International Journal of Fracture Fatigue and Wear, Volume 3

Proceedings of the 4th International Conference On
Fracture Fatigue and Wear, pp. 272-278, 2015

MULTISCALE MODELLING OF ROUGHNESS EFFECT IN FRETTING WEAR

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Abstract: This paper is a literature review of multiscale techniques and their possible applications to fretting wear simulations. Firstly, a brief introduction on fretting phenomenon is given, followed by an overview of the recent FEM modelling techniques used in fretting wear. The surface roughness effects is neglected on the majority of the FEM fretting wear models, mainly because modelling all the small geometrical details of the surface is very computationally demanding. Therefore, the use of methodologies that could provide information about these small-scale features to the macro-scale model is of great interest. Multiscale techniques (hierarchical, semi-concurrent and concurrent), discussed in this paper, may be a viable option. More specifically, the use of hierarchical homogenization techniques to contact problems and a possible application in fretting wear are discussed in detail.

Keywords: fretting wear, multiscale techniques, homogenization

1 INTRODUCTION

Fretting happens when two contacting surfaces, normally loaded, are submitted to small amplitude oscillatory relative movement. The amplitude generally varies from 5 to 100 μm [1]. However, it can be as low as, or even below, 1 μm [2].

This phenomenon can be observed in many mechanical assemblies such as dovetail joints, bearings and gears, or more generally in situations where contacting surfaces may be subjected to sliding motion. Depending on the conditions (surface finishing, coefficient of friction, normal load, slip amplitude), fretting may lead to catastrophic failure due to fatigue (known as fretting fatigue), may produce loss of fitting due to wear (fretting wear) or a combination of both. Therefore, in order to design and predict service life of mechanical components, it is important to be able to control and anticipate the effects of fretting.

The type of failure that may happen depends primarily on the fretting regime that the component is subjected to. Vingsbo and Söderberg [2] used a “fretting map" to describe the behaviour of the wear volume and fatigue life as function of the slip displacement for different fretting regimes. They defined three different fretting regimes: stick, mixed stick-slip and gross slip, as shown in Figure 1. At stick conditions, the surfaces are considered to be stuck to each other and no visible damage is generated. As the slip displacement increases, the fretting is characterized by mixed stick-slip conditions, the fatigue life decreases and the wear rate is reasonably low. This indicates that the main failure here is due to fretting fatigue. For even higher slip displacements, the regime changes to gross slip conditions where a considerable increase of the wear rate can be noticed. Fretting fatigue is not significant at this regime, because the cracks nucleated are removed by the intense amount of wear.

It is important to notice the difference between reciprocating wear and fretting wear. Different from reciprocating regime, the slip displacement at fretting wear conditions is small with respect to the contact width between the surfaces, causing the wear debris to be kept inside the contact region. This makes the fretting wear very hard to be noticeable, since it is necessary to disassemble the structure to have access to the affected region.

As shown by the Kubiak et al. [3], the effect of surface roughness in the fretting wear profile can be significant and must, therefore, be considered. However, most of the finite element (FE) models that are used to predict fretting wear do not take into consideration the effect of roughness. Since it is very computationally demanding to add all small surfaces features in a macro FE model, another techniques that allow the roughness information to be analysed are of great importance.

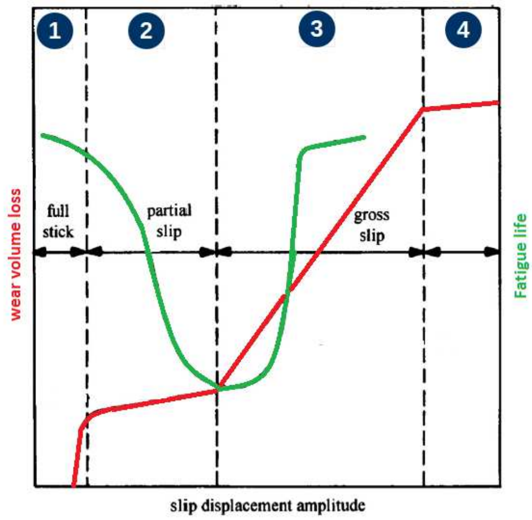

Fig. 1 Fretting map used by Vingsbo and Söderberg [2], showing the stick (1), mixed stick-slip(2) and gross slip (3) fretting regimes and also the reciprocating regime (4).

2 MULTISCALE MODELLING TECHNIQUES

The multiscale modelling techniques are used to connect results from models at different scales, sharing the efficiency of the macroscopic models with the accuracy of microscopic models. Aboudi et al. [4] classify the multiscale techniques in three main groups: hierarchical, concurrent and semi-concurrent.

2.1 Hierarchical homogenization

The hierarchical, or sequential, methodology is used to transfer information from a small scale to a larger model as a boundary condition or as an effective property. In order to do that, constitutive relations are precomputed by homogenizing (averaging) the material response at micro level and then this response is used on a large scale model. It is important to notice that the micro and macro models are independent from each other, i.e., the hierarchical approach deals with a one-way coupling (bottom-up or top-down), but not both of them.

In fracture analysis, Talebi et al. [5] applied hierarchical multi-scaling to estimate the material behaviour of nanocomposites. Figure 2 shows the procedure used to estimate material properties using homogenization. In their work, they predicted the elastic modulus of a clay/epoxy nanocomposite using a representative volume element (RVE) and then used this property in a macro model simulation. Eftekhari et al. [6] studied the fracture behaviour of CNT-reinforced concrete in a tree scale sequential scheme. The material properties of carbon nanotubes were extracted from molecular dynamics simulations and used in a micromodel, where a FE model is conducted to acquire the mechanical and damage properties. Finally, the response of the micromodel is upscale to the macro-model, where an extended finite element analysis is done.

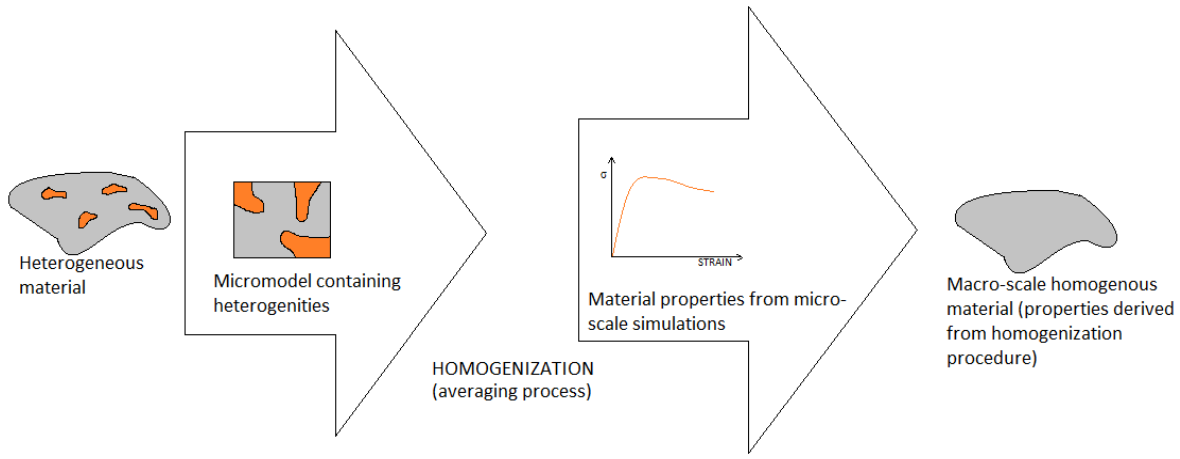

Fig. 2 Homogenization procedure adopted by Talebi et al. [5]

2.2 Semi-concurrent approach

In a semi-concurrent approach, the fine scale model is analysed at each integration point of the coarse scale model. Therefore, the semi-concurrent approach may produce better results than the homogenization method, but with a higher computational cost.

The deformation at macro level is sent to the micro model as boundary conditions and a homogenized stress tensor is calculate. This information is then sent back to the coarse model. In this way, the semi-concurrent technique can be considered as a two-way coupling [4], i.e., in order to solve the micro-model, the input from macro-model is necessary and vice-versa. The scales are interlaced in a parallel way (see Figure 3 for a schematic of the method).

Talebi et al. [5], Silani et al. [7] and Feyel and Chaboche [8] used semi-coupled schemes to connect the response of the micromodel to the macro model in a semi-concurrent way. They were interested in considering the materials heterogeneities impact in the response of the macroscale composite structures.

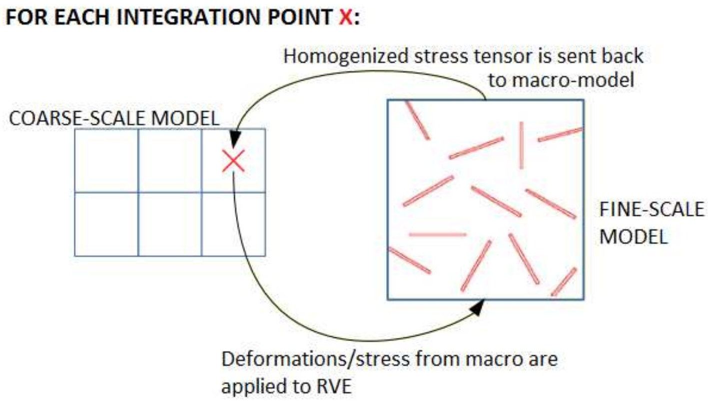

Fig. 3 Schematic of the semi-concurrent analysis of a nanocomposite done by Talebi et al. [5]

2.3 Concurrent technique

According to Aboudi et al. [4], concurrent techniques are fully coupled, which means that all scales are handled at once in the same numerical model. This technique provides the highest fidelity among all the other ones, but with the lowest computational efficiency. Figure 4 shows a comparison between the multiscale techniques.

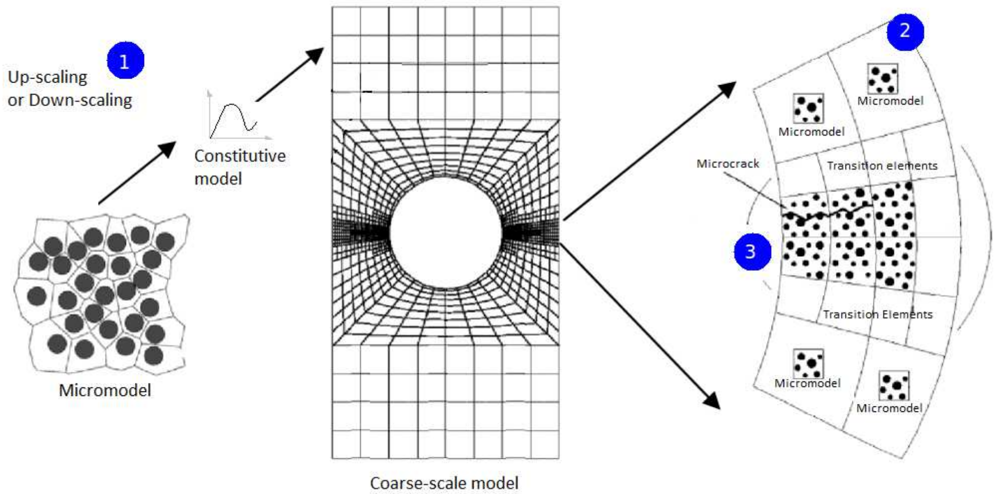

Fig. 4 Schematic of the types of multiscale analysis by Known et al. [9]: (1) homogenization, (2) semi-concurrent and (3) concurrent.

It is possible to couple different continuum to continuum and also atomistic to continuum scales in the same model. Silani et al. [10] illustrated a method to couple two continuum domains in different scales using concurrent technique. Aubertin et al. [11], Guo-Wu and Tie-Gang [12] and Yamakov et al. [13] presented results for crack propagation in a concurrent fashion, where the region near the crack tip was modelled with molecular dynamics (MD), while the region distant from the crack was modelled with finite element method (FEM). There are many other works done in the crack propagation analysis using concurrent technique. For instance, Talebi et al. [14] coupled molecular dynamics to extended finite element method (XFEM) and Yang et al. [15] coupled molecular dynamics to meshless method.

Concurrent approach is also applicable in contact mechanics, when nanoscale features of the interface are modelled using molecular dynamics and the region far from it using continuous mechanics, e.g. Luan et al. [16] did a 2D analysis of the contact, while Anciaux and Molinari [17, 18] considered a 3D problem. Figure 5 shows details of their models.

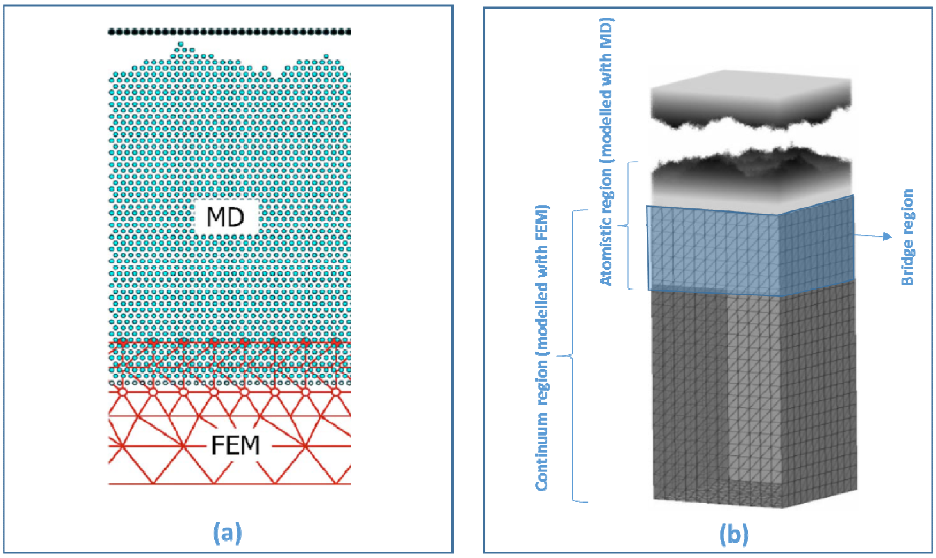

Fig. 5 Multiscale models using concurrent technique to model contact interactions. (a) model developed by Luan et al. [16] (b) model done by Anciaux and Molinari [18]

3 MULTISCALE IN FRETTING WEAR PROBLEMS

In fretting wear problems, some work have been done using multi-scaling techniques. Gallego et al. [19] presented a computational method, with three scales, for analysing dovetail joint (titanium-titanium) on blade/disk interface. Their goals was to obtain wear kinetics and worn out profile on a fast computational analysis. The scales used for analysis were: micro-scale and meso-scale, using a semi-analytical model to calculate the wear depth increments based on the solicitations derived by the forces and moments at a given point of the contact, and complete model of the blade/disk. The complete FE analysis for the whole system provided information regarding the forces and moments for calculation at meso-scale.

Leonard et al. [20] combined finite-discrete method to model the effect of third bodies in fretting. The third body is modelled as discrete elements, while the first bodies are modelled with finite elements.

Note that little or none work has been done to consider the roughness effect on fretting wear using multiscale analysis.

4 HOMOGENIZATION TECHNIQUES FOR CONTACT PROBLEMS

Hierarchical homogenization has been widely used for contact problems, as elucidated by Stupkiewicz et al. [21]. Homogenization is used in contact as a tool to derive a macroscopic constitutive relations for the contact stiffness based on microscopic simulations. It counts with the advantage of low computational cost, being able to incorporate many physical phenomena in the contact analysis. It is possible to consider many different effects, such as: hysteretic effects of rubber contact (Wriggers and Reinelt [22]), inelastic contact considering effect of third bodies (Temizer and Wriggers [23]) and also friction of soft matter (Temizer [24]).

Regarding the effect of roughness on the contact, Jerier and Molinari [25] presented a methodology to analyse the nonadhesive and frictionless contact between a flat elastic body and a rigid surface with fractal roughness (modelled by spheres). They used discrete element method and homogenization techniques in order to study the real contact area.

Another simpler way to deal with contact of rough surfaces is to model the rough surface in a micro-scale model and then upscale the results to a macro-model. Wriggers and Nettingsmeier [26] presented a methodology to derive a homogenized constitutive equations for normal frictionless contact based on those micro-scale models. This equation would have information regarding the effect of the roughness and then could be used on the macro-model. Their methodology is described in more detail in the following.

The macroscopic constitutive equation for normal frictionless contact can be written as:

$$p = c_n \delta^m. \qquad (1)$$

where p is the average normal pressure, δ the normal approach between the two bodies and c_n and m are contact stiffness parameters. The normal approach δ can be replaced by maximum asperities height ξ and mean plane distance d.

The homogenization technique allows the estimation of the parameters c_n and m of Eq.1. They are obtained by the average response of the two deformable bodies in contact with rough surfaces modelled at microscale. One body is positioned on the top of the other and the bottom one is fixed. The top body is then moved downwards by a set of given displacements. The average contact pressure and the normal approach δ (see Fig. 6 for details) are calculated for each displacement of the top body. The simulation ends when the mean distance plane is relatively close to zero.

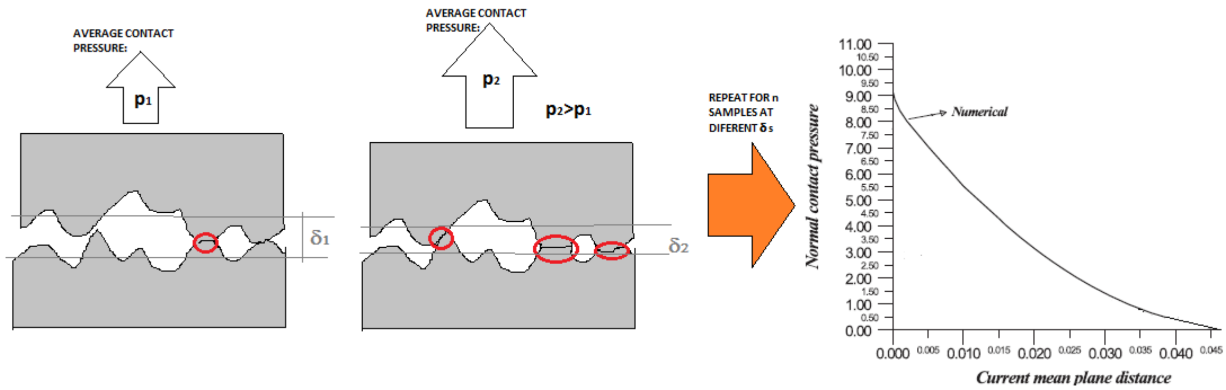

Fig. 6 Analysis process to estimate the parameters c_n and m of Eq. 1, based on Wriggers & Nettingsmeier [26].

In order to consider the randomness effect of the roughness and the geometry of the real surface, the above procedure is repeated for a large number of micro-models, each one with a different distribution of asperities, but with the same maximum asperities height. The results are statistically analysed and the parameters for the constitutive equation 1 are estimated. This equation can then be used as an input in the macro-model.

An elastoplastic analysis of the contact at micro-scale was considered in Bandeira et al. [27], which can be treated as an extension of the work discussed above.

5 CONCLUSIONS

This review presented a possible methodology to take into account the effect of roughness in contact problems. This approach could be used in computational simulations of fretting wear, providing better understanding of the fretting phenomenon and more accurate wear profile predictions.

As future work, we intend to apply the discussed methodology in fretting simulations and validate the results with experimental (or literature) data. Firstly, we intend to develop a micro-scale model in which all the small features of the rough surfaces are considered. Then, after an estimation of the contact stiffness parameters, we intend to use the average normal pressure from the micro model in a macro model simulation. This would enable us to calculate the wear depth profile in a fretting wear situation considering the effect of roughness.

This homogenization technique would be a simple approach and, in the future, a more detailed analysis may be needed. If that is the case, we may also try to implement a concurrent approach, considering even nano-features of the surface and its impact on fretting wear or may be a coupled continuum to continuum model with different scales or even a coupled atomistic to continuum analysis.

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