Virtual Crack Closure Technique (VCCT)
Lecture 7
Overview

• Introduction
• VCCT Criterion
• Output
• VCCT Plug-in
• Comparison with Cohesive Behavior
• Examples
• Workshop 5
Introduction
Introduction

- Motivation is aircraft composite structural analysis
  - To reduce the cost of laminated composite structures, large integrated bonded structures are being considered.
    - In primary structures, bondlines and interfaces between plies are required to carry interlaminar loads.
    - Damage tolerance requirements dictate that bondlines and interfaces carry required loads with damage.

Modeling debonding along skin-stringer interface
Introduction

- **Analysis requirements for composite damage**
  - Apply Linear Elastic Fracture Mechanics (LEFM) to bondlines and interfaces
    - 2D and 3D delaminations
    - Propagation
    - Mode separation
    - Multiple cracks
    - Non-linear behavior (e.g., postbuckling)
    - Composite structure
    - Practical (CPU time, minimum set of models)
Introduction

• VCCT uses LEFM concepts
  • Based on computing the energy release rates for normal and shear crack-tip deformation modes.
  • Compare energy release rates to interlaminar fracture toughness.


Nodes 2 and 5 will start to release when:

\[
\frac{1}{2} \frac{v_{1,6} F_{v,2,5}}{b d} = G_I \geq G_{IC}
\]

where

- \( G_I \) = mode I energy release rate
- \( G_{IC} \) = critical mode I energy release rate
- \( b \) = width
- \( F_{v,2,5} \) = vertical force between nodes 2 and 5
- \( v_{1,6} \) = vertical displacement between nodes 1 and 6

Mode II treated similarly

Pure Mode I

Modified VCCT

Node numbers are shown
VCCT Criterion
VCCT Criterion

- The debond capability is used to perform the crack propagation analysis for initially bonded crack surfaces.

- The crack propagation analysis allows for five types of fracture criteria:
  1. Critical stress criterion
  2. Crack opening displacement criterion
  3. Crack length vs. time criterion
  4. VCCT criterion
  5. Low-cycle fatigue criterion

- Defining case 4, “VCCT criterion,” is the subject of this lecture.

- The details of cases 1, 2, and 3 are not discussed here. Please consult the Abaqus Analysis User’s Manual for more details.

- The details of case 5 will be discussed later in Lecture 8 “Low-cycle Fatigue.”
VCCT Criterion

• When using VCCT to model crack propagation,
  • you must:
    1. define contact pairs for potential crack surfaces;
    2. define initially bonded crack surfaces;
    3. activate the crack propagation capability; and
    4. specify the VCCT criterion.
  • you also may:
    • define spatially varying critical energy release rates;
    • use viscous regularization, contact stabilization, and/or automatic stabilization to overcome convergence difficulties for unstable propagating cracks;
    • use a linear scaling technique to accelerate convergence for VCCT.
VCCT Criterion

• Defining the VCCT criterion is not currently supported in Abaqus/CAE.
  • However, the VCCT plug-in is available and allows you to interactively define the debond interface(s).
    • The details of the VCCT plug-in will be discussed later in this lecture.
    • Downloaded from “VCCT plug-in utility,” SIMULIA Answer 3235.
VCCT Criterion

- **Example: Double cantilever beam (DCB)**
  - Analyze debonding of a DCB model using the VCCT criterion.
  - Steps required for setting up the model include:
    - Define slave (TopSurf) and master (BotSurf) surfaces along the debond interface.
    - Define a set (bond) containing the initially bonded region (part of TopSurf in this example).
  - The Keywords interface is illustrated in this example.
VCCT Criterion

1 Define contact pairs for potential crack surfaces

- Potential crack surfaces are modeled as slave and master contact surfaces.
  - Any contact formulation except the finite-sliding, surface-to-surface formulation can be used.
  - Cannot be used with self-contact.

Note: The frictionless interaction property is assumed.

*NSET, NSET=bond, GENERATE 1, 121, 1
*SURFACE, NAME=TopSurf _TopBeam_S1, S1
*SURFACE, NAME=BotSurf _BotBeam_S1, S1
*CONTACT PAIR, INTER=...
TopSurf, BotSurf

slave surface          master surface
VCCT Criterion

2 Define initially bonded crack surfaces

- The initially bonded contact pair is identified with the *INITIAL CONDITIONS, TYPE=CONTACT option.

```plaintext
*INITIAL CONDITIONS, TYPE=CONTACT
TopSurf, BotSurf, bond
```

*NSET, NSET=bond, GENERATE 1, 121, 1

*SURFACE, NAME=TopSurf_TopBeam_S1, S1
*SURFACE, NAME=BotSurf_BotBeam_S1, S1

*CONTACT PAIR, INTER=...
TopSurf, BotSurf

- a list of slave nodes that are initially bonded
VCCT Criterion

- The unbonded portion of the slave surface will behave as a regular contact surface.
- If the node set that includes the initially bonded slave nodes is not specified, the initial contact condition will apply to the entire contact pair.
  - In this case, no crack tips can be identified, and the bonded surfaces cannot separate.
- For the VCCT criterion, the initially bonded nodes are bonded in all directions.
**VCCT Criterion**

3 **Activate the crack propagation capability**

- The *DEBOND* option is used to activate crack propagation in a given step.
- The SLAVE and MASTER parameters identify the surfaces to be debonded.

```
*SET, NSET=bond, GENERATE 1, 121, 1
*SURFACE, NAME=TopSurf_TopBeam_S1, S1
*SURFACE, NAME=BotSurf_BotBeam_S1, S1
*CONTACT PAIR, INTER=... TopSurf, BotSurf
*INITIAL CONDITIONS, TYPE=CONTACT TopSurf, BotSurf, bond
*STEP, NLGEOM
*STATIC
...
*DEBOND, SLAVE=TopSurf, MASTER=BotSurf
```
VCCT Criterion

4 Specify the VCCT criterion

- The **BK law** model is used in this example.

**BK law:**

\[
G_{equivC} = G_{IC} + \left( G_{IIC} - G_{IC} \right) \left( \frac{G_{II} + G_{III}}{G_{I} + G_{II} + G_{III}} \right) \eta
\]

*NSET, NSET=bond, GENERATE 1, 121, 1
*SURFACE, NAME=TopSurf _TopBeam_S1, S1
*SURFACE, NAME=BotSurf _BotBeam_S1, S1
*CONTACT PAIR, INTER=...
TopSurf, BotSurf
*INITIAL CONDITIONS, TYPE=CONTACT
TopSurf, BotSurf, bond
*STEP, NLGEOM
*STATIC
...
*DEBOND, SLAVE=TopSurf, MASTER=BotSurf
*FRACTURE CRITERION, TYPE=VCCT,
MIXED MODE BEHAVIOIR=BK
280.0, 280.0, 0.0, 2.284

\[G_{IC} G_{IIC} G_{III} \eta\]
VCCT Criterion

• The crack-tip node debonds when the fracture criterion, $f$,

$$f = \frac{G_{\text{equiv}}}{G_{\text{equivC}}}$$

reaches the value 1.0 within a given tolerance, $f_{\text{tol}}$:

$$1 \leq f \leq 1 + f_{\text{tol}}.$$ 

where

- $G_{\text{equiv}}$ is the equivalent strain energy release rate, and
- $G_{\text{equivC}}$ is the critical equivalent strain energy release rate calculated based on the user-specified mode-mix criterion and the bond strength of the interface.

• For the VCCT criterion, the default value of $f_{\text{tol}}$ is 0.2.

• Use following option to control $f_{\text{tol}}$:

*FRACTURE CRITERION, TYPE=VCCT, TOLERANCE=$f_{\text{tol}}$
VCCT Criterion

- In the DCB model, the tolerance is set to 0.1.

```plaintext
*SET, NSET=bond, GENERATE 1, 121, 1
*SURFACE, NAME=TopSurf_TopBeam_S1, S1
*SURFACE, NAME=BotSurf_BotBeam_S1, S1
*CONTACT PAIR, INTER=TopSurf, BotSurf
*INITIAL CONDITIONS, TYPE=CONTACT
TopSurf, BotSurf, bond
*STEP, NLGEOM
*STATIC
...
*DEBOND, SLAVE=TopSurf, MASTER=BotSurf
*FRACTURE CRITERION, TYPE=VCCT,
MIXED MODE BEHAVIOUR=BK, TOLERANCE=0.1
280.0, 280.0, 0.0, 2.284
```
VCCT Criterion

- In addition to the BK law model, Abaqus/Standard also provides two other commonly used mode-mix criteria for computing $G_{equivC}$: the Power law and the Reeder law models.
  - An appropriate model is best selected empirically.

- **Power law**
  
  \[
  \frac{G_{equiv}}{G_{equivC}} = \left( \frac{G_I}{G_{IC}} \right)^{am} + \left( \frac{G_{II}}{G_{IIC}} \right)^{an} + \left( \frac{G_{III}}{G_{IIIC}} \right)^{ao}
  \]

  *FRACTURE CRITERION, TYPE=VCCT, MIXED MODE BEHAVIOR=POWER
  $G_{IC}, G_{IIC}, G_{IIIC}, am, an, ao$

- **Reeder law**
  
  \[
  G_{equivC} = G_{IC} + \left( G_{IIC} - G_{IC} + (G_{IIIC} - G_{IIC}) \left( \frac{G_{III}}{G_{II} + G_{III}} \right) \right) \left( \sum G_i \right)^{\eta}
  \]

  *FRACTURE CRITERION, TYPE=VCCT, MIXED MODE BEHAVIOR=REEDER
  $G_{IC}, G_{IIC}, G_{IIIC}, \eta$
VCCT Criterion

• Spatially varying critical energy release rates

  • The VCCT criterion can be defined with varying energy release rates by specifying the critical energy release rates at all nodes on the slave surface.

  • In this case, the critical energy release rates should be interpolated from the critical energy release rates specified at the nodes with the *NODAL ENERGY RATE option.

  • However, the exponents (e.g., $\eta$) are still read from the data lines under the *FRACTURE CRITERION option.

*NODAL ENERGY RATE

node ID1, $G_{IC}, G_{IIC}, G_{III}$
node ID2, $G_{IC}, G_{IIC}, G_{III}$

...  

*STEP
*STATIC

...  

*FRACTURE CRITERION, TYPE=VCCT, MIXED MODE BEHAVIOR=BK, NODAL ENERGY RATE

$G_{IC}, G_{IIC}, G_{III}, \eta$
VCCT Criterion

- Viscous regularization for VCCT
  - Can be used to overcome some convergence difficulties for unstable propagating cracks.
  - Example: DCB
    - Set the value of the viscosity coefficient to 0.1.

```
*SET, NSET=bond, GENERATE 1, 121, 1
*SURFACE, NAME=TopSurf_TopBeam_S1, S1
*SURFACE, NAME=BotSurf_BotBeam_S1, S1
*CONTACT PAIR, INTER=...
  TopSurf, BotSurf
*INITIAL CONDITIONS, TYPE=CONTACT
  TopSurf, BotSurf, bond
*STEP, NLGEOM
*STATIC
...
*DEBOND, SLAVE=TopSurf,
  MASTER=BotSurf, VISCOSITY=0.1
*FRACTURE CRITERION, TYPE=VCCT, MIXED
  MODE BEHAVIOIR=BK, TOLERANCE=0.1
  280.0, 280.0, 0.0, 2.284
```
VCCT Criterion

• In addition, contact and automatic stabilization that are not specific to VCCT can be also used to aid convergence.
  • They are built into Abaqus/Standard and are compatible with VCCT.
• Note that the crack propagation behavior may be modified by the damping forces.
  • Therefore, monitor the damping energy (ALLVD or ALLSD) and compare it with the total strain energy in the model (ALLSE) to ensure that the results are reasonable in the presence of damping.
    • ALLVD stores the damping energy generated from viscous regularization.
    • ALLSD stores the damping energy generated from contact stabilization and automatic stabilization.
VCCT Criterion

• Linear scaling to accelerate convergence for VCCT
  • Abaqus provides a linear scaling technique to quickly converge to the critical load state. This reduces the solution time required to reach the onset of crack growth.
    • This technique works best for models in which the deformation is nearly linear before the onset of crack growth.
  • Once the first crack-tip node releases, the linear scaling calculations will no longer be valid and the time increment will be set to the default value.

• Usage:

  \[ \text{*CONTROLS, LINEAR SCALING } \]

  \[ \beta \]

  where $\beta$ is the coefficient of linear scaling.

• For details of linear scaling to accelerate convergence for VCCT, see “Crack propagation analysis,” Section 11.4.3 of the Abaqus Analysis User’s Manual.
VCCT Criterion

• **Tips for using the VCCT criterion**
  
  • Crack propagation problems using the VCCT criterion are numerically challenging.
  
  • To help you create a successful model, several tips for using the VCCT criterion are provided:
    
    • The master debonding surfaces must be continuous.
    
    • The tie MPCs should NOT be used for the slave debonding surface to avoid overconstraints.
    
    • A small clearance between the debonding surfaces can be specified to eliminate unnecessary severe discontinuity iterations during incrementation as the crack begins to progress.

  ...

  • **Note**: More tips are provided in “Crack propagation analysis,” Section 11.4.3 of the Abaqus Analysis User’s Manual.
Output
Output

- The following output options are provided to support the VCCT criterion:
  - Abaqus/CAE supports the surface output requests for VCCT.

*OUTPUT, FIELD, FREQUENCY=freq
*CONTACT OUTPUT, MASTER=master, SLAVE=slave

*OUTPUT, HISTORY, FREQUENCY=freq
*CONTACT OUTPUT, [ (MASTER=master, SLAVE=slave) | (NSET=nset) ]
Output

- The following bond failure quantities can be requested as surface output:
  - **DBT**: The time when bond failure occurred
  - **DBSF**: Fraction of stress at bond failure that still remains
  - **DBS**: Stress in the failed bond that remains
  - **OPENBC**: Relative displacement behind crack.
  - **CRSTS**: Critical stress at failure.
  - **ENRRT**: Strain energy release rate.
  - **EFENRRTR**: Effective energy release rate ratio.
  - **BDSTAT**: Bond state (=1.0 if bonded, 0.0 if unbonded)

- All of the above variables can be visualized in Abaqus/Viewer.
- The initial contact status of all of the slave nodes is printed in the data (.dat) file.
Output

- Example: DCB
  - Request surface output:

  ```plaintext
  *INITIAL CONDITIONS, TYPE=CONTACT
  TopSurf, BotSurf, bond
  *STEP, NLGEOM
  *STATIC
  ...
  *DEBOND, SLAVE=TopSurf, MASTER=BotSurf, VISCOSITY=0.1
  *FRACTURE CRITERION, TYPE=VCCT, MIXED MODE BEHAVIOIR=BK, TOLERANCE=0.1
  280, 280, 280, 2.284
  ...
  *OUTPUT, FIELD, VAR=PRESELECT
  *CONTACT OUTPUT, SLAVE=TopSurf, MASTER=BotSurf
  DBT, DBS, OPENBC, CRSTS, ENRRT, BDSTAT
  *OUTPUT, HISTORY
  *CONTACT OUTPUT, SLAVE=TopSurf, MASTER=BotSurf, NSET=bond
  DBT, DBS, OPENBC, CRSTS, ENRRT, BDSTAT
  *NODE OUTPUT, NSET=tip
  U2, RF2
  *END STEP
  ```
Output

• Results

![Graph showing force vs. displacement with VCCT and cohesive elements comparison.]

VCCT

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Modeling Fracture and Failure with Abaqus
VCCT Plug-in
VCCT Plug-in

- VCCT plug-in
  - provides an interactive interface to define the debond interface(s).
  - supports the following keyword options required for VCCT analysis:

*INITIAL CONDITIONS, TYPE=CONTACT

*DEBOND, SLAVE=slave, MASTER=master, OUTPUT=[fil|dat|both], VISCOSITY=\( \mu \)

*FRACTURE CRITERION, TYPE=VCCT,
  MIXED MODE BEHAVIOR=[BK|POWER|REEDER], TOLERANCE=\( f_{tol} \),
  NODAL ENERGY RATE

*NODAL ENERGY RATE

*CONTROLS, LINEAR SCALING

- For details please refer to “VCCT plug-in utility,” SIMULIA Answer 3235.
VCCT Plug-in

- **Example: Double Cantilever Beam (DCB)**
  - The VCCT plug-in is discussed in the context of the Keywords interface presented earlier.

![Diagram of VCCT Plug-in](image.png)
VCCT Plug-in

1. Define contact pairs for potential crack surfaces
   - Frictionless contact is assumed.

*SURFACE INTERACTION, NAME=IntProp-1

*FRICTION
0.0

*CONTACT PAIR, INTERACTION=IntProp-1
TopSurf, BotSurf
** VCCT Plug-in

** Define the VCCT criterion

- Select the fracture criterion, viscosity coefficient, and cutback tolerance.

... 
*STEP, NLGEOM
*STATIC
...
*DEBOND, SLAVE=TopSurf, MASTER=BotSurf, VICOISITY=0.1
*FRACTURE CRITERION, TYPE=VCCT, TOLERANCE=0.2, MIXED MODE BEHAVIOIR=BK
280, 280, 280, 2.284

...
VCCT Plug-in

Specify critical strain energy release rates

...?
*STEP, NLGEOM
*STATIC
...
*DEBOND, SLAVE=TopSurf, MASTER=BotSurf,
VICOSITY=0.1
*FRACTURE CRITERION, TYPE=VCCT, TOLERANCE=0.2,
MIXED MODE BEHAVIOIR=BK
280, 280, 280, 2.284
VCCT Plug-in

- The VCCT plug-in also supports defining spatially varying critical energy release rates.
  - Click mouse button 3 to manage the table.

```plaintext
*NODAL ENERGY RATE
node ID1, G_{IC}, G_{IIC}, G_{IIIC}
node ID2, G_{IC}, G_{IIC}, G_{IIIC}
...

*STEP
*STATIC
...

*FRACTURE CRITERION, TYPE=VCCT,
MIXED MODE BEHAVIOR=BK, NODAL ENERGY RATE
G_{IC}, G_{IIC}, G_{IIIC}, \eta
```
**VCCT Plug-in**

3 Define the VCCT bonded interface

- Select the initially bonded region, the crack propagation output file and frequency, and the debond initiation step.
  
- Note: The VCCT plug-in allows specification of linear scaling.

*INITIAL CONDITIONS, TYPE=CONTACT  
TopSurf, BotSurf, bond  
*STEP, NAME=Step-1  
*STATIC, NLGEOM  
...

*DEBOND, SLAVE=TopSurf, MASTER=BotSurf, VISCOSITY=0.1  
*FRACTURE CRITERION, TYPE=VCCT, MIXED MODE BEHAVIOR=BK  
280, 280, 280, 2.284
VCCT Plug-in

- The relevant keywords will be generated when Abaqus/CAE writes the input file.

---

**Interaction: Int-1**

*Contact Pair, interaction=IntProp-1
TopSurf, BotSurf

*initial conditions, type=contact
TopSurf, BotSurf, bond

**

** OUTPUT REQUESTS

**

*Debond, slave=TopSurf, master=BotSurf, FREQUENCY=1, viscosity=0.1
*Fracture Criterion, tolerance=0.2, type=vctt, MIXED MODE BEHAVIOR=BK 228, 228, 228, 2.285

**

** FIELD OUTPUT: F-Output-1

**

*Output, field

  *Element Output, directions=YES
  E, S

*Contact Output
BDSTAT, CRSTS, DBS, DBSF, DBT, EFENRTR, ENRRT, OPENBC

**

** HISTORY OUTPUT: H-Output-1

**

*Output, history

*Contact Output, master=BotSurf, slave=TopSurf
BDSTAT, CRSTS, DBS, DBSF, DBT, EFENRTR, ENRRT, OPENBC
Comparison with Cohesive Behavior
Comparison with Cohesive Behavior

VCCT and cohesive behavior are very similar in their application and formulation.

Both theories

- are used to model interfacial shearing and delamination crack propagation and failure,
- use an elastic damage constitutive theory to model the material's response once damage has initiated, and
- dissipate the same amount of fracture energy between damage initiation and complete failure.
Comparison with Cohesive Behavior

- The fundamental difference between VCCT and cohesive behavior is in the way crack propagation is predicted.
  - In VCCT an existing flaw is assumed.
    - VCCT is appropriate for brittle crack propagation problems.
  - However, cohesive behavior can model damage initiation.
    - Damage initiation in cohesive behavior is based strictly on the predefined ultimate (normal and/or shear) stress/strain limit.
    - Cohesive behavior can be used for both brittle and ductile crack propagation problems.
Comparison with Cohesive Behavior

• VCCT may be viewed as more fundamentally based on fracture mechanics.
  • The damage initiation and damage evolution are both based on fracture energy, whereas cohesive behavior use the fracture energy only during damage evolution.

• Applicability of VCCT is limited to “self-similar” crack propagation analyses.
  • This implies a steady-state running crack.
  • Difficult to reproduce in practice.
## Comparison with Cohesive Behavior

- **Summary:** Complementary techniques for modeling of debonding

<table>
<thead>
<tr>
<th>VCCT</th>
<th>Cohesive behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use the debond framework (surface based)</td>
<td>Interface elements (element based) or contact (surface based)</td>
</tr>
<tr>
<td>Assumes an existing flaw</td>
<td>Can model crack initiation</td>
</tr>
<tr>
<td>Brittle fracture using LEFM occurring along a well defined crack front</td>
<td>Ductile fracture occurring over a smeared crack front modeled with spanning cohesive elements or cohesive contact</td>
</tr>
<tr>
<td>Requires GI, GII, and GIII</td>
<td>Requires $E$, $\sigma_{\text{max}}$, GI, GII, and GIII</td>
</tr>
<tr>
<td>Crack propagates when strain energy release rate exceeds fracture toughness</td>
<td>Crack initiates when cohesive traction exceeds critical value and releases critical strain energy when fully open</td>
</tr>
<tr>
<td>Crack surfaces are rigidly bonded when uncracked.</td>
<td>Crack surfaces are joined elastically when uncracked.</td>
</tr>
<tr>
<td>Available only in Abaqus/Standard</td>
<td>Available in Abaqus/Standard and Abaqus/Explicit</td>
</tr>
</tbody>
</table>

- Both are needed to satisfy general fracture requirements
Examples
Examples

• Verification problems
  • DCB
  • SLB
  • ENF
  • Alfano-Crisfield
    • Also available as Abaqus Benchmark Problem 2.7.1 with cohesive elements
  • NASA Panel
Examples

- Compression Buckling/Delamination Single Disbond (Unreinforced)

![Graph showing load vs. displacement with Euler buckling and FEA data.]

Multiple crack tips
Buckling driven delaminations
Examples
Examples

• Compression Buckling/Delamination Multiple Disbonds (Unreinforced)

Multiple cracks can also be addressed
Examples

Step: 0  Frame: 41

Modeling Fracture and Failure with Abaqus
Examples

• T-Joint Pull-off Model
Examples

• Postbuckling Behavior of Skin-Stringer Panels

• VCCT can be applied to determine the global strength and failure mode for typical aerospace composite structures like this skin/stringer panel

Courtesy Boeing
Examples

Displacement imposed at corner nodes

Contact surfaces defined for region of fracture

Modeling Fracture and Failure with Abaqus
Examples

Initially bonded nodes

Initially debonded nodes

Crack tip
Examples

The Abaqus Tech Brief on skin/stringer bonded joint analysis can be downloaded from [www.simulia.com](http://www.simulia.com)
Examples
Workshop 5
Workshop 5

- Crack growth in a three-point bend specimen using VCCT
  - Repeat the cohesive-based exercises using VCCT and compare results