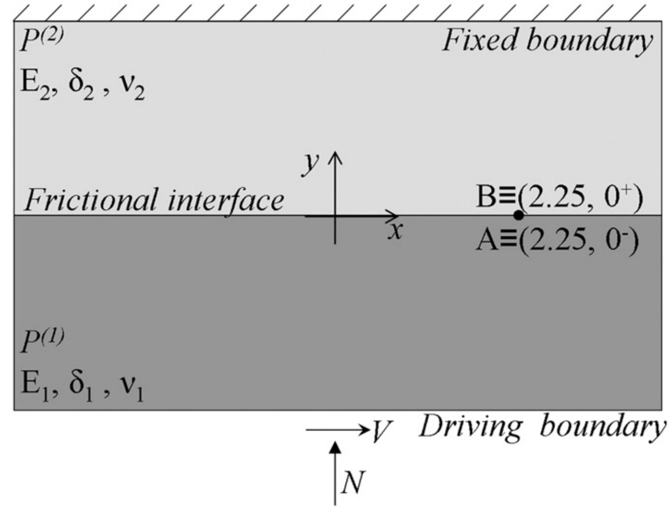

Fig. 1. Geometry of the 2D bimaterial model consisting their two bodies of 3×10 mm. The mesh consists of quadrilateral elements. The dimension l_1 of the element of the lower body remains in constant ratio r with the dimension of the element of the upper body l_2: $r = l_1/l_2 = 2.3$. This difference helps to ensure efficient implementation of the contact algorithm, avoiding possible numerical noise due to the symmetric mesh. N is compressive force and V translation velocity. Node $A \in P^{(1)}$ and node $B \in P^{(2)}$.

displacement conditions imposed on the slave node at time t^{i+1}:

$$\left\{ \boldsymbol{M}\ddot{\boldsymbol{u}}^i + \boldsymbol{C}\dot{\boldsymbol{u}}^i + \boldsymbol{K}\boldsymbol{u}^i + \boldsymbol{G}^{i+1^T}\boldsymbol{\lambda}^i = \boldsymbol{F}^i\boldsymbol{G}^{i+1}\{\boldsymbol{X}^i + \boldsymbol{u}^{i+1} - \boldsymbol{u}^i\} \le 0 \right. \tag{1}$$

where $\boldsymbol{M}$ and $\boldsymbol{K}$ are, respectively, symmetric and positively defined matrices of mass and stiffness of the system. $\boldsymbol{C}$ is the Rayleigh proportional damping matrix:

$$\boldsymbol{C} = (\alpha\boldsymbol{M} + \beta\boldsymbol{K}) \tag{2}$$

$\boldsymbol{X}^i$ is the coordinate vector at time t^i. $\boldsymbol{u}, \dot{\boldsymbol{u}}, \ddot{\boldsymbol{u}}$ are the vectors of nodal displacements, nodal velocities and accelerations respectively. $\boldsymbol{F}$ is the vector of nodal external forces. $\boldsymbol{\lambda} = [\boldsymbol{\lambda}_n \boldsymbol{\lambda}_t]^T$ contains, respectively normal and tangential contact forces acting on the slaves nodes at the contact surface. $\boldsymbol{G}^T = [\boldsymbol{G}_n^T \boldsymbol{G}_t^T]$ is the global matrix of the displacement conditions ensuring non-penetration and the contact law of the bodies in contact.

Vectors $\ddot{\boldsymbol{u}}^i$ and $\dot{\boldsymbol{u}}^i$ are expressed at each time step using a time scheme of type β_2 ($\beta_2 \in [0.5;1[$):

$$\left\{ \begin{array}{l} \ddot{\boldsymbol{u}}^i = \frac{2}{\Delta t^2}(\boldsymbol{u}^{i+1} - \boldsymbol{u}^i - \Delta t\dot{\boldsymbol{u}}^i) \\ \dot{\boldsymbol{u}}^i = \frac{1}{1+2\beta_2}\left\{ \dot{\boldsymbol{u}}^{i+1} + \Delta t(1-\beta_2)\ddot{\boldsymbol{u}}^{i\text{-}1} + \frac{2\beta_2}{\Delta t}(\boldsymbol{u}^{i+1} - \boldsymbol{u}^i) \right\} \end{array} \right. \tag{3}$$

The displacements $^*\boldsymbol{u}^{i+1}$ of the nodes situated on the contact surface ($P^{(1)}$ and $P^{(2)}$) are first computed with $\boldsymbol{\lambda}^i$ equal to $\boldsymbol{0}$. When β_2 is fixed to 0.5 (central difference method) the nodal displacements at time $^*t^{i+1}$ are obtained so that:

$$^*\boldsymbol{u}^{i+1} = \Delta t^2\boldsymbol{M}^{-1}(\boldsymbol{F}^i - \boldsymbol{K}\boldsymbol{u}^i) + 2\boldsymbol{u}^i - \boldsymbol{u}^{i-1} \tag{4}$$

A constraint matrix $\boldsymbol{G}^{i+1}$ is formulated for the slave nodes if they have penetrated through a target segment. Calculations of contact forces $\boldsymbol{\lambda}^i$ and nodal displacement at time t^{i+1} are then performed:

$$\left\{ \begin{array}{l} \boldsymbol{\lambda}^i = (\Delta t^2\boldsymbol{G}^{i+1}\boldsymbol{M}^{-1}\boldsymbol{G}^{i+1^T})^{-1}\boldsymbol{G}^{i+1}(^*\boldsymbol{u}^{i+1}) \\ \boldsymbol{u}^{i+1} = {}^*\boldsymbol{u}^{i+1} - (\Delta t^2\boldsymbol{M}^{-1}\boldsymbol{G}^{i+1^T}\boldsymbol{\lambda}^i) \end{array} \right. \tag{5}$$

Eq. (5) are solved using the Gauss–Seidel method.

If the Coulomb friction law is used, the following two contact conditions for each slave node k are checked during each