Three-dimensional Finite Element Analysis
Based C(t) Calculation

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Abstract:
3D Fracture Mechanics based C* computation is highly desirable to enable evaluation of real components under creep conditions. The methodology presented in this work builds upon 3D Fracture Mechanics capabilities to insert, mesh and analyze cracks in real components under various loading scenarios. Results are presented for CT specimen and a surface crack in a plate and an edge crack in a thin sheet .

Introduction

There has been considerable research work in creep crack growth over the past 25 years. It is accepted that a 3D volume integral C* or its modified version Ct can be used successfully to correlate creep crack growth data. There have been some attempts to use this parameter for residual life calculation of power plant components like boiler tubes. One of the main challenges in extending this capability to a broad range of components has been lack of a reasonable methodology to actually compute such parameter (C* or Ct) for components (or features) where 2D approximations of the geometry are either impractical or result in excessive conservatism in life calculations. The ability to compute 3D C* values efficiently will enable us to compute residual life of power plant components subjected to severe creep conditions.

3D Fracture Mechanics research program at GE has aimed at developing 3D Fracture tools for life assessment. The capability of 3D Fracture tool includes C* calculation for any arbitrary geometry and loading situations by using commercial FE package ANSYS. The GE proprietary 3D Fracture Mechanics software allows the analyst to create cracked models of components for different types of simulations (linear or nonlinear stress analysis, creep etc.). The implicit creep analysis is performed in commercial FE package and C* values are computed as a function of time as well as contours using customized macros. A systematic study was performed to evaluate mesh sensitivity of C* for simple geometries. For two examples - CT specimen and center crack in thin sheet - only 2D solutions have been published till date. With 3D capabilities, 2D plane strain results have been reproduced and variation of C* along the thickness of the specimens is computed.

Motivation for 3D Fracture Mechanics based Creep Analysis

In this paper, a procedure of performing creep analysis in the presence of a crack and the computation of C*, a relevant crack parameter characterizing crack tip fields under creep conditions is described. The results of these computations on three benchmark cases are presented and compared the results with closed form solutions available in literature.

Steam turbine components are exposed to high operating temperatures (1000 F to 1100 F) during a major part of their life. Hence, the life estimation of such components requires consideration of creep effects. Some of the common approaches followed in evaluating creep life are: Creep analysis using appropriate primary and secondary creep laws or Isochronous creep analysis, which allows running a set of elastic-plastic analysis instead more expensive creep analysis in a typical structural analysis software [1]. In both of these approaches, the life predicted is essentially the time required for crack initiation. The propagation of crack is not considered. Hence such approaches are conservative and do not provide adequate guidance for damage tolerant designs or In-service recommendations.

In contrast to the above approaches, the flaw-tolerant approach assumes a crack to be present in the model (which might, for example, have initiated at some stress-raiser location). A creep analysis is conducted in the flawed component to obtain crack tip fields. With the knowledge of these fields, C*, a parameter which characterizes Crack tip fields and also governs crack propagation, is calculated. With the knowledge of C*, the crack size is updated according to some power law governing crack growth and the entire procedure is repeated. Final life estimation might be based on maximum allowable flaw size.

Creep analysis procedure:

As described above, the approach involves repeated creep analysis with various crack lengths. Typical pre-processing steps in a single creep analysis include crack insertion, meshing the model with due consideration to crack and application of loads and boundary conditions. All the above steps are done efficiently in the in-house software 3DFAS [2,3,4]. The inputs to the software include the parasolid model of the uncracked component along with the size and location of the crack and mesh control parameters. The outputs from the software are the element and node lists of cracked model mesh. There is also provision to apply the loads and boundary conditions in 3DFAS in which case we also get the necessary ANSYS commands for applying the loads as outputs from 3DFAS. These steps are summarized in Figure 1 below.

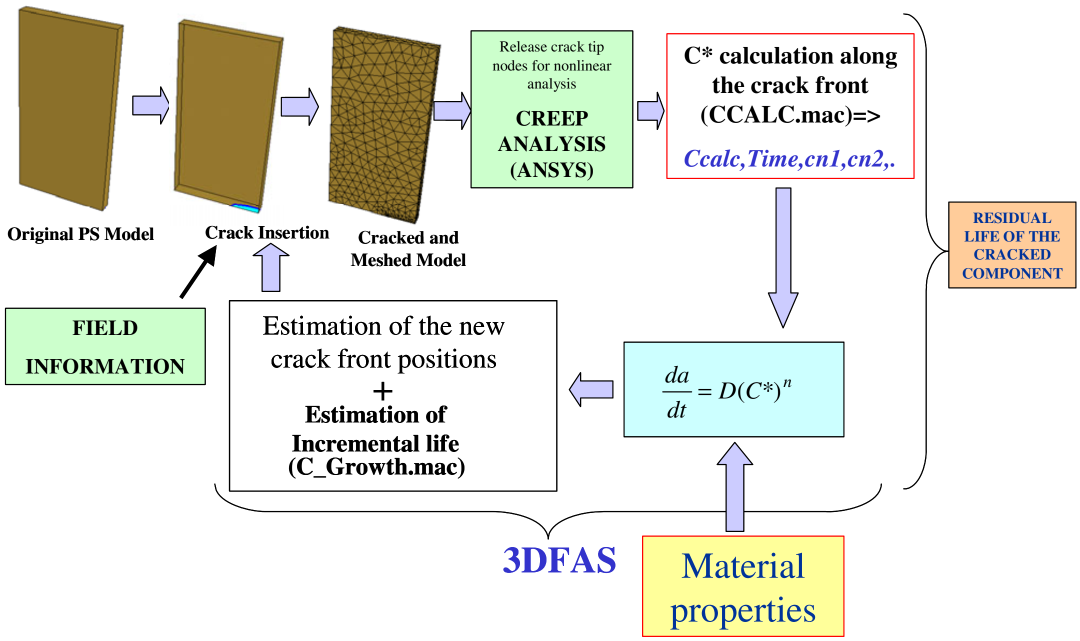


Figure 1: 3D Fracture Mechanics based Creep crack growth methodology

1. COMPACT TENSION SPECIMEN:

The compact tension specimen (CT) is one of the standard specimens used in fracture testing. In reference [5] results of creep crack growth experiments performed on turbine rotor steels are reported. The experiments were conducted on various sizes of CT specimens, Single Edge Notched specimen (SENT) and Double Edged Notched specimen (DENT).

The general procedure of fracture testing of these specimens include application of load on the holes (see the figure above) and monitor the crack length as well as the load-line displacement rate. The crack length and load line displacement rates are then used to determine C* values and the computed C* values are correlated with the crack growth rate.

A CT specimen of width (W – in the above figure) 200 mm is analyzed for this study. Also, the crack length (a) was determined from the ratio a/w = 0.55 given in [5] Other dimensions get fixed according to the chosen width. The loads used were taken from [5]. The problem has symmetry of geometry and loading about XY plane and XZ plane (Z axis is normal to plane of paper). Note that loading used is for illustration of the method itself and the procedure can be applied to other materials and conditions. The following cases were analyzed: Quarter model utilizing XZ and XY symmetry resulting in CT specimen of thickness B/2 and length 0.6W (Figure 2); Half model utilizing XZ symmetry alone resulting in CT specimen of length 0.6W and full thickness B (Figure 3)

Additional two cases were also analysed with the CT specimen under plane strain conditions to enable comparison with closed form solutions. Figure 4 shows an example of the deformed shape (exaggerated for visualization) of CT specimen.

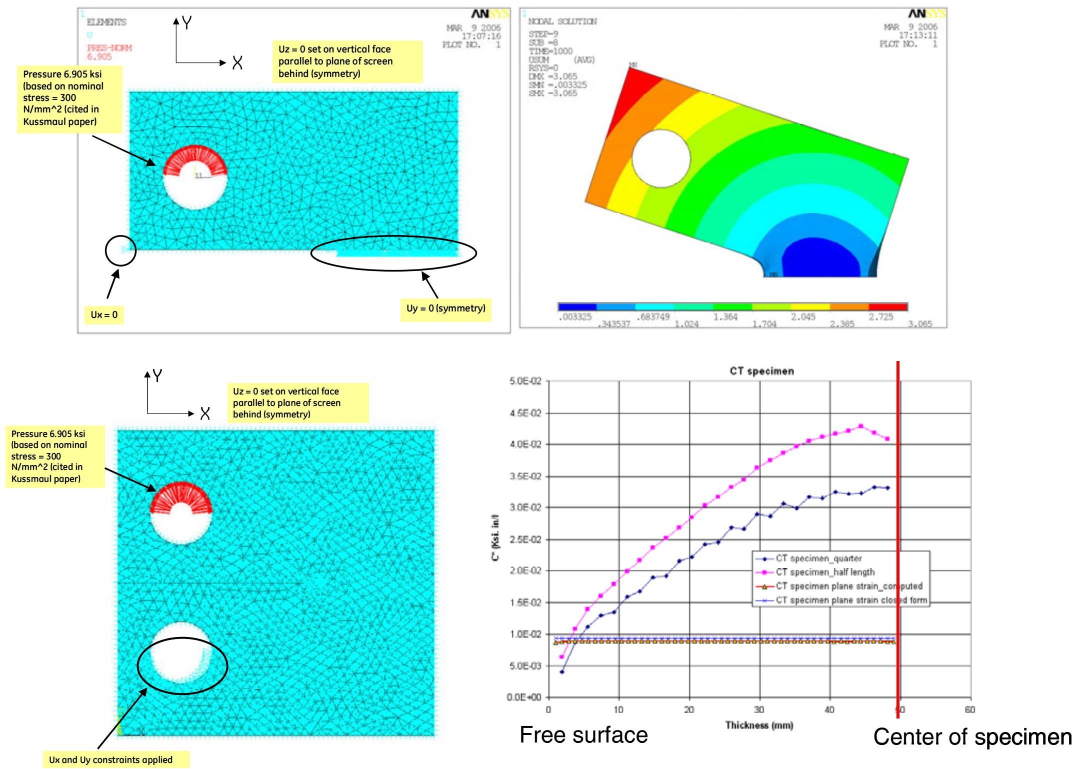


Figure 2: CT specimen – Geometry, mesh and deformed shape. Comparison of Plane strain C* values (analytical and based on 3D computations) and through the thickness calculations is shown in chart.

2. EDGE CRACK IN A THIN SHEET

The problem analyzed here is based on [6] where in authors describe several experiments conducted on a thin single edge notched specimen to evaluate creep crack growth rates. The tests were conducted for about 146 hours.

Load is applied on the top of the specimen. The geometry (X direction -> width, Y direction -> length, Z-direction -> thickness) and the loading have symmetry about Z plane as well as about Y plane (along the length direction). This symmetry is exploited in creating the model with half-length and half the thickness of the original specimen. A model with full thickness and half-length was also analyzed.

Loads and BCs:

In [6], a load of 1174 N is applied to the specimen. This amounts to a distributed load of 29.9 MPa on the top surface. Symmetry boundary conditions (Y-direction constraint) are applied to the nodes on the Y plane. Also, symmetry boundary conditions (Z direction constraint) are applied on the nodes on the Z plane.

The procedure for creep analysis is exactly the same as explained for the compact tension specimen. The system of units adopted here are such that Stresses are in MPa, time is expressed in hours and length is expressed in meters. The Norton model's constants, in this system, for this specimen as A = 4.9e-15 and n=4.7. Young's modulus is 154e3 MPa and Poisson's ratio is 0.3. The analysis was carried out up to 160 hours. We did not consider nonlinear geometry effects in this analysis. The analysis results at 100 hours were utilized to compute C* along the crack front nodes.

Half symmetry

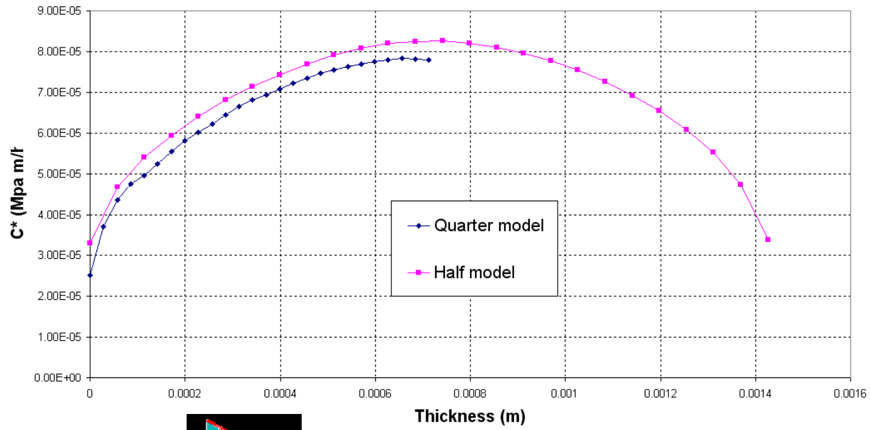
The half symmetry model exploits symmetry along Y plane, but ignores the symmetry along Z plane. The crack insertion and meshing are performed in 3DFAS. The crack tunnel mesh parameters are the same as for quarter symmetry model.

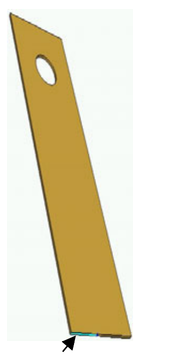
The pressure applied was the same as for quarter symmetry model. Symmetry boundary conditions were applied along the Y plane nodes. Two nodes were constrained along the crack front to avoid rigid body motions. Creep analysis was run for 160 hours and C* values were computed using 100-hour results.

C* for three cases – comparison

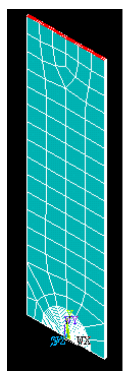
For the quarter symmetry specimen, the C* values ranged from 24 Pa m/hr to 78 Pa m/hr. For the half symmetry case, the C* values increase from 33 Pa M/hr to 83 Pa m/hr and then decrease back to 33 Pa m/hour. It is observed that the C* values near the free faces (no displacement constraints) are less than those near the faces with symmetry displacement constraints. In general we have plane stress-like conditions near the free faces and plane strain-like conditions near the middle of the thickness or near the constrained faces.

For the quarter symmetry case, we have plane stress – like situation near the free face and plane strain-like condition near the constrained end. For the half symmetry case, at half the thickness we have situations close to plane strain and near the free faces we have conditions similar to plane stress loading. The average along the crack front is compared in Figure with values reported in [5]. Note that the numerical values in [5] are obtained from Plane stress 2D model.

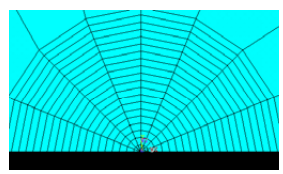




Edge crack



half symmetry model



tunnel mesh around the crack tip

$$\dot{\varepsilon}^{cr} = A\sigma^{n} \quad \text{(secondary creep)}$$

$$A = 4.9E-15$$

$$n = 4.7$$

$$E = 154GPa$$

$$\nu = 0.3(assumed)$$

$$t = 146.7h$$

Figure 3: Edge crack in a thin sheet: model and comparison C* values through thickness using Half & Quarter models. Relevant material properties used as per Ref [5].

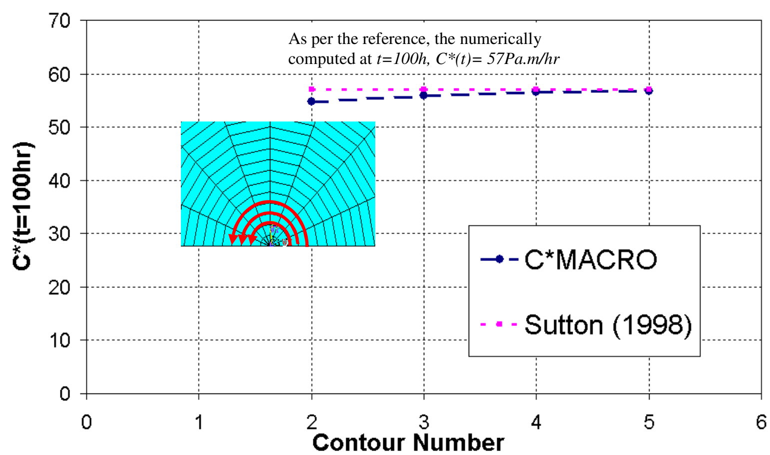
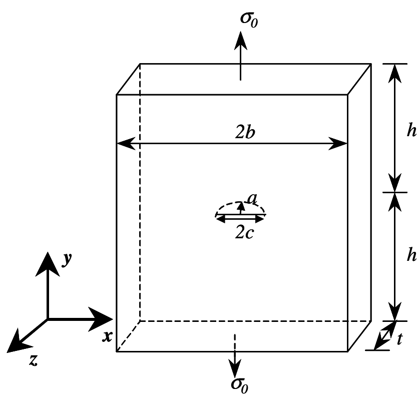


Figure 4: Comparison of Average C* computed in the present work with literature [6]

3. SEMI-ELLIPITC SURFACE CRACK IN A PLATE

An elliptical surface crack in a plate is studied for computation of C* parameter. The following figure shows a schematic of the plate with the crack.



h=26.555

b=13.333

t=1.667

a=1

c=4.1667

σ=14.5

Material Properties:

E=30 E3

v=0.3

Creep Material Properties:

$\dot{\varepsilon}^{cr} = A\sigma^{n}$ (secondary creep)

$A = 6400836\mathrm{E}-9$

$n = 3.0$

Figure 5: Schematic of surface crack geometry and values used in analysis (Note material properties used were in British units – stress (ksi), Young's modulus (ksi), creep rate (per hour)

The above problem has symmetry of geometry and loading along the YZ and XZ planes. The following cases have been analyzed on this model: 1. Quarter symmetry model (half height, h, and half width, with nonlinear geometry effects turned OFF & On and 2. Full plate with the semi-elliptic crack embedded in it (NLGEOM=OFF)

In this problem, we have computed C* with and without the nonlinear geometry effects to evaluate their effect on C*. The load is applied in the form of distributed tensile load of magnitude 100Mpa (14.5 ksi) on the top face in the Y direction.

C* for the three cases:

The C* values for the three cases at 100 hours is shown in Figure 6. The problem was also simulated in commercial software ABAQUS and C* was calculated using an internal routine in ABAQUS. The C* values from the three cases as well as from ABAQUS are plotted as functions of the angle along the elliptical crack front. It is seen that the C* values with nonlinear geometric effects are less by about 5% from those without nonlinear geometric effects. Also, the C* values keep increasing as we go deep inside the thickness of the plate. The full plate results are consistently higher than the symmetry cases.

The ABAQUS results differ significantly (by about 16%) from the Ansys full plate solution near the free surface. However, the discrepancy between ABAQUS and the Ansys full plate solution cases decreases to about 8% at the deepest point in the thickness direction where C* values reach their maximum. This is at least partially attributed to creep model implementations in two packages and the mesh refinements are also different. In general, computation of parameters like C* and J-integral near surface is very sensitive to numerical implementation and remains an active area of research.

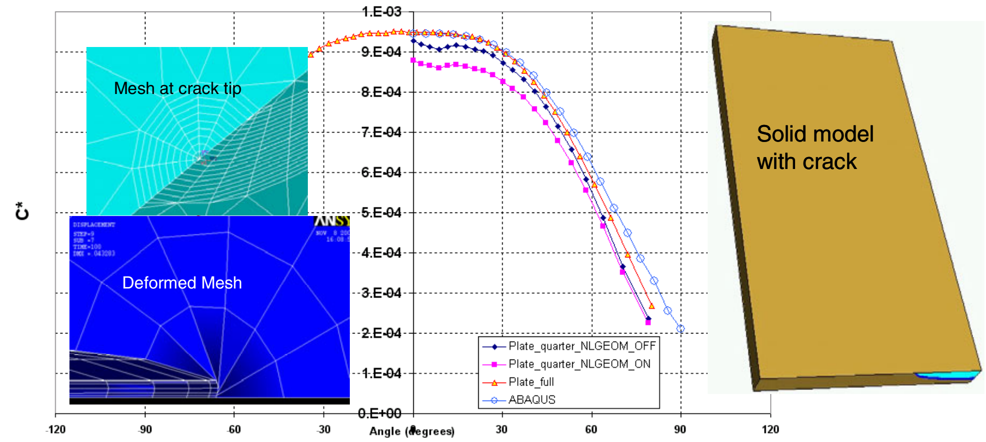


Figure 6: Surface crack in a plate: Comparison of numerical solutions (C* units: N/mm.hr)

Summary:

Analysis methodology is developed for computing C* parameter for a 3D Finite Element model with a crack explicitly modeled and meshed. The process is implemented as standard user macros in a commercial FE package – ANSYS. The computations are performed on several standard geometries and compare very well with available literature solutions. This capability enables further development of residual life calculations for creep crack growth in real power generation structures.

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