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AN INTEGRATED SOFTWARE TOOL FOR HIGH FIDELITY PROBABILISTIC ASSESSMENTS OF METALLIC AERO-ENGINE COMPONENTS

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ABSTRACT

Most current tools and methodologies to predict the life and reliability of fracture critical gas turbine engine components rely on stress intensity factor solutions that assume highly idealized component and crack geometries, and this can lead to highly conservative results in some cases. This paper describes a new integrated methodology to perform these assessments that combines one software tool for creating high fidelity crack growth simulations (FRANC3D) with another software tool for performing probabilistic fatigue crack growth life assessments of turbine engine components (DARWIN). DARWIN employs finite element models of component stresses, while FRANC3D performs automatic adaptive re-meshing of these models to simulate crack growth. Modifications have been performed to both codes to allow them to share and exchange data and to enhance their shared computational capabilities. Most notably, a new methodology was developed to predict the shape evolution and the fatigue lifetime for cracks that are geometrically complex and not easily parameterized by a small number of degrees of freedom. This paper describes the integrated software system and the typical combined work flow, and it shows the results from a number of analyses that demonstrate the significant features of the system.

INTRODUCTION

In recent years, the aero-engine industry and its regulators have been placing increasing emphasis on damage tolerance methods for life management of metallic high-energy rotating components. For some applications, probabilistic methods are used to predict the reliability of fracture-critical engine components [1, 2], thereby reducing the potential for over-conservatism in deterministic approaches that always assume worst-case conditions. However, the fracture mechanics methods themselves can also introduce excessive conservatism for some problems. This occurs because current engineering tools usually rely on stress intensity factor (SIF) values that assume highly idealized component and crack geometries, such as part-elliptical planar cracks in rectangular prisms.

A new integrated methodology has been developed to perform improved deterministic and probabilistic damage tolerance assessments. The methodology combines a software tool for performing fatigue crack growth (FCG) life and fracture reliability assessments of turbine engine components with another software tool for creating high fidelity crack growth simulations. Modifications were performed to both codes to allow them to share and exchange data. A number of enhancements were performed to the shared computational aspects of both codes. Most significantly, a new methodology was developed to predict the shape evolution and the FCG lifetime for cracks that are geometrically complex and not easily parameterized by a small number of degrees of freedom.

This paper will first briefly introduce the two software tools, their combined workflow and interfaces, and the most significant enhancements in the methods. The results from a number of demonstration analyses will be shown to illustrate some of the key features and capabilities of the integrated tool.

APPROACH

The DARWIN® (Design Assessment of Reliability With INspection) computer program integrates a life assessment based on linear elastic fracture mechanics (LEFM) with a finite element (FE) analysis of component stresses, material anomaly data, probability of crack detection, and inspection schedules to determine the probability of fracture as a function of the applied operating cycles [3-5]. DARWIN includes a fully integrated fracture mechanics module with a library of crack models for simple geometries (e.g., planar part-elliptical or straight through cracks in rectangular prisms under stress control) [6-7]. These simple models are entirely adequate to assess FCG life accurately at many locations in highly stressed aero-engine components. However, some cracks are not adequately modeled by these methods.

The FRacture ANalysis Code 3D (FRANC3D) performs automatic adaptive meshing of FE models to simulate crack growth [8-9]. The use of FE models facilitates the modeling of arbitrarily complex crack shapes and incorporates the effects of complex stress fields, including those due to geometry-induced stress concentrations, contact stresses, and residual stresses.

The integrated software system contains not only DARWIN and FRANC3D but also an FE analysis package. The relationships between these three components of the system are shown in Figure 1, which is a slightly simplified view of the software organization, workflow, and data transfer.

Currently, the ABAQUS® and ANSYS® FE packages are supported. These are used to generate uncracked FE models and to perform FE analyses of cracked and uncracked models.

DARWIN plays two roles. In the pre-FRANC3D phase, it imports an uncracked FE model and through its GUI allows an analyst to specify an initial crack location, size, shape, and orientation. The initial crack location may be a stress hot spot, for example. The initial crack orientation is determined by DARWIN as the plane of maximum principle stress at the initial crack location, but this plane can be arbitrarily adjusted by the user if desired.

The user will also specify a fatigue loading sequence, and a FCG rate model and parameters. Available FCG rate models include Paris, bi-linear Paris, Sigmoidal, Hyperbolic Sine, table lookup, and the NASGRO 4.0 equation. Stress ratio effects can be included by using the Walker equation, the Newman crack closure equations, or by table lookup. The material property parameters in all crack growth models can be made temperature dependent.

For a fracture risk analysis, the user will also specify distributions of initial flaw sizes, scatter factors for material properties and stresses, probability of detection curves for in-service inspection, and a statistical description of the time(s) of inspection. In the post-FRANC3D phase, DARWIN performs FCG life predictions using the FRANC3D-generated SIF solutions, and if requested, determines probability of fracture (POF). POF is calculated here using conventional Monte Carlo methods, but DARWIN also includes tailored importance sampling methods for improved computational efficiency.

FRANC3D's role in the system is to perform an incremental crack growth simulation based on LEFM methods and to report the predicted crack geometry and computed SIFs. FRANC3D will adaptively re-mesh a portion of the FE model for each crack growth step. It will then invoke the FE package to perform a deformation analysis for the updated mesh.

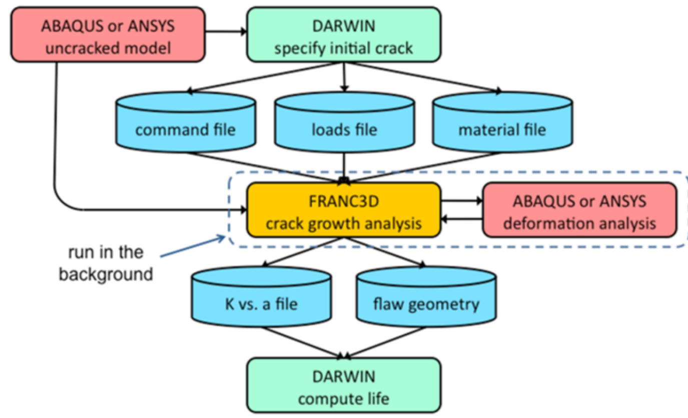


Figure 1. WORKFLOW AND INTERFACES FOR INTEGRATED SOFTWARE TOOL

Arbitrarily complex crack geometries are included in the FE meshes explicitly. Conventional quarter-point wedge-shaped elements are placed adjacent to the crack front. These are surrounded by "rings" of brick elements to form a pattern of well-shaped elements that are "extruded" along the crack front. This pattern of singular and brick elements, placed in a radial symmetric pattern about the crack front, enables the computation of highly accurate SIFs (typical meshes yield computed SIFs within 1% of reference values). Unstructured tetrahedral meshes are used to join the crack-front meshes to portions of the initial mesh that are not modified during crack growth.

Within FRANC3D, SIFs are computed for all elements along a crack front using the *M*-Integral approach (sometimes called an interaction integral). Numerically, the *M*-Integral is similar to an equivalent domain formation of a *J*-Integral, but it yields separate values for each of the three modes of fracture (K_I, K_{II}, and K_{III}).

When growing from one crack step to the next, the extent and direction of crack growth is computed for all nodes on the crack front. Local extensions are computed based on an equivalent stress intensity factor range (ΔK_{equiv}), a crack growth rate model ($da/dN = f\,(\Delta K_{equiv}, R, temperature, \ldots)$) and a user specified number of applied load cycles. The ΔK_{equiv} parameter accounts for mixed-mode loading. Here $\Delta K_{equiv} = \sqrt{\Delta K_I^2 + (\gamma_{II} \Delta K_{II})^2 + (\gamma_{III} \Delta K_{III})^2}$, where γ_{II} and γ_{III} are user-provided parameters. For consistency, FRANC3D offers the same FCG rate models and stress ratio models as DARWIN.

A number of different options are available to predict the direction of crack propagation (kink angle) including the direction of maximum tensile stress, maximum shear stress, and maximum weighted resolved stress intensity factor, $\max(K_I(\theta)^2 + (\eta_{II} K_{II}(\theta)^2) + (\eta_{III} K_{III}(\theta)^2)$, where η_{II} and η_{III} are user supplied parameters.

FRANC3D has a complete GUI, but in the DARWIN/FRANC3D environment, FRANC3D will normally run in a "background" non-graphical mode. This approach was adopted because one objective was to create an integrated tool accessible to users who were not fracture specialists and who did not need to be trained in the details of FRANC3D. Mechanisms for accessing parts or all of the FRANC3D GUI were also created for users who are fracture specialists.

As shown in Figure 1, in the simplest case DARWIN will pass three files to FRANC3D: a command file, which is a sequence of instructions for FRANC3D, a loads file, which specifies a fatigue loading schedule, and a material file, which specifies a FCG rate model and its parameters. FRANC3D returns to DARWIN two files: a file containing computed SIFs and a file containing predicted crack geometry.

Conventionally, simple crack geometries are characterized by a small number of degrees of freedom (e.g., crack lengths for through-the-thickness cracks and semi-axis lengths for partial or full elliptical cracks). Load cycle integration is performed with respect to one or more of these degrees of freedom (DOF). This approach is insufficient for complex crack geometries because often there are no easily identifiable geometrical measurements that will characterize a crack's size or shape throughout the full crack growth simulation.

A new methodology has been developed that performs load cycle integration based on the incremental crack growth steps modeled in each of the FE analyses. For each crack growth step, a series of simple integration is performed for degrees of freedom defined at each FE crack front node.

As illustrated in Figure 2, for each node on the crack front for crack step i, a DOF is defined that is perpendicular to the local crack front tangent and falls on the crack surface. It starts at crack front i and ends at crack front i+1. ΔK_i is computed directly from the FE results. ΔK_{i+1} is interpolated from values computed at nodes that bracket the intersection point. A linear variation is assumed between ΔK_i and ΔK_{i+1}, and integration is performed to determine the number of cycles for this DOF for growth from crack front i to front i+1.

The cycle count is computed for all DOF's defined on the crack front, and the results are averaged to give one predicted cycle count to grow from one predicted crack front to the next. For example, Figure 3 is a cutaway view showing predicted crack growth in a thick-walled cylinder. Figure 4 shows the analyzed crack fronts and the multiple and variable number of DOF's used for cycle integration. Note how this approach easily negotiates the relatively complex transition from one to two crack fronts when the crack reaches the inner bore.

Once the relationship between crack front and cycles has been established, load cycles can be expressed with respect to geometrical measurements that are meaningful for any specific situation. For example, Figure 5 shows the relationship between cycles and surface breaking half crack length for the crack shown in Figure 3. Significantly, while this plot gives information about surface crack lengths, it incorporates SIF information from the full crack front for all fronts.

Residual stresses can have a significant impact on the fatigue performance of turbomachinery components, and a superposition approach is used to incorporate their effects. If the nodal stresses for a residual stress load step are defined for an uncracked mesh, an equivalent set of crack-face tractions are automatically defined for a mesh containing a crack. Under the assumption that small scale yielding conditions still hold at the crack front for the combined service and residual stresses, the SIFs computed for this crack-face traction load step will simulate the effect of residual stress "relaxation" as the crack grows through the affected region. The maximum and minimum superimposed service and residual stress SIFs are used to compute the stress ratio, R, which can be used with a stress ratio sensitive crack growth rate model.

A similar approach is used to address possible high cycle fatigue (HCF) and low cycle fatigue (LCF) interaction. If nodal stresses are provided for an HCF load case (usually derived from a modal analysis), crack face tractions will be generated to simulate the effect of these stresses on a cracked model. The resulting SIF range is monitored, and if it reaches a threshold value (based on the stress ratio for combined service, residual, and HCF loads, the crack growth simulation is terminated.

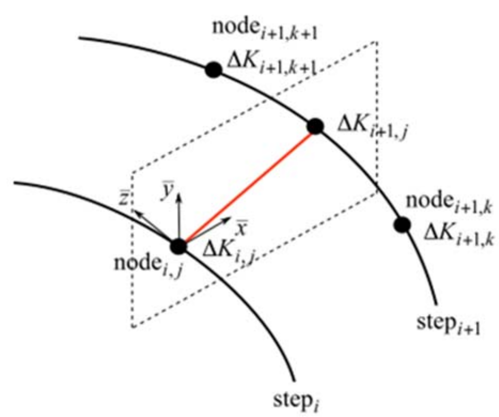


Figure 2. SIMPLE DOF FOR LOAD CYCLE INTEGRATION BETWEEN CRACK STEPS FOR ONE CRACK-FRONT NODE

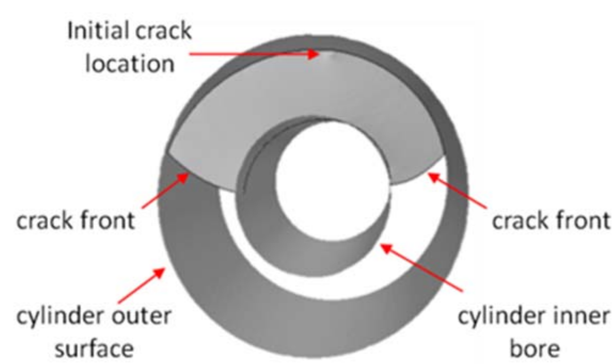


Figure 3. EXAMPLE CRACK GROWTH SIMULATION IN A THICK-WALLED CYLINDER

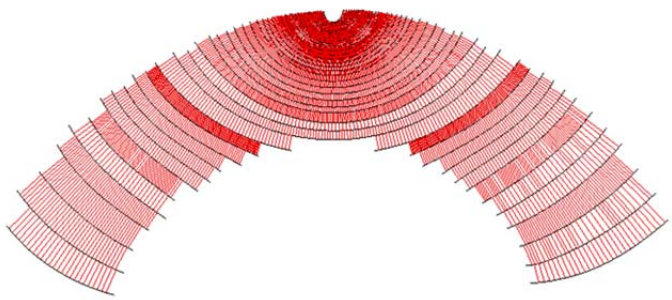


Figure 4. THE MULTIPLE AND VARIABLE SIMPLE DEGREES OF FREEDOM USED FOR CYCLE INTEGRATION FOR THE CRACK SHOWN IN FIGURE 3

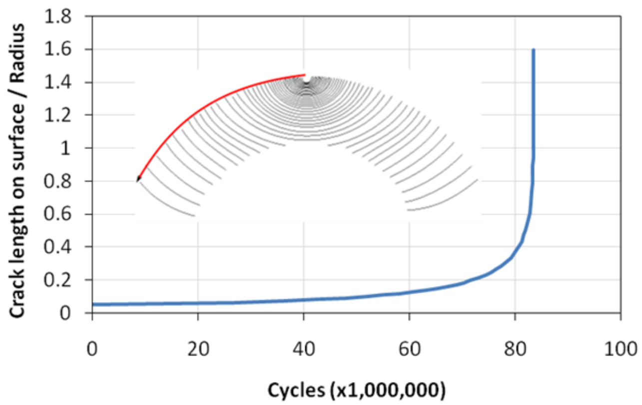


Figure 5. THE COMPUTED CYCLES VERSUS SURFACE BREAKING CRACK LENGTH FOR THE CRACK SHOWN IN FIGURE 3

DARWIN was enhanced to enable the user to execute FRANC3D directly from the DARWIN GUI. The DARWIN zone editor now includes a new FRANC3D crack type that enables the user to specify use of FRANC3D and to define execution options for selected zones in an FE model. DARWIN was also enhanced to monitor the status of FRANC3D runs. During execution, FRANC3D writes a file documenting the execution status of a run that has been initiated by DARWIN. DARWIN monitors the output file directory, opens the file when available, and provides the FRANC3D execution status to the user. Upon successful SIF table generation, the user can execute DARWIN to compute crack growth life and associated risk of fracture.

DARWIN was further enhanced to provide visualization of growing cracks based on data from FRANC3D in the form of surface-breaking lines and crack fronts that are superimposed directly on the 3D FE model geometry in the DARWIN GUI. The visualization tool includes controls for animating the sequence of crack growth steps to enable the user to view the crack size and surface breaking lines at a specified number of flight cycles. When computing the risk of fracture with inspection, the surface breaking line data from FRANC3D are used to determine surface crack sizes for simulated inspections.

FRANC3D was enhanced in a number of small ways to generalize the available crack growth rate models, improve and make consistent the handling of units, add criteria for terminating an automatic crack growth simulation, and to coarsen crack face meshes away from the crack front.

A major enhancement to FRANC3D was to improve significantly the accuracy and stability of the geometrical calculations performed to compute the intersection of a (in general, doubly curved) crack surface with the uncracked mesh, and to construct a "watertight" solid model for use with subsequent adaptive meshing.

Another major FRANC3D enhancement was the development of an interactive tool to define a crack growth sub-region quickly and easily. If a crack growth sub-region is defined, during crack growth only that portion of the model is re-meshed to simulate crack growth. The updated portion of the mesh is automatically reinserted into the remaining portion of the global and the fully merged FE model is solved. For maximum accuracy, full node-to-node compatibility is maintained on the boundary between the global mesh and the sub-region. The use of crack sub-regions improves performance because only a small portion of the model is re-meshed for each crack growth step, and can improve accuracy in some models by reducing or eliminating the need to map boundary conditions from an uncracked to a cracked mesh.

RESULTS

Surface Crack Test Model

Simple models of a surface crack in a plate were used to test and exercise the exchange of data and control between the programs. The purpose here was not to demonstrate a new capability, but rather to test the basic interaction of two codes without the complication of complex geometry and advanced analysis capabilities. These simple geometries can be handled well by the crack growth capabilities built into DARWIN, and FRANC3D would not be needed for such cases in practice. Two surface crack instances were studied. In the first, the complete FE model was read and processed by FRANC3D. In the second, the submodeling tool was used to segregate the model into “global” and “submodel” portions. Only the submodel portion is read and modified by FRANC3D.

Figure 6 shows images from FRANC3D after the model was read and re-meshed to insert the initial crack. Notice in the upper image that the structured mesh on top surface of the model has been retained. This facilitates the retention of boundary conditions without needing to map values from one mesh to another. The lower image is a “cut-away” view looking inside the structure and showing the mesh on the crack surface. The FRANC3D GUI was run just to generate these images. Normally in the DARWIN/FRANC3D system FRANC3D runs in the background.

The loading in the model was constant amplitude with a stress ratio of zero. The crack growth rate model used in this analysis was a Paris equation. The initial crack was semi-circular with a depth of 0.125 in.

The resulting prediction of surface crack length versus cycles is shown in Figure 7. Figure 8 shows the crack fronts for cycle numbers 0, 62233, 74069, and 77123, as displayed in the DARWIN GUI. In this figure, and others like it, representative "beachmarks" of successive crack fronts are shown to indicate how the crack grew. The actual increments of crack growth in the FRANC3D analysis are, in general, much smaller than the increments shown here. The beachmarks shown in the DARWIN GUI are generated during the DARWIN crack growth analysis, and they are shown at intervals of life chosen for visualization convenience. The red line indicates the intersection of the crack with the surface.

DARWIN also calculates the probability of fracture, considering selected random variables. Figure 9 shows the calculated fracture risk based on an assumed distribution of initial crack sizes, using the FRANC3D interface.

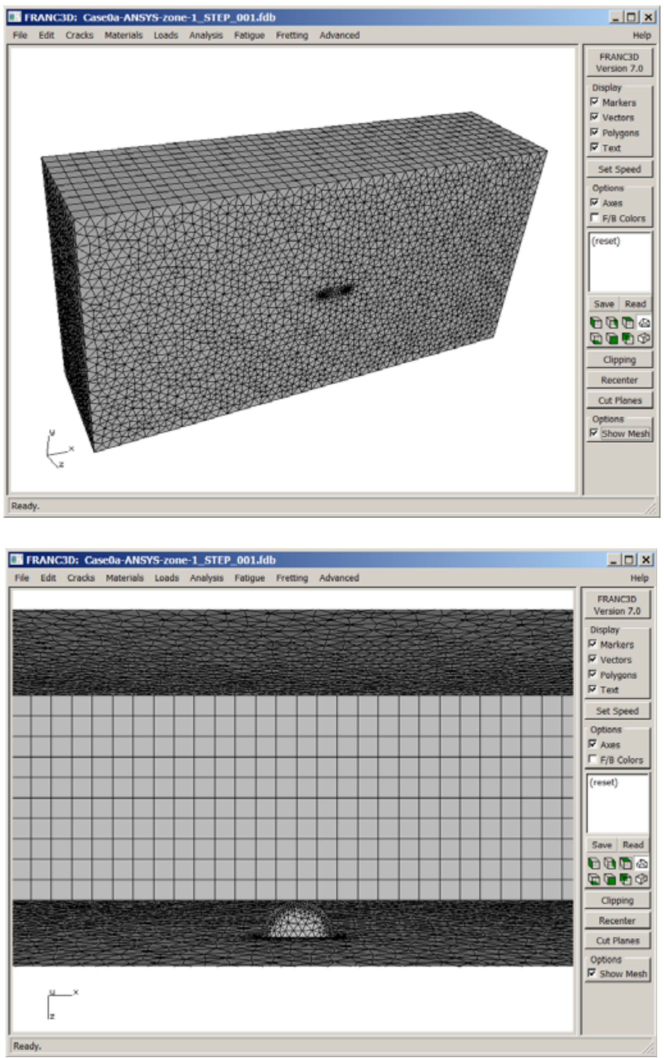


Figure 6. IMAGES FROM THE FRANC3D GUI SHOWING THE MESH AFTER THE INITIAL CRACK HAS BEEN INSERTED. THE BOTTOM IMAGE IS A CUT-AWAY VIEW SHOWING THE INTERIOR OF THE MODEL.

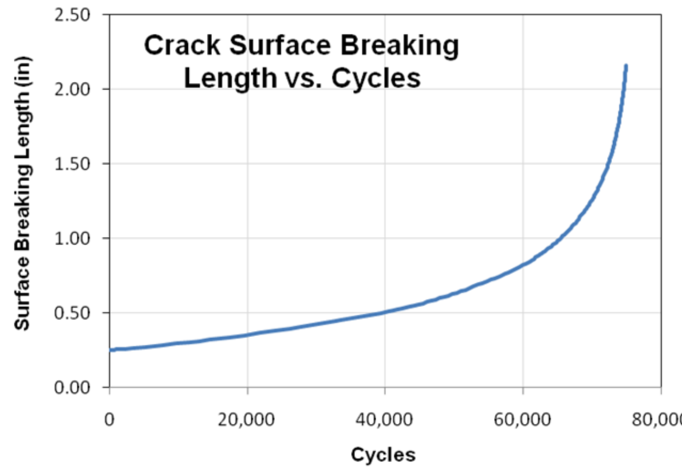


Figure 7. PREDICTED SURFACE BREAKING CRACK LENGTH AS A FUNCTION OF CYCLES

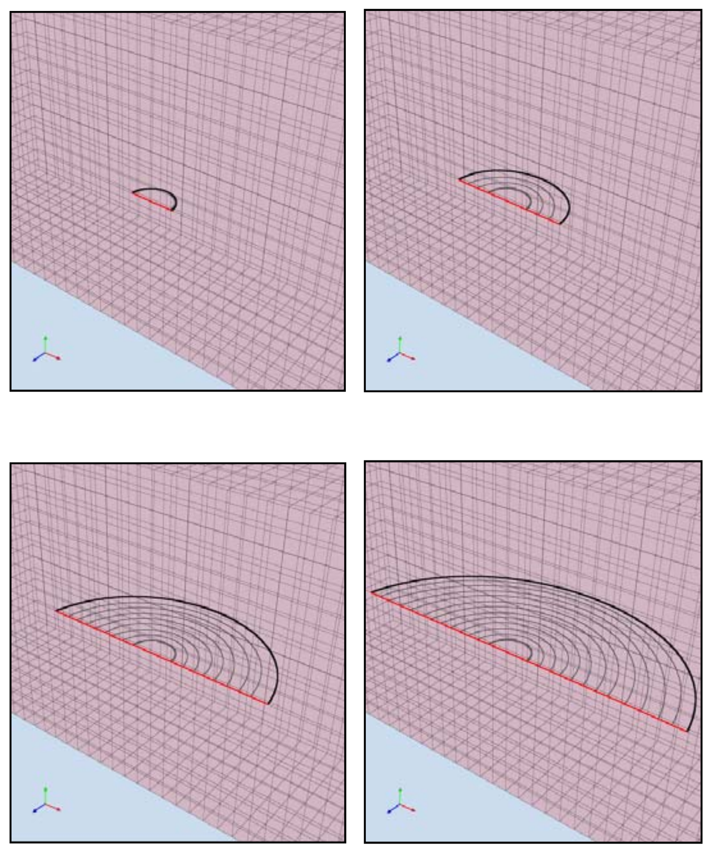


Figure 8. THE PREDICTED SURFACE CRACK FRONTS AT CYCLES 0, 62233, 74069, AND 77123, AS SHOWN IN THE DARWIN GUI

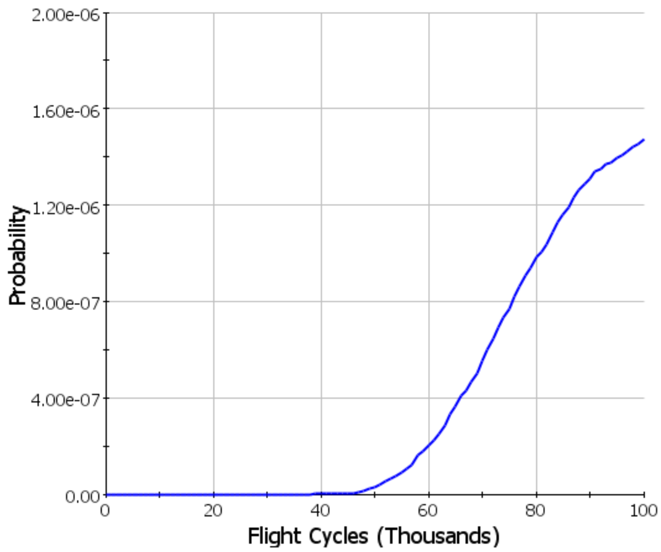
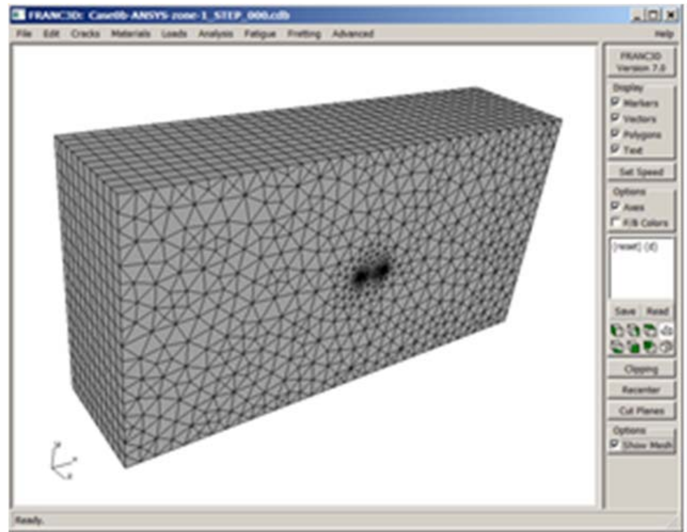


Figure 9. PREDICTED PROBABILITY OF FRACTURE AS A FUNCTION OF FLIGHTS (CYCLES) FOR AN ASSUMED DISTRIBUTION OF INITIAL CRACK SIZES, AS SHOWN IN THE DARWIN GUI

In the second surface crack example, global and submodels are defined. In a typical crack growth simulation, cracking takes place in a relatively small portion of the total FE model. It is inefficient to completely re-mesh the full model and remap all the boundary conditions for each crack growth step. As described previously, FRANC3D supports the approach of dividing a model into a "global" portion that remains unchanged throughout a crack growth simulation and a small "submodel" portion that is re-meshed for each step. It also provides a tool for defining the global and submodel portions.

Figure 10 shows the submodel and the global model in the FRANC3D GUI. Notice that the original surface mesh is retained on all the cut surfaces. This allows the submodel to be "plugged" into the global model retaining node-to-node compatibility. The FE analyses are performed using the merged model.

The predicted maximum SIF versus flights (cycles) is shown in Figure 11. Note that the loads in this example were different from the loads in the previous surface crack test case.



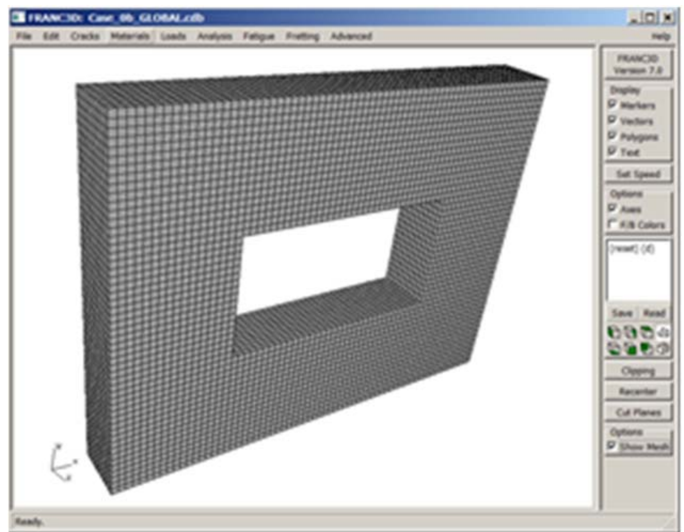


Figure 10. THE CRACKED AND RE-MESHED SUBMODEL (TOP) AND THE GLOBAL MODEL (BOTTOM), AS SHOWN IN THE FRANC3D GUI

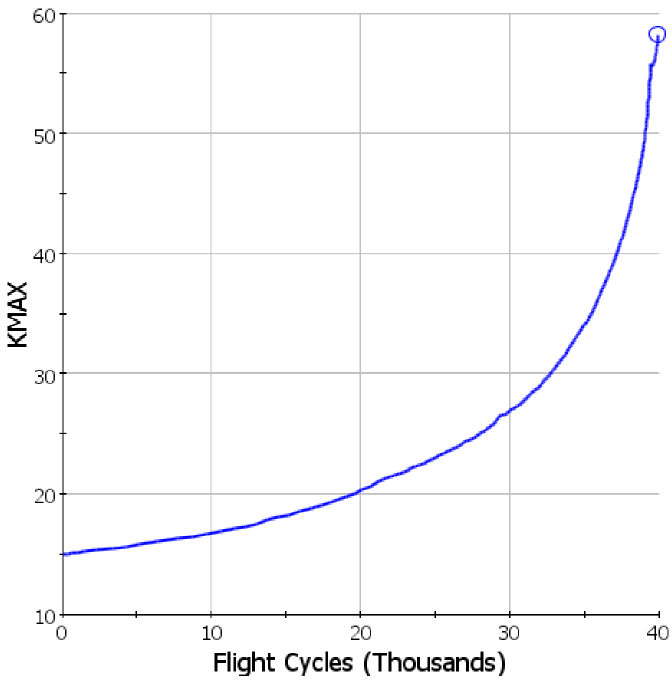


Figure 11. THE PREDICTED MAXIMUM STRESS INTENSITY FACTOR (UNITS ARE KSI√IN) VERSUS FLIGHTS (CYCLES) FOR AN EXAMPLE SURFACE CRACK, AS SHOWN IN THE DARWIN GUI

Dovetail Attachment Test Model

It is very common for cracks to initiate and grow in regions where components come into contact. The purpose of this idealized dovetail blade attachment model was to demonstrate crack growth where the primary loading is through contact. Figure 12 shows the full model and details that show the initial crack location and orientation, as depicted in the DARWIN GUI. The FE analysis for this case included non-linear contact between the “blade” and “disk” portions of the model. The nonlinearity increased the FE solution times considerably.

Figure 13 shows some images of the predicted growth, again taken from the DARWIN GUI. Here the initial corner crack has grown into the disk post. Crack growth was terminated when the maximum SIF on a crack front reached a critical value. In this case, the crack surface is non-planar, but the non-planarity is subtle. The three views show the same results from different perspectives: the top view shows the crack with respect to the overall dovetail attachment geometry (see again Figure 12), the middle view shows the crack growth beachmarks, and the bottom view shows the non-planarity of the crack.

Figure 14 shows the predicted surface breaking crack length as a function of the number of load cycles. In this case, the surface length is the sum of the individual corner crack lengths on both faces.

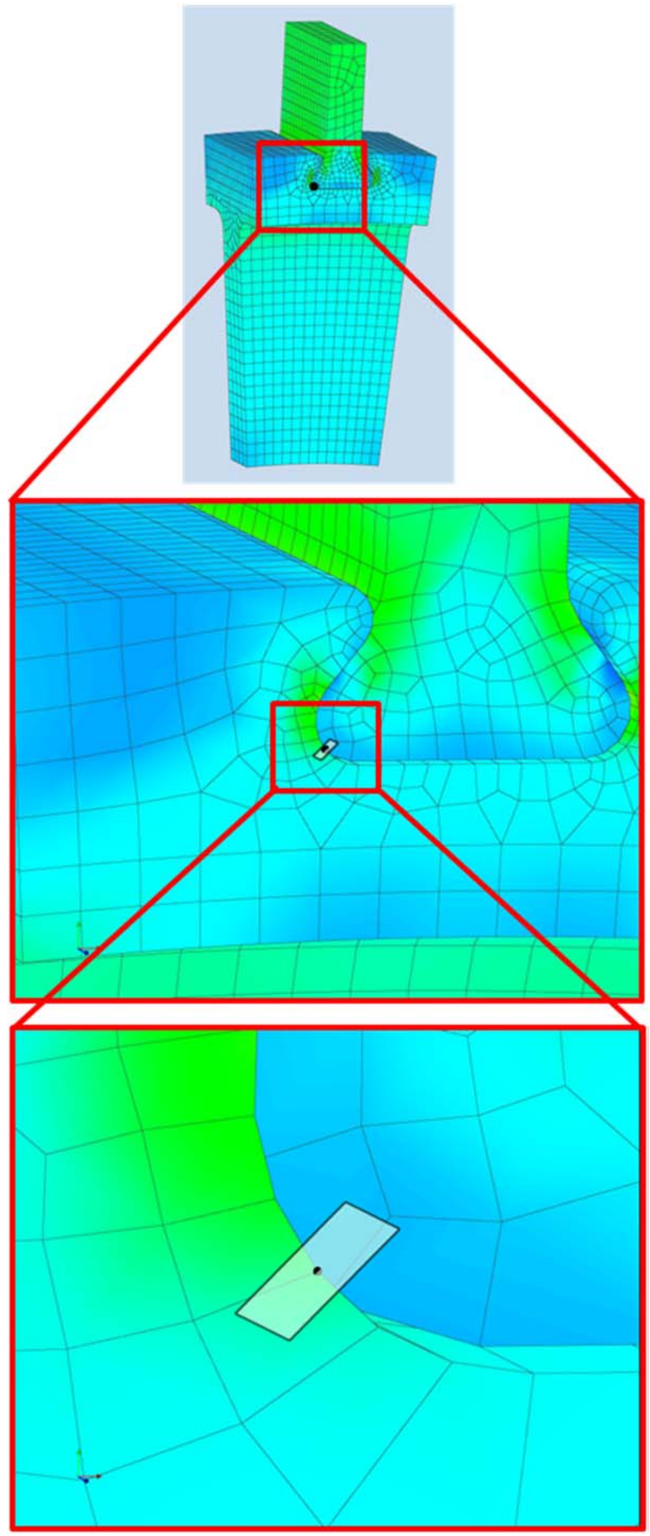


Figure 12. THE FULL DOVETAIL ATTACHMENT MODEL AND DETAILS INDICATING THE INITIAL CRACK LOCATION AND ORIENTATION, AS SHOWN IN THE DARWIN GUI

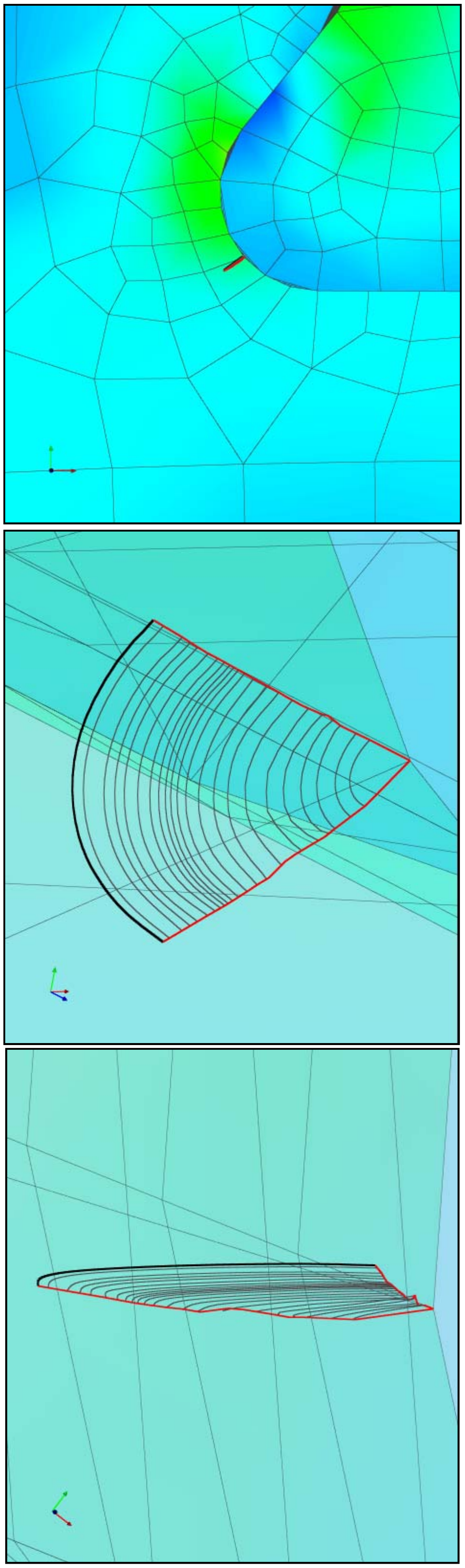


Figure 13. VIEW OF THE PREDICTED CRACK GROWTH IN THE DARWIN GUI FOR THE DOVETAIL MODEL

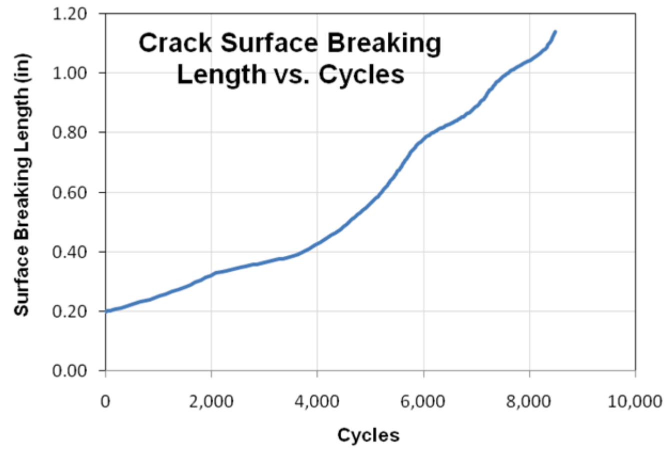


Figure 14. THE PREDICTED SURFACE BREAKING CRACK LENGTH AS A FUNCTION OF LOAD CYCLES FOR THE DOVETAIL MODEL

Integrally-Bladed Rotor Test Model

The objective of this test case was to demonstrate the high cycle fatigue (HCF) threshold capability described previously. The FE model is a sector of an integrally bladed rotor (IBR). The model is a non-proprietary design provided by an aircraft engine manufacturer. Both static (centrifugal loading) and modal analyses were performed. For demonstration purposes, one vibration mode that gives high stresses in the leading edge of the airfoil (mode 117, 9047.45 Hz) was selected as a HCF load case. This mode and the corresponding principal stresses are shown in Figure 15. For testing purposes, the stresses were scaled so that the high cycle threshold would be reached in a modest number of crack growth steps. The NASGRO 4.0 crack growth rate equation was used for this analysis. In the NASGRO equation, the threshold ΔK value is a function of the stress ratio. The FRANC3D submodel approach was used in this analysis.

The predicted crack evolution is shown in Figure 16 at two levels of magnification. Again, the beachmarks indicate successive crack fronts (at convenient intervals of cycles) as the crack grows into the leading edge of the airfoil and its shape evolves, and the red line indicates its final intersection with the IBR surface. The crack growth was stopped when the SIF range for the HCF load case exceed a threshold value for the corresponding stress ratio. This is shown in Figure 17.

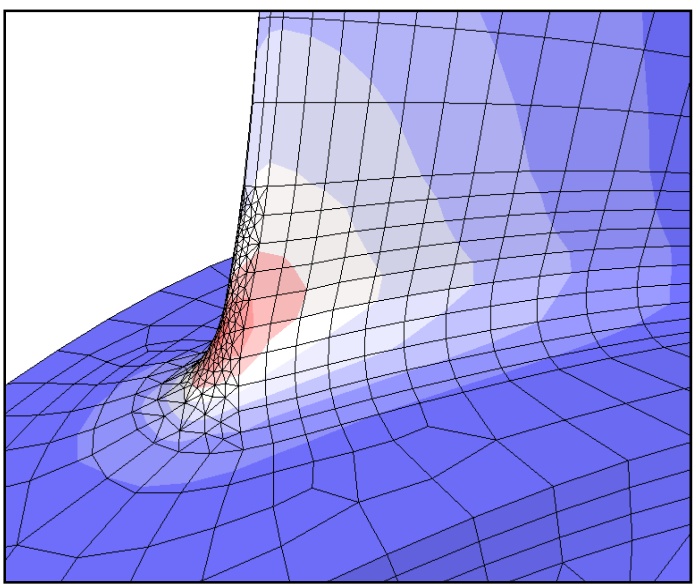


Figure 15. THE SELECTED HCF MODE AND THE CORRESPONDING PRINCIPAL STRESSES FOR THE IBR MODEL

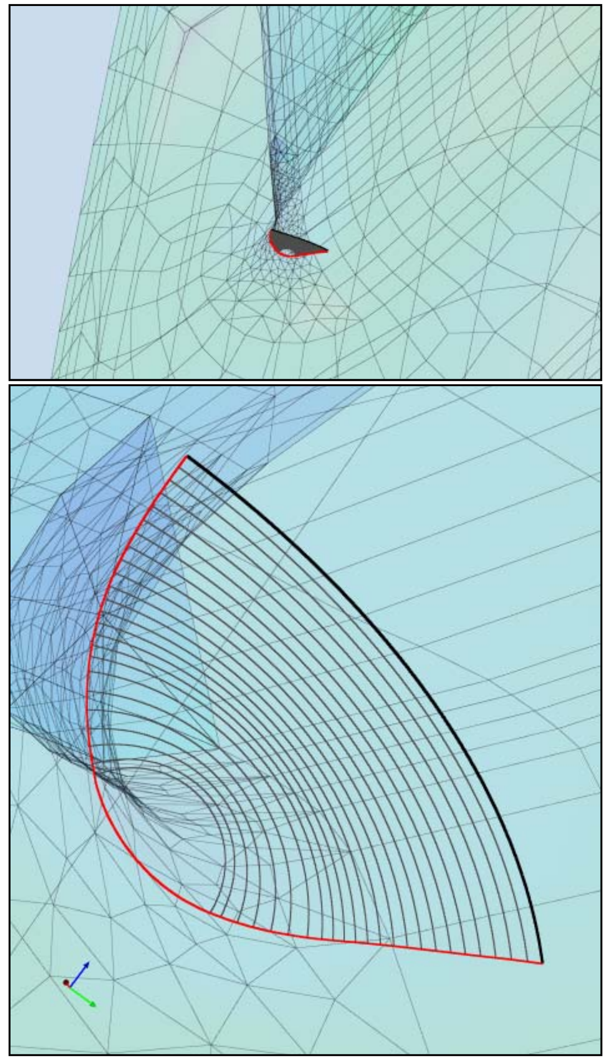


Figure 16. THE PREDICTED CRACK GROWTH STEPS IN THE IBR MODEL, AS SHOWN IN THE DARWIN GUI

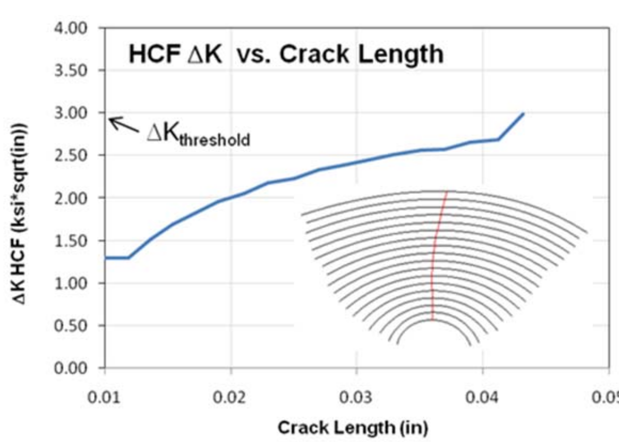


Figure 17. THE PREDICTED HCF ΔK ALONG THE CENTER OF EACH CRACK STEP FRONT (RED PATH)

Residual Stress Test Model

Many turbine engine components contain residual stresses due to material processesing and are subjected to variable amplitude loading. An idealized rotor model was analyzed to test these capabilities of the DARWIN/FRANC3D system.

Figure 18 shows the radial residual stress distribution in the disk as predicted by the DEFORM™ program [10]. An axisymmetric model was used for the forming analysis but it has been swept through 90 degrees to create a 3D model.

The variable amplitude service loads for this model are shown in Figure 19. This is a simple load sequence representative of a transport aircraft. Figure 20 shows the location and orientation of a 0.025 x 0.025 inch initial crack. The submodeling capabilitiy was used.

The analysis was performed with and without the residual stress load case. In both cases the analysis was stopped when a critical SIF was reached. A comparison of the predicted surface breaking crack lengths versus flights is shown in Figure 21.

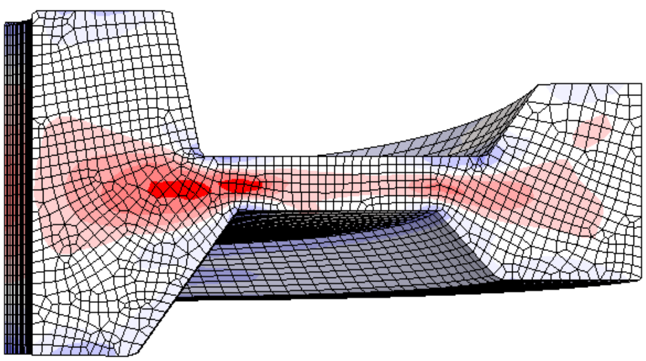


Figure 18. THE RADIAL RESIDUAL STRESS DISTRIBUTION DUE TO MATERIAL PROCESSING AS PREDICTED BY THE DEFORM™ PROGRAM

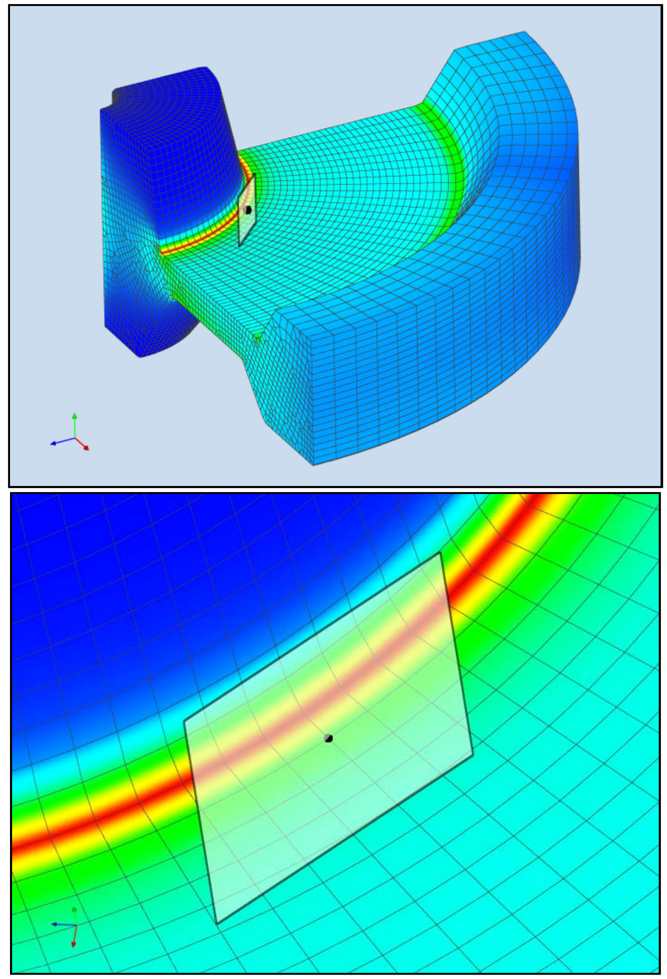


Figure 20. THE LOCATION AND ORIENTATION OF AN INITIAL 0.025 X 0.025 INCH CRACK IN THE ROTOR MODEL

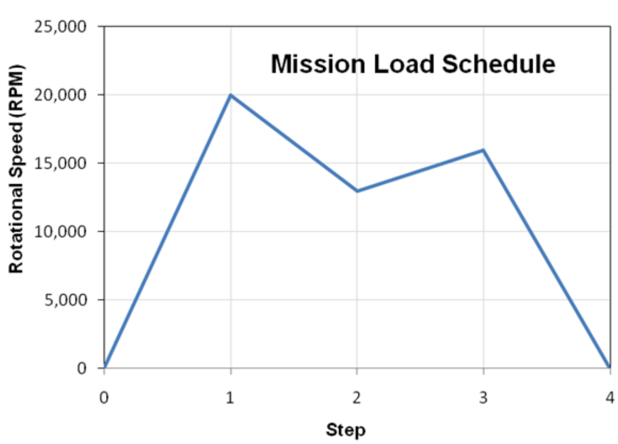


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Figure 19. THE VARIABLE AMPLITUDE SERVICE LOADS USED FOR THE ANALYSIS OF THE RESIDUAL STRESS TEST MODEL

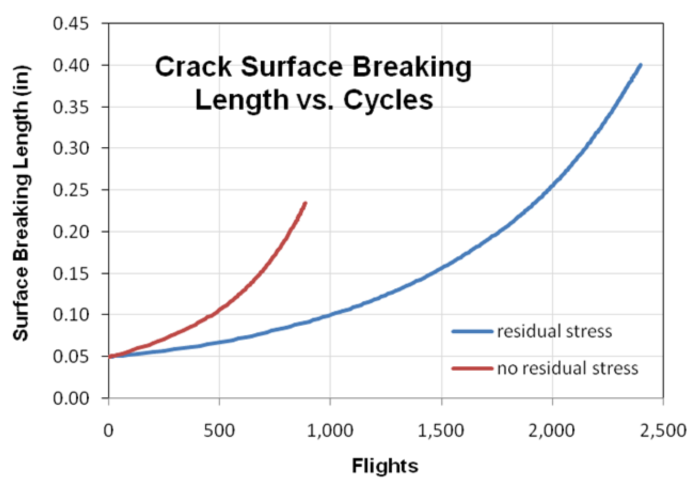

Figure 21. PREDICTED SURFACE BREAKING CRACK LENGTHS AS A FUNCTION OF FLIGHTS WITH AND WITHOUT RESIDUAL STRESSES

DISCUSSION

The integrated combination of DARWIN, FRANC3D, and a FE analysis code provides a unique state-of-the-art tool for highest fidelity FCG predictions, offering several unique advantages compared to other methods.

Some other proprietary and commercially available crack growth programs employ a library of "stored" SIF solutions. These programs are limited to relatively simple geometries (as mentioned in the Introduction, planar part-elliptical or straight through cracks in rectangular prisms under stress control) and simple loading (constant, linear, or bi-linear, are typical). Some other codes (including the built-in fracture mechanics module in DARWIN) use a weight function (WF) approach in conjunction with a finite element analysis of stresses in the uncracked body. This allows locally complex stress fields to be considered, but is limited to simple geometries.

There are also other sophisticated numerical methods available for FCG analysis. Recently, the XFEM approach has gained popularity as a way of modeling crack growth. While it is simpler to program XFEM compared to the adaptive meshing of conventional elements approach that is used here, published 3D XFEM results typically show computed SIFs that are less accurate than conventional elements for curved crack fronts in unstructured meshes, and are usually characterized by large jumps in the computed values for neighboring crack front points [11].

Another commercially available numerical approach uses "crack blocks" [12]. These are typically parameterized hexahedral domains partially cut by a portion of a crack, with an associated template for inserting a mesh into the block. Because conventional elements are used, accurate SIFs can be computed. However, the need for an uncracked mesh that will accommodate the crack blocks places some restrictions on the approach. Most published examples show the technique used with structured hexahedral initial meshes. However, many cracks initiate and grow in regions of complex geometry that are difficult or impossible to model with a structured mesh.

The integrated software tool described here provides convenient, appropriate alternatives for a wide range of crack growth problems. When crack and/or component geometry is complex, the user can invoke the rigorous FRANC3D crack growth model and obtain highly accurate SIF solutions. On the other hand, when crack and (local) component geometry are relatively simple, the user can invoke the integrated WF SIF solutions in DARWIN, obtaining life and risk results in a fracture of the time required for a 3D numerical calculation. This simpler approach can provide highly accurate results for many (not all) gas turbine engine applications. Both approaches are immediately accessible in the same DARWIN GUI.

The integrated software tool also provides both of these options in a highly user-friendly interface. The user does not have to be an expert in manipulating 3D numerical crack growth tools, or know much of anything about the 3D tool at all, because all the steps required to build, execute, and retrieve the results of the 3D numerical model can be handled automatically "behind the scenes" of the analysis. On the other hand, the user who does have experience/expertise with the 3D tool and wishes to employ the full capabilities of FRANC3D can access the FRANC3D GUI and make manual adjustments as desired.

Finally, the integrated tool is unique because it allows the results of the 3D numerical analysis to be fed directly into a probabilistic assessment of fracture risk, using the existing DARWIN framework. The computational cost of the 3D analysis is currently too large to perform a probabilistic assessment of many different locations in a large component, as might be required (for example) in evaluating the risk of fracture due to inherent material anomalies [1, 3, 4]. However, the 3D model can be used selectively at critical locations in the component that are both geometrically complex and significant contributors to fracture risk.

SUMMARY

An integrated methodology has been developed to perform life and reliability assessments of fracture critical gas turbine engine components. A software tool that creates high fidelity crack growth simulations has been linked to another software tool that performs probabilistic fatigue crack growth life assessments of turbine engine components. Modifications were performed to both codes to allow them to share and exchange data and to enhance their shared computational capabilities. A new methodology was developed to predict the shape evolution and the fatigue lifetime for cracks that are geometrically complex and not easily parameterized by a small number of degrees of freedom. The integrated tool has been successfully demonstrated by solving a number of test problems. The specific capabilities demonstrated here include FCG growth analysis with and without sub-modeling; FCG under contact loading; non-planar crack growth; non-elliptical crack shapes; assessment of failure due to high-cycle fatigue from independent vibration loading; and residual stress effects on FCG.

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