

Automatic Crack Growth Prediction in Rails with BEM

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Abstract

Durability and damage tolerance calculations are typically based on experimental data or analytical studies of simplified cases. In this paper, a new numerical approach is described which can be used with the full model loading to compute the stress intensity factors and also to automatically predict how cracks will propagate.

The benefits of the full numerical computation of the stress field are numerous, accurate prediction of crack growth, improved stress intensity data and more accurate prediction of life, thus providing an accurate method for the forensic analysis of failures.

The crack growth process can be modelled with a variety of crack growth models relating the rate of crack growth to the computed stress intensity factors. The crack growth itself can include the effects of multiple load cases including the effect of residual stress fields.

The crack growth process itself is fully automated by automatically re-meshing the crack surface and the nearby surfaces of the structure. The crack growth process is aided by the use of a fracture wizard that enables the necessary components for the analysis to be selected and the analysis to be controlled.

Applications will be presented describing the potential applications of the method to the growth of cracks in rail components.

Keywords: BEM, Fracture Mechanics, Railways, Cracks, Fatigue, Contact

1. Introduction

Fracture analysis can be required in numerous railway components and under a wide range of loading scenarios. Some of these are highly complex involving rolling contact fatigue and crack branching behaviour. The parts to be investigated could include the wheel, axle or the rail itself and all of these could present significant operational safety risks.

The accurate computation of the load transfer within a model is vital when looking at the problem of fracture damage in rail application. Fractures often occur in small features and under complex contact loading conditions. In addition there may be the requirement to simulate moving and

cycling loading requiring analysis with multiple load cases. Therefore for a detailed study of the effects of fractures and how they grow it is necessary to use a realistic analysis tool.

This type of work has been carried out using various analysis techniques, for example finite elements are used to analyse the crack and to represent the contact loading in a 2D representation by Kabo and Ekberg^[1] and by Komvopoulos and Cho^[2] and the effect of anisotropic material properties is included by Ekberg and Sotkovszki^[3].

In the work presented here the analysis of crack is performed using the boundary elements rather than finite elements. With boundary elements a mesh is generated only the boundary of the model rather than the finite element type of mesh which requires the full model to be split into individual elements. This gave an important advantage when performing crack growth studies as the tasks required to remesh the model as the crack grows is significantly simplified.

Other work has been presented with boundary elements, for example Akama and Mori^[4] presented a boundary element analysis with Herzian contact in two dimensional simulations of a rolling contact problem. The code presented here, BEASY^[5], enables the computations to be performed in full 3D analysis, along with the combination of contact analysis, crack growth and, if required, thermal loading.

It is also possible to use finite element results to automatically generate the input data for the BEM crack analysis. In this way models can be quickly developed and the correct loading automatically applied.

For this work the growth will be simulated using a boundary elements model. This will allow the crack to be modelled by simply choosing the crack from a library of available parts and allowing the full combination of both crack growth and contact simulations. Also, in addition to the full analysis tools, loading is generated automatically in a local area using results from a pre-existing finite element analysis of the model without the crack. This can either be used to generate a sub-model from a larger FE model or it can be used to compute residual stresses at crack positions.

The computed stresses can be used to predict the direction and rate of growth of a crack. The crack is selected using an analysis wizard, which has available a library of crack shapes and the crack growth analysis is performed automatically. During the analysis, the full stress solution is computed for each crack increment and this is used to compute the stress intensity factors on the crack front. These stress intensity factors include full Mode 1, 2 and 3 computations which are used to compute the crack growth direction and the rate of crack growth.

2. Boundary Element Analysis

The analysis method used in this paper is the Boundary Element Method (BEM). In this method only the boundary of the model needs to be meshed and the analysis is performed on the surface mesh only.

Boundary element analysis has advantages in two important areas – those of contact analysis and of fracture analysis. The simplicity of the mesh generation which required only surface elements rather than volume elements gives additional flexibility to allow changes to the geometry. The ability to represent small detailed features without complex meshing is also a major benefit of BEM. In addition BEM provides highly accurate stress and displacement data on the contact surfaces.

Crack analysis within the code is based on the Dual Boundary Element Method^[10], where only a single crack face is modelled and a second “Dual” surface is generated automatically. The Dual Boundary Element Method has been developed for a range of analysis types, for example 2D Stress problems by Portela, Aliabadi & Rooke^[6], 3D Stress problems by Mi & Aliabadi^[7] and thermo-elastic problems by Prasad, Aliabadi & Rooke^[8] and dell’Erba, Aliabadi & Rooke^[9].

Contact Analysis

The contact analysis functions allow the contact conditions for two structural components to be evaluated. This include the computation of the regions that are in contact and the regions where there are gaps along with the evaluation of contact pressures, contact stresses and slip distances. This gives the full load transfer between the two structural members.

Both node to node and node to surface contact algorithms have been developed using a constraint based approach which avoids many of the problems associated with penalty function algorithms and methods which use “spring type elements” to represent the contact^[12]. This approach is convenient to implement with BEM as the tractions and displacements are predicted directly on the surface and are not extrapolated

Fracture Analysis

Fractures are generally analysed using the Dual Boundary Element Method, where the crack is modelled by a single surface (or line in two dimensions) of elements. This allows very simple modelling of the crack faces without the need to define special elements or grade elements near to the crack. This task is further simplified with the provision of a tool that is used to automatically add the cracks into a model, with the required crack being selected from a library of initial cracks.

In BEM model a crack is a simple surfaces mesh of one of the crack faces. Figure 1 shows an example of a simple “thumbnail” shaped crack that can be used in a BEM model.

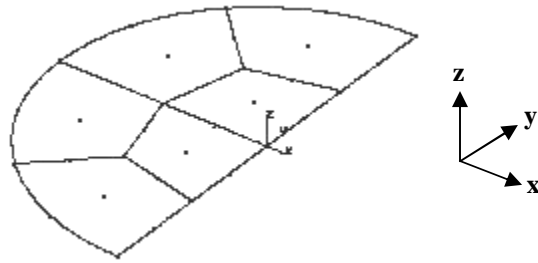


Figure 1 The mesh used to describe a thumbnail type crack

Fracture analysis is implemented into an automatic crack growth procedure. In this procedure a wizard is used to select library crack and define the orientation of the crack. The wizard can also be used to control the load cycling and fatigue growth law required for the model and will also launch the analysis tasks.

During the analysis an initial crack is inserted in the model and the stress intensity factors are computed. Once the stress intensity factors are known, the crack growth can be modelled. This requires two computations – the crack growth direction and the crack growth rate.

The crack growth direction is computed based on the stress field around the crack front. Two criteria are used for computing the crack growth direction – the minimum strain energy and the maximum principle stress directions. These compute for any given loading the direction for the crack growth.

The rate of crack growth is computed using a crack growth model. This usually gives the rate of crack growth model, in terms of the distance growth for a given number of cycles. This equation is of the form $\frac{da}{dN} = f(\Delta K)$, where ΔK is the stress intensity factor range, a is the crack growth distance and N is the number of loading cycles, giving $\frac{da}{dN}$ as the crack growth rate. A collection

of different crack growth models are implemented into the analysis code, including Paris, Forman, Rhodes, Nasgro2 and Nasgro3. All of these crack growth laws utilise material properties to relate the stress intensity factor range to the rate of crack growth. In the case of the NASGRO crack growth laws, the crack wizard includes the NASGRO^[11] databases of these material properties for a range of materials.

Using these two computations, the crack is grown and the new cracked part is modelled. The process is repeated until the required number of steps are completed.

3. Crack Growth with a Sequence of Moving Loads

The analysis is performed using quasi-static analysis. However it is possible to represent cyclic load using a load spectrum file. This can be used, for example, to represent moving load by generating sequences of loads moving along a rail.

An example of this approach is shown in Figure 2 where a two dimensional cross section of the rail is modelled. The figure shows the deformation due to one of the load cases used to simulate the moving load.

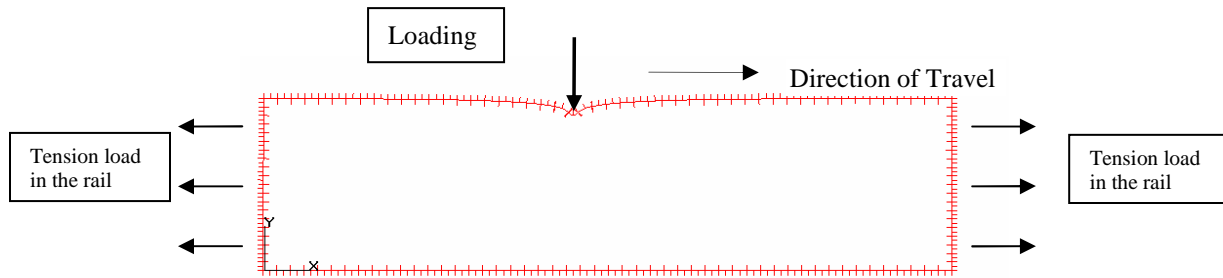


Figure 2 Moving Load Sequence – Basic Loading

Using this method a crack growth process can be generated. Each loading in the sequence is analysed and then using a load spectrum definition file the load cases are combined together. Figure 3 shows an example of crack growth using this load sequence approach and the graph in Figure 4 shows the crack size after various numbers of cycles.

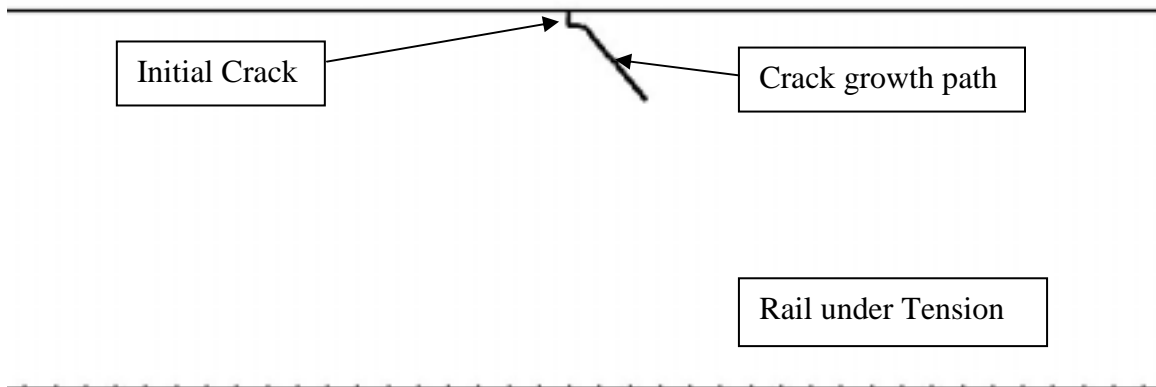


Figure 3 Crack growth path and rate under simulated moving load

Changes in the crack growth direction can be clearly seen. The crack grows at a fairly shallow angle near the surface where the major stresses are due to the contact. As the crack grows further from the surface the direction becomes dominated by the tensile stress in the rail and the crack grows at a steeper angle.

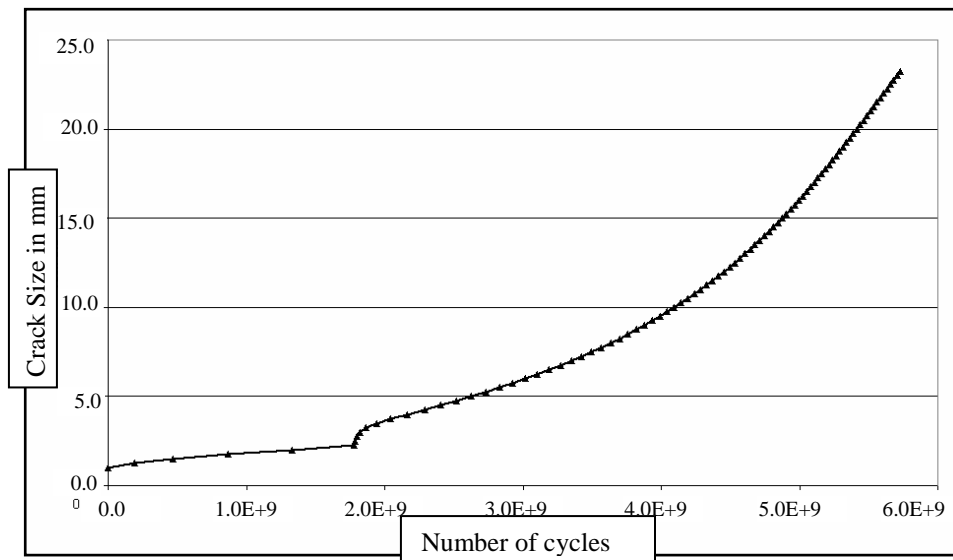


Figure 4 Crack growth rate under simulated moving load – Crack size for a given number of cycles

4. Representing Residual Stresses

Residual stress fields cause static loads that can accelerate or retard the rate of crack growth in a component. The residual stress fields can be caused by manufacturing process or post-manufacturing surface treatment operations and in the case of rails the rolling contact fatigue.

An example of the application of residual stresses can be seen in the hole in a plate shown in Figure 5. The figure shows contours of the residual stress which in this case have been defined using an analytic expression that describes the residual stress as a function varying with the distance from the surface of the hole.

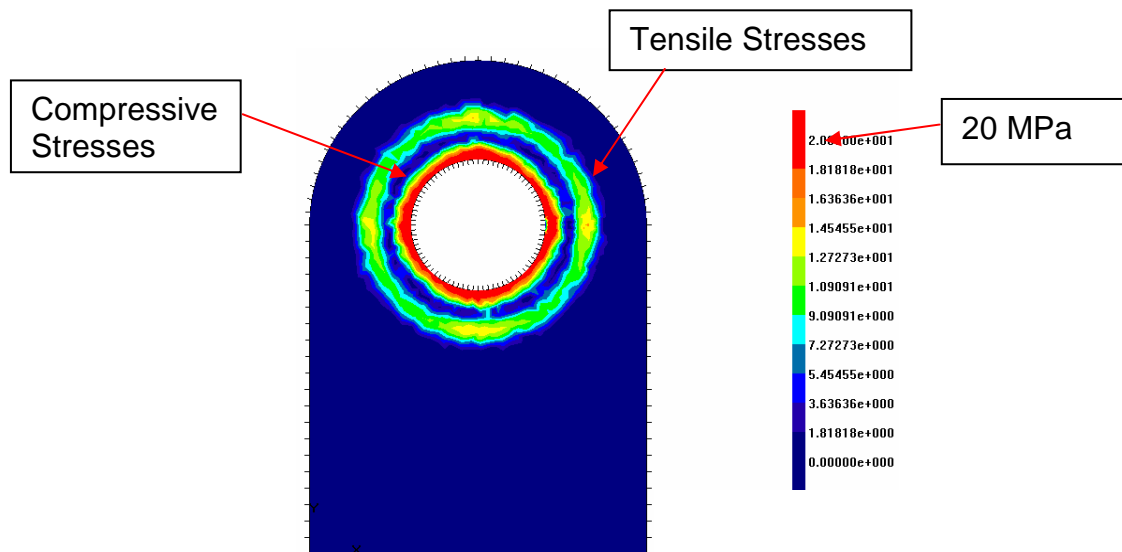


Figure 5 Example of a Von Mises Residual Stress Field Distribution Around a Hole in a Plate

The material around the hole is in compression at the surface and then there is tension further into material of the plate. The stress field can be computed with any analysis code and the are applied to

the model. These stresses are then used to generate additional loads on the crack faces in the model which by a principle of superposition represents the effect of the residual stress field.

In the analysis the residual stress load case is defined as a static load case in a load spectrum file and a cyclic tension load, applied to the upper edge of the hole, is defined as a dynamic load case. The combination of the two load cases is used to compute the crack growth rate in the model.

Figure 6 shows the crack growth rate with and without the residual stresses load case for this model. This shows that the residual stresses allow more loading cycles before the crack reaches a specific size, thus increasing the life of the component. The loading on the model was compressive near to the surface of the hole, therefore there is a retarding effect on the crack growth.

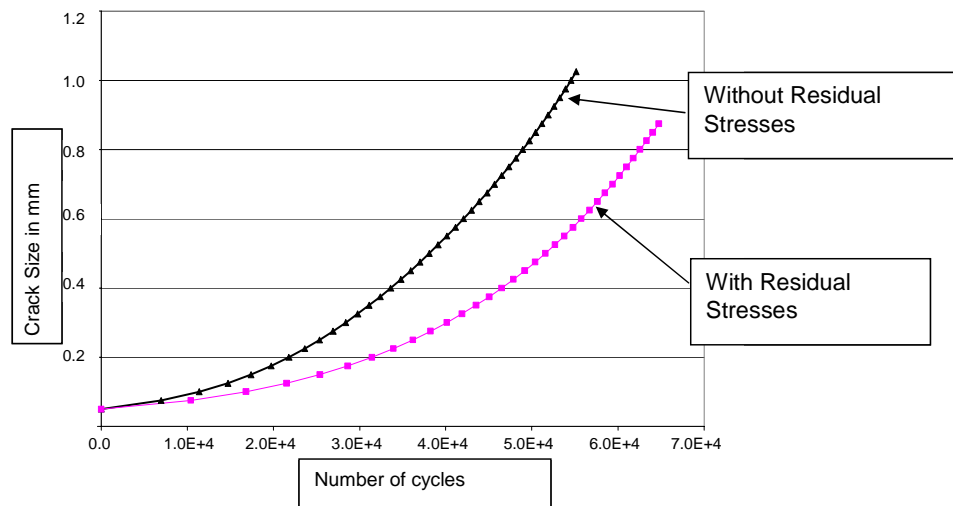


Figure 6 Comparison of crack growth rate with and without residual stress field

5. Crack Growth in Rail with Contact Pressures

The above examples showed crack growth analysis using a two-dimensional idealisation of a model with a crack modelled completely through the body and with a perfectly straight crack front. However cracks do not always grow completely through bodies and two-dimensional representations are often insufficient.

In addition to this, the above examples show loading applied directly to the cracked part whereas often this loading is applied to a secondary body that is in contact with the cracked part. This causes complex loading in the load transfer area. In this next example, the contact loads are computed using a full contact load analysis.

Figure 7 shows a three dimensional section of a wheel and rail where due to the curvature there is only a small area of contact which is dependent upon the load. The objective of the initial model is to compute the contact area and the traction distribution.

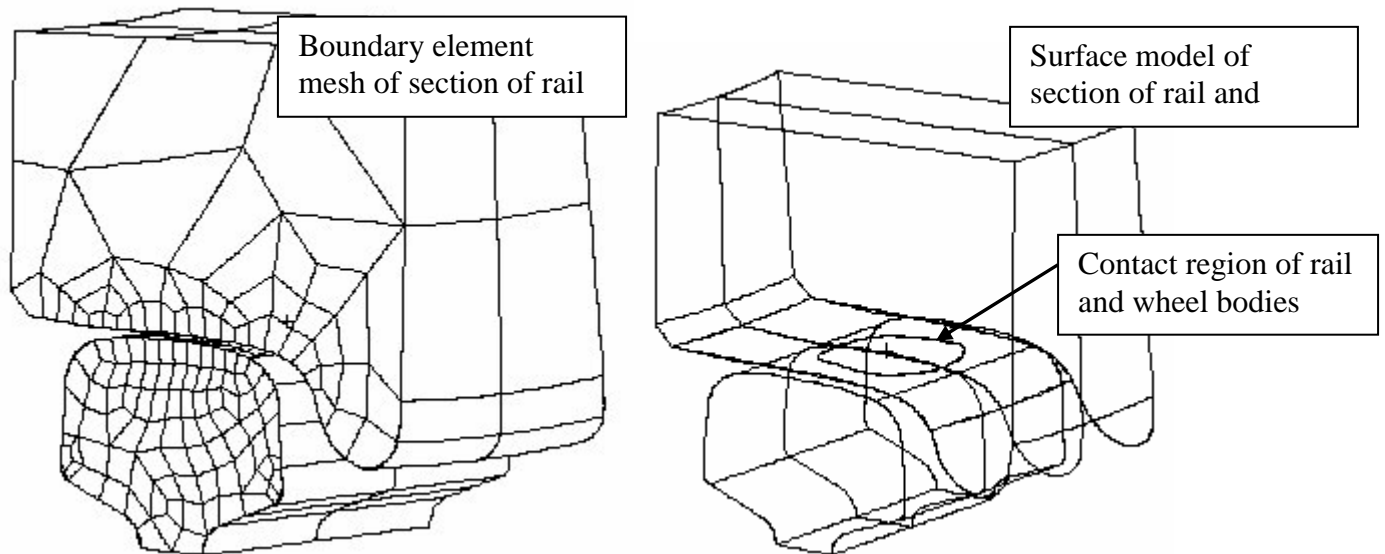


Figure 7 Model of Rail and Wheel with Mesh and contact region shown

The contact mode is analysed without any crack and the tractions on the contact area extracted and applied to a model of the rail only. Another method could be to perform the contact analysis for each of the crack analysis models that is generated during the crack growth procedure, but in this case this is not necessary as the crack will not affect the extent of the contact area or the distribution of the load itself.

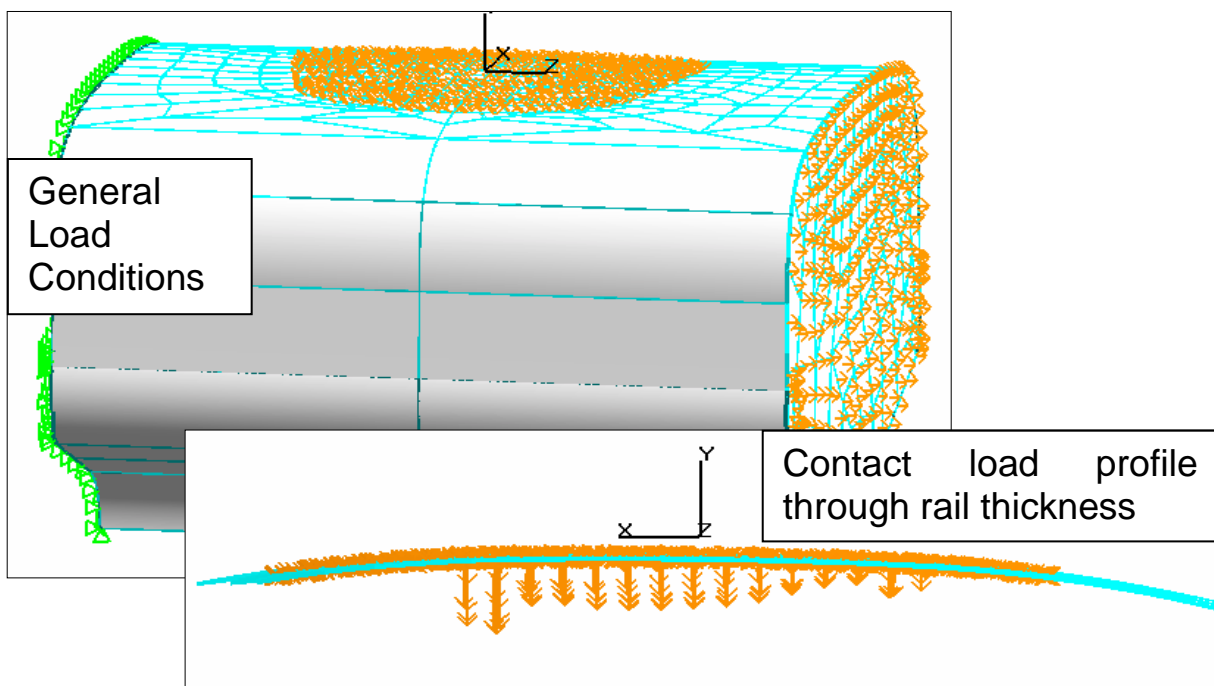


Figure 8 Loading on Rail - Extracted from Contact Model

The fracture study will be performed using an initial subsurface defect. This will be modelled as an embedded penny shaped crack near the top of the rail and the crack will be selected from the library of crack shapes.

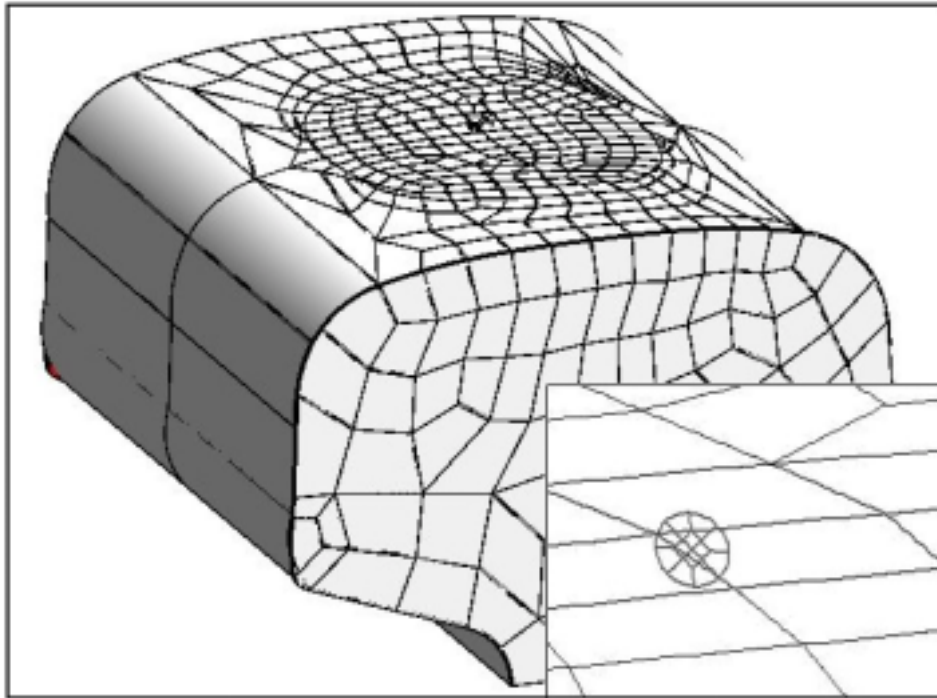


Figure 9 Sub-surface crack initiated in rail model

During the crack growth the crack shape is not constrained to remain planar and can grow in any direction, based entirely on the stress intensity factors arising experienced along the crack front. In this case the loading turns the crack growth away from the plane of the initial defect and the crack grows in a new direction.

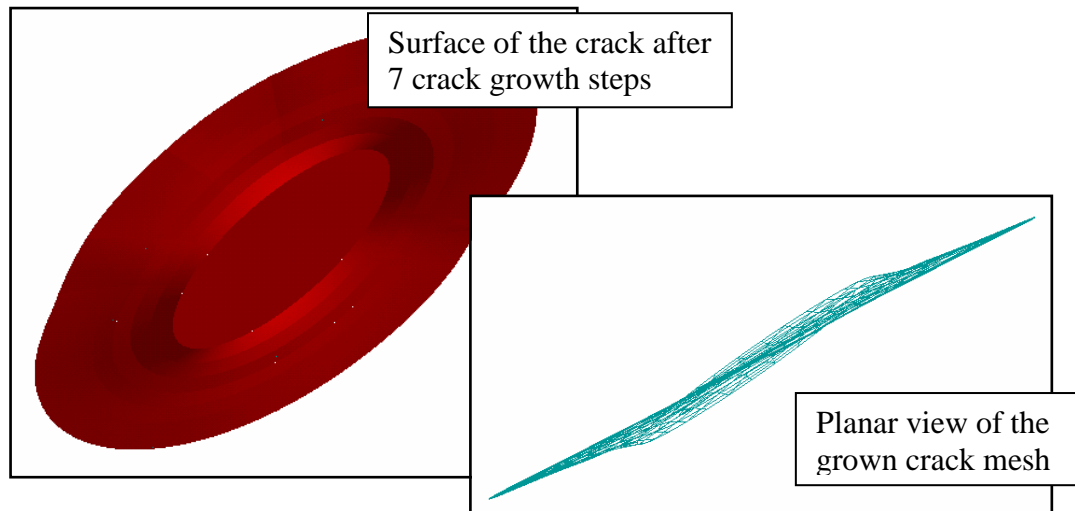


Figure 10 Sub-surface crack grown for 7 increments where the change in crack growth direction can clearly be seen.

An alternative approach, if an FEM model of the wheel and rail without any modelled crack is available, is to use FEM results to create the BEM model. The BEM model can simply consist of a section of the rail where the crack is located. This is explained further in the next section.

6. Crack Growth Using Finite Element Data

Many analysis models are generated and analysed using finite elements. It is possible to use existing FEM models to perform crack growth studies. In this case the geometry, stresses and displacements from the finite elements model are automatically extracted and used to generate a boundary element sub-model containing only the area near the crack. For example, Figure 11 shows a bracket has been modelled with TET10 finite elements.

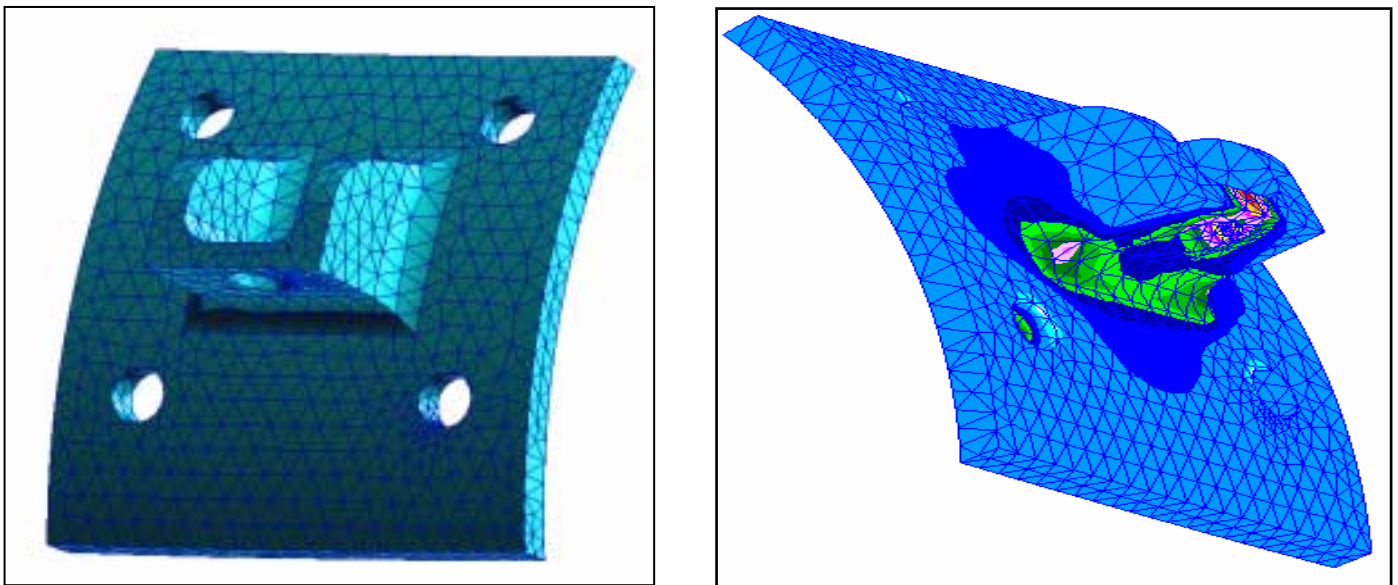


Figure 11 Bracket modelled and analysed using finite elements

From this model a sub-model will be generated close to a region of high stress and this sub-model will be used to provide a fracture study of the local area. The resulting BEM model is shown in Figure 12. The BEM model uses the surfaces of the FEM elements selected to form the new model. A field mapping approach is used to extract the stresses on the “cut” surfaces of the FEM model and convert them into equivalent tractions on the BEM model. A similar approach is used for the displacements. The “cut” surfaces are those surfaces created by the FEM elements which in the original model were internal, but in the extracted model are now external surfaces.

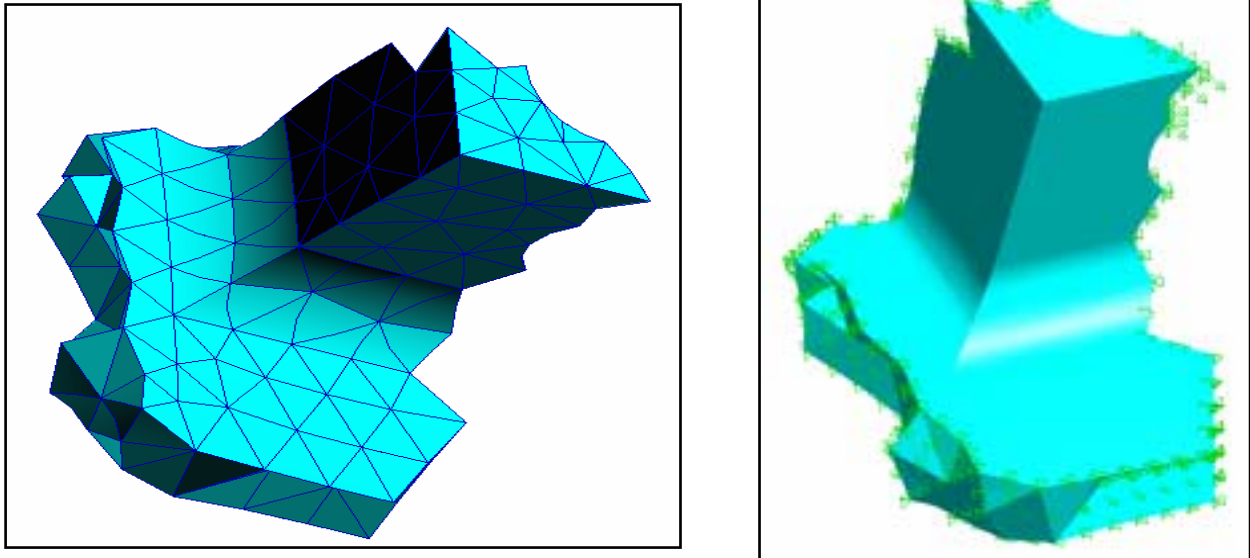


Figure 12 Extracted finite elements and BEASY sub model around required crack initiation site

These elements are then converted in to a Boundary Element zone and a model file is generated. This model file can then be used as an initial model in the automatic crack growth analysis and a corner crack is selected from the crack library and is initiated into the model. Again the crack is allowed to grow based purely on the computed stress intensity factor values. This gives a crack with a complex shape as shown in Figure 13.

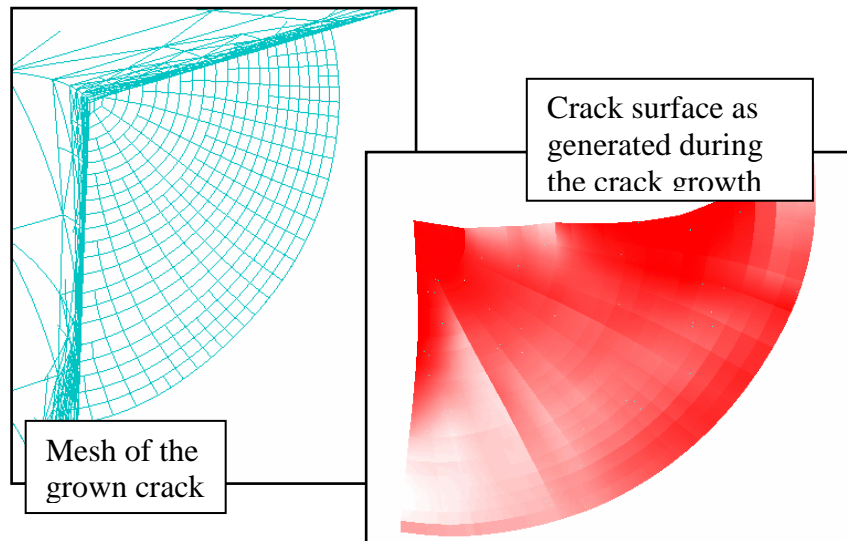


Figure 13 Crack grown in sub-model for 21 increments

7. Conclusions

Crack growth prediction in rails has been demonstrated with simple surface meshing and with a high degree of accuracy on the surface. The combination of contact analysis and automatic crack growth prediction in two and three dimensional analysis has also been demonstrated.

It is also possible, as seen to generate load sequence analysis to simulate moving loads and to extract models and results from existing FE analysis models.

The software has been successfully used to model crack growth in a wide range of railways applications. This task is simplified by the simple surface meshing method, as demonstrated by these examples, and the natural modelling of both cracks and contact areas. The advantage of only modelling the surface details and the removal the necessity to create fine domain meshes makes the meshing tasks relatively simple and removes additional constraints on the crack growth path that may occur due to the domain mesh that is required in many finite element methods.

The ease of modelling also allows the crack growth to be performed automatically, with cracks allowed to grow dependent only on the loading of the model, without pre-knowledge of the crack growth directions being required.

A range of techniques has been presented to allow models to be analysed with varying degrees of complexity and detail. These include 2D representations of structures, allowing both plane strain and plane stress calculations and full 3D analysis. The loading on the model can be applied using defined traction and displacement loading values and this can incorporate the load transfer conditions arising from contact loading. In addition BEM easily allows the effect of a residual stresses field to be considered. It has been shown that this can be introduced into a 2D BEM model and used to influence the results. The next stage in this analysis is to consider the introduction of a residual stress field into a 3D cracked rail problem.

Load sequences can be modelled in any of these techniques by specifying a series of load cases and defining the cycling between these load cases. Multiple load cases can then be combined to give the full loading history.

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