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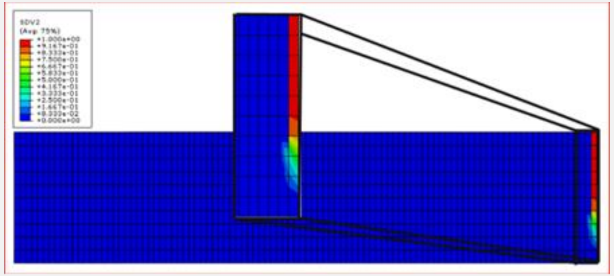
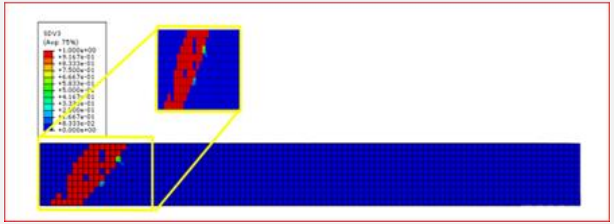
3D Hashin Failure Criteria with Exponential Damage Evolution in Abaqus





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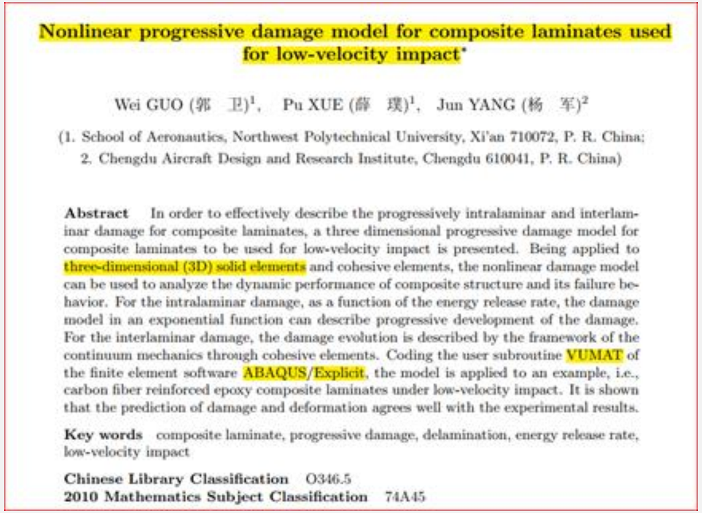

Nonlinear progressive damage model for composite laminates used for low-velocity impact*

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Abstract In order to effectively describe the progressively intralaminar and interlaminar damage for composite laminates, a three dimensional progressive damage model for composite laminates to be used for low-velocity impact is presented. Being applied to three-dimensional (3D) solid elements and cohesive elements, the nonlinear damage model can be used to analyze the dynamic performance of composite structure and its failure behavior. For the intralaminar damage, as a function of the energy release rate, the damage model in an exponential function can describe progressive development of the damage. For the interlaminar damage, the damage evolution is described by the framework of the continuum mechanics through cohesive elements. Coding the user subroutine VUMAT of the finite element software ABAQUS/Explicit, the model is applied to an example, i.e., carbon fiber reinforced epoxy composite laminates under low-velocity impact. It is shown that the prediction of damage and deformation agrees well with the experimental results.

Key words composite laminate, progressive damage, delamination, energy release rate, low-velocity impact

Chinese Library Classification O346.5
2010 Mathematics Subject Classification 74A45

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3D Hashin Failure Criteria

The Hashin failure criteria includes fiber tensile, fiber compression, matrix tensile failure, and matrix compression failure. Each failure can be described by a corresponding equivalent stress e_i, where i may be ft, fc, mt, and mc, named failure mode index. When the value of the failure mode index achieve to 1, the material at this point is regarded as failure.

Criteria	Condition	Failure
$e_{ft} = \left(\frac{\sigma_{11}}{X_t}\right)^2 \geq 1$	$\sigma_{11} \geq 0$	Fiber
$e_{fc} = \left(\frac{\sigma_{11}}{X_c}\right)^2 \geq 1$	$\sigma_{11} < 0$	
$e_{mt} = \frac{(\sigma_{22}+\sigma_{33})^2}{{Y_t}^2} + \frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S_{23}^2} + (\frac{\sigma_{12}}{S_{12}})^2 + (\frac{\sigma_{13}}{S_{13}})^2 \geq 1$	$\sigma_{22} + \sigma_{33} \geq 0$	Matrix
$e_{mc} = \frac{1}{Y_c}\left(\left(\frac{Y_c}{2S_{23}}\right)^2 - 1\right)(\sigma_{22}+\sigma_{33}) + \frac{(\sigma_{22}+\sigma_{33})^2}{4S_{23}^2} + \frac{\sigma_{23}^2 - \sigma_{22}\sigma_{33}}{S_{23}^2} + (\frac{\sigma_{12}}{S_{12}})^2 + (\frac{\sigma_{13}}{S_{13}})^2 \geq 1$	$\sigma_{22} + \sigma_{33} < 0$	
$e_{S12} = \left(\frac{\lvert\sigma_{12}\rvert}{S_{12}}\right)$, $e_{S13} = \left(\frac{\lvert\sigma_{13}\rvert}{S_{13}}\right)$, $e_{S23} = \left(\frac{\lvert\sigma_{23}\rvert}{\gamma S_{23}}\right)$		Shear

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Modified 3D Hashin Failure Criteria

- In order to effectively describe the progressively intralaminar and interlaminar damage for composite laminates, a three dimensional progressive damage model for composite laminates to be used for low-velocity impact is presented.
- Being applied to three-dimensional (3D) solid elements and cohesive elements, the nonlinear damage model can be used to analyze the dynamic performance of composite structure and its failure behavior.
- For the intralaminar damage, as a function of the energy release rate, the damage model in an exponential function can describe progressive development of the damage.
- The Modified 3D Hashin Failure Criteria model is based in continuum damage mechanics (CDM).

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Abstract

In order to effectively describe the progressively intralaminar and interlaminar damage for composite laminates, a three dimensional progressive damage model for composite laminates to be used for low-velocity impact is presented. Being applied to three-dimensional (3D) solid elements and cohesive elements, the nonlinear damage model can be used to analyze the dynamic performance of composite structure and its failure behavior. For the intralaminar damage, as a function of the energy release rate, the damage model in an exponential function can describe progressive development of the damage. For the interlaminar damage, the damage evolution is described by the framework of the continuum mechanics through cohesive elements. Coding the user subroutine VUMAT of the finite element software ABAQUS/Explicit, the model is applied to an example, i.e., carbon fiber reinforced epoxy composite laminates under low-velocity impact. It is shown that the prediction of damage and deformation agrees well with the experimental results.

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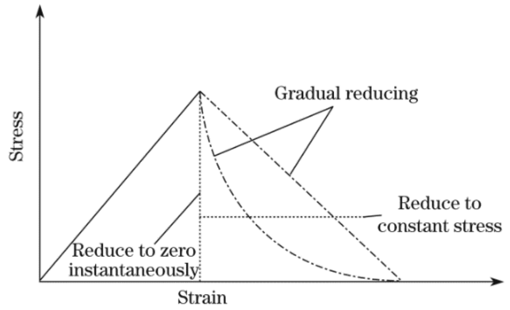
Degradation Behavior

If failure is detected in a material point of the composite laminates, its material properties have to be adjusted according to a material degradation model. The mode of the degradation can be one of the three modes:

1. Instantaneous reduce to zero,
2. Reduce to a constant stress, and
3. Gradually reduce in a given path.

In this study, an exponential function of energies dissipated by damage is established. It can not only describe progressive development of the damages, but also avoid the stiffness matrix singularity due to the material stiffness abrupt variation.

When implementation for a stress softening constitutive model, the results are mesh-dependent, e.g., the solution is non-objective with respect to the mesh refinement, and the computed energy dissipated decreases with the reduction of the element dimension. Thus, the energy dissipation and characteristic length are introduced into the damage evolution law to reduce the mesh sensitivity.



Damage Variables

The exponential functions for the damage variables are shown in the table.

$d_{ft} = 1 - \left(\frac{1}{e_{ft}}\right) e^{\left(-\frac{C_{11}\varepsilon_{11}^{ft}\varepsilon_{11}^{ft}(e_{ft}-1)L_c}{G_{ft}}\right)}$	Fiber tensile
$d_{fc} = 1 - \left(\frac{1}{e_{fc}}\right) e^{\left(-\frac{C_{11}\varepsilon_{11}^{fc}\varepsilon_{11}^{fc}(e_{fc}-1)L_c}{G_{fc}}\right)}$	Fiber Compression
$d_{mt} = 1 - \left(\frac{1}{e_{mt}}\right) e^{\left(-\frac{C_{22}\varepsilon_{22}^{mt}\varepsilon_{22}^{mt}(e_{mt}-1)L_c}{G_{mt}}\right)}$	Matrix Tensile
$d_{mc} = 1 - \left(\frac{1}{e_{mc}}\right) e^{\left(-\frac{C_{22}\varepsilon_{22}^{mc}\varepsilon_{22}^{mc}(e_{mc}-1)L_c}{G_{mc}}\right)}$	Matrix Compression
$d_{S12} = 1 - \left(\frac{1}{e_{S12}}\right) e^{\left(-\frac{C_{44}\varepsilon_{12}^{m}\varepsilon_{12}^{m}(e_{S12}-1)L_c}{G_{mt}}\right)}$	
$d_{S32} = 1 - \left(\frac{1}{e_{S32}}\right) e^{\left(-\frac{C_{55}\varepsilon_{32}^{m}\varepsilon_{32}^{mc}(e_{S32}-1)L_c}{G_{mt}}\right)}$	Shear Mode
$d_{S13} = 1 - \left(\frac{1}{e_{S13}}\right) e^{\left(-\frac{C_{66}\varepsilon_{13}^{m}\varepsilon_{13}^{m}(e_{S13}-1)L_c}{G_{mt}}\right)}$	

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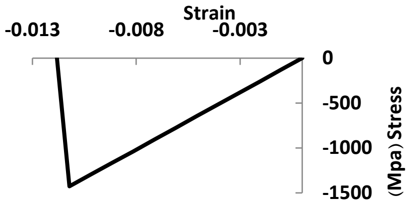
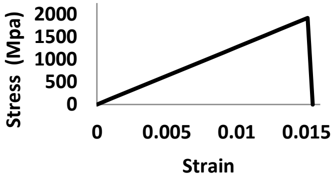
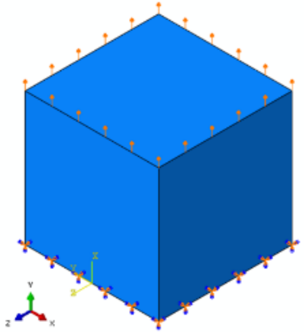
Verification & Validation (V&V)

1. Single Elements
   I. Tensile
   II. Compressive
   III. Simple Shear





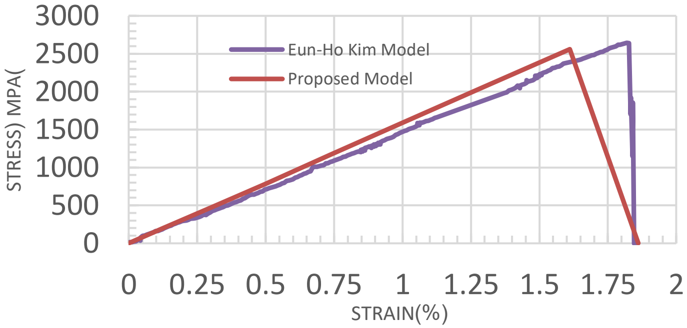
Test	Error (%) Compare to Experiment
Tensile	1.55 - 11.95
Compressive	3.63
Simple Shear	3.5 – 14.28

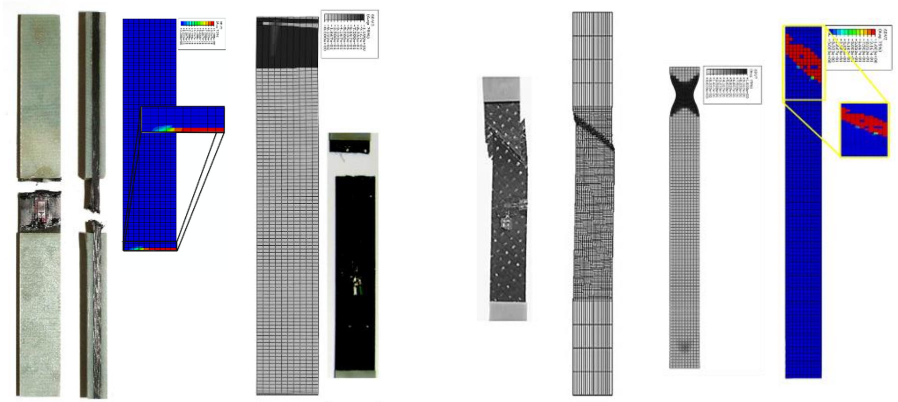


Verification & Validation (V&V)

1. Single Elements
   - I. Tensile
   - II. Compressive
   - III. Simple Shear

2. ASTM Sample
   - I. Tensile
   - II. Transverse Tensile (ASTM D3039/D3039M-08)
   - III. Compressive
   - IV. Simple Shear (ASTM D3518/3518M-94)



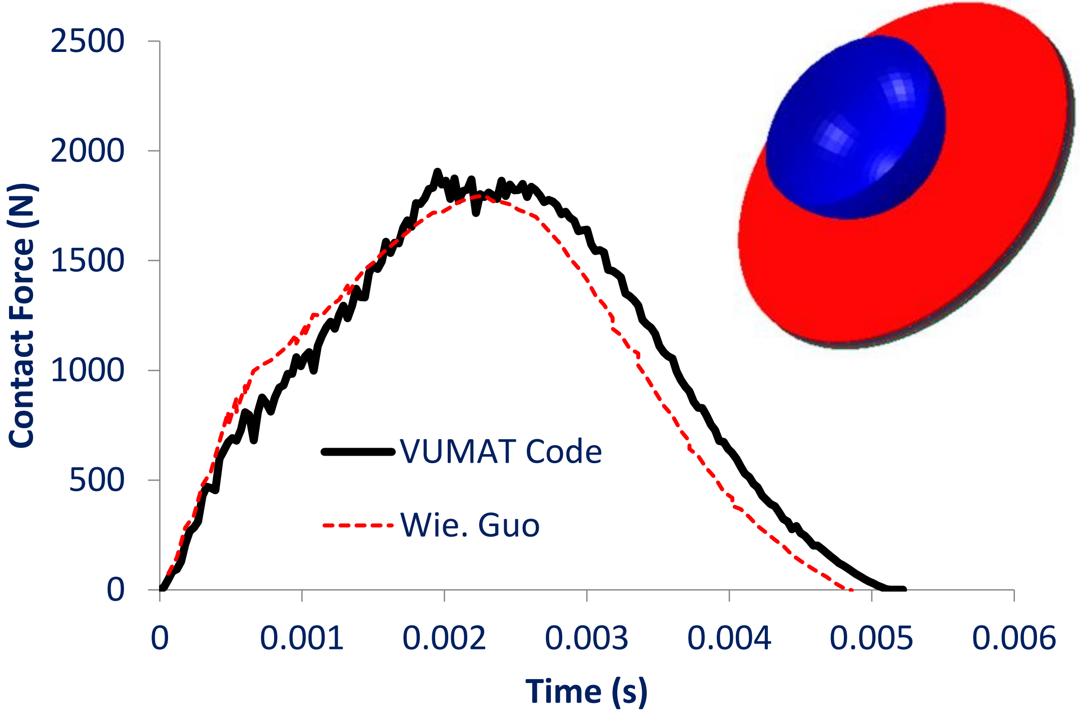


Compression Tensile Simple Shear

Test	Error (%) Compare to Experiment
Tensile	1.5 - 11.66
Compressive	-
Simple Shear	-

Verification & Validation (V&V)

1. Single Elements
   - I. Tensile
   - II. Compressive
   - III. Simple Shear
2. ASTM Sample
   1. Tensile
   2. Transverse Tensile (ASTM D3039/D3039M-08)
   3. Compressive
   4. Simple Shear (ASTM D3518/3518M-94)
3. Low Velocity Impact
   - I. Contact Force

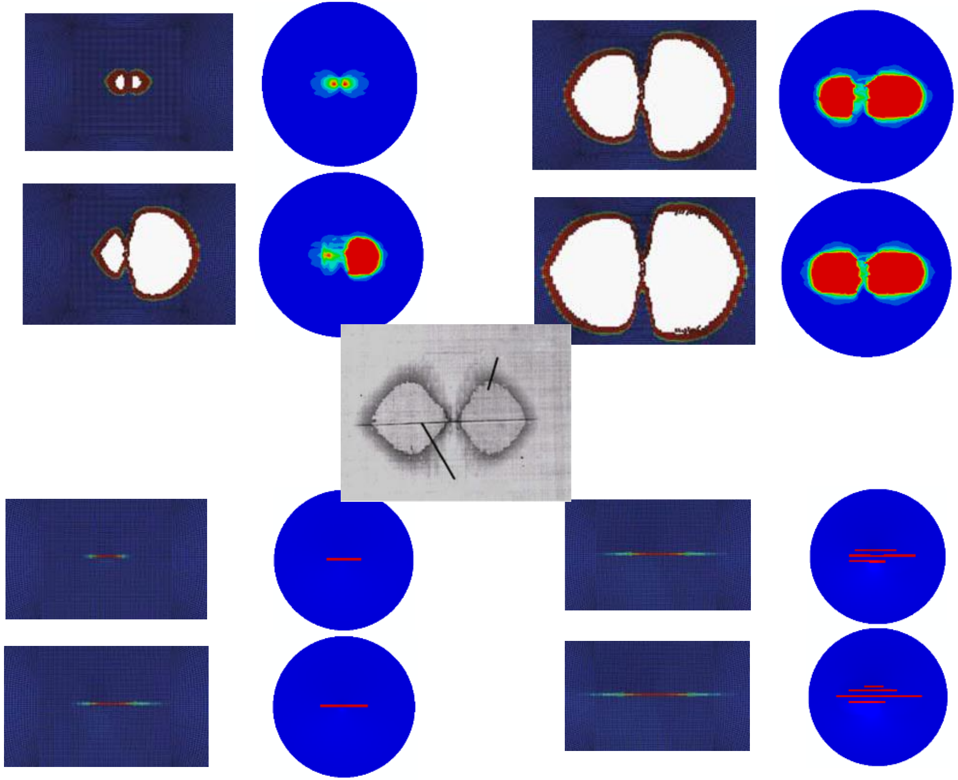


Verification & Validation (V&V)

1. Single Elements
   - I. Tensile
   - II. Compressive
   - III. Simple Shear

2. ASTM Sample
   1. Tensile
   2. Transverse Tensile (ASTM D3039/D3039M-08)
   3. Compressive
   4. Simple Shear (ASTM D3518/3518M-94)

3. Low Velocity Impact
   - I. Contact Force
   - II. Damages
     - i. Interlaminar (Delamination)
     - ii. Intralaminar



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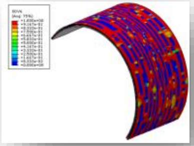
Verification & Validation (V&V)

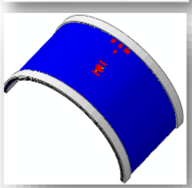
1. Single Elements
   - I. Tensile
   - II. Compressive
   - III. Simple Shear

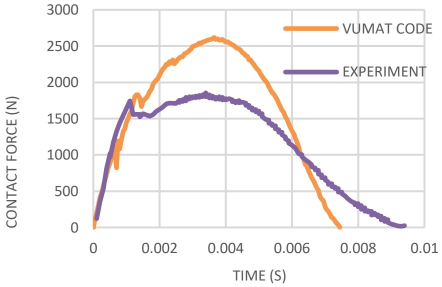
2. ASTM Sample
   1. Tensile
   2. Transverse Tensile (ASTM D3039/D3039M-08)
   3. Compressive
   4. Simple Shear (ASTM D3518/3518M-94)

3. Low Velocity Impact
   - I. Contact Force
   - II. Damages
     - i. Interlaminar (Delamination)
     - ii. Intralaminar

4. Composite Pressure Vessel (COPV)
   - I. Burst Pressure
   - II. Low Velocity Impact (ASME Sec. X)







Test	Error (%) BanuMusa Code Compare to Experiment	Error (%) Abaqus Built-in Model Compare to Experiment
Burst Pressure	2 - 13	5
Low Velocity Impact	5-20	300

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BanuMusa 3D Hashin Model

The code developed by BanuMusa R&D is based on the model provided by Guo et al. , 2013 and then the Shear effect was added. Some important specifications are shown in the table.

Specifications	BanuMusa 3D Hashin	Abaqus Built-in 2D Hashin
Solver	Abaqus/Explicit	Implicit & Explicit
Subroutine	VUMAT	-
Number of Properties (nprops)	28	21
Number of State Variables (statev)	29	19
Number of Subroutines & Functions	2	Unknown
Initiation damage	Hashin 1980 & Max. Stress	Hashin 1980
Elements	3D Solid	Plane stress
V&V	Guo et al., 2013 Eun-Ho Kim 2012 Donadon et. Al., 2008	Unknown
Shear	Max. Stress	No
Evolution Law	Energy-based	Energy-based
Softening	Exponential	Linear
Element Removal	Yes	Yes

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Database

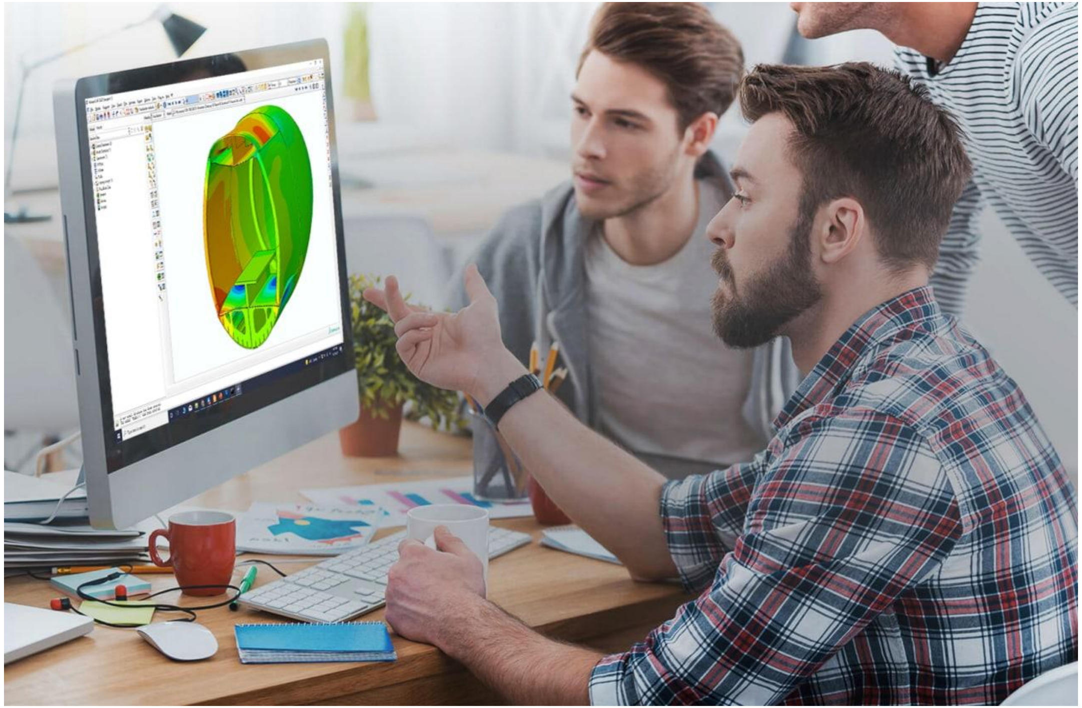
This package contains all data you want to do damage analysis of UD composite materials.

	Details	Files
Abaqus Files	1. Tensile Test Validation 2. Compression Test Validation 3. Shear Test Validation 4. Low Velocity Impact Validation	*.cae, *.inp, *.jnl, *.odb
VUMAT Subroutine		*.for
User Manual		*.PDF

Users

This code is useful for all those working on material damage models and they care about more accuracy of FEA simulation.

- Developers
- Abaqus Application Engineers
- Graduate Students
- FEA Analysts
- CAE Engineers



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