

Durability prediction using automatic crack growth simulation in stiffened panel structures

S. Mellings¹, J. Baynham¹, R A Adey¹, T Curtin²

¹*Computational Mechanics BEASY, Ashurst Lodge, Southampton, UK*

²*Computational Mechanics Inc, Billerica, MA, USA.*

Abstract

A new method is presented for automatically predicting the growth of cracks in stiffened panel structures. The procedure simplifies the modelling of stiffened panels by allowing definition of beams and use of multiple overlapping boundary element zones joined by connector elements. Applications are presented to demonstrate the effect of the stiffeners on crack growth.

Introduction

In order to be competitive aerospace companies need to produce cheaper, stronger, safer and more durable products. Environmental pressures have also highlighted the need to minimise the use of energy and the need for lighter vehicles. All these objectives have to be achieved while maintaining safety and durability. At the same time there is a worldwide trend towards operating aircraft beyond their initial design life thus dramatically increasing the possibility of reduction or loss of structural integrity.

Durability and damage tolerance calculations are typically based on experimental data or analytical studies of simplified cases. In this paper, a new method is presented for representing stiffened structures made up of panels and beams attached at discrete points by fasteners. The method allows the user to initiate a crack in a model by selection from a library of crack shapes. The crack and structure are automatically meshed and the crack is grown fully automatically.

The benefits of the approach are numerous: accurate prediction of crack growth, improved stress intensity data and more accurate prediction of life, thus providing a tool which can be used to investigate damage control strategies and optimise durability.

The crack growth process is simulated by integrating a model of the structure, a model of the crack (or cracks), the crack growth model relating da/dN and ΔK and the multiaxial loading history. The process is fully automated by automatically re-meshing the crack surface and the nearby surfaces of the structure. Because the technique is based on the boundary element method only a surface mesh is required.

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 [1-7]. 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.

Theoretical Foundations

A number of authors have studied the numerical simulation of crack growth using a variety of numerical techniques. Finite element methods have been developed^[10,11,12] using mesh generation techniques and cohesive elements. They however still require a discretization of the three-dimensional volume mesh. Boundary element solutions^[1-10] benefit from a surface only representation of the crack.

BEASY uses the Dual Boundary Element Method (DBEM) to predict the stress field for cracked structures and hence to predict the stress intensity factors along the crack front. The analysis method implemented is based on the theoretical foundations developed for two-dimensional analysis by Portela, Aliabadi and Rooke^[2] and for three-dimensional analysis by Mi and Aliabadi^[3]. This method has been further developed to include the effect of thermal stresses by Prasad, Aliabadi and Rooke^[4] and dell'Erba, Aliabadi and Rooke^[5]. In the Dual Boundary Element method, the crack in a structure is represented by special "Dual" elements that allow the stress and displacement fields to be computed on both crack faces without the need to subdivide the body along the crack boundary.

The Dual Boundary element method is a powerful solution tool for fracture mechanics, because it is a boundary only representation, it is highly accurate, and is able to represent the rapidly changing stress fields near the crack front.

Stiffened Panel Modelling

Previously Salgado and Aliabadi [15] investigated this problem and presented a solution based on a boundary element formulation. This paper presents a new methodology to enable not only beams to be connected to the panel but also “doublers” made up of multiple panels, as well as structures made up of finite element beams. The fundamental difference in the approach presented is that special “hole” boundary elements have been developed to which fastener (or “rivet”) elements can be connected thus enabling the general coupling of finite element and boundary element models. The method has been implemented in the BEASY analysis package so that stiffening beams and panels attached at discrete points can be used in a simple two dimensional model.

Often in industrial applications – and particularly in the aircraft industry - structures which need to be analysed are made up of flat panels stiffened by either beams (ribs and stringers) or panel structures (doublers). In the past this required complex three-dimensional models of the ribs or doublers, along with the connections between the two parts of the structure, but the methodology described here greatly simplifies the modelling. The remainder of this paper will describe the new hole element types, followed by the load transfer elements and finally the stiffening elements. Examples will then be presented to demonstrate the new features.



Figure 1 Typical model found in the aerospace industry with a panel riveted to a doubler panel

Hole Elements

Two-dimensional panels can be modelled by defining boundary elements around the edge of the panel. For riveted structures, a hole exists in the panel at each position at which a connection is made to stiffening ribs (or doublers). These holes are modelled using a new element type, known as a hole element. This models the hole in the base panel and allows a load to be applied to the panel.

Hole elements are a special type of boundary element that have a single mesh point, defined at the centre of the hole, and a radius. The displacement and traction components are taken to be constant around the hole itself.

Connector Elements

When modelling stiffened structures, it is necessary to provide a means of load transfer between the different parts of the structure. For example in the case a of stiffening panel (or doubler) the load must transfer between the base panel and the stiffening panel.

This load transfer is provided by connector elements, which can either be rigid, linear or non-linear. Rigid connectors provide load transfer between the two parts, such that the displacements at either end of the connector are identical. Linear connectors allow a stiffness to be defined giving a differential displacement between the ends of the connector. Finally the non-linear connectors allow a non-linear stiffness-displacement relationship to be defined.

Connector elements can be used either to join multiple boundary element zones, or to join beam elements into a boundary element model.

Beam Elements

Beam elements are used to model the stiffening beams themselves. The elements can represent the longitudinal and bending stiffness of the beams. Each element is modelled using two mesh points, which can be shared with other beam elements or with a connector element.

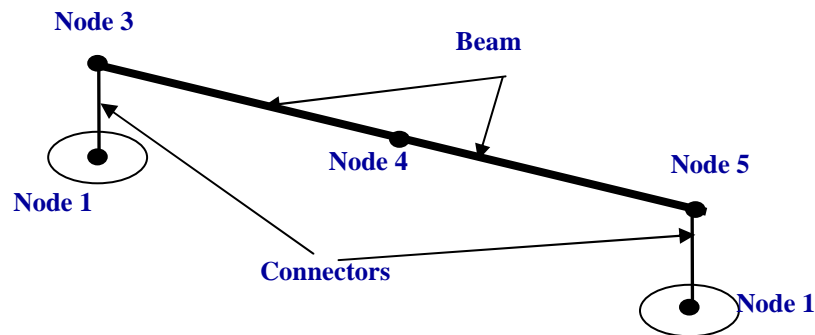


Figure 2 View of the beam elements showing how they can be connected to the hole elements in the panel

Example 1: Panel Modelled with Stiffening Beam

A panel has been modelled with stiffening beams as shown in the picture below. The beams are attached to the panel at 12 connector positions (at the end of each beam and also at the beam intersections).

The mesh and boundary conditions are shown in Figure 3. The plate is loaded vertically at the top edge, while the base is restrained in X and Y directions.

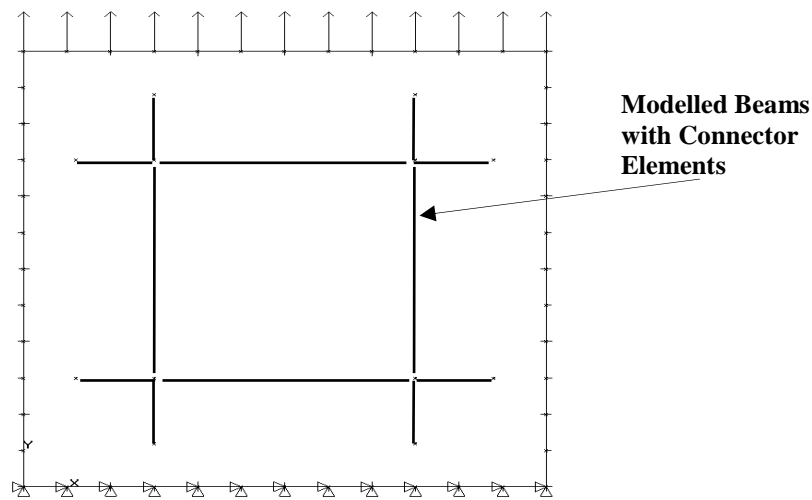


Figure 3 Test model showing the square panel and the location of the stiffening beams

In the results shown in Figure 4, the effect of the beams can be seen both in the deformation of the panel and in the stress contour close to the connection positions.

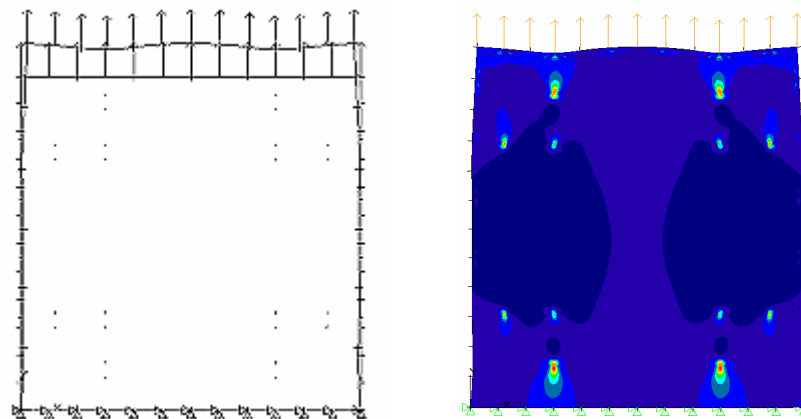


Figure 4 Deformed shape and stress distribution in the panel. Note the stress concentrations around the fastener holes in the panel can be clearly seen

Example 2: Effect of Stiffeners on Crack

It is often necessary to examine the behaviour of cracks close to stiffening beams to examine the effect of the beams on the crack growth. In this example an edge crack has been introduced into the panel, as shown in Figure 5, and the crack has been allowed to grow, assuming cyclic loading.

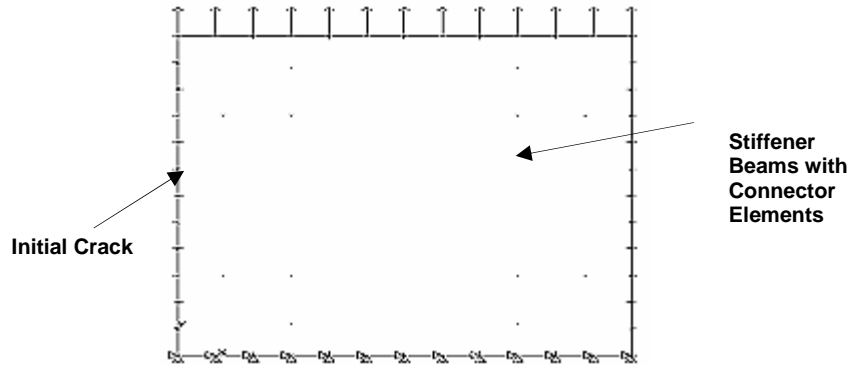


Figure 5 Model showing the location of an initial edge crack in the panel

The highly exaggerated deformed shapes for the cracked plate with and without stiffeners are shown in Figure 6. The reduced displacement when stiffeners are present can clearly be seen.

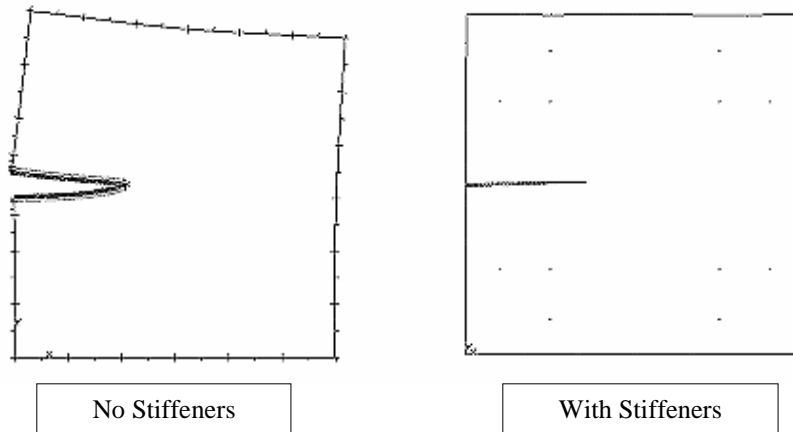


Figure 6 Exaggerated deformed plots of the panel

This difference can further be seen by comparing the crack growth rates of the two models. The above results were obtained using the BEASY automatic crack growth system which generates a summary file with full history of the

crack growth fatigue results. These results can be processed in excel and give the following comparative graph of the crack growth rates.

The effect on crack growth rate is of great interest. Automatic simulation of fatigue crack growth under cyclic loading of the non-stiffened and stiffened panels was performed using BEASY. The resulting crack growth history was processed using Excel templates. Figure 7 shows change of crack size with number of cycles for each structure. It is clear that the rate of growth is reduced dramatically when stiffeners are present, and that the “life” is extended correspondingly.

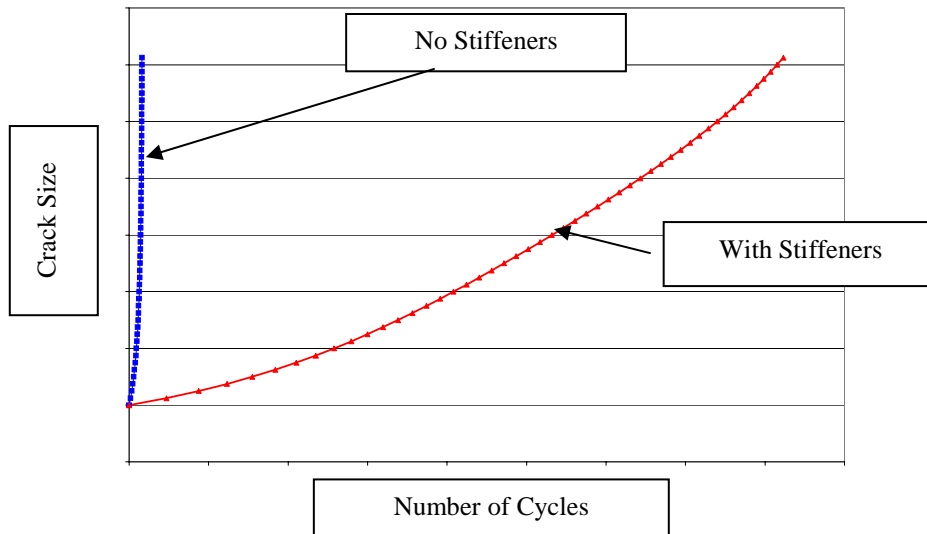


Figure 7 Predicted crack growth rate in the panel

Example 3: Beam Breaking

It is possible to simulate the breakage of the stiffening beams as the crack grows. This can be done by stopping the crack growth process at some stage and dividing one or more of the beams at the break point. The previous model was used to simulate breakage of a stiffener when the crack reaches it (Figure 8). The effect on crack growth rate can clearly be seen in Figure 9.

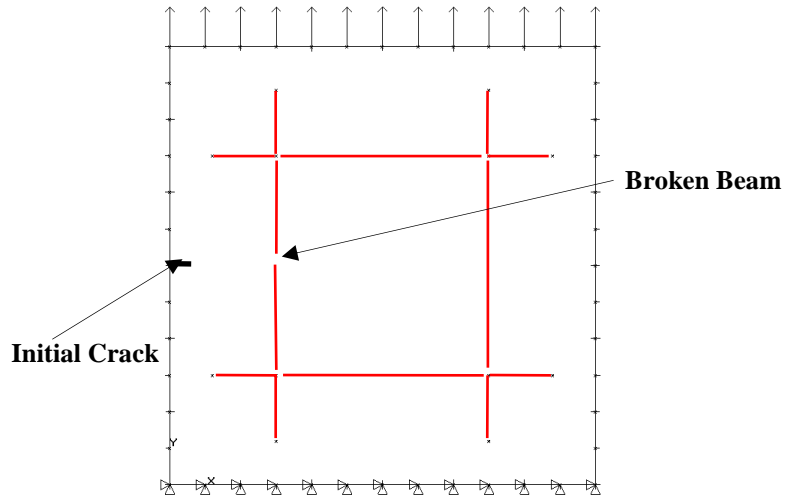


Figure 8 Stiffened panel model showing the location of the broken stiffener

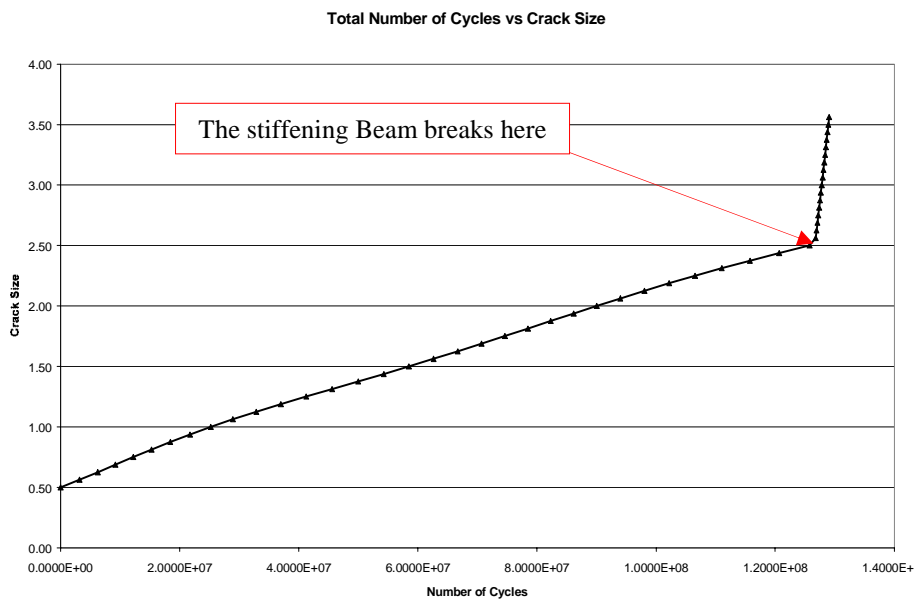


Figure 9 Predicted acceleration of the crack growth rate when the stiffener breaks

Example 4: Crack Growth In Stiffened Panel

In this final example the crack path and the rate of growth are predicted for a more complex panel both with and without stiffeners. The model shown in Figure 10 is a panel with a grid of stiffeners attached. A crack has been initiated near one of the horizontal stiffeners and allowed to grow under a fatigue load. The crack path is significantly altered by the stiffeners and the growth rate is much faster without the stiffeners as shown in Figure 11.

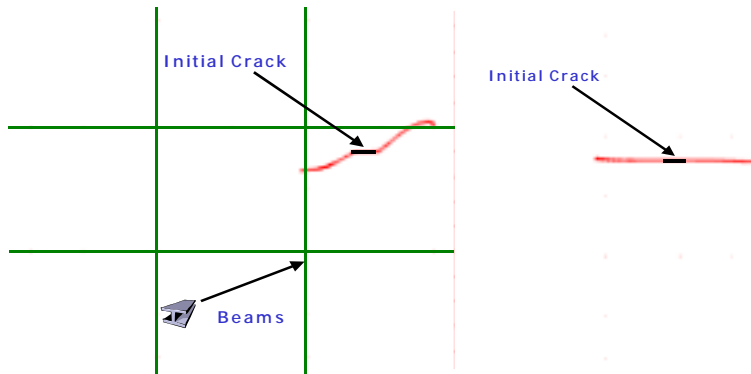


Figure 10 Crack growth prediction for a panel stiffened by a series of beams attached to the panel with rivets. On the right the crack growth in the panel without the stiffeners is shown.

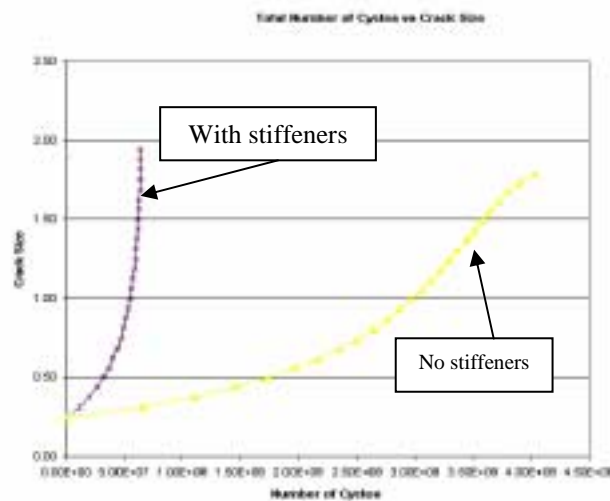


Figure 11 Crack growth rate predictions for the cracks in the panel with and without stiffeners. Note the much reduced crack growth rate in the structure when the stiffeners are present

Conclusions

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

The method automates the process of initiating the crack in the model, the prediction of the crack growth rate, crack path and the remeshing of the model as the crack grows.

A new approach to coupling BEM and FEM elements has been presented using special hole type elements in the BEM to represent the fastener positions. These allow load transfer between the panels and any supporting structure.

The process integrates with standard modelling tools such as MSC PATRAN where the user can define all the data for the simulation in much the same way as for a normal stress analysis.

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