Growth of multiple rolling contact fatigue cracks driven by rail bending modelled using a boundary element technique

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Abstract: Examination of rails on which large rolling contact fatigue cracks have developed, either at the gauge corner or on the rail head, typically reveals that the cracks have not developed in isolation but occur at intervals along a length of track. Individual cracks are typically separated from one another by a few millimetres, although the reasons for this spacing between the cracks are not yet understood.

This paper presents an investigation into the interaction between adjacent long cracks (tens of millimetres) that are at the beginning of their bending-stress-driven propagation phase. Results are presented as plots of stress intensity factor around crack fronts for single- and multiple-crack situations, for which crack growth rates are predicted. The work focuses particularly on the degree to which single-crack models may be misleading when dealing with a rail containing multiple cracks. The work has application in improving the modelling of crack growth in rails, leading to improved asset management and risk assessment.

Keywords: rail, bending, crack, branch, modelling

NOTATION

\(da/dN\) crack growth rate
\(E\) Young's modulus
\(I\) second moment of area
\(\Delta K_{eq}\) equivalent stress intensity factor range
\(\Delta K_I\) mode I stress intensity factor range
\(\Delta K_{II}\) mode II stress intensity factor range

1 INTRODUCTION

Rolling contact fatigue cracking and wear are two of the main railway rail problems worldwide. Over recent years spending on rail replacement in the UK to combat the effect of rolling contact fatigue and wear has risen sharply (\(£3.7 \times 10^9\) in 2002–3 on maintenance and renewals [1]) but the fundamental understanding of these processes is still being developed.

The majority of models of crack growth in rails consider only a single crack; however, rolling contact fatigue is typically associated with a series of adjacent cracks separated by a few millimetres on the rail surface. This is shown schematically in Fig. 1. Cracks which are separated by a distance smaller than their own characteristic dimensions (depth, length, etc.) would be expected to influence one another through modification of the stress field which is driving their growth (further guidance on crack interaction is given in BS 7910 [2]).

To investigate this it was decided to model the growth of single and multiple cracks, and to examine the effect of multiple cracks on the stress levels around the cracks and on the stress intensity factors for the cracks, which can be used to predict crack growth rates.

1.1 Investigation of multiple cracks

Failure in the presence of multiple cracks or by the coalescence of multiple cracks has been studied by several workers. Lam and Phua [3] presented a numerical method for calculating the effect of multiple-crack interactions on stress intensity factors based...
on using distributions of edge dislocations to represent the cracks. Plane strain conditions were studied, indicating positions around a crack in which a second crack either would be shielded or would have its growth enhanced. Similar positions were identified in the work of Kuo et al. [4]. In this study, parallel and coplanar (i.e. aligned end to end) semicircular cracks under contact fatigue loading were examined, and it was found that coplanar cracks interact to increase the stress intensity factors driving their growth, but that parallel cracks have slower propagation than single cracks. Wang et al. [5] examined the joining and growth of multiple small, closely spaced cracks. Experiments showed that the growth direction of crack tips was altered as cracks became close to one another, and a model was developed to predict these changes.

For a series of parallel cracks in a sheet under uniform tension, Rooke and Cartwright [6] presented results predicting the reduction in the stress intensity factor relative to that for a single crack. The cases considered are of cracks which are small relative to their separation, but it is predicted that an infinite run of cracks will produce a reduction in mode I stress intensity factor of around 70 per cent for a ratio of the crack width to separation of 0.7.

More applicable to rail–wheel contact is the work of Noda et al. [7] in which two-dimensional inclined edge cracks subject to tensile loading are studied, including variations in crack size, spacing and inclination. It was found that for the cases examined, which had crack depth-to-separation ratios of less than 0.5, it was necessary to model between 9 and 13 cracks to predict the stress intensity for an infinite run of cracks accurately to three significant figures. In a later study by Moussa et al. [8], two parallel semi-elliptical surface cracks in an infinite plate under both tension and bending were investigated. Although many parameters such as crack shape were investigated, the use of only two cracks and the plate configuration prevents direct application to the railway rail case. For comparison with results in the current investigation, the work of Noda et al. [7] is most valuable, and this comparison is made in section 2.2.

1.2 Rail failure modelling

Crack growth in rails may be split into a series of three phases, as illustrated in Fig. 2. Treatment of these phases together allows the combination of previously separate models of crack growth and rail wear to assess the interaction of these processes and their overall impact on rail life*. Phase I crack growth is by ratcheting (incremental accumulation of plastic strain) [11] which continues until the limiting ductility of the material is reached, at which point wear or crack growth takes place at the rail surface. This phase is relevant only to very short cracks and to crack initiation [12, 13]. Phase II growth is relevant to longer cracks (up to 10–30 mm) and describes crack growth driven by rail–wheel contact stress. It is this phase of crack growth that people typically think of when referring to rolling contact fatigue [14]. Phase III crack growth is relevant to longer cracks, which are driven primarily by rail bending under the action of multiple wheel loads in combination with the track support structures.

The changes produced by the presence of multiple rather than single cracks are likely to affect all three phases of crack growth. As a first stage in the investigation of multiple cracks it was decided to examine phase III crack growth, during which cracks are subject to rail bending stress, but not complications such as extensive plasticity or compressive loading which affect phases I and II. Also, in this first stage it was decided not to include in the model any intermittent or infrequently applied peak stresses such as those

* This is the scientific basis of the so-called ‘whole life rail model’.
caused by wheel flats, the possible effect of which is considered in the discussion. Crack sizes for the investigation were chosen to represent multiple cracks before they have coalesced; therefore distortion of the running band and contact patch which can occur when large cracks or networks of cracks are present was not considered.

1.3 Rail bending

Models of rail bending and rail support movement have been developed by several workers. However, these analyses have been concerned almost exclusively with the development of rail corrugations [15, 16], with vehicle dynamics (vibration, ride quality, etc.) [17], or with noise [18], and little consideration has been given to crack growth. Figure 3a illustrates typical results for rail deflection, indicating how cracks in the surface of the rail will be opened both ahead of and behind a wheel. From the deflection illustrated in Fig. 3a the bending moment present on the rail can be estimated by treating the rail as a simple beam using an approximated second moment of area of $31 \times 10^{-6}$ m$^4$. The results of this calculation indicate a peak crack opening bending stress of 4000 Nm, and it is this value that is used in the modelling described below. The actual value will vary when the influence of several wheels, dynamic loading of the track support and flexure of the rail head on the web is included in the model. However, for this preliminary investigation of the effect of multiple cracks on stress intensity factor predictions, a figure of the right order is all that is required.

1.4 Boundary element modelling

The modelling described here was carried out using the FRANC3D boundary element modelling software developed by the Fracture Group at Cornell University [19]. This software was selected for its ability to model large three-dimensional objects efficiently, and to produce output in the form of stress intensity factors. It has been under development since 1987 and is specifically designed to model multiple non-planar, arbitrarily shaped cracks.

1.5 Programme

The modelling runs undertaken (Table 1) were designed to reveal whether modelling multiple adjacent cracks rather than a single isolated crack in a railway rail made a significant difference in the stress intensity factors and crack-opening displacement predicted. A single rail profile was chosen, equivalent to BS 11 normal grade rail [20]. The rail was taken to have Young’s modulus equal to 210 GPa and Poisson’s ratio equal to 0.3. For the majority of runs with multiple cracks a crack separation of 5 mm was used, this distance being chosen as representative of the separation of cracks seen on rails in curves where rolling contact fatigue cracking is taking place. An overview of the rail model is shown in Fig. 4.

Validation of the modelling results using track data was not possible. However, the capabilities of the software were verified by modelling a single semicircular crack lying normal to the surface of a rectangular block in bending, for which a standard solution was available [21]. Mesh refinement was carried out on this model, and it was found that the solution converged with a very low number of crack front elements. With 20 crack front elements (and a correspondingly fine mesh across the model in the neighbourhood of the crack) solutions within 5 per cent of the standard solution could be produced. To obtain a smooth distribution of stress intensity factor along the crack front the central crack in each model was constructed using 60 crack front elements. Outer cracks, whose main purpose was to relieve stress, were constructed using lower numbers of elements so as to maintain reasonable computing times and memory requirements. A typical mesh is shown in Fig. 5.

Fig. 3 A rail in bending loaded by a single wheel: (a) deflection of the rail [17]; (b) bending moment in the rail when treated as a simple beam with a second moment of area of $31 \times 10^{-6}$ m$^4$
For the runs with multiple cracks, cracks at an angle of 30° below the rail surface were used. This value was chosen to give a reasonable representation of shallow-angle rolling contact fatigue cracks which are reaching the end of phase II propagation (contact stress driven) and are moving into phase III crack growth (bending stress driven). To complement these runs a series of single-crack runs at a variety of angles were undertaken. Although not including multiple cracks, these runs provided a link back to the validation runs, which had used a crack normal to the surface. A smooth transition between the results for the different angles modelled was taken to indicate that decreasing the inclination of the crack had not made the model unstable or non-convergent.

<table>
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<th>Number of cracks</th>
<th>Crack angle to surface (deg)</th>
<th>Crack front elements for central crack</th>
<th>Crack front elements for outer cracks</th>
<th>Crack separation (mm)</th>
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</table>

2 RESULTS

2.1 Crack-opening displacement at the surface

Figure 6 illustrates the effect of modelling multiple cracks on the longitudinal rail displacement at the rail surface. Longitudinal crack-opening displacements on the crack centre-line at the crack mouth are summarized in Table 2.

Modelling a single crack produces the widest (i.e. most open) crack of all those modelled (Fig. 6a). When multiple cracks were modelled, the central cracks have a much reduced opening. This would be expected, because they are shielded from the majority of the tensile stresses, which peak at the running surface of a hogging rail. Cracks at the ends of series of multiple cracks are...
not shielded to the same extent as central cracks. One of the aims of modelling different numbers of cracks was to assess when the shielding effect on the central cracks is closest to what would be seen for an infinite run of multiple cracks. Judging by the crack mouth-opening displacements, even when modelling three cracks the opening displacement for the central crack is very similar to those for the inner cracks in a run of five or seven cracks.

In multiple-crack models the widest opening is for the outer crack which has another crack in the material ‘above’ it. In Fig. 6 this end of the series of cracks is labelled A. The second widest is the crack at the other end of the series, which has another crack ‘below’ it.

2.2 Effect of multiple cracks on the central crack relative to the single-crack case

Considering only the central cracks of the multiple-crack models is a good way to reduce the amount of data to manageable amounts, and to reveal the impact of multiple adjacent cracks on the stress intensity factor.

Table 2  Longitudinal opening distance at the widest point of the crack mouth on the rail surface. Values for the central crack in each case are underlined. Crack 1 in each case is at position B in Fig. 6

<table>
<thead>
<tr>
<th>Run</th>
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<th>2</th>
<th>3</th>
<th>4</th>
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<td>313.63</td>
<td>241.48</td>
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<td>299.38</td>
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<td>845.94</td>
<td>1004.57</td>
<td>—</td>
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Fig. 7  The effect of modelling multiple cracks on the stress intensity factor predicted for the central crack. Cases of a single crack, three cracks, five cracks and seven cracks are illustrated for (a) mode I, (b) mode II and (c) mode III.
difference between the results for the three-, five- and seven-crack models indicates that a three- or five-crack model may not capture all the effects of a long series of cracks. Modelling a longer series of cracks (9 or more) would make this possibility clearer but was beyond the capacity of the computing facilities available. Work by Noda et al. [7] showed that between 9 and 13 cracks were required to simulate an infinite run of cracks, although the change in mode I results between models with 7 and 13 cracks was less than 1 per cent, indicating that a smaller number of cracks can give reasonably accurate results.

Mode II (shearing) stress intensity factors were found to be sensitive to the presence of multiple cracks to a similar degree that mode I values were. Figure 7b presents results which indicate a maximum drop of around 50 per cent in stress intensity value at the deepest point in the cracks, with values close to where the crack breaks the surface little affected. Mode III (tearing) stress intensity factors (Fig. 7c) were reduced to around 74 per cent of the single-crack value by considering three cracks, with marginally greater reductions for five- and seven-crack cases. For both mode II and mode III the results for three-, five- and seven-crack models were close, but there was a trend to reduction in stress intensity factor with increasing number of cracks in the multiple-crack models. As for mode I, this suggests that, although the three-crack model captures the main impact of multiple cracks on the stress intensity factor, the results may be refined by considering more cracks.

The reductions in stress intensity factor found in the current study are very similar to those predicted by Noda et al. [7], despite the difference in applied stress and crack size-to-separation ratio between the two simulations. Noda et al. predicted reductions in mode I and II stress intensity factors to 46 and 56 per cent respectively for an infinite run of edge cracks with a depth equal to half their separation (the largest cracks examined in the study) at 30° below the surface under a tensile load. The current work is on cracks in bending with a depth equal to twice their separation and predicts corresponding reductions of 40–50 per cent in mode I and around 50 per cent in mode II. Despite the difference in applied stresses, the cracks modelled are in the upper surface of the rail, for which tensile stresses dominate; therefore it is reasonable to compare the results for bending with those for the purely tensile case.

From Fig. 7 it is clear that the stress intensities predicted are low and would be below the threshold for fatigue crack growth in rail steel (typical threshold value are 4–6 MPa m$^{1/2}$ for mode I). Low stress intensity values are a consequence of modelling cracks which are just at the start of the bending phase of growth (phase III in Fig. 2). Stress intensity factors exceeding threshold for the crack size modelled here could have been generated by use of a higher bending load. For example, increased dynamic loading or poorly and unevenly supported track would lead to greater bending of the rail. In addition, longer cracks would be expected to give higher stress intensity factors for the bending load currently applied. However, the relationship between the stress intensity factors and the crack size is not expected to be simple because larger cracks at the same spacing will overlap each other more and shield each other more; i.e. the system does not have self-similarity as the cracks change length. The effect of different crack sizes is to be investigated in future work.

2.3 Stress intensity factors for each crack in a multiple-crack case

Figure 8 presents mode I (crack-opening) stress intensity factors around the crack front for all the cracks in the

![Fig. 8 Stress intensity factor variation around the crack front for a single crack, and a model with seven cracks. Figure 6 indicates which crack is in position A and which is in position B](image-url)
seven-crack model, together with results for the single-crack model. Considering the majority of the crack front, the highest stress intensity factors are predicted for the single-crack model. The crack in position B at the end of the run of seven cracks (Fig. 6d) shows the next-highest predicted stress intensity factor and is only marginally below that for the single-crack case. The lowest predicted value is for the central crack of the multiple-crack model, with around 40 per cent of the value predicted for the single crack. The other ‘inner’ cracks of the multiple-crack model show around 55 per cent of the value for a single crack. While these reductions are clearly large, their real impact can only be judged by their effect on crack growth rate. This is discussed in section 3.2. It is interesting to note that, while the crack at position A has a mode I stress intensity factor below that of crack B over the majority of its length, the crack-opening results for these cracks [measured at the surface and not at the crack tip (Table 2 and Fig. 6)] indicate that the crack at position A is opened more widely than the crack at position B. This behaviour was also present in the three- and five-crack models. A difference between the trends in the stress intensity factor and crack opening is possible because, although the stress intensity factor and crack-opening displacement close to the crack tip are closely linked, the crack-opening predictions here are for the crack mouth at the rail surface and are therefore only weakly linked to the stress intensity factor.

2.4 Effect of crack angle on stress intensity factor predictions

The detailed investigation of multiple cracks was for cracks at 30° below the rail surface, and multiple cracks at angles other than 30° were not investigated. However, to gain insight into the effect of crack angle on the stress intensity factor, a range of single-crack models was generated for different crack angles. Considering the mode I stress intensity factor results (Fig. 9) a clear trend can be seen between the results for cracks at 90° to the surface through to those at 25°. Changes in stress intensity factor are most pronounced at the ends of the crack front, but over the majority of the crack front length the mode I stress intensity factor for a crack at 25° to the surface is around 30 per cent of the result for a crack normal to the surface.

2.5 Effect of crack separation on the stress intensity factor ratio for multiple versus single cracks

The multiple-crack models discussed above are all for a crack separation of 5 mm. To investigate the influence of this spacing on the predicted stress intensity factors, run S26 was conducted using three cracks separated by 15 mm. It was found that the change in spacing from 5 to 15 mm produced a very significant difference in predicted stress intensity factor. For the central crack, and over the majority of the crack front length the mode I stress intensity factor for a crack at 25° to the surface is around 85 per cent of its value for a single crack. The change from a single crack to three cracks spaced at 5 mm produced a reduction to around 50 per cent of the single-crack value.

2.6 Effect on surface stress levels between cracks

Between cracks it would be expected that the stress present in the uncracked material is reduced. Figure 10 shows a plot of longitudinal rail stress for the top centre of the rail head. Also shown in the figure is a schematic

Fig. 9 The effect of crack angle on the mode I stress intensity factor for a single crack
representation of the cracks present in the model. In section 2.1 it was found that the crack opening of the outer crack at position A was greater than that for position B, and from Fig. 10 it can be seen that this corresponds to the differences in longitudinal stress acting on these cracks. The right-hand side of the crack at A is subject to a large value of longitudinal stress, while its left-hand face is in a stress-relieved region. For crack B the position is reversed but, because of the geometry of the cracks, even the more highly stressed left-hand face of the crack at B is not as stressed as the crack at A, and so the crack opens less.

3 DISCUSSION

3.1 Crack shielding

Cracks in the surface of railway rails typically develop with intervals of a few millimetres between adjacent cracks. Results presented here indicate that the material between cracks is relieved of stress in the longitudinal direction, but that material at either end of a run of cracks remains highly stressed. This may at first appear to offer some explanation of the interval at which cracks develop. Cracks will not form in material which is relieved of stress since there is nothing to initiate them or to drive their growth. As crack spacing reduces, the stress between cracks becomes too low for the growth of further cracks to be supported. However, this argument does not fully explain the typical crack intervals observed because only bending stresses have been considered here. Small cracks are generated by contact stress, which acts only locally to the rail–wheel contact, and are driven by bending only at longer crack lengths.

Inclusion in the model of localized rail–wheel contact stress and residual stresses in the rail is required before a firm conclusion can be reached on how further crack development is controlled by shielding of material by existing cracks. This work is planned as an extension to the current modelling.

3.2 Crack growth rates

Crack growth in railway rails is a mixed-mode problem (i.e. both opening and shearing stresses are present simultaneously); therefore special crack growth laws are required to convert the calculated stress intensity factors into a crack growth rate. A law specific to rail steel is available from the work of Brown and co-workers [23–26] who conducted and analysed an extensive series of biaxial fatigue tests on rail steels. The tests were conducted using a combined mode I–II non-proportional cycle of stress predicted by Bower [14]. Following this extensive testing, the equations

\[
\frac{da}{dN} = 0.000507 (\Delta K_{eq}^{3.74} - 4^{3.74}) \\
\Delta K_{eq} = \sqrt{\Delta K_I^2 + \left(\frac{614}{507} \Delta K_{II}^{3.21}\right)^{2/3.74}}
\]

were developed to describe the crack growth. \( \Delta K_{eq} \) is a combination of mode I stress intensity factor \( \Delta K_I \) and mode II \( \Delta K_{II} \) stress intensity factor. Mode III stress intensity factors are not considered. The growth rate \( da/dN \) is given in nm/cycle, and the stress intensity factors are in MPa m\(^{1/2}\). A threshold stress intensity of 4 MPa m\(^{1/2}\) is included, below which the crack growth rate is taken to be zero.
Results presented in section 2.2 showed that for the seven-crack model, the mode I stress intensity factor was reduced to around 40 per cent of its value for the single-crack model, and mode II stress intensity factor was reduced to around 50 per cent. These values are taken from the central part of the crack front and are sufficient for the current calculation, although the extent of this reduction varied around the crack front. If it is assumed that these values represent the change in stress intensity factor range, using these values with equation (2) indicates that the effective stress intensity factor will be reduced to around 71 per cent of the value for the single-crack case. Using equation (1) and neglecting the level of effective stress intensity factor relative to the threshold value of $4 \text{ MPa m}^{1/2}$ indicates that this reduction in effective stress intensity factor would produce a reduction in predicted crack growth rate to around 27 per cent of its value for the single-crack case. Although the stress intensity factors predicted here are low relative to the threshold value, consideration of higher dynamic loads or poorly and unevenly supported track would leave the ratio between single- and multiple-crack cases unchanged while increasing the actual stress intensity factor values.

One dynamic load that may be considered in a future version of the model is the impact caused by a wheel flat. Assessing the effect of such a load may at first appear to be possible by simply scaling the current stress intensity factor results by the increase in stress applied by the wheel. However, rail bending takes place under the action of multiple wheel loads, and so the stress experienced by a crack does not scale directly with a peak load present at only a single wheel. Moreover, the distance of the peak load application from the crack would be an important parameter. It is also known that peak loads can even retard crack growth in some cases due to the development of protective plastic strain and residual stress around the crack tip.

3.3 Comparison with field experience

During previous modelling work [27, 28] it has been found that crack growth rates predicted in phase II crack growth (contact stress driven) using single-crack models tend to be higher than the rates observed on rails in service. The results presented in this paper indicate that, for crack growth in bending, the crack growth rate in the presence of multiple cracks (which is the majority of cases) is less than a third of that for a single-crack configuration. If a similar reduction is predicted for the phase II contact stress-driven cracks the agreement between the predicted rates and those observed in the field would be improved.

Work is currently under way to investigate the effect of multiple cracks on crack growth rates in phase II. The major differences between the bending and contact stress-driven crack growth are the importance of crack closure and crack face friction [14] under contact loading, and the highly localized nature of the contact stress field. Such localized loading may diminish the influence of cracks far from the contact on the growth of cracks beneath the contact, but the full details have yet to be established. Phase I (ratcheting-based) crack growth may also be influenced by the presence of multiple cracks in the material. In phase I, modelling shows that many small cracks will be present in the material beneath the contact [29], and each will modify the stress field around it, thereby changing the crack growth rate of adjacent cracks.

4 CONCLUSIONS

Examination of rails on which large rolling contact fatigue cracks have developed, either at the gauge corner or on the rail head, frequently reveals that the cracks have not developed in isolation but occur at intervals along a length of track. However, current models of cracks in rails are almost exclusively single-crack models. Based on a boundary element model of a rail in bending (the primary driver of long cracks in rails) it has been found that for 10 mm radius cracks separated by 5 mm, the mode I and II stress intensity factors are reduced to between 40 and 55 per cent of the value predicted for a single crack when multiple cracks are considered. Using a crack growth law developed for mixed-mode loading of rail steel, this translates to a reduction in crack growth rate to around 27 per cent of its value for single-crack models. If this reduction translates to other crack sizes and separations, it is large enough to have a significant effect on the predictions of integrated rail wear and crack growth models.

The majority of the stress intensity factor reductions predicted can be found by looking at the central crack of a three- or five-crack model, but at the expense of increased computing time some refinement was produced by enlarging the model to include seven cracks. Further investigations will concentrate on the effect of multiple cracks at the gauge corner (the current model was for cracks in the centre of the rail head) and on multiple cracks in ratcheting and contact stress-driven crack growth.

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