Numerical and experimental study of C/C composites under tribological loading

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NUMERICAL AND EXPERIMENTAL STUDY OF C/C COMPOSITES UNDER TRIBOLOGICAL LOADING

ETUDE NUMERIQUE ET EXPERIMENTALE D'UN COMPOSITE C/C SOUS SOLLICITATION TRIBOLOGIQUE

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Abstract

This work is devoted to the numerical study of a composite under dynamic tribological loading. The aim of this study is to define an homogeneous model, obtained for static loading and built from an heterogeneous one, that represents the real behavior of the composite. The equivalence of the vibratory behavior between homogeneous and heterogeneous models is emphasized. This equivalence has been studied under dynamical loading without contact. Then a non linear dynamical explicit finite element model is used to check if the homogeneous model represents the heterogeneous ones under dynamic tribological loading. Finally an experimental work, that confirms presence of high frequencies obtained numerically, is discussed.

Résumé

Ce travail est dédié à l'étude numérique d'un composite sous sollicitation tribologique dynamique. Le but de cette étude est de définir un modèle homogène, obtenu pour des sollicitations statiques et construit à partir d'un modèle hétérogène, qui représente le comportement rée du composite. L'équivalence du comportement vibratoire entre un modèle hétérogène et un modèle homogène est mise en lumière. Cette équivalence a été étudiée sous sollicitation dynamique sans contact. Puis un modèle éléments finis en dynamique explicite non linéaire est utilisé pour vérifier si le modèle homogène représente le modèle hétérogène sous sollicitation dynamique tribologique. Finalement un travail expérimental, qui confirme la présence de hautes fréquences obtenues numériquement, est présenté.

1. INTRODUCTION

Nowadays most of the aircraft are equipped with C/C composites brakes which enables good braking and a low weight. The system consists in several discs of C/C composite which are rubbing against one another. Although this system is very efficient and used since the mid eighties, many things are still unknowns concerning this efficiency and the reason why the C/C composite is so much adapted to this type of loadings. Numerous studies have been devoted to this material but many of them don't take into account the specificities of the loading [1], while the others failed to explain the entire mechanism of the system, due to difficulty to instrument the interface of contact [2]. C/C composite under tribological loading is a difficult problem because it is a dynamic, multiphysical and multi-scale problem. Dynamic because vibrations may occur during the braking. Multiscale because of the particular structure of the material. It owns three scales, a microscopic one, which is made of fibers (ϕ_{fibre} =8µm) and matrix, a mesoscopic (characteristic length: 100µm), and a macroscopic (characteristic length: 10cm). At this last scale the material is transversely isotropic. Moreover the physicochemical problem is coupled with the mechanical one, that's why we have also a multiphysical problem. Some studies allowed to improve the comprehension of the physicochemical side, [2] [3], but the mechanical side is still under investigation. In order to dissociate the two sides of the problem, a model has been built that takes into account all the specificities of loading and the material, though from a purely mechanical point of view. The first part of this paper will be devoted to the comparison between two scales of the material: mesoscopic and macroscopic. In the following, mesoscopic scale stands for heterogeneous and homogeneous for macroscopic scale. Finally, experimental work is presented.

2. COMPARISON OF TWO SCALES FOR MODELING THE TRIBOLOGICAL BEHAVIOR OF A COMPOSITE

2.1 Description of the composite

The mesoscopic scale is of main interest here. The composite (figure 1) consists in a collection of heterogeneities embedded in a matrix. For each morphology the rate of heterogeneities is ten percent. The properties of the matrix and the heterogeneities are resumed in the table 1. The heterogeneities are vertical because it is a characteristic of the real composite. The size of those heterogeneities is about hundred microns width and between 1,2 and 3,6 millimeters high. For each morphology the repartition of the heterogeneities along x and y is randomized but there is at least 0.8mm, along x, between two heterogeneities and the ordinate of the bottom of the heterogeneities is a multiple of 1.2 mm.

	Mesoscopic model		Homogeneous model
	Heterogeneities	Matrix	Homogenized properties
Young modulus	E = 80 GPa	E = 30 GPa	E_L = 31.9 GPa E_T = 34 GPa
Poisson coefficients	ν = 0.2	ν= 0.2	ν_{LT}= 0.2 ν_L = 0.2
Shear modulus	G=33.33 GPa	G=12.5 GPa	G_{LT} = 13.3 GPa
Density	1770 kg/m^3	1770 kg/m^3	1770 kg/m^3

Tab. 1 Mechanical properties of the models. (L and T stand for longitudinal and transversal).
Propriétés mécaniques des modèles. (L et T signifient longitudinal et transversal).

In order to develop a multiscale approach that could determine the stress in the heterogeneities or in the matrix without modelizing all the morphology, it is necessary to take into account a part of the composite by the means of an homogeneous model. The aim of this study is to define an homogeneous model that represents the real behavior of the composite. In fact the homogeneous model takes into account the presence of heterogeneities by the means of a homogenized Young modulus. The goal of the three following paragraphs is to check if the homogeneous model obtained for static loading may correctly represent the behavior of the composite under dynamical tribological loading.

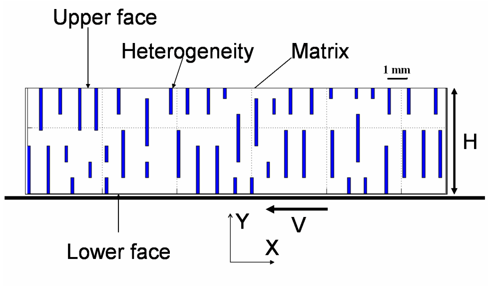


Fig. 1 Morphology of the model composite.
Morphologie du composite modèle.

2.2 Homogenization of the properties of the composite

In order to determine the homogenized properties of the composite (table 1), a volume, which is assumed to be representative of the material, with a given morphology (figure 1) has been modelized with the standard commercial code Abaqus. Different static loadings have been applied in order to determine the five constants that defined the behavior of a transversely isotropic material [4]. The determination of those constants is allowed by the classical theory of homogenization. The Hill's lemma, [5], links the strain's average, $\langle\varepsilon\rangle$, to the stress average, $\langle\sigma\rangle$, over the representative volume element thanks to the matrix of homogenized properties D:

$$\langle\sigma\rangle=D\langle\varepsilon\rangle \quad (1)$$

This theory is valid only if the volume, over which the mean calculation is made, is representative of the material. In order to be sure that the volume chosen is representative, the homogenized constants are calculated on multiple randomized morphologies, each of them having the characteristics described in the paragraph 2.1, and with static or kinematic boundary conditions. The very low standard deviance between the results proves that the volume is representative of the material for a static loading.

2.3 Comparison of homogeneous and mesoscopic models under dynamical loading without contact

This section deals with a comparison between a homogeneous model, with the properties described in the fourth column of table 1, and a mesoscopic one, defined by heterogeneities embedded in the matrix whose properties are those of the second and third column of table 1. The goal of this paragraph is to establish if the macroscopic scale can describe, with a good quality, the vibratory behavior of the composite. In order to study the vibratory behavior of the two models, a modal analysis is used. The nodes of the upper face are blocked. Nodes of the lower face are free (BC1) or blocked along the y direction (BC2)(see figure 2). The table 2 gives the frequencies of vibrations of the mesoscopic and homogeneous models for the first six free modes obtained with the two boundary conditions (BC1 and BC2). There is a good correlation between the two models. The figure 3 compares the first mode of vibration of the structure for the two types of boundary conditions. It is clear that the mode of the homogeneous model is very close to the corresponding one of the mesoscopic model. For the first modes of vibration, the wavelength is much bigger than the size of the characteristic length of the mesostructure. So the phenomenon of diffraction/reflection of the acoustic waves is not predominant in our model and it explains the good quality of the vibratory behavior of the homogenized model. Homogenization theory is still under investigation for all nonlinear problems and for the "dynamical homogenization" problem [6], [7].

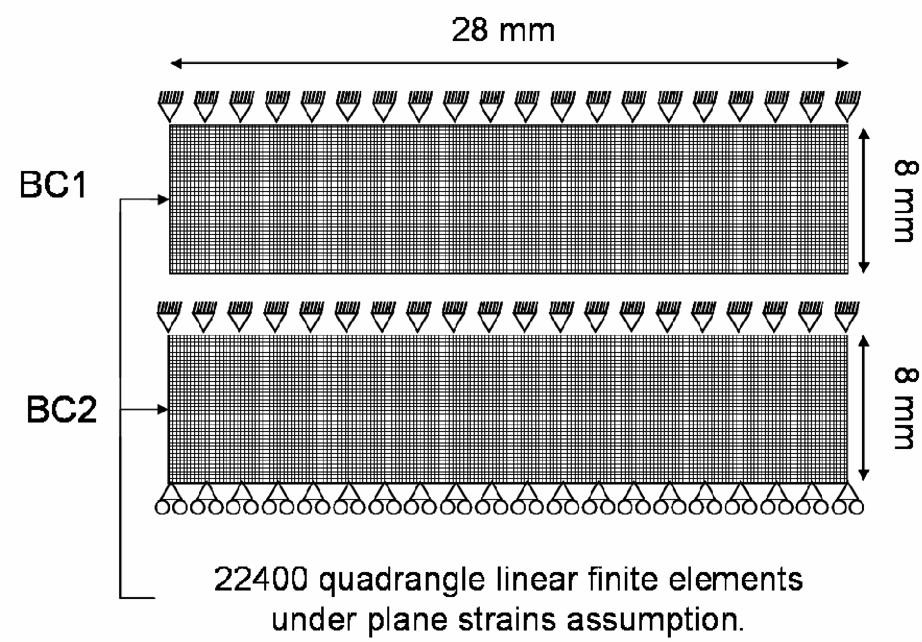


Fig. 2 Boundary conditions and mesh used for the modal analysis of mesoscopic and homogeneous models.
Conditions aux limites et maillage utilisé pour l'analyse modale des modèles mésoscopique et homogène.

Boundary conditions	BC1			BC2		
	Meso.	Hom.		Meso.	Hom.	
Mode	Fq (Hz)	Fq (Hz)	Difference	Fq (Hz)	Fq (Hz)	Difference
1	77598	77545	0,07%	81362	81218	0,18%
2	101808	101893	0,08%	108831	108793	0,03%
3	143283	143929	0,45%	170665	170753	0,05%
4	143690	143951	0,18%	232929	232723	0,09%
5	152678	153228	0,36%	238676	238953	0,12%
6	154404	155014	0,39%	239900	239534	0,15%

Tab. 2 Frequencies (Fq) obtained by modal analysis for mesoscopic (Meso.) and homogeneous (Hom.) models and for two different boundary conditions (BC1 and BC2).
Fréquences (Fq) obtenues par analyse modale pour le modèle mésoscopique (Meso.) et homogène (Hom.) et pour deux conditions aux limites différentes (BC1 et BC2).

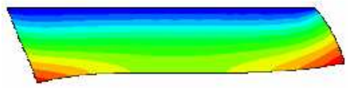
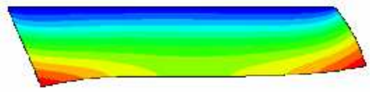
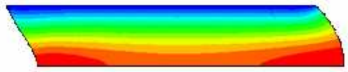
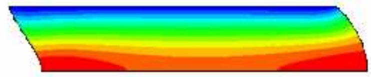
	Mesoscopic	Homogeneous
BC1		
BC2		

Fig. 3 First modes of vibration for a mesoscopic model and for the homogenized one and for two boundary conditions (BC1 and BC2).
Premiers modes de vibration pour un modèle mésoscopique et pour le modèle homogène, pour deux types de conditions aux limites.

2.4 Homogenized properties with friction contact dynamic loading

In this part, the contact, which is the main non linearity of the problem, has been introduced. The model chosen for this study is described on the figure 4. It consists in a rectangular pin (Ω1) rubbing against a rigid flat surface having a speed of translation of -2ms^{-1}. The resolution technique for this kind of non linear dynamic problems is based on dynamic explicit finite elements procedure. Contact forces are determined thanks to Lagrange Multipliers.

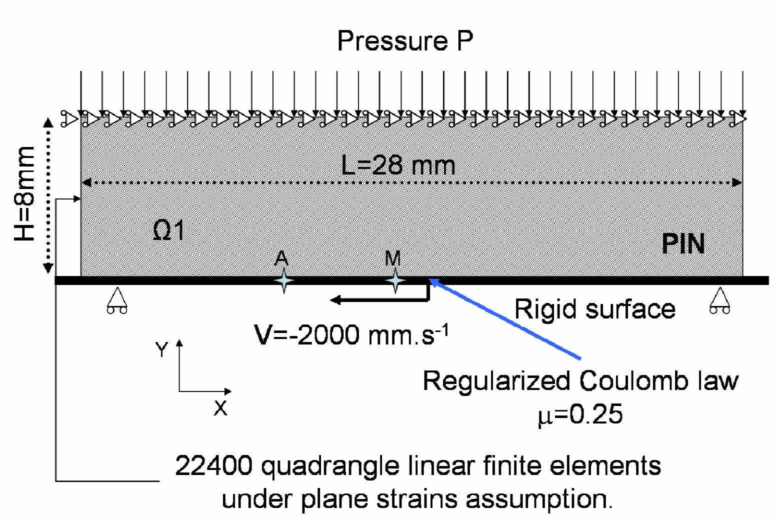


Fig. 4 Deformable/rigid contact model.
Modèle de contact déformable/rigide.

The model (figure 4) used a regularized friction law described in [8]. Convergence is achieved thanks to this particular friction law. It consists in introducing a delay, δ, in the response of the classical Coulomb law. The friction coefficient, μ, has a value of 0.25 and the delay, δ, has a value of 1500 ns. The time step, Δt, has a value of 5ns and respect the Friedrich-Courant-Levy condition. Comparison between the results given by the homogenized model and those given by mesoscopic models are investigated. The material properties of the models are those described in table 1 and the damping matrix, C, is proportional to the stiffness matrix, K, (C=βK and β=1.1E-09).

Three different loading have been modelized. The pressure P applied on the finite element model takes successively the values 0.5 MPa, 2.5 MPa and finally 5 MPa. These three cases correspond to three types of instabilities arising in the interface of contact. Under low pressure, an arbitrarily chosen contact node is sliding on the rigid surface or separated from it. This instability is called the ”slip separation” one. In the middle range of pressure ”stick slip separation” instability appears. It means that a contact node can be sticking to the surface (the rigid surface and the node have the same speed V) or it can be sliding on the surface or it can even be separated from it. Under high pressure, all the contact nodes are sliding on the surface. For each of those loading conditions, a homogeneous and multiple randomized mesoscopic models (i.e multiple randomized morphologies), each of them respecting the characteristics described in the paragraph 2.1, have been tested. All the mesoscopic models give approximately the same results so only results of one mesoscopic model are presented below. Due to the morphology, the contact stresses may change locally whereas for all the contact nodes the vibratory behavior in the tangential direction is the same (see figure 5). Comparison of the vibratory behavior in the tangential direction (x direction) between the different models is made because it’s a ”global” phenomena. Moreover it is worthwhile to note that the amplitude of vibration along x is much higher than those along y. The figure 6 shows the same vibratory behavior of a contact node for all the load cases and for the two models. It is clear that globally the two different models have the same behavior. Moreover it is important to note that the frequencies of vibration along x correspond to those found in the modal analysis in subsection 2.3 for the first mode of vibration. It is interesting to note that the dynamic contact with friction may strongly increase the stress in the material even in the case of planar surface under low applied pressure P. For example with the lower pressure (i.e. 0.5 MPa), the normal contact stress can reach about 2.5 MPa and the maximal tangential stress is near 0.4 MPa. Those maximum are found for the contact nodes belonging to the heterogeneities, because locally the material is more rigid than the matrix. The stress may increase in the case of rough surfaces, when the contact is localized.

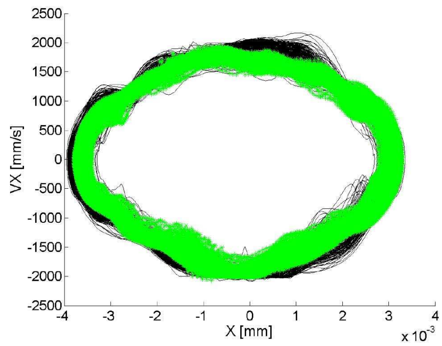
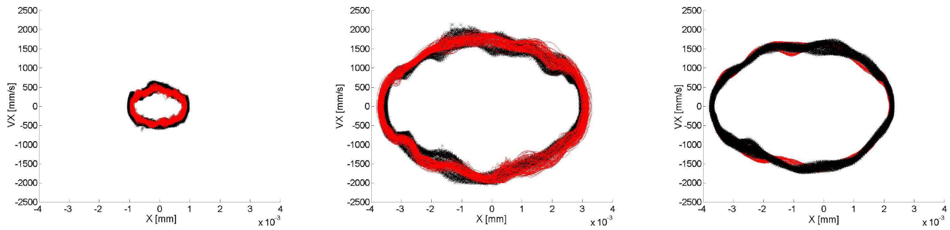


Fig. 5 Phase diagram along x. Tangential speed (mm/s) of the nodes as a function of its tangential displacement (mm).
Comparison of the vibratory behavior of two different contact nodes in the same mesoscopic model; continuous line stands for point A and stars for point M (see figure 4). Point A is arbitrarily chosen at the contact zone. Point M is at the center of the contact zone.
Diagramme de phase selon x. Vitesse tangentielle (mm/s) du nœud en fonction de son déplacement tangentiel (mm). Comparaison du comportement vibratoire de deux noeuds différents ; la ligne continue représente le point A et les étoiles le point M (voir figure 4). Le point A est choisi arbitrairement sur la zone de contact. Le point M est au centre de la zone de contact.



(a) P=0.5MPa (b) P=2.5MPa (c) P=5MPa

Fig. 6 Phase diagrams of the tangential movement (along X) of the central contact node, M. Results for three different loads and two different models: continuous line stands for the homogeneous model and triangles for randomized mesoscopic model.
Diagrammes de phase du mouvement tangentiel (selon X) du nœud central au contact, M. Résultats pour trois chargement différents et pour deux modèles distincts ; la ligne continue représente le modèle homogène et les triangles représente un modèle mésoscopique aléatoire.

3. EXPERIMENTS

It has been observed in the numerical simulations that the main frequency obtained in the models is about 80 kHz. In order to validate the existence of such high frequencies experiments, where a C/C pin rubs against a rigid flat surface, have been done. A pin on disk tribometer is used (figure 7). The steel disk stands for that rigid surface. The pin is about 30 mm in diameter and 8mm high. The shape of the real pin is not exactly the same as the shape of the numerical pin. Moreover, due to its idealization, the material taken into account in the numerical model is not exactly the real one. So the goal of this experiment is not to represent exactly the numerical model, but to validate the existence of high frequencies vibrations in the pin.

The applied pressure on the pin is the one applied in the numerical model and its value is 0.5 MPa, and the linear speed of the disk is 2 m.s^{-1}, identical in the numerical models.

The tangential speed of a point owning to the face of the pin is measured by the mean of a laser vibrometer (figure 7). The vibrometer used is a monopoint one. The laser is a HeNe one and has a power of 2 mW. The wavelength used has a value of 620-690 nm. A spectrum analysis is made and frequencies of vibrations of the pin are obtained.

In the experiments the arm which is hanging the pin has been blocked in order to obtain a system as rigid as possible. In fact in the numerical models there is no tribometer taken into account, so the only compliance introduced is the one of the pin. As the experiments are to be compared with the numerical models then the tribometer should be as rigid as possible.

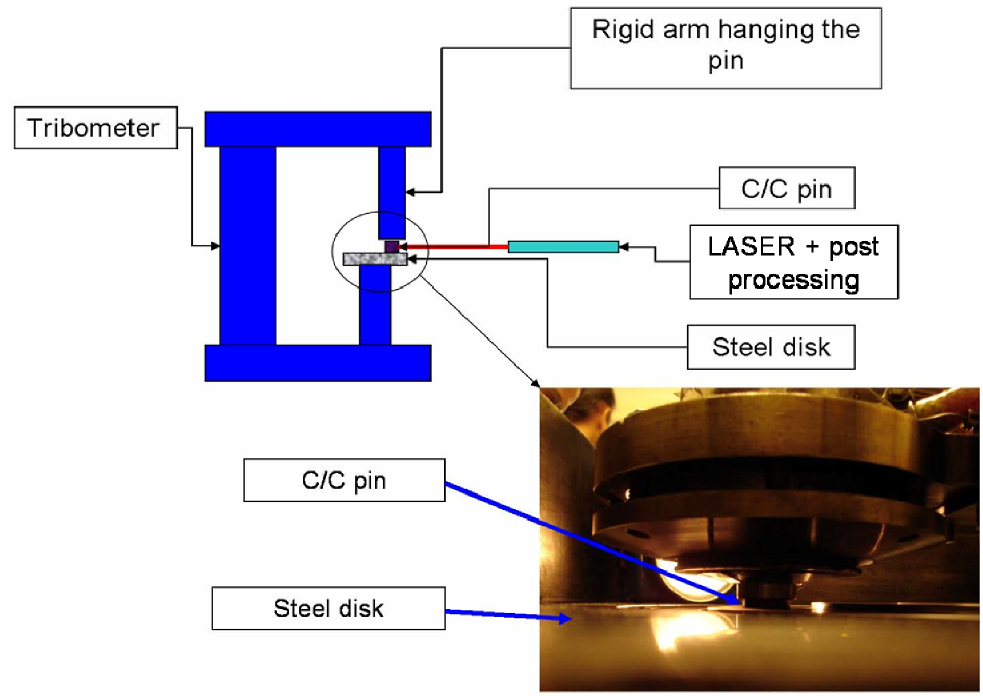


Fig. 7 Experiments scheme.
Schéma du montage expérimental

The figure 8 shows the results of the experiment. The frequencies present in the spectrum near 100 Hz represent the dynamical behavior of the tribometer. There are no more frequencies due to the tribometer structure above 2000 Hz. The main frequency obtained in this experiment is about 60 kHz. Some harmonic of the main frequency are present in the spectrum (120 and 180 kHz) which is similar to the spectrum obtained in case of brake squealing [9]. This experiment proved that in such system (i.e. a small pin rubbing against a rigid rotating disk), high frequency vibrations may arise. It is interesting to note that such high frequencies are also present in the numerical model although that model is not exactly representative of the real experiment (material properties, geometrical definition of the pin and disk...). However it is worthwhile to note that, by creating fatigue cycles, such high frequencies may play a role in the creation of wear particles, called third body particles ([2]).

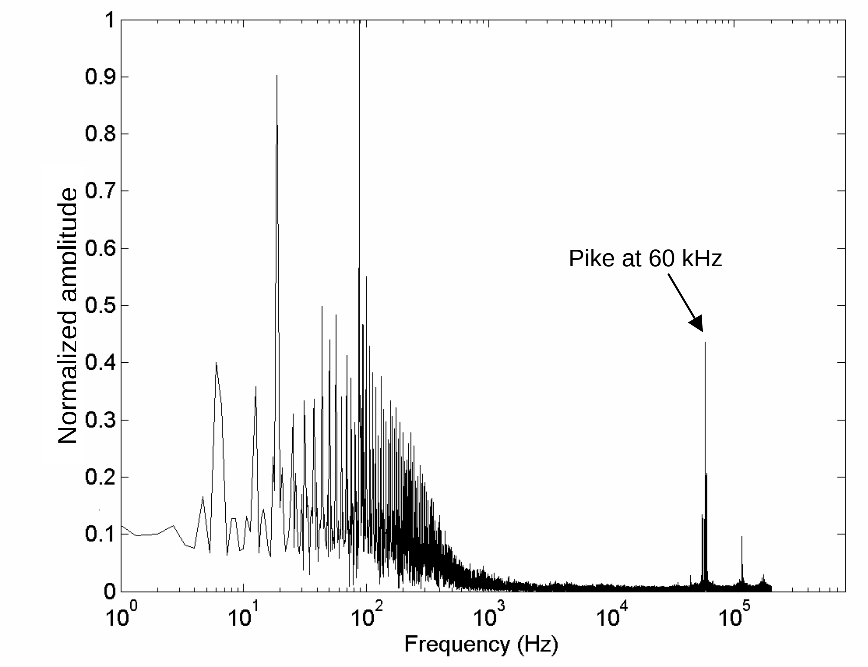


Fig. 8 Spectrum of the movement of the pin in friction contact with the rigid rotating disk.
Spectre du mouvement du pion en contact frottant sur le disque rigide.

4. CONCLUSION

It has been shown in this work that, for a given rate of heterogeneities (10%) with a given contrast of properties, it is possible to find homogenized properties of the composite that give a representative behavior of the composite under dynamical friction contact loading. If the global vibration behavior of the composite is under investigation there is no utility to represent all the micro structure, whereas if an order of magnitude of the stresses present in the matrix, or in the heterogeneities, is looked for, it is necessary to take into account the heterogeneities by a multiscale model.

Another result of this study is that presence of high frequency vibrations in the model are confirmed by experiments. Further experiment will explore the contact dynamics of C/C pin rubbing on C/C disk in order to confirm the presence of such high frequencies in an experiment closer to the aeronautic reality.

5. ACKNOWLEDGMENTS

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