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## ADVANCES IN THE MODELLING OF CARBON/CARBON COMPOSITE UNDER TRIBOLOGICAL CONSTRAINTS

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### ABSTRACT

Thermo mechanical properties of Carbon-Carbon composite (C/C) allow them to support high temperatures without hard degradation. It is probably the main reason for their utilisation in industrial applications such as plane brake manufacture where are submitted to hard tribological stress (pressure and shear) during the landing phase.

To understand their behaviour under such sollicitations, the use of numerical tools appears as essential and thus for two principal reasons: the expensive cost of experimental tests as well as their limitations and their multi-scale feature.

Tools such as Finite element methods (FEM) (3) allow to separate the different scales and phenomena, and consequently to bring out their different role and to determine their impact on the dynamical behaviour of a contact. But using heterogeneous models to study the dynamical behaviour of such composites could lead to long time simulations. If numerical approaches such as homogenization techniques could be really efficient, the main difficulty is to use such techniques under dynamical contact conditions.

The present paper present the results based on an approach coupling an explicit integration of dynamics and an implicit global treatment of contacts (1). The local contact problem is solved using Lagrange multipliers and a Prakash-Clifton (5) law to manage the local friction. Comparison have been made between different heterogeneous models, called morphologies and the corresponding homogeneous model. The contact contrast is investigated (deformable/rigid (2) or deformable/deformable/contact (4)) and in each cases, instabilities regimes and morphologies are connected. Results are compared in terms of global friction amplitude, dissipated energy and instability regimes.

### INTRODUCTION

Due to their thermo-mechanical properties whose allow them to support high temperatures without degradation, the Carbon-Carbon composites (C/C) are materials frequently used in industrial applications such as plane brake manufacture, nozzles of propulsive systems or space shuttle wings. The structure of the composite relies on a combination of a pyrocarbone matrix and carbon strands. The matrix is stiffened by carbon fibres and is structured in strata. The strands are orthogonal to the strata and have a higher rigidity than the simple carbon fibres.

As for several composites, three scales could be distinguished in a first approximation. First of all, the scale of the whole composite could be considered as the macroscopic scale. Secondly, the scale of the carbon fibre could be called the microscopic scale. Finally, between

the two opposite scales, one can exhibit an intermediate scale, representing a Representative Elementary Volume of the composite, called the mesoscopic scale, mixture of carbon inclusions and carbon matrix.

Under aeronautical braking conditions, strong couplings occur between these different scales (7). These couplings concern the mechanical properties of the material but also thermal and physico-chemical ones. For example, during frictional processes, C/C composite exhibit a rapid transition of the friction value which takes place systematically from a weak value (0.15) to a high value (0.35). Some authors have shown recently that this specific behaviour could be understood only if the different physics are investigated simultaneously (6).

But even if the material have a multi-scale and a multi-physics behaviour, it is important to understand and determine the importance of each scale and each physics. For these purposes and overcome such problems, numerical tools have been developed and used to control each scale, each physics and also, when it is possible, their different interactions. Moreover contrary to experimental set-up, numerical tools offer the possibility to observe the behaviour of the interface during the dynamical process contrary.

In the way to understand the mechanical behaviour of C/C composite, in a previous study , a numerical model has been developed (2) to connect the different regimes of instabilities (8) and models morphologies. Random heterogeneous models have been used with the same strand volume ratio. Homogenization techniques have been used to obtain an average homogeneous composite equivalent to the different morphologies. However under certain loads (different pressures) and dynamic conditions, the heterogeneous models present different regimes of instabilities and in consequence a different behaviour of the average homogeneous model.

The purpose of the present works is to determine the origin of the local dynamics and related such phenomena to the structure of the material. For this reason, the influence of the contact contrast (rigidity of the plate versus the rigidity of the REV) is investigated.

After a short presentation of the mechanical background and the numerical model, simulations with different contact contrasts are performed and presented. A discussion concludes the paper.

## NUMERICAL FRAMEWORK

### Numerical approach

The finite element method used in the present work is based on a forward increment Lagrange multiplier method (1). This approach appears as an alternative formulation of the Lagrange multiplier which is compatible with explicit time integration scheme, useful when fast physical phenomena are studied. The approach is implemented in the code PLAST2 (11). This explicit approach have been already used for the analysis of contact instabilities (9) and several applications such as wheel-rail contact (10) and carbone composite (4).

The global equation of motion is discretised using a 2 time integrator (Newmark scheme). The information contains in the nodes of the system is transferred to the contact nodes using linear mappings. To obtain a solution of the contact problem, at each time step, a Gauss-Seidel per block algorithm is used, but is slightly modified to ensure that the contact force vectors satisfy contact conditions. For more details on the global scheme, refer to the initial works (1).

Each local contact vector are composed of a normal and a tangential part. The normal part is directly related to the unilateral constraint describe by the linear complementarity relation:

$$u_n \leq 0, \quad \sigma_n(\mathbf{u}) \leq 0, \quad u_n \cdot \sigma_n(\mathbf{u}) = 0 \quad [1]$$

where  $u_n$  represents the local violation or relative displacement and  $\sigma_n(\mathbf{u})$  the normal constraint associate to the displacement  $\mathbf{u}$ .

The tangential part is managed by a Prakash-Clifton law (5). The law suggests that there is no direct relation between the normal and tangential evolution of the constraints. The law proposes a gradual change of the tangential constraint which intervenes after a certain time or on a certain distance. To traduce this purpose, two parameters are necessary: The standard coefficient of friction  $\mu$  describes the relationship between the normal and the tangential constraint, and a time of regularization  $\kappa$  which intervenes the disturbance. This behaviour could be represent by the following system of equations:

$$|\sigma_t'| \leq \mu |\sigma_n| \rightarrow \dot{u} = 0 \quad \text{and} \quad \sigma_t = \sigma_t' \quad [2]$$

$$|\sigma_t'| > \mu |\sigma_n| \rightarrow \begin{cases} \dot{\sigma}_t = \frac{-\dot{u}_t}{u_t} (\sigma_t - \alpha \mu |\sigma_n|) \\ \alpha = \text{sign}(\sigma_t') \end{cases} \quad [3]$$

For more details of the law, the readers are invited to read the initial papers ().

### Numerical models

Four heterogeneous models with a random distribution of heterogeneities (strands) have been used. These models (56mm length and 16mm height) have an identical volume ratio of heterogeneities (~10%). The matrix and the strands have the same density (1770kg.m<sup>-3</sup>) and the same Poisson ratio (0.2) but have different Young modulus: 240GPa for the heterogeneities and 30GPa for the matrix.

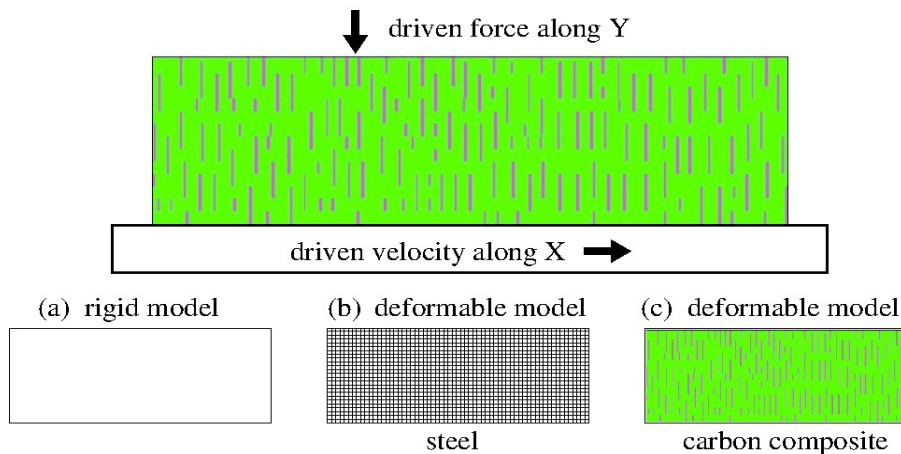


Fig. 1: Simulation models

For each model, a homogenisation is performed, leading to a set of four homogeneous models with variation in their properties less than 0.3%. From this set, an unique equivalent homogeneous model is build for which the properties are obtained from the average of four homogenous models properties.

To investigate the influence of the contact contrast, the study perform in (2) with a contact

between a deformable structure and a rigid plate (rigid contact) is performed with a contact between a deformable structure and a deformable plate (deformable contact) and a deformable composite (composite contact). The Young modulus of the steel plate is equal to  $210GPa$ . The driven sliding velocity  $V$  is equal to  $2m.s^{-1}$ , the friction coefficient is equal to 0.25, and the time of regularisation given by the relationship  $\kappa = u_t / \dot{u}_t$  is equal to  $300dt$  (with  $dt = 5ns$ ).

## RESULTS

### Evolution of global friction coefficient

First, simulations have been performed between morphologies and a rigid steel plate. The graph on the left of Fig. 2 shows the evolution of the global friction coefficient during the simulation process for a rigid contact. All morphologies present as well as the equivalent homogeneous mode present the same instability regime (sliding-detachment regime) with a sliding ratio of 75%, which correspond to the percent of sliding over the contact nodes and the simulation time. The mean vibration frequency is equal to  $41233Hz$  and the mean global friction is equal to 0.17.

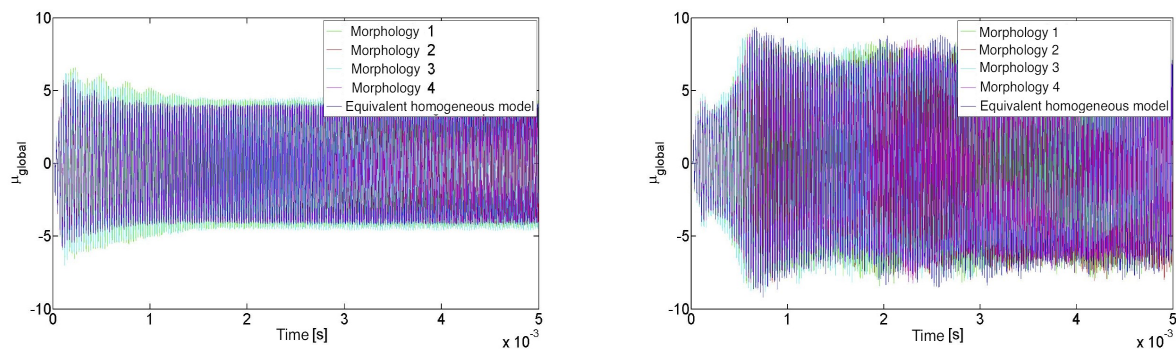


Fig. 2: Evolution of global friction coefficient for a rigid contact (left) and a deformable contact (right) for the set of parameters  $P=0.5 MPa$ ,  $\mu = 0.25$  and  $\kappa = 1500 ns$ .

The graph on the right of Fig. 2 shows the evolution of the global friction coefficient during the simulation process for a deformable contact. The evolution is characterized by a transient regime of  $0.75ms$ , follows from a steady state. Morphologies and equivalent homogeneous model present a quasi-equivalent evolution. They present a sliding-detachment regime with a detachment ratio of 80%. The mean vibration frequency is equal to  $39932Hz$  and the mean global friction is equal to 0.2.

Thus according to the rigidity of the plate, instability regimes could be different. Nevertheless the morphologies evolve in the same regime equivalent to the equivalent homogeneous model regime.

After using a steel plate as antagonist body, a contact between morphologies and equivalent homogeneous model is performed (composite contact). Such a contact allows to check the influence of the heterogeneities distribution in the morphology by taking into account only the distribution of upper body. The evolution of global friction coefficient  $\langle \mu \rangle$  for the different morphologies are represented by their envelop (Fig. 3). This evolution is characterized by periodic amplitude variation, that not occur previously. This phenomenon, well known in acoustic, is called “beat phenomenon” and its the result of vibration of two bodies in contact with closed eigenfrequencies.

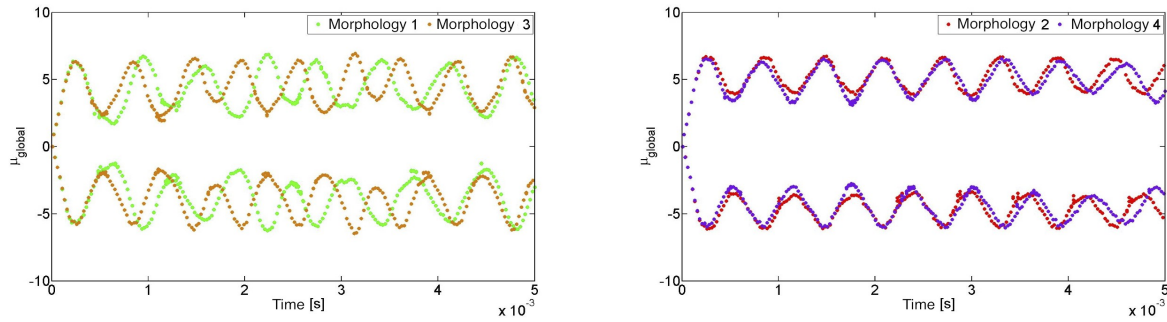


Fig. 3: Evolution of global friction coefficient for a contact between heterogeneous and homogeneous models for the set of parameters  $P=0.5 \text{ MPa}$ ,  $\nu = 0.25$  and  $\tau = 1500 \text{ ns}$ .

Morphologies 2 and 4 present an evolution of  $\langle \mu \rangle$  characterised by constant periodic variation with the same amplitude. This grouping corresponds with the grouping observed in a contact between morphologies and steel plate but for higher pressure (2). Morphologies 1 and 3 present the same kind of evolution but, even if the amplitude in the variation of  $\langle \mu \rangle$  are equal, the period of oscillations is different. The mean vibration frequency is equal to  $38732 \text{ Hz}$  and the mean global friction is equal to 0.219.

Finally a contact between morphologies is performed. The figure shows the evolution of the global friction coefficient for a contact between morphologies  $i$  and  $i$  (called contact  $i_i$ ). Morphologies 2 and 4 present an evolution of  $\langle \mu \rangle$  characterised by constant periodic variation with the same amplitude.

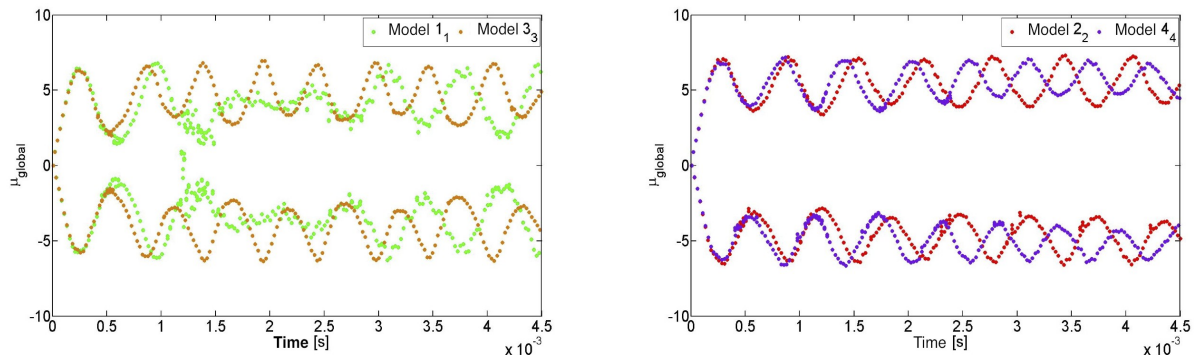


Fig. 4: Evolution of global friction coefficient for a contact between two heterogeneous morphologies for the set of parameters  $P=0.5 \text{ MPa}$ ,  $\nu = 0.25$  and  $\tau = 1500 \text{ ns}$ .

But one can observe a temporal shift during the simulation. For morphologies 1 and 3, even if the first steps of the simulations are really closed, the comparison is nearly impossible due to the presence of a perturbation in the evolution of  $\langle \mu \rangle$  for contact  $1_1$ .

Thus as second conclusion according to the contrast of rigidity of the antagonist body, the morphologies could evolve with different instability regime and consequently exhibit a behaviour different of the behaviour of the equivalent homogeneous model.

### Evolution of upper composite internal energy

To check the differences observed with the *composite contact* in regard of the *rigid* and *deformable contact*, the evolution of the internal cumulated energy have been plotted on Fig. 5.

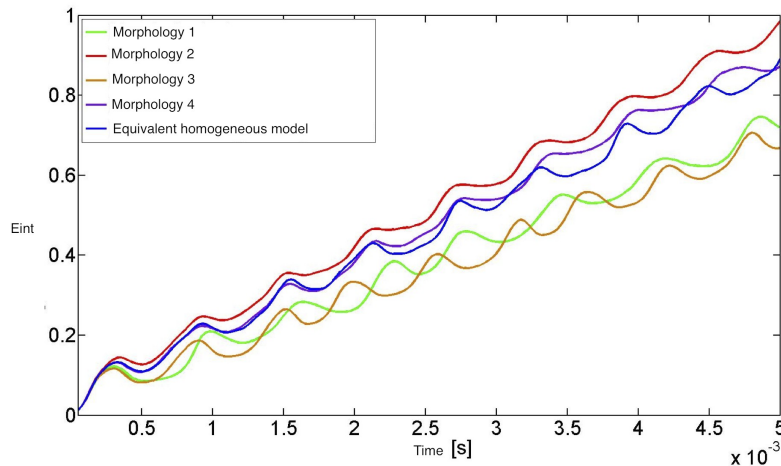


Fig. 5: Evolution of the cumulated internal energy  $E_{int}$  for a composite contact

One can observe again the grouping of morphologies 2 and 4 as well as the grouping of morphologies 1 and 3. The slope coefficient of the cumulated energy of morphologies 2 and 4 is respectively equal to  $185J.s^{-1}$  and  $171J.s^{-1}$ . For the morphologies 1 and 3 the slope coefficient is smaller, respectively equal to  $139J.s^{-1}$  and  $131J.s^{-1}$ . The equivalent homogeneous model exhibits a behaviour closed to the first group (morphologies 2 and 4).

## CONCLUSION

For a pressure and a given contact contrast, a heterogeneous model may have distinct regimes of instabilities, however, a set of heterogeneous models which has a similar instability in contact deformable / rigid, has a similar instability contact deformable / deformable. But the regimes of instabilities in contact deformable / deformable and deformable / rigid may be different.

Moreover one could observe that the choice of the model could have a strong influence on the macroscopic results and their consequences. This last point underlines the fact that, in view to tend to predictive models, one must be careful in the choice of the different parameters as well as in the interpretation of corresponding results.

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