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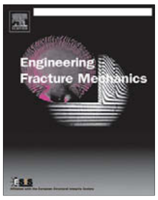

Rail rolling contact fatigue dependence on friction, predicted using fracture mechanics with a three-dimensional boundary element model

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ABSTRACT

Rolling contact fatigue crack growth continues to affect many railways worldwide. It is most often controlled through rail grinding in a preventive maintenance strategy, but to plan the required frequency and depth of grinding, prediction of crack growth rates has a vital role.

This paper presents crack growth rate results from a new three-dimensional rail model containing an inclined surface breaking rolling contact fatigue crack. The calculations are based on a shear mode of crack growth, driven by the Hertzian contact pressure on the railhead and moderated by friction between the crack faces ("crack face friction"). The results from the model show good correlation with those from the previously published work in the area, with particularly good agreement at higher levels of surface friction coefficient.

Applying the new model to a range of surface and crack face friction coefficients predicted that crack growth rate will rise with reduced internal crack face friction at all crack sizes. For small cracks (2 and 5 mm radius) rates were predicted to rise with increased surface traction, but this trend was reversed at larger crack sizes (10 and 19 mm radius). Identical trends were found when the modelling was repeated using the previously developed half-space based "2.5d" model, indicating that although this older model cannot represent the rail geometry its high speed means it remains a useful tool for investigating the effects of contact parameters on rail rolling contact fatigue. The next study in this area could therefore consider if there is a uniform or crack size related ratio for mapping 2.5d results to three-dimensional rail geometry to produce closer agreement in crack growth rates as well as trends. For the three-dimensional model, consideration of alternative crack morphologies and movement of the contact running band away from the rail centreline would provide additional data on the effect of rail grinding and re-profiling on rolling contact fatigue.

1. Introduction

Rolling contact fatigue (RCF) crack growth in rails is caused by the repeated rail/wheel contact. It is an important problem for the railway industry since undetected cracks have serious safety implications and can lead to the development of rail breaks if they turn down into the rail. Preventative maintenance through the use of grinding is currently the primary method of controlling RCF in the UK, however, predicting the required frequency and depth of grinding is vital for preventing costly over-maintenance. Vehicle traffic characteristics such as heavier axle loads, increased traffic density, and changes to rail

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materials mean that historical performance of the system my not be a good guide to future rail degradation. Accurate prediction of rail crack growth through modelling can ensure system safety whilst reducing the costs of maintaining the system infrastructure.

Fracture mechanics may be used to predict the growth rate of a rolling contact fatigue crack and several authors have developed models for the prediction of stress intensity factors (SIFs). Bower [1] developed a two-dimensional numerical model of surface initiated rolling contact fatigue cracks to study mode I and mode II stress intensity factors. Bogdanski et al. [2–4] have used the finite element method to examine the growth of rolling contact fatigue cracks and to predict crack tip stress intensity factors, increasing the understanding of mixed mode stress intensity factors. In Japan development of a boundary element model for mixed mode stress intensity factor calculation for inclined surface breaking cracks has been conducted by Akama and Mori [5]. Accompanying experimental work was also conducted to develop crack growth laws and branching criteria for rolling contact fatigue cracks [6,7].

Kaneta et al. [8] presented a method of calculating stress intensity factor based upon the body force method developed by Murakami and Nemat-Nasser [9]. Methods of calculation are presented for both mode I (opening) and mode II (shearing) stress intensity factor values at the crack tip in an elastic half-space. This method has been developed for semi-elliptical and semi-circular cracks with circular and elliptical contacts [10,11].

Models developed by Kaneta et al. [8,10,11] included fluid pressure, which was assumed to decrease linearly along the length of the crack, being equal to the contact pressure at the crack mouth (e.g. at a railway wheel rail contact) and falling to zero at the crack tip. This system was chosen to represent the dynamic nature of a fluid briefly pressurised at the crack mouth and then allowed to depressurise after the wheel has passed. These pressure distributions were also applied in the later work of Fletcher and Beynon [12,13]. Crack growth in a shear mode modified by friction between the crack faces, i.e. “crack face friction” has also been considered using the body force method [10,11]. Stress intensity factors were calculated for circular and elliptical contact patches and semi-elliptical cracks.

Taking an alternative approach Fletcher and Beynon [12,13] developed a simple two dimensional method for the calculation of stress intensity factors for semi-circular fluid filled cracks and cracks growing by a shear mechanism under Hertzian contact loading. Crack face friction could be considered for cracks growing by a shear mechanism, while the fluid pressure approach adopted the tapering crack face pressure profile of Kaneta et al. [8]. Both cases treat the resultant stress present along the line of an inclined surface breaking crack from contact, crack face friction or fluid pressure as a series of point loads. The total stress intensity factor is assessed through summation of the individual contributions of the point forces calculated using the Green’s functions developed by Rooke et al. [14].

The two dimensional model by Fletcher and Beynon has been further developed by Fletcher and Kapoor [15] through the use of the two-dimensional Green’s functions with the sub-surface stress distribution produced by an elliptical Hertzian contact patch (a Hertzian line contact was used previously). This combination allows the growth of semi-elliptical cracks beneath elliptical contact patches to be assessed, and has become known as the “2.5d” approach. It has been used in the investigation of why cracks may turn downwards leading to a rail break [16] indicating that residual stress from manufacture and plastic deformation of the steel during use can influence the direction of crack growth [17].

This paper presents a three-dimensional model of crack growth in a rail using the true geometry of a rail, rather than the half space assumptions often used previously. The model utilises the boundary element technique and is able to predict stress intensity factors, and in turn crack growth rates, for inclined surface breaking rolling contact fatigue cracks. In developing the model the choice was made to focus on shear mode crack growth and crack face friction, rather than on fluid pressurised crack growth mechanisms. This followed earlier modelling which indicated that growth rates for fluid pressure driven growth were much higher than those found for real cracks in rails [18]. The over-prediction of rates was attributed to the assumption that fluid was sealed in cracks of all sizes, when this is unlikely to occur for larger cracks which exceed the wheel contact patch dimensions, or for networks of interconnected cracks. It is also possible that the pressurised fluid is expelled from a crack after the first wheel pass, and subsequent wheels cannot then apply fluid pressure inside the crack. For all these reasons it was thought that the majority of wheels will drive growth through a shear mechanism assisted by fluid lubrication of the cracks, but not by fluid pressurisation, so the shear based mechanism is modelled here.

2. Model development

Previous work on growth of rolling contact fatigue cracks driven by rail bending has used a boundary element (BE) technique to create three-dimensional rail model [19]. It was decided to continue with this technique for the three-dimensional model of shallow angle crack growth, its primary advantage being that BE removes the need to finely mesh the region of high stress gradients immediately ahead of the crack tip. This is possible because boundary element models define the mechanics of the problem in terms of integrals over the surface of the body rather than through its volume, with the assumption that internal behaviour is elastic. This is similar to the treatment of crack growth by linear elastic fracture mechanics in which behaviour is elastic with the exception of a very small process zone just ahead of any crack. The elastic crack opening and sliding displacements observed on the surfaces of a crack modelled using boundary elements can then be used to calculate the stress intensity factors at the crack tip, just as in any fracture mechanics analysis. The models were developed in BEASY versions 8 and 9 [20] on an Intel Pentium 4 based PC computer system, and achieved run times of between 6 and 24 h for the entire passage of the wheel over the crack.