PHYSICALLY BASED FAILURE CRITERIA FOR PREDICTION OF DAMAGE EVOLUTION IN COMPOSITE MATERIALS SUBJECTED TO IMPACT LOADING

Jens Wiegand, Nik Petrinic, Ben Elliott
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• INTRODUCTION
• CONSTITUTIVE MODEL
• INVERSE MODELLING
• MODEL APPLICATION
• CONCLUSIONS
The work presented here is carried out within the frame of the EU project VITAL (enVIronmenTALy friendly aero engine)

Aim of the project is the application of lightweight materials such as carbon reinforced polymers in highly dynamically loaded engine components like fan blades

The model development is carried out in DYNA3D and DEST (in-house code), whereby the already existing material model MAT22 has been extended

The model presented here shows the initial stage of the model development, which incorporates failure and subsequent damage propagation due to tensile loading only
Continuum Damage Mechanics approach adopted

Major assumptions:

Material is represented in a ‘smeared’ manner
properties of fibre and matrix are smeared within a
Representative Volume Element (RVE)

RVE can represent various material configurations
Now: laminates (UD, fabrics, single ply, multiple plies)
Future: 3D reinforced structures

Material remains orthotropic
HOW IS DAMAGE REPRESENTED

When the material is loaded above load carrying capability cracks will be initiated: fibre rupture, matrix cracking, delamination.
In CDM this local phenomena can be represented in a smeared manner only.
As the 'virtual' crack propagates the mechanical properties of the respective RVE diminish … damage accumulates.
Instead of growing a crack, the entire volume of the element is damaged.
The constitutive model relies upon the continuum representation of material behaviour within a representative volume element (RVE)

The size of the RVE is given by a characteristic element length which is calculated by projecting the finite element space diagonals on the material directions.

The RVE is aligned with the material directions.

x, y, z: global coordinate system
1, 2, 3: material coordinate system

$l^c$: characteristic element length
The characteristic element length takes into account the size of the element and reduces mesh dependency of damage. The characteristic element length is given by the largest projection of the element space diagonals in material coordinates.

\[ A \approx \frac{V}{l} \]

- \(A\): area of an expected crack
- \(V\): volume of element
- \(l\): characteristic element length
The element’s load carrying capacity is assessed by means of the stress based failure criteria which address all experimentally observable failure modes.

The failure criteria are therefore assessed on the respective faces of the RVE.

Failure is caused by the normal stress and the two shear stresses acting on the fracture plane.
FAILURE CRITERIA (example: UD)

Failure is caused by the normal stress and the two shear stresses acting on the fracture plane.

\[

e_1 = \left(\frac{\sigma_{11}}{F_{11}}\right)^2 + \left(\frac{\sigma_{12}}{F_{12}}\right)^2 + \left(\frac{\sigma_{31}}{F_{13}}\right)^2
\]

\[

e_2 = \left(\frac{\sigma_{22}}{F_{22}}\right)^2 + \left(\frac{\sigma_{12}}{F_{21}}\right)^2 + \left(\frac{\sigma_{23}}{F_{23}}\right)^2
\]

\[

e_3 = \left(\frac{\sigma_{33}}{F_{33}}\right)^2 + \left(\frac{\sigma_{23}}{F_{32}}\right)^2 + \left(\frac{\sigma_{31}}{F_{31}}\right)^2
\]
Damage grows incrementally
The damage increment is given by how much the current state of stress exceeds the respective failure surface

\[ e_1 = \left( \frac{\sigma_{11}}{F_{11}} \right)^2 + \left( \frac{\sigma_{12}}{F_{12}} \right)^2 + \left( \frac{\sigma_{31}}{F_{13}} \right)^2 \]

\[ \Delta d = e_1 - 1 \]
Incremental damage evolution is controlled by the damage evolution function $r$:

$$r_t = r_{t-1} + \Delta d \cdot l^c$$

The damage coefficient is given as a function of $r$ and two material dependent parameters $(f_1, f_2)$:

$$d_t = f(r_t, f_1, f_2)$$
Failure surface shrinks due to damage

\[ e_f = \left( \frac{\sigma_{11}}{F_{11} \cdot (1 - d_{11})} \right)^2 + \left( \frac{\sigma_{12}}{F_{12} \cdot (1 - d_{12})} \right)^2 + \left( \frac{\sigma_{13}}{F_{13} \cdot (1 - d_{13})} \right)^2 \]

3D dimensional stress return algorithm returns the state of stress on the now damaged failure surface

original failure surface

stress return vector

stress increment

predicted stress increment

loading path

updated failure surface
VISUALISATION OF THE ALGORITHM

Single element pulled in 1-direction
VISUALISATION OF THE ALGORITHM

Single element pulled in 1-direction

CONSTITUTIVE MODEL
VISUALISATION OF THE ALGORITHM

INTRODUCTION

CONSTITUTIVE MODEL

INVERSE MODELLING

MODEL APPLICATION

CONCLUSIONS

Single element pulled in 1-direction

time 3

failure surface
VISUALISATION OF THE ALGORITHM

Single element pulled in 1-direction

time 4

failure surface

time 1

time 2

time 3
STIFFNESS CORRECTION

- The model does not consider inelastic deformation
- The stiffness has to be reduced so that there is no residual deformation in case of unloading
- Stiffness is reduced by additional damage coefficients which are driven by the strength damage coefficients
Calculate mass and internal forces
Get external forces
Set prescribed motion
Solve for unknown motion
Calculate reactions
Update energy
Update nodal coordinates
Update time

Rotate stress and strain increment in material coordinates
Update stiffness and strength with accumulated damage
Predict stress

Check for failure
no
yes
Find increment of damage
Shrink failure surface
Return stress to failure surface
Adapt stiffness
Update elastic energy
Update nodal coordinates

INTRODUCTION
CONSTITUTIVE MODEL
INVERSE MODELLING
MODEL APPLICATION
CONCLUSIONS
The parameter identification inverse problem is
Given that we can do FE simulations of calibration experiments, what should the material parameters be to get the most accurate simulations?

Major assumption:
the constitutive model is capable of representing the observed behaviour
OPTIMISATION FRAMEWORK

INTRODUCTION

CONSTITUTIVE MODEL

INVERSE MODELLING

MODEL APPLICATION

CONCLUSIONS
Objective function to minimise (e.g. least squared differences between experimental and numerical results)
WHY INVERSE MODELLING?

Better parameter identification
- Many parameters cannot be identified simply from experiments
- Some ‘idealised’ experiments are impossible in practice
- Identification by hand is very time-consuming with large models
- Repeatable, objective results with measurable accuracy and sensitivity
- Can use multiple measurements and multiple experiments simultaneously

Feedback to other areas
- Characterisation experiments
  - Identify loading conditions not exercised by experiments
  - Identify experiments poorly conditioned for parameter identification
- Constitutive modelling
  - Fast profiling of model performance on several complex experiments
  - Identify areas of poor performance by models and the parameters associated with these (model validation)
The model has been implemented into the DYNA3D
The model has been applied to a 3 point impact bending simulation
Model parameters:
  • the specimen has been discretised by 8543 elements
  • a velocity time profile from a conducted test is given to the impactor, impact with 4.6 m/s
  • the support is rigid
The model does not represent an actual test because of missing material parameters but shows the improvements of the model capabilities.

Example what a test might look like.
The model improved modelling capabilities and numerical stability has been improved

Future work:
Implementation of rate dependency

Model for compression
Implementation of numerical stable model which addresses all observable composite failure modes in compression
Coupling of compressive damage and tensile damage

Continuous – discontinuous
How can damage be represented in a discontinuous manner

Inverse modelling
Deriving/optimising damage parameters numerically by inverse modelling