Application of Abaqus to Analysis of 3D Cracks and Fatigue Crack Growth Prediction

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Overview

• General requirements for 3D crack simulation

• Historical perspective
  – Zencrack development

• Typical workflow and interaction of Zencrack with Abaqus

• Examples

• Zencrack GUI
Three key areas for crack simulation

Fracture mechanics parameters
- $K$, $G$, $J$
- Closed form
- Numerical evaluation - BEM, FEM

Crack simulation

Topology issues
- Initial crack
- Mixed mode / non-planar growth
- Crack shape development
- Multiple cracks

Crack growth integration
- Cycle-by-cycle
- Finite evaluations of fracture parameters
- Crack growth data, threshold effects
- Load spectrum, flight cycles
The solution provided by Zencrack

- **Zencrack:**
  - uses commercially available finite element codes to calculate fracture mechanics parameters  
    » e.g. Abaqus/Standard
  - has meshing algorithms for modelling and updating crack fronts in 3D components
  - has a crack growth integration scheme to allow generalised non-planar crack growth prediction

Four point bend specimen
Two different initial crack positions
Zencrack historical perspective

3 year DISPLACE project led by Rolls-Royce ended Dec 2011
- Input from Zentech, Serco, Universities of Birmingham and Southampton
- Improved time dependent capability
- General “full cycle” capability

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C. Timbrell, P.W. Claydon, G. Cook
Abaqus Users’ Conference, Rhode Island, U.S.A., June 1-3 1994
Applications

- Life extension, durability & damage tolerance assessment
- Engine disks and blades and their dovetail connections
- Power generation components
- Pipeline defects
- Welded connections
- Stiffened panels (integral & riveted)
Zencrack workflow for crack growth

- Geometry model
- Uncracked mesh
- Zencrack input data
- Growth analysis
- Post-processing
A crack in a 3D finite element mesh

Cut-away at the mid-section showing the corner crack that must be analysed
A crack in a 3D finite element mesh

Typical finite element mesh for an elliptic crack
A crack in a 3D finite element mesh

“Collapsed” crack front elements

Focused mesh of rings of elements around the crack front

Typical finite element mesh for an elliptic crack
A crack in a 3D finite element mesh

Crack face opens under load

Typical Von Mises stress contours showing the singularity at the crack front

Typical finite element mesh for an elliptic crack
1. Mesh of intact component

The user must supply Zencrack with a mesh of an intact component e.g. an Abaqus input file (.inp):

- any suitable pre-processor
- 8 or 20 noded bricks where cracks are required

![Geometry model]

![Uncracked mesh]

How does Zencrack work?

**Simplified flowchart**

- **USER INPUT**
  - An existing f.e. mesh of an uncracked component
- **ZENCRAK**
  - Creates f.e. mesh of the cracked component
- **USER INPUT**
  - Additional data e.g. crack location, size & crack growth data
- **F.E. CODE**
  - Analysis
- **ZENCRAK**
  - Evaluates crack growth
- **ZENCRAK**
  - Updates f.e. model
- **STOP**
  - no
- **ZENCRAK**
  - Next f.e. analysis? yes
2. Zencrack input file

This includes the required location, orientation and size of the initial crack front.

For crack growth prediction additional data such as the crack growth law data is required.

Creation of the input file via plug-ins for Abaqus/CAE is now replaced by the Zencrack GUI.
How does Zencrack work?

3. Zencrack creates mesh with initial crack

Target elements in the uncracked mesh are replaced by “crack-blocks” to generate the desired initial crack front(s)

How does Zencrack work?

+ Uncracked mesh

- Crack-block(s)

Cracked mesh

Simplified flowchart

USER INPUT
An existing f.e. mesh of an uncracked component

ZENCrack
Creates f.e. mesh of the cracked component

USER INPUT
Additional data e.g. crack location, size & crack growth data

F.E. CODE Analysis

ZENCrack
Evaluates crack growth

ZENCrack
Updates f.e. model

STOP

Next f.e. analysis?

no

yes
How does Zencrack work?

3. Zencrack creates mesh with initial crack

Boundary conditions, pressure loads, temperatures and surfaces are updated near the crack front if necessary

i.e. updates to keywords including:
* SURFACE
* DLOAD
* BOUNDARY
* TEMPERATURE
* INITIAL CONDITIONS, TYPE=TEMPERATURE

Contour integral and displacement requests at the crack(s) are generated for the new mesh
4. Finite element analysis

The cracked component mesh is automatically submitted for analysis in Abaqus/Standard.

When the f.e. run completes, results are extracted from the .odb file and processed to allow reporting of fracture mechanics parameters for the crack(s).

This is the last step if the user only wants to evaluate stress intensity factors or the energy release rate for a given crack.
5. Crack growth prediction

If crack growth is to take place the information from the f.e. analysis is combined with cyclic load history data and the crack growth law given by the user.

An integration scheme calculates an updated position for each crack front.

The mesh is updated to contain crack(s) in the new position(s).
6. Another f.e. analysis?

If limits defining the end of the analysis have not been reached, a new finite element job is submitted.

Analysis and update is repeated until user defined limits or failure are reached e.g. KIC has been reached.

**Simplified flowchart**

1. **USER INPUT**
   - An existing f.e. mesh of an uncracked component

2. **ZENCRACK**
   - Creates f.e. mesh of the cracked component

3. **USER INPUT**
   - Additional data e.g. crack location, size & crack growth data

4. **F.E. CODE**
   - Analysis

5. **ZENCRACK**
   - Evaluates crack growth

6. **ZENCRACK**
   - Updates f.e. model

7. **STOP**
   - No
   - Yes

8. **Next f.e. analysis?**

   - STOP

   - Yes
Overview of fatigue calculations

- A "linear elastic fracture mechanics" approach is most often used for crack propagation
  - Loading & history
    » Calculate SIF range, \( \Delta K \)
  - Crack growth law
    » Relates \( \Delta K \) to the growth rate, \( \frac{da}{dn} \)
  - Advance the crack by \( da \) over the next \( dn \) cycles
  - Each crack front node may have different "local" conditions allowing for generalised crack shape development

\[
\frac{da}{dn} = f(\Delta K, R, T, f, \ldots)
\]
Load systems

- Many different load types may need to be analysed e.g.:
  - Thermal transients, internal pressure, aerodynamic loads, contact forces
- The f.e. analysis may have
  - A single step with one increment
  - Multiple steps each having multiple increments

- Zencrack uses a “load system” methodology to relate the f.e. results to the load history needed for crack growth prediction
Load systems

- The load system approach is extremely powerful and flexible.
- It can handle simple cases such as constant amplitude loading through to general load cycles in which stresses and temperatures may be varying out-of-phase.
- Fatigue and/or time dependent load scenarios can be considered.

Typical aero engine data with out-of-phase stress and temperature time histories.
Example – threaded connection

- For this example, the geometry is defined for a coarse (UNC) 0.5 inch major diameter thread
  - the major diameter is \( D_{maj} = 0.5'' \), pitch is \( P = 1/13'' \)
- The model is a simplified one in which the circumferential effect of the pitch is not included
- A 90° sector is modelled with the crack extending around the full 90 degrees of the model (180° expansion is shown below)
Example – threaded connection
Example – threaded connection

Contours of a complete load cycle for one crack position during the growth sequence

Contours of snapshots at the maximum load condition as the crack grows
Example – pin/lug interaction

- Cyclic loading applied on a tight-fitting pin in a lug
- Initial crack is a through crack located in the lug

Contact surface updated on the lug side for the initial cracked mesh
Example – pin/lug interaction
Example – pin/lug interaction
Example – header/nozzle intersection

- This example considers a crack in a pressurised header nozzle connection
  - Response to a pressurised thermal shock
  - Crack growth for a cyclic pressure load case

- The quarter symmetry model has the following main dimensions
  - Header
    » OD 30″, wall 3 1/8″
  - Nozzle
    » OD 10 5/8″, wall 1 5/16″
Example – header/nozzle intersection

- Temperature dependent steel data has been used
- The data for Young’s modulus and Poisson ratio is also part of the Zencrack input data
- The transient analysis is carried out as a sequential thermal-stress analysis:
  - Heat transfer run to develop spatial temperature distribution as a function of time
  - Stress analysis using the heat transfer results as one of the inputs, plus pressure loading
  - Abaqus allows interpolation of temperatures from one mesh to a dissimilar mesh
    » an uncracked model heat transfer analysis can provide the temperature input for the Zencrack stress analysis of the cracked component
    » assumes the crack does not influence the temperatures

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Material, name=Steel
Conductivity
0.0518, 20.
0.0503, 100.
0.0476, 200.
0.0445, 300.
0.0414, 400.
Density
7.85e+06,
Elastic
209000., 0.3, 20.
205000., 0.3, 100.
199000., 0.3, 200.
191000., 0.3, 300.
181000., 0.3, 400.
Expansion, zero=20.
1.15e-05, 20.
1.17e-05, 50.
1.2e-05, 100.
1.23e-05, 150.
1.27e-05, 200.
1.3e-05, 250.
1.33e-05, 300.
1.35e-05, 350.
1.38e-05, 400.
Specific Heat
460., 20.
480., 50.
500., 100.
520., 150.
530., 200.
540., 250.
560., 300.
570., 350.
590., 400.
Example – header/nozzle intersection

• Transient definition for pressurised thermal shock

  - Internal temperature is defined in the heat transfer analysis using an Abaqus *AMPLITUDE definition.
  - Internal and end cap pressures are defined during the stress analysis using an Abaqus *AMPLITUDE definition.
  - Pressure load is also applied on the crack face.
Example – header/nozzle intersection

Temperature

Von Mises stress

Cracked model transient analysis
Example – header/nozzle intersection

Temperature history

- Header end
- 45 degree plane
- Nozzle end

Temperature [degrees C] vs. Time [s]
Example – header/nozzle intersection

$\Delta K$ range at each crack front node drives the crack growth prediction for that node.
Example – header/nozzle intersection

Crack growth due to cyclic internal pressure load of 1.6MPa to 16MPa
Zencrack GUI

- The Zencrack GUI allows:
  - creation, review and modification of input files
  - submission of Zencrack jobs
  - visualisation of crack growth profiles and creation of XY plots
  - import of one or more uncracked or cracked meshes

- Replaces the earlier plug-ins for Abaqus/CAE
Define a crack front
Preview the cracked mesh
Submit analysis
Visualise crack profiles and surface
Create XY plot
“Growth” XY plot

Example of results plotted through an entire crack growth analysis
“FE increment” XY plot

Example of results plotted through multiple increments of a single f.e. analysis
Thank you.

Any questions?