Fully Automatic 3D Crack Growth with BEM

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Abstract

In this paper, a new method is presented for the automatic growth of edge cracks in three-dimensional fracture analysis using BEM. The procedure described overcomes the current problems with crack growth analysis that currently has to be performed manually. Applications are presented which demonstrate the effectiveness of the technique.

1 Introduction

The analysis of cracks within structures is an important application if the damage tolerance and life of structures and components are to be predicted. Often cracks cannot be avoided in structures, however the fatigue life of the structure depends on the location and size of these cracks. In order to predict the fatigue life for any component, a crack growth study needs to be performed.

The boundary element method is an ideal solution for performing crack growth analysis due to the high accuracy of the stress results computed on the surface of the structure. In addition, since only the boundary of the body needs to be discretised for boundary element analysis, the meshing time can be significantly reduced over other analysis methods.

For a few years now, the BEASY analysis code has been capable of performing fully automatic crack growth of embedded cracks. For an embedded crack the addition of new elements as the crack grows can be performed automatically as the new elements are not connected to the surface mesh. This is another benefit of the boundary element method.

In the case of an edge crack, however, previously BEASY only allowed a single crack growth step to be performed. The user was then required to generate a new crack analysis model from the predicted crack front and repeat the process for each required step. This can often be a complicated task and requires a significant amount of the users time.

In this paper, a new method is presented for growing edge cracks fully automatically. In addition, the method allows the user to add an initial crack into a model from a library of crack shapes, removing from the user the task of meshing the crack.

2 Crack Growth Prediction

The BEASY analysis code uses the Dual Boundary Element Method (DBEM)[2,3] to compute the stress field in a cracked body, predicting displacement and stress fields in the entire structure. The analysis code then uses the crack opening displacement method to compute the stress intensity factors at the crack front. In order to predict where the crack will grow to and the number of loading cycles, it will take an integrated crack growth model is required. Figure 1 shows the components necessary and complete details can be found in the BEASY userguide[1].

To re-compute the values of the Stress Intensity Factors as the crack grows, an incremental approach is adopted. The crack growth model predicts the rate and direction of growth of the crack and, after a defined increment size, a new crack front is predicted.

In the analysis of embedded crack, at each iteration a series of new elements are added to the crack front. These elements are formed from the positions of the old crack front and the predicted positions of the new crack front.

When looking at an edge crack, the crack can be grown in the same way, with new elements added to model the new portion of the crack surface. However, problems arise at the edge of the crack where the crack intersects the surface of the body. The new predicted positions are based only on the geometry of the crack and the results of the stress analysis itself. The positions are not based on the mesh defined in the model. Therefore the new crack front will not match the mesh defined on the external surface of the body and may not even lie on the surface itself. So, when manually re-meshing the model, the user initially must identify where the crack front intersects the external surface and then the surface itself must be re-meshed.

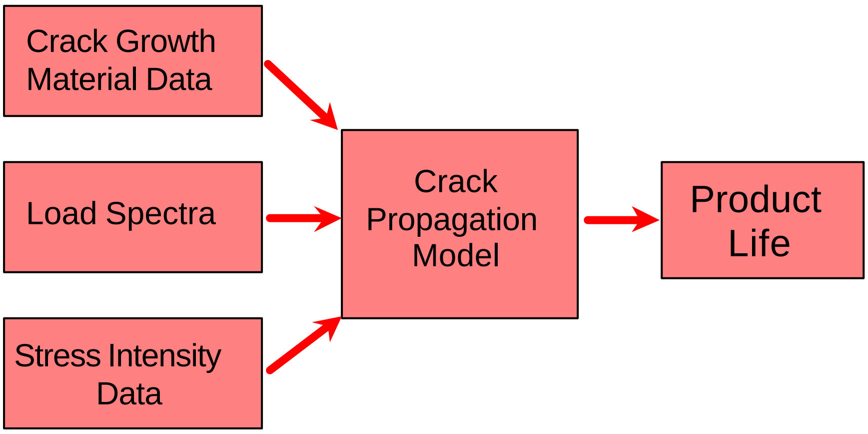


Figure 1: Components necessary for crack growth prediction

In some models the crack re-meshing can be very complex and time constraints and model complexity can prohibit crack growth beyond a few iterations. The aim of the automatic remeshing is to remove this manual work from the user to allow more detailed study of crack growth models to be performed automatically.

3 Automatic Remeshing

The new crack growth meshing software is designed for use along with the BEASY analysis code. As described above, at each crack growth step, the crack growth model produces a set of new mesh point positions for the new crack front. The meshing program uses these new positions to compute a set of new elements on the crack surface. The edges of the new crack front are modified so that they will intersect with the external surface of the body and the external surfaces are also re-meshed in a region close to the crack itself. In addition, if the new elements on the crack front become distorted, they are divided into two elements, allowing for a much more accurate stress computation to be made.

The remeshing of the boundary element model is performed using remesh areas in the model. These remesh areas are collections of elements with similar orientation that can be re-meshed together. These areas are re-meshed using a mapped meshing technique, where the elements are projected onto a flat surface and are then meshed on that surface. Therefore the remesh areas must have similar outward normal directions otherwise the new mesh will be distorted. For example, in a structure such as a box, with sharp corners, the faces of the box will need to be in different remesh areas.

The algorithm identifies the line where the crack interests with the re-mesh areas and selects elements close to this line. These elements are then deleted and new elements are created to replace them. The new elements created are forced to have mesh points along the crack edge line, in order to give a good mesh solution in the local remeshing area.

4 Crack Addition

One important extension of this technique is that it is possible to use the same algorithm to add a crack into a model that has simply been defined to perform a stress analysis. This allows the user to generate the boundary element model without having the expense of modelling the crack. The crack can then be added in anywhere on the model and, providing suitable remesh areas have been defined, a new BEASY data file will be automatically generated containing the crack.

This will allow the user greater flexibility in testing different initial positions, sizes and orientations for the crack, without any additional effort in remeshing the boundary element model itself.

5 Crack Growth Automation

This crack growth procedure requires the running of the crack growth remesher followed by the BEASY analysis code once for each crack growth step that is required. This provides flexibility in allowing the user to control the number of crack steps grown and provides automatic storage of the data files for each of the analysis steps. However it is often an advantage to allow the crack growth analysis to carry on without the need for any user intervention.

Therefore, an additional option is to allow the process to be performed completely automatically.

6 Examples of Crack Growth Algorithm

In order to explain the methodology for automatic crack growth a simple example is presented which consists of a cylinder under uni-axial loading with a flat central edge crack. The first step in the process is to generate a BEM model of the cylinder sufficient to provide accurate displacements and stresses.

The cylinder has been given a very simple uniaxial loading as shown in Figure 2. The model has been meshed with the same size mesh over the entire model, with no consideration given to where the crack will be placed. In some cases, the area where the crack will be placed may need to be meshed with a finer mesh, since this will be the area of high stress concentration. However, this may not always prove necessary as the remeshing code will refine the mesh in the immediate area of the crack.

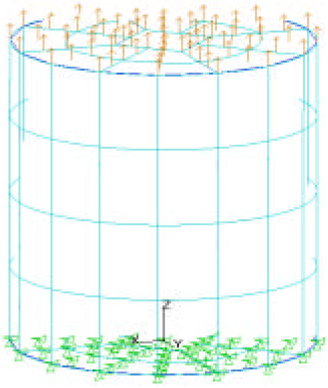


Figure 2: Cylinder Example - Base Model

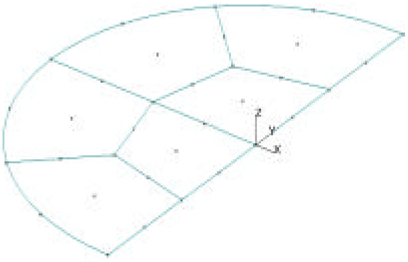


Figure 3: 6 Element Edge Crack Definition

The crack is then added in during the analysis using the BEASY crack remesher program. The crack itself has been taken from a crack library file and is defined to be an edge crack, modelled with 6 boundary elements. The library crack is centred at the origin, it has a radius of 1 unit and is modelled only in the x-y plane, with the crack front along the y-axis, as shown in Figure 3.

The crack is to be added in at a specified mesh point in the model. The crack will be placed at coordinates (1.0,1.0,2.5) and the crack will be scaled to be of radius 0.1. The crack meshing program is then used to add the crack into the model and to remesh the surrounding region. The library crack that was selected for this model had a straight edge, however the surface that the crack is going to be attached to is not straight. This is taken care of in the remeshing code, with the edge where the crack intersects the geometry surface being trimmed back to the required size. The resulting mesh is shown in Figure 4.

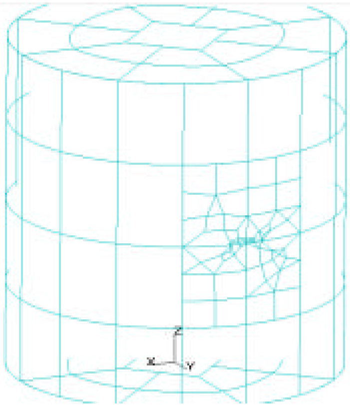


Figure 4: Cylinder Example – Initial Crack Mesh

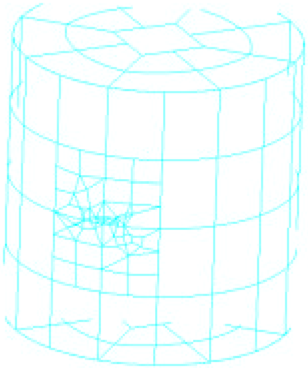


Figure 5: Cylinder Example – First Crack Growth Step

The model generated using this remeshing program can then be analysed in the usual way. A single analysis is done on this model and a set of new crack front positions is predicted. The crack growth remeshing code can then be re-used in order to generate new elements defining this crack front and to remesh the surfaces around the area of the crack itself. This produces a new geometry for the first crack growth step, as shown in Figure 5.

This procedure can be repeated until the crack grows the required distance, number of cycles, stops growing or fails. Here the crack was grown for 5 crack growth steps and the resulting mesh is shown in Figure 6 and the crack surface is shown in Figure 7.

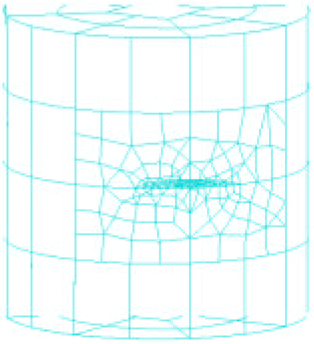


Figure 6: Cylinder Example - Mesh after 5 Steps

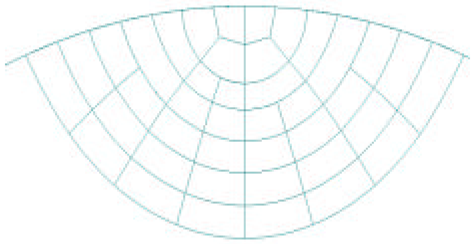


Figure 7: Cylinder Example - Crack Mesh after 5 Steps

Example 2: Box under Non-Uniform Loading

In this example a corner crack, show in Figure 8 is attached into a box model. Again the box has been modelled without an initial crack (see Figure 9) and the crack has been added in to give the initial mesh (Figure 10).

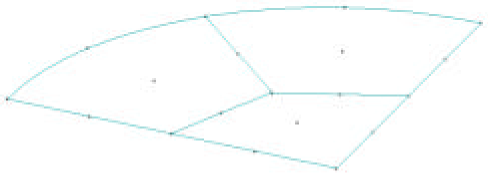


Figure 8: Corner Crack With 3 Elements

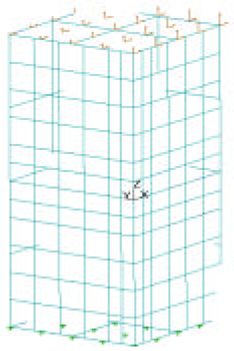


Figure 9: Initial Box Mesh

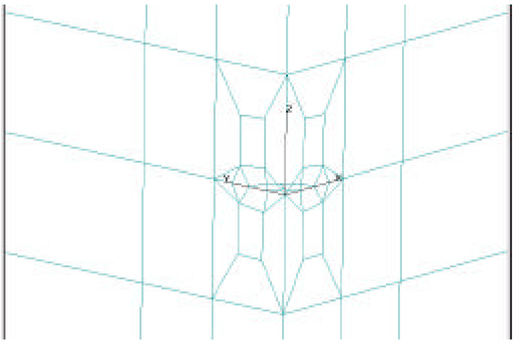


Figure 10: Box Example - Initial Mesh With Added Crack

In this example, the loading is not uniform, so after a number of crack growth steps (18 steps are shown here), the crack is surface is no longer planar (see Figures 11 and 12).

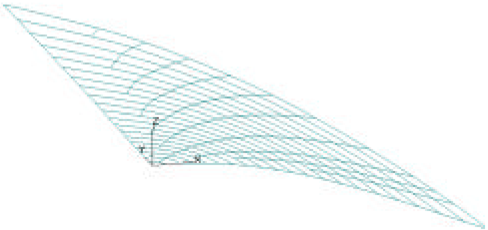


Figure 11: Box Example - Crack Mesh After 18 Increments

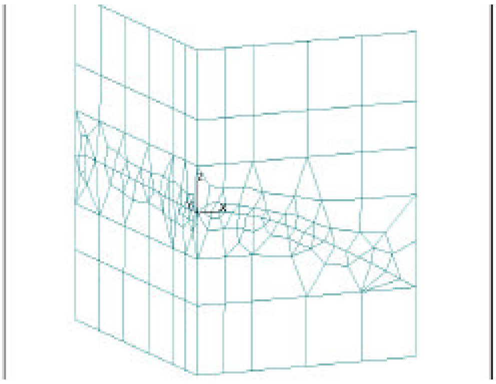


Figure 12: Box Example. Surface Mesh After 18 Growth Increments

Example 3: Predicting the life of a crank shaft

In this application a crank shaft Figure 13 subject to fatigue loads is analysed to predict how the component will behave once a crack has initiated. The results of the stress analysis suggested that a crack would initiate in the area of a sharp fillet radius. Figure 14 shows how the crack library simplifies the modification of the model to include the crack even in complex geometric regions subject to high stress concentration.

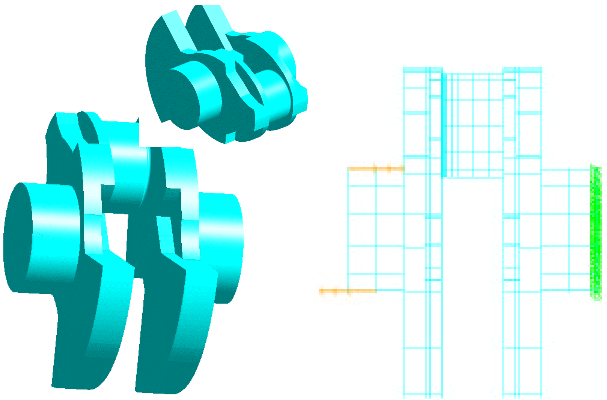


Figure 13: Crank shaft model and BEM mesh

- Simply choose the crack from the crack library.
- The crack is automatically added and remeshed to include the crack.

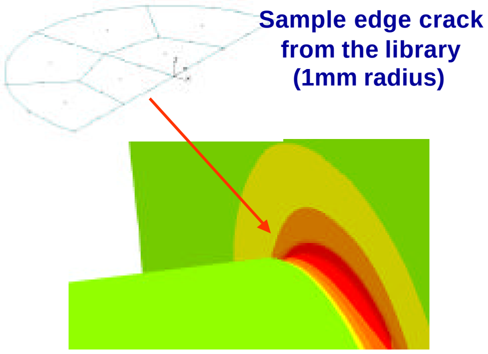
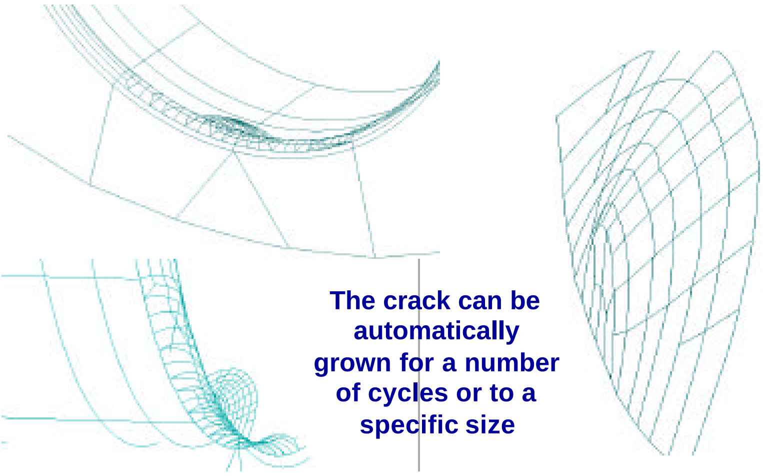


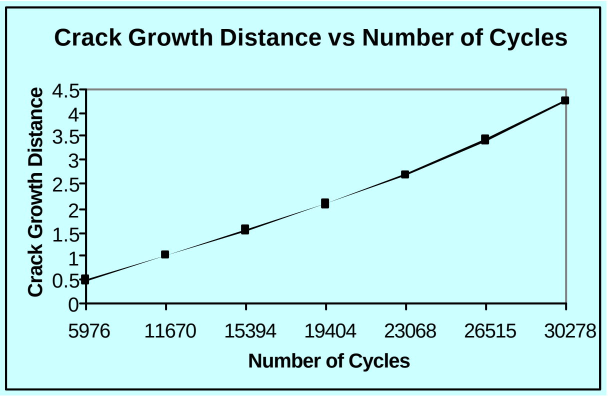
Figure 14: The initial crack is added to the crank shaft

The crank shaft was subjected to a loading spectra which can consist of multi-axial loadings as well as combined mechanical and thermal loads. Figure 15 shows the results of the simulation where the crack has been automatically grown. The direction of growth and shape of the crack can be clearly seen. However, the important design information can be seen in Figure 16 where the crack size variation with the number of loading cycles is shown. Similar information can be displayed for the crank shaft residual strength and Stress Intensity data.



The crack can be automatically grown for a number of cycles or to a specific size

Figure 15: The crank shaft is subjected to the loading history and the behaviour of the crack predicted



At this point the crack has grown 4.5 mm

Figure 16: The key life data can be predicted. In this case the rate of growth of the crack is predicted.

7 Conclusions

A completely automatic approach to predicting crack growth in complex components under thermal and mechanical loads has been presented.

The combination of the boundary element method and automatic surface meshing simplifies the process.

The automation of this process fundamentally changes how this type of calculation will be performed in the future. The user effort required to perform a real accurate crack growth calculation is now similar to that required for approximate methods based on standard text book cases.

It is inappropriate to use approximate and unreliable methods when it requires just as much effort to obtain precise data with the methodology presented.

References

[1] BEASY User Guide, Computational Mechanics BEASY Ltd, Ashurst, Southampton, UK, 2000.

[2] Mi Y; Aliabadi M.H., "Three-dimensional crack growth simulation using BEM", Computers & Structures, Vol. 52, No. 5, pp 871-878, (1994).

[3] Neves A; Niku S.M., Baynham J.M.W., Adey, R.A., "Automatic 3D crack growth using BEASY", Proceedings of 19th Boundary Element Method Conference, Computational Mechanics Publications, Southampton, pp 819-827, 1997.