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X-FEM crack propagation under rolling contact fatigue accounting for actual residual stresses in the rail

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KEYWORDS

Fatigue crack growth simulation, Rolling-sliding contact fatigue of rails, X-FEM

ABSTRACT

For a more cost efficient railway system, it is essential to optimize the maintenance of rails and the scheduling of the rail replacement operations.

To support this process a numerical modelling tool has been developed thanks to a long-term collaboration between railway organizations (SNCF, RFF, RATP), rail producer (Tata Steel) and research institutes and universities (INRETS, LMS, MECAMIX, INSA) within the IDR2 consortium (Initiative for Development and for Research on Rail). This modelling starts with a dynamic simulation of the vehicle rolling on a track, from which the cyclic mechanical state of the rail is calculated by means of a 3D finite element simulation and an original and time-cost efficient direct stationary algorithm. Finally, a fatigue analysis of the rail is performed using the Dang Van criterion.

The modelling tool has been recently completed with the simulation of the crack propagation in the rails. A two-scale frictional contact fatigue crack model developed within the X-FEM framework is used to solve the crack problem. Using this approach, contact and friction between the crack faces is taken into account in the simulation. Realistic residual stresses, using dedicated software developed by SNCF are introduced in the propagation simulation via projection of the asymptotic mechanical fields. Crack growth is performed taking into account this permanent non-uniform field. 2D results and 3D preliminary results are shown in this paper showing the high influence of the residual stresses on the crack growth rate.

INTRODUCTION

Due to the repeated passage of wheels, rolling contact fatigue cracks can form on the surface of the rail. These defects, such as squats and head-checks, can propagate and lead to the rail fracture and potentially to a derailment. When a rail break is detected, the traffic must be stopped or a speed limitation is imposed until the rail is replaced or welded. To avoid such a disruption in service, detailed monitoring and maintenance procedures for the fatigue of rails are set up by infrastructure managers. This is costly and increases with increased traffic intensification and speed. In order to go towards a more cost efficient railway system, it is essential to optimize the maintenance of rails and particularly the scheduling of the rail replacement operations. One key to reach this target is to have a better understanding of the physical phenomena occurring during fatigue crack propagation to predict the residual life time of the rails (Fig. 1).

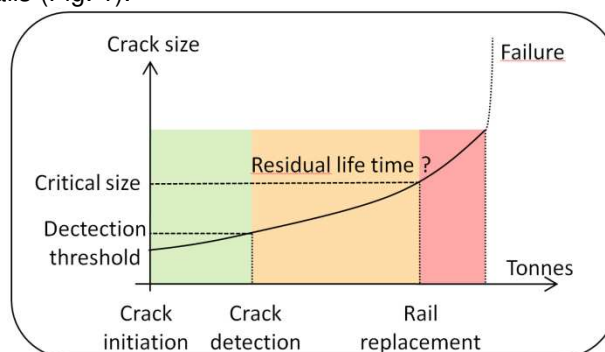


Figure 1. Definition of the residual life time of the rails.

To progress in this area, a numerical modelling tool has been developed thanks to a long-term collaboration between railway organizations (SNCF, RFF, RATP), rail producer (Tata Steel) and research institutes and universities (INRETS, LMS, MECAMIX, INSA) within the IDR2 consortium (Initiative for Development and for Research on Rail). This modelling (see Fig. 2) starts with a dynamic simulation of the vehicle rolling on a track, from which the cyclic mechanical state of the rail is calculated by means of a 3D finite element simulation and an original and time-cost efficient direct stationary algorithm. Finally, a fatigue analysis of the rail is performed using the Dang Van criterion.

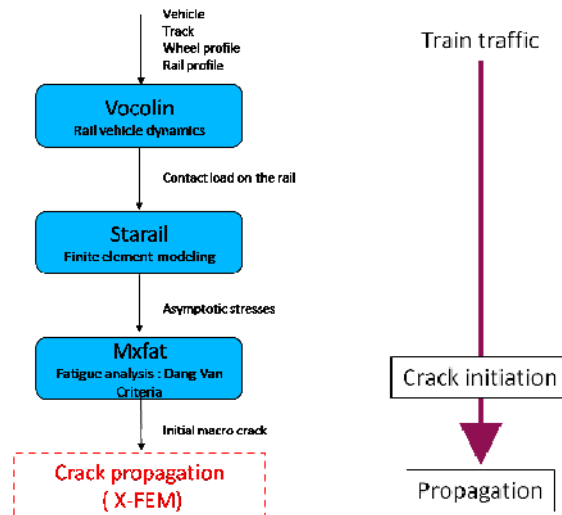


Figure 2. the numerical modelling process for the rail rolling contact fatigue assessment.

The final step consists of modeling the crack growth. This paper focuses on this last point: modeling fatigue crack growth in the rails taking into account frictional contact between the crack faces, mixed-mode propagation and realistic residual stresses. Numerical fatigue crack growth is a large research topic which involves the understanding and the modelling of numerous local phenomena like confined plasticity or interfacial frictional contact. Contact with friction between the crack faces notably occurs in rolling contact fatigue problems. These possible time-dependent, multi-axial, non-proportional loadings may lead to a crack, up to the development of a very complex 3D crack network.

Modeling the crack propagation under rolling contact fatigue (RCF) requires considering different phenomena acting on different scales. At the structure scale, the wheel-rail contact imposes a very high gradient close to the wheel-rail contact area and leads to a multi-axial non-proportional loading of the cracks. Moreover the repeated traffic of the wheel over the rail leads to residual stresses in the rail that will influence the crack propagation. All these considerations result in complex sequences of opening, sticking and sliding conditions at the crack scale (Fig. 3).

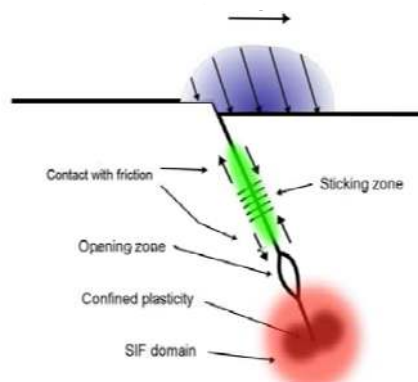


Figure 3. Schematic representation of the phenomena occurring at the crack scale.

Previous works on fatigue crack growth in the rails are available in the literature. Some authors have studied the role of liquid entrapment using FEM analysis [1,2,3] or BEM analysis [4,5] in the crack growth mechanism. This effect is not considered in this work. Other works studied the influence of different parameters such as elastic foundation [6], the crack initial geometry [6,7,8,9] or the crack

face friction coefficient [6,8,9,10] on the stress intensity factors (SIFs). In this paper we present 2D results and 3D preliminary results of a fatigue crack growth in the rails taking into account realistic residual stresses using a two-scale X-FEM/LATIN crack model with interfacial frictional contact [11,12,13]. The eXtended Finite Element Method [14] is used to model the crack propagation. In this method no explicit representation of the crack is needed. The crack is modelled using function enrichments. The crack discontinuity is introduced as a Heaviside step function. In addition, branch functions are introduced for all elements containing the crack front. Hence, the mesh does not necessarily conform to the crack and both field interpolation and re-meshing are not required during the possible crack propagation.

INTRODUCTION OF REALISTIC RESIDUAL STRESSES

The evaluation of the mechanical state in the rail due to the contact stress induced by the train traffic is crucial for the modelling of the rail resistance: plastic deformations occur in the region near the contact zone due to repeated rolling–sliding contacts between the wheels and the rail. To be realistic, it is necessary to take into account this phenomenon which may be very significant for crack initiation and propagation in the rail head. It is well known that under repeated rolling contacts, different asymptotic mechanical states could occur in the structure: elasticity, elastic shakedown, plastic shakedown or ratcheting.

Determination of the stabilized state in the rail is performed by using sequentially VOCOLIN software and the stationary algorithm [14]. First, the contact between wheel and rail is evaluated by means of VOCOLIN. Its characteristics, which are number and dimensions of contact areas, normal and tangential pressure, can be Hertzian or non-Hertzian (Fig. 4(a)). Then, using the stationary algorithm, the stabilized mechanical state (residual stresses and plastic strain distribution) is computed. An elastic shakedown is obtained (Fig. 4(b)); all components of the plastic deformation tensor are constant along all the streamlines of the gauge corner. As a consequence, high cycle fatigue is likely to occur [15].

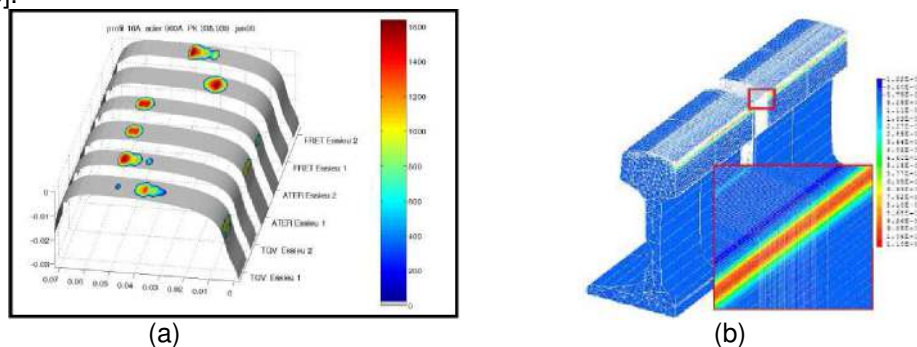


Figure 4. (a) Examples of calculated rail/wheel contact area obtained by simulation (VOCOLIN).
(b) Stabilized longitudinal plastic strain distribution [18].

The meshes used for the computation of the asymptotic mechanical fields and the one used for the crack propagation are different (Fig. 5). Indeed, for the crack propagation, fine elements are required in the area where the crack propagates and the mesh can be coarser in the depth of the rail. Therefore the asymptotic mechanical fields are projected on the mesh used to model the crack propagation (see Fig. 5). Those fields are considered as the initial state of the propagation simulation. This state is permanent and non-uniform. No redistribution of residual stresses is considered throughout the crack growth. Since only elastic shakedown is considered, the fields after projection do not required to be re-balanced.

CRACK GROWTH PROCEDURE

A wheel passage on the crack corresponds to one cyclic loading. In this paper, wheel-rail contact is simply modeled as a fully sliding Hertzian load. Each cycle is divided in time steps corresponding to the position of the wheel with respect to the crack. For each position of the wheel, the crack body problem is solved and SIFs are computed using integral methods. At the end of a simulated cycle, the history of SIFs throughout the cycle is determined. Using this history, the crack growth path (direction) is predicted according to Hourlier and Pineau's criterion, which already gave good agreements with experiments under non-proportional loading [16].

Finally a dedicated mixed-mode propagation law for RCF is used to predict the crack growth rate [9]. In the end of the cycle the new crack is created and the corresponding jump cycle is computed thanks to the propagation law. The procedure is repeated until no more cycles are required (Fig. 6).

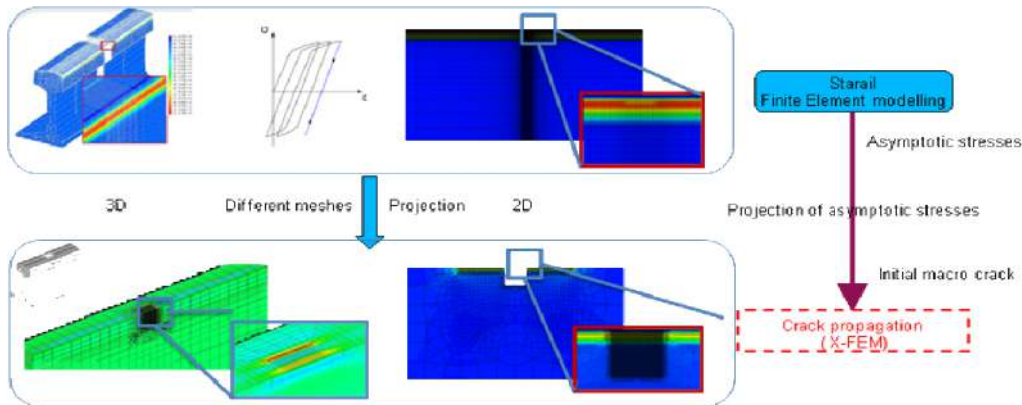


Figure 5. 2D and 3D projection of the asymptotic mechanical fields on the mesh used for the crack propagation simulation.

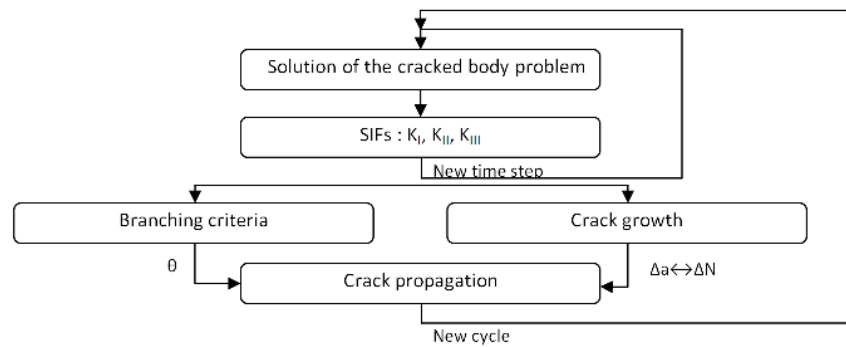


Figure 6. Flow charts of the propagation procedure.

2D RESULTS WITH ACTUAL RESIDUAL STRESSES

2D parametric studies have been performed to study and quantify the influence of the friction coefficient between the crack faces, the initial crack length, the crack orientation with the upper rail surface and the introduction of the residual stresses.

The corresponding stress intensity factors with and without residual stresses are computed along the cycle and shown on Fig. 7. The results without residual stresses have been compared with [9] and show very good agreements. Introducing results stressed in such a configuration leads to a crack always closed since the crack tip is in an area where high compressive stresses occur (Fig. 7). This can be seen with K_I always equal to 0. We can also see the residual stress effect on K_{II} . It can be observed a translation of the K_{II} values. The sliding between the crack faces is increased in one direction and decreased in the other one. This effect will influence the ratio K_I/K_{II} leading to a different crack growth rate.

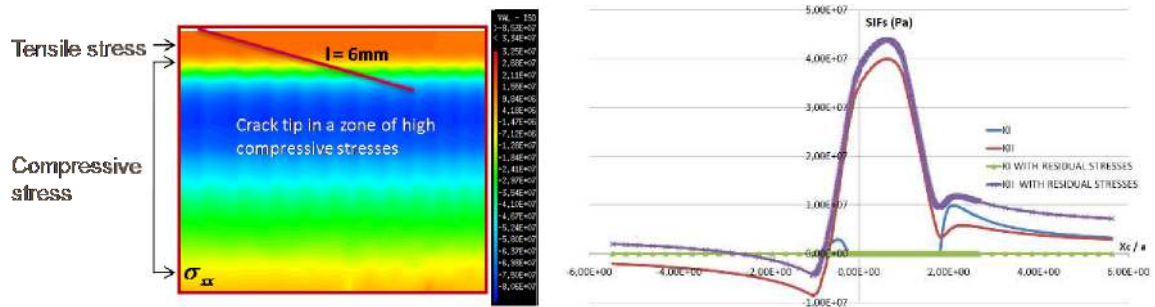


Figure 7. Initial crack geometry in the residual stress field σ_{xx} and the corresponding stress intensity factors K_I and K_{II} .

We can compare on Fig. 8 the two crack growth path with and without residual stresses (free on Fig. 8). It first must be pointed out that in this case the crack growth path is mainly driven by the direction of the tangential loading. This is the reason why the crack tends to propagate downwards on Fig.8. The two crack growth path are similar, but to reach the same length, it takes five times more cycle for the crack propagating in the residual stress field.

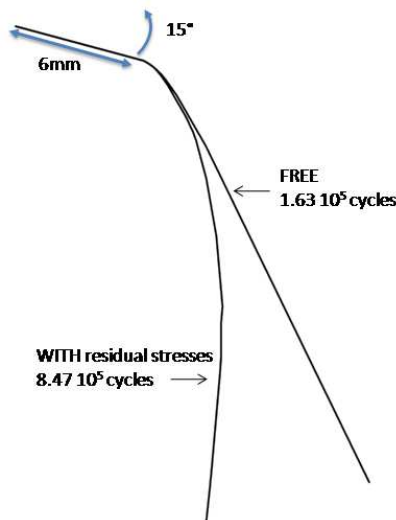


Figure 8. Comparison of the crack growth path with and without residual stresses for a 6mm long crack inclined of 15°.

Different initial crack lengths with a fixed angle θ have also been investigated to compute the evolution of the crack growth rate with the crack length (Fig. 9). We can see that the residual stresses decrease the crack growth rate.

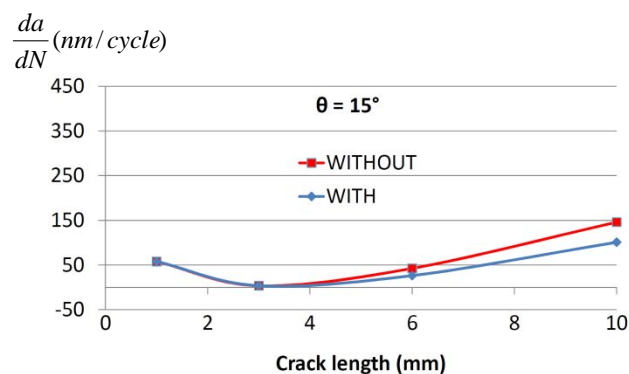


Figure 9. Comparison of the crack growth rate with and without residual stresses for different initial crack length.

3D PRELIMINARY RESULTS

The development of the whole strategy implemented in CAST3M [17] has been done not only for 2d cases but also for 3d simulations. Only 3d preliminary results are available. A semi elliptic initial crack inclined of 90° has been considered. Fig. 10 illustrates the 3d crack behavior for the considered case.

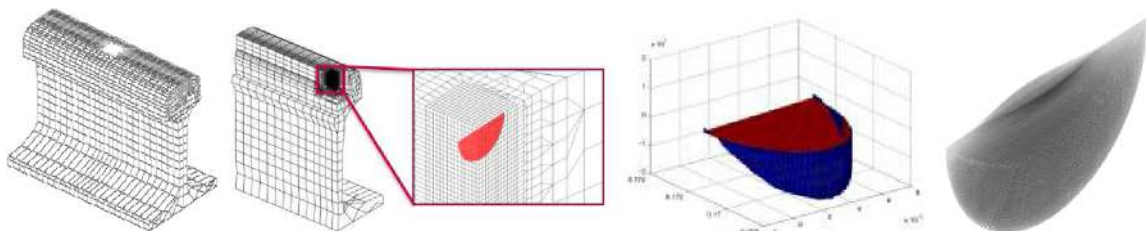


Figure 10. 3D mesh used for the crack propagation, K_{II} along the front and traction field between the crack faces for a given time step.

The goals of this work is to be able to predict, depending on the tonnage seen by the track and the traffic conditions, the growth rate and the direction of the fatigue cracks. To validate the numerical results, they are being compared with data collected from the railway network (Fig. 11).

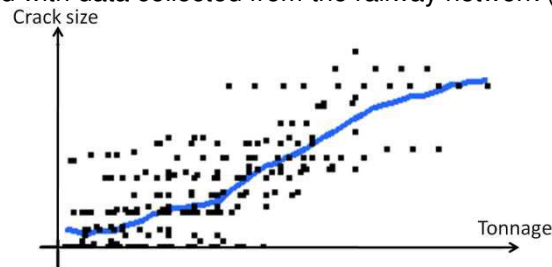


Figure 11. Interpolation of the crack growth rate measured on the railway network.

With such a tool we can predict the evolution of the detected cracks to plan the rail replacement operations.

CONCLUSION AND PROSPECTS

This paper aims at predicting fatigue crack growth and branch conditions under RCF. A two-dimensional linear elastic numerical model for fatigue crack growth has been presented, including contact with friction at crack interface. The model rests on a three weak field formulation using X-FEM and an iterative scheme dedicated to non-linear interface problems adapted from the LATIN method. Using the tools already developed by SNCF to solve the wheel-rail contact problem and to compute the asymptotic stresses in the rail, realistic residual stresses have been introduced in the propagation model assuming elastic shakedown for the rail. 2d parametric studies are easily performed using this strategy. The same mesh is used for all the simulations. 2d quantitative results are already available and emphasize the role of residual stresses in the crack growth rate.

Some short prospects for this work are to reach quantitative results for 3d crack growth, add the contribution of the rail bending by coupling the model with a macro model dedicated to the simulation of the rail bending.

Once the numerical tool would be definitely validated, it would be able to give quantitative results for the residual life time of the rails.

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