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4th International Conference on
Composites Testing and Model Identification

Progressive Failure Modelling of Composite Laminates Containing Tapered Holes

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OUTLINE

Objective
Recent developments
Experiments
Predictive Models
Results and Discussion
Summary

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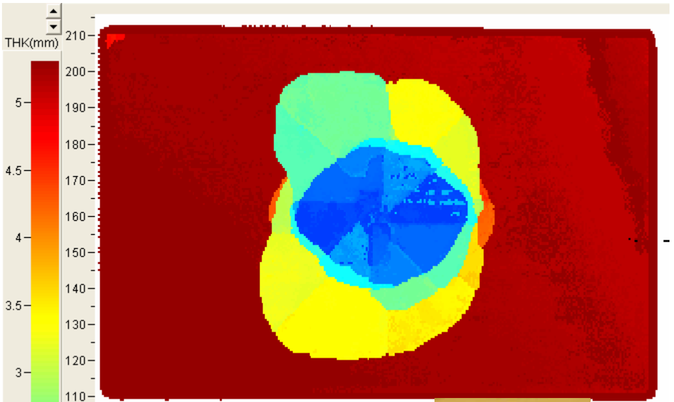
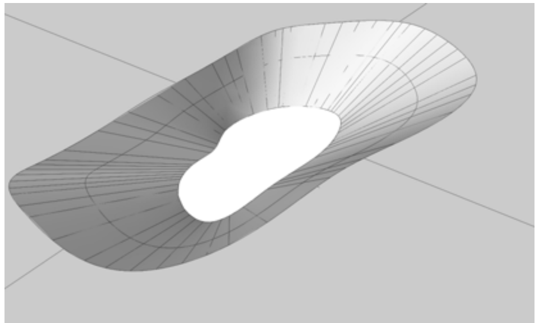
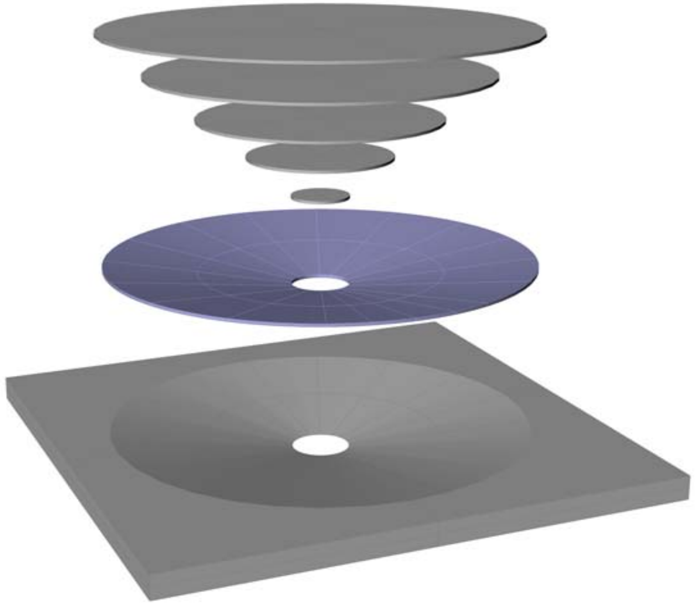
Objective

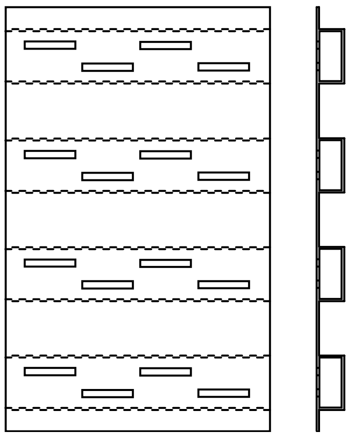
Strength Prediction capability for composites

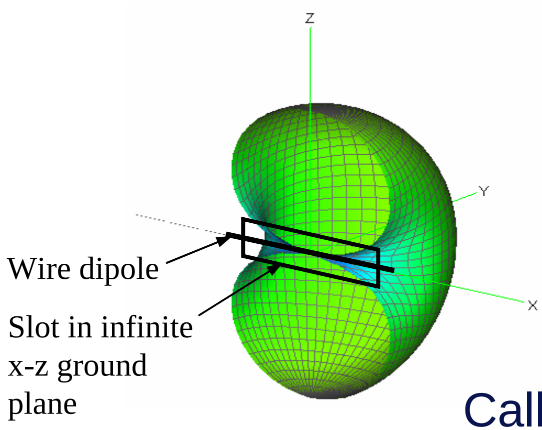
- Prediction of residual strength after damage
- Optimise damage cutout
- Design of conformal antenna slots
- Design and certification of repairs











Callus (DSTO)

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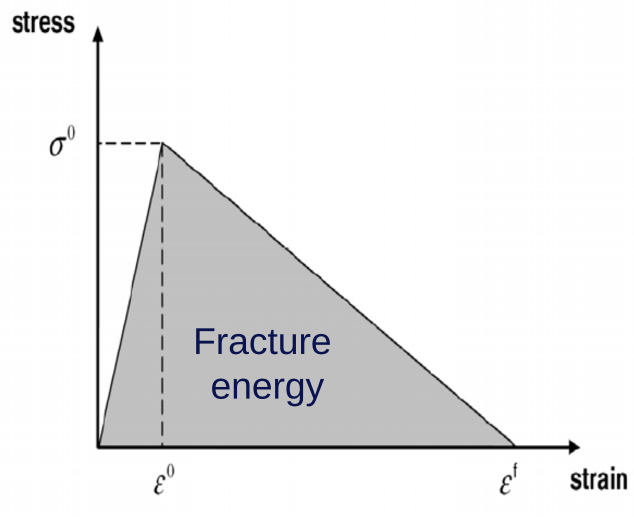
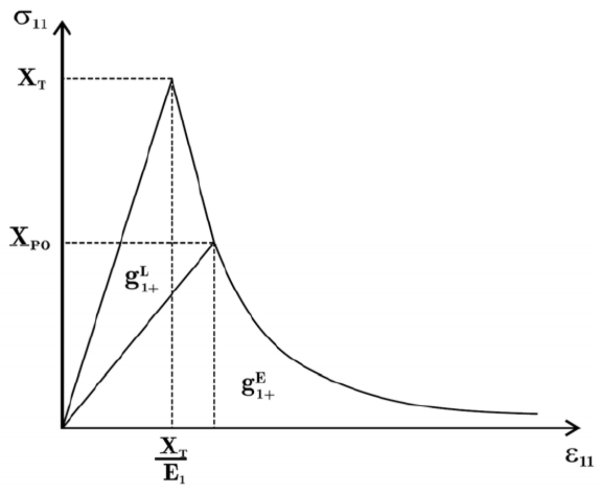
Some Examples of Recent Developments

- Abaqus damage model (2006)
  - Milestone: research→engineering
    - Lapczyk and Hurtado (2007):
    - Camanho *et al* (2007): 38.5% accuracy for tension of bolted joint
- Inherent-flaw fracture mechanics
  - IBOLT: method of choice at LM Aero (Eisenmann and Rousseau 2004)
  - Empirical correction for countersunk holes
- Continuum damage mechanics
  - Camanho *et al* (2007): 10.5% accuracy for OHT
  - Bogert *et al* (2006): 21.4% accuracy for slits



(a) Abaqus-model [8]



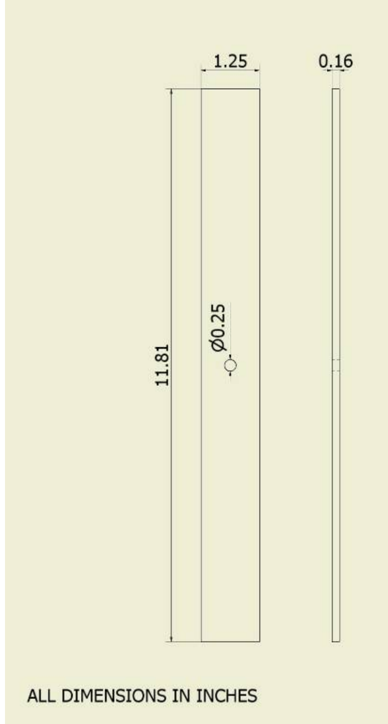
(b) VUMAT-model [9]

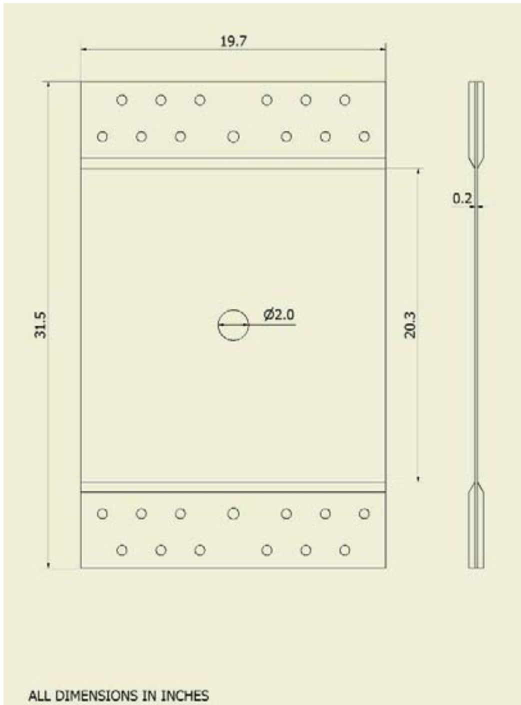
Camanho *et al* (2007)

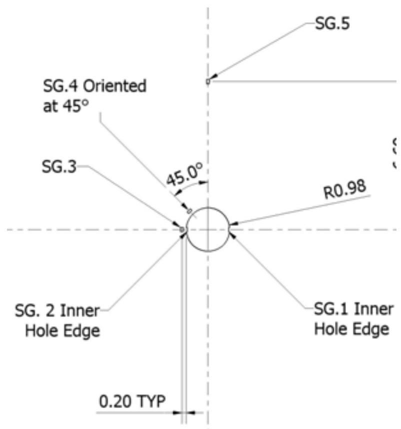
Experiments

Three types of specimens subjected to tension

- Straight through-hole (diameter=6.35mm)
- Straight through-hole (diameter=50mm)
- Scarfed hole (diameter=50→200mm)
- Stiff and soft laminates:
    - [40/40/20]%
    - [20/40/40]%
- Stacking sequences
    - Panel: $[45/90/-45/0_2]_{3S}$
    - OHT coupons:
        - $[45/0_2/-45/90]_{3S}$
        - $[-45/90_2/45/0]_{3S}$







Experiments

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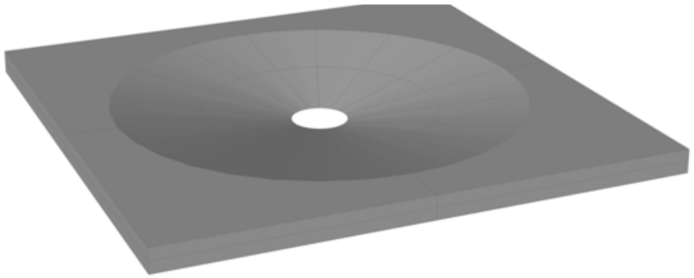
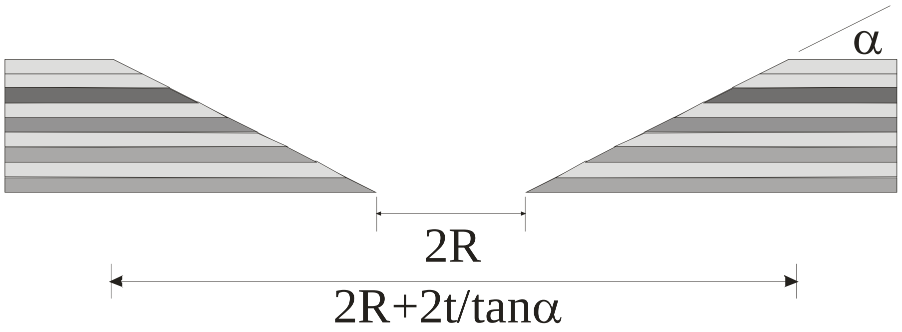
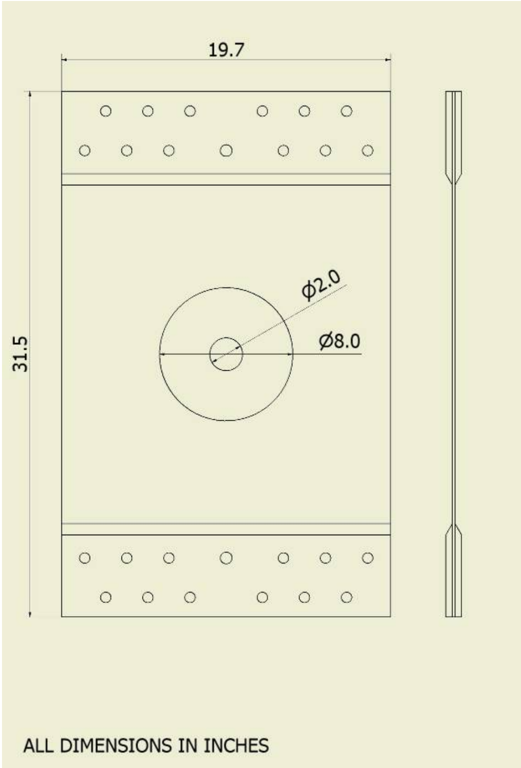
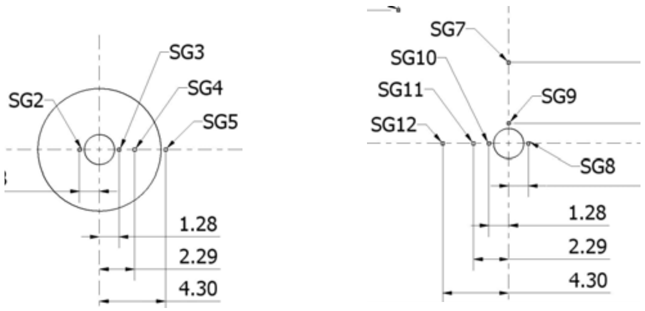
Scarfed hole









Tensile strength of stiff laminates

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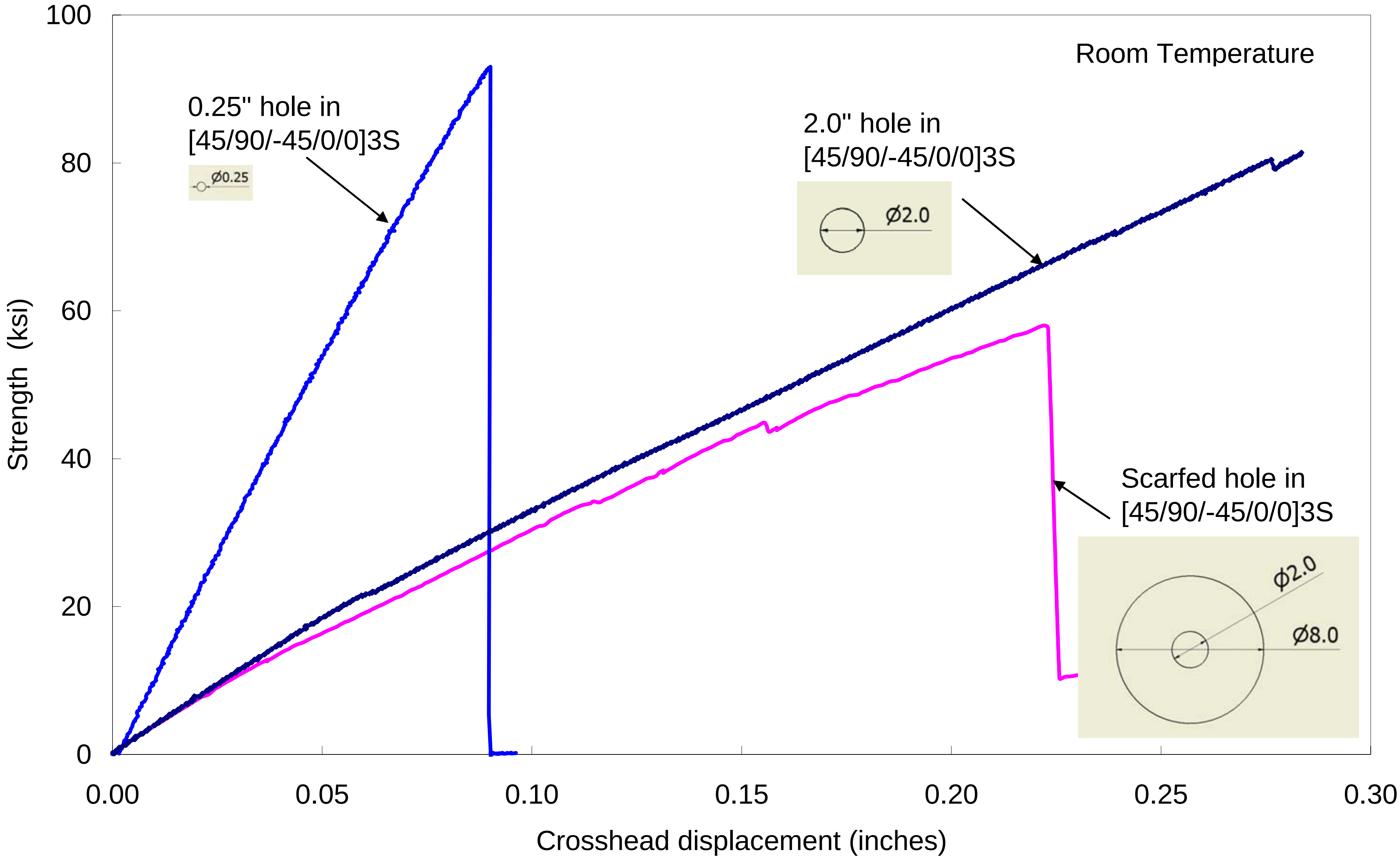

Failure modes

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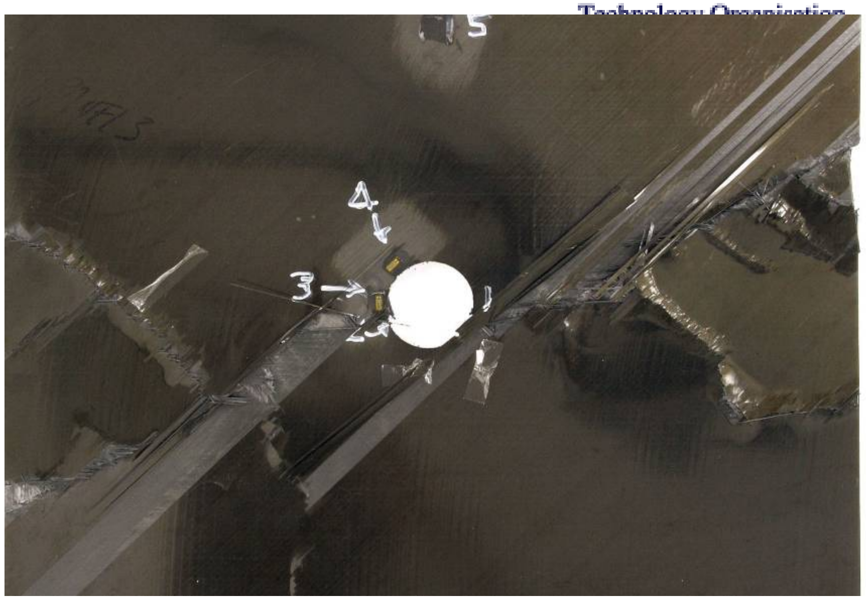

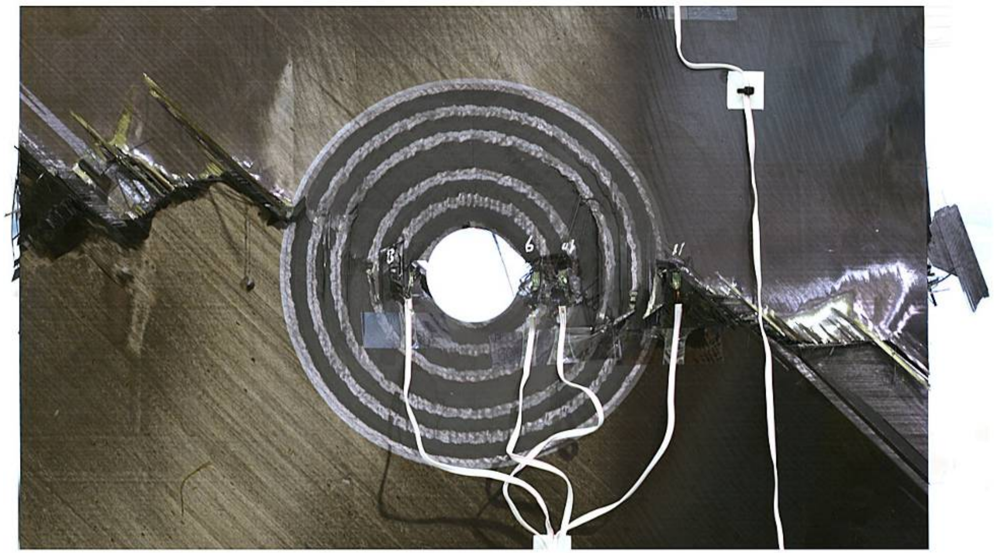

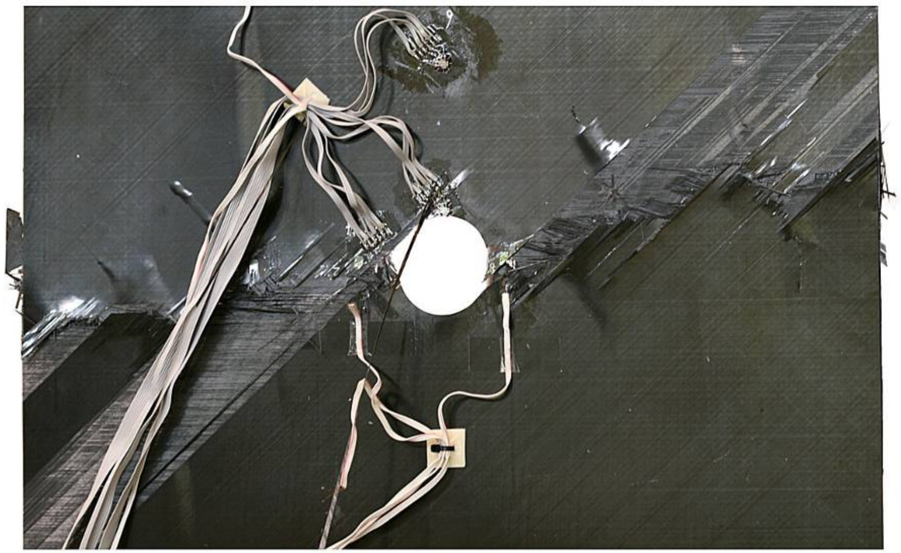

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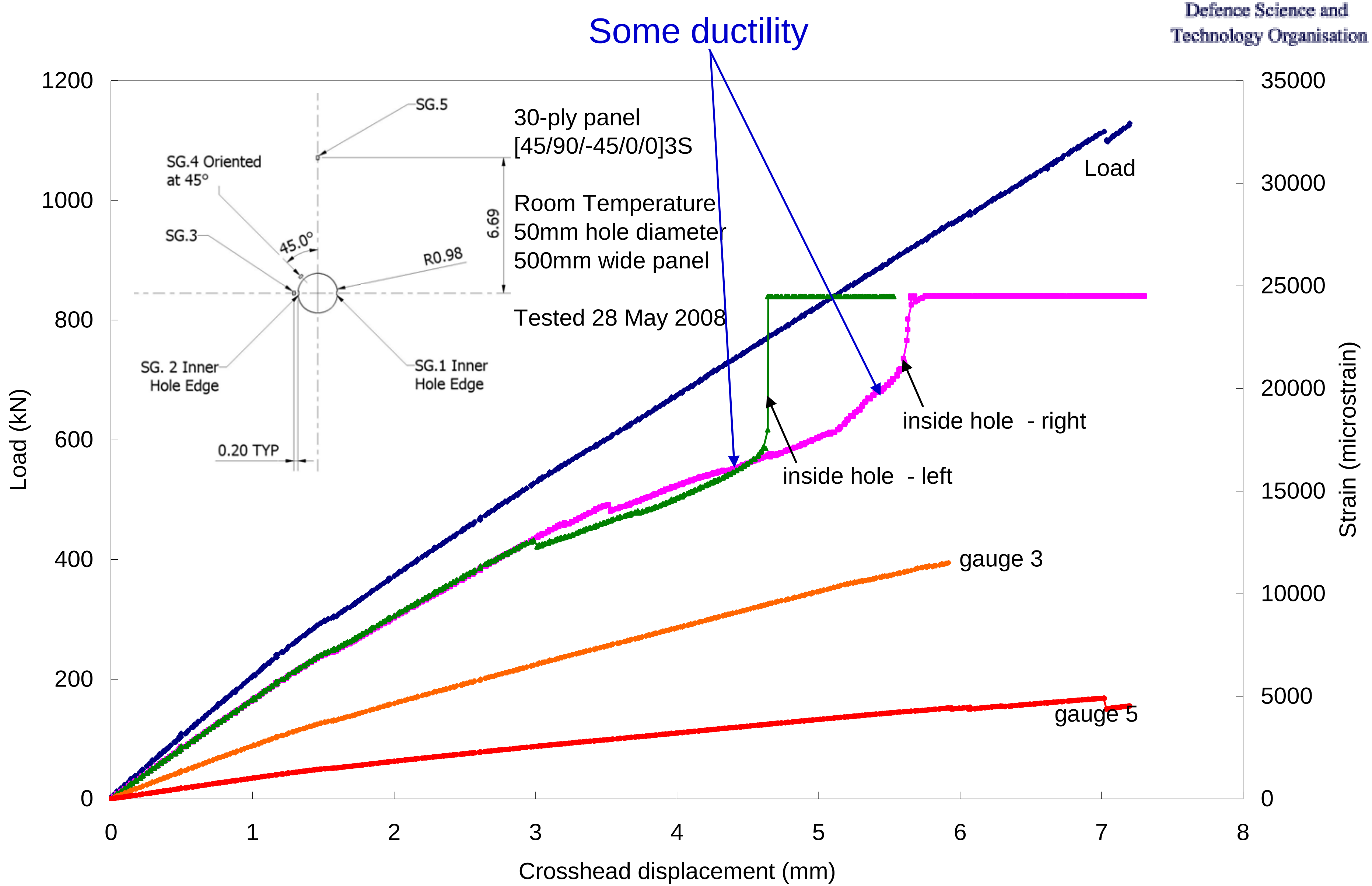
Strains in straight-hole panel



Strain in scarfed-hole panel

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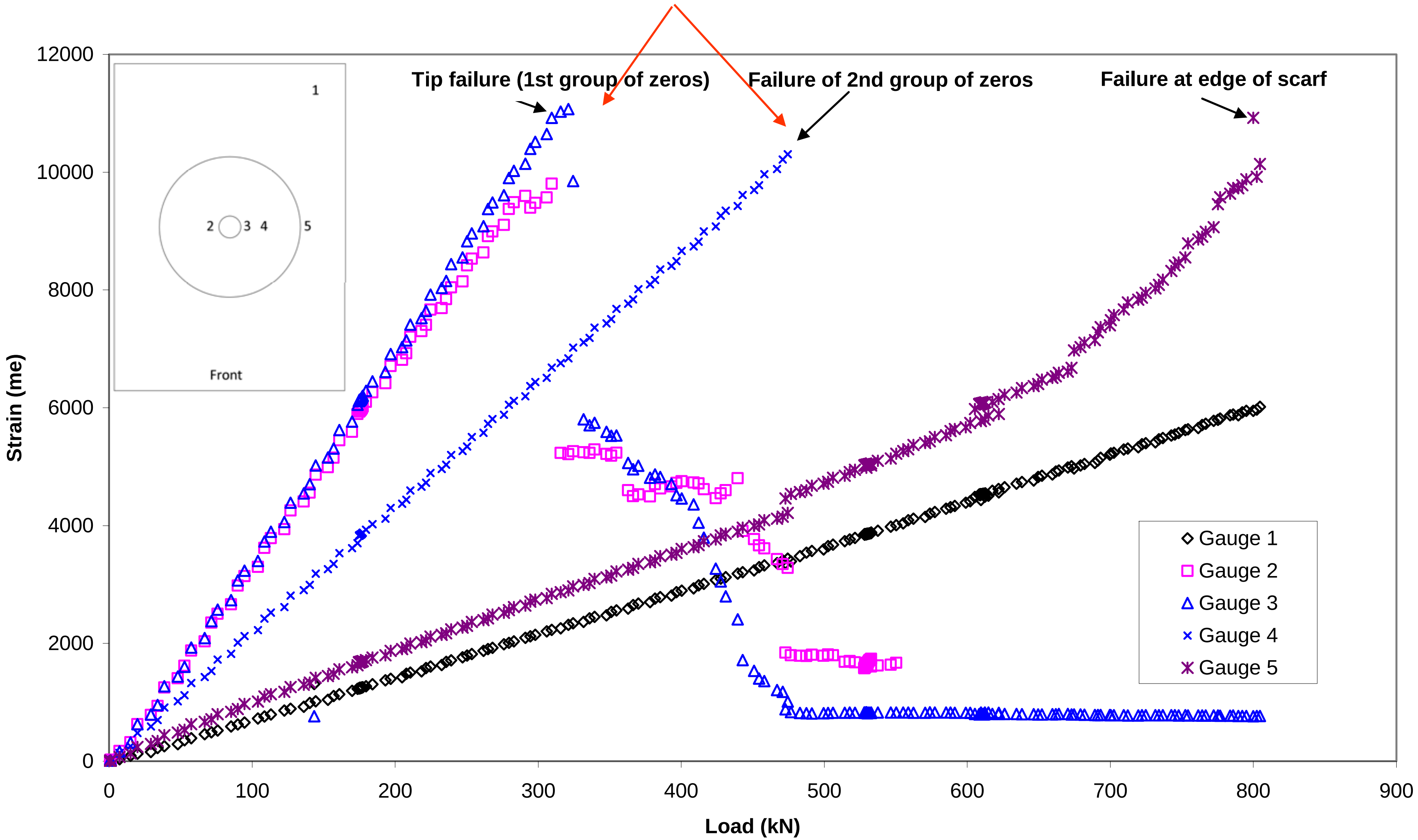
Suspected premature failure of strain gauges



Fracture Mechanics Model

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Critical flaw determined from fracture energy and ply percentage

$$a = \frac{n_0 G_0 + n_{45} G_{45} + n_{90} G_{90}}{C \pi \sigma^2_{un-notched}}$$

$$\sigma_{notched} = \frac{\sigma_{un-notched}}{f(a/R)}$$

- Predicted strength is identical to cohesive zone model prediction
  - Independent of actual bridging law or the softening behaviour
- Reported to be hole-size dependent

Identification of Fracture Parameters

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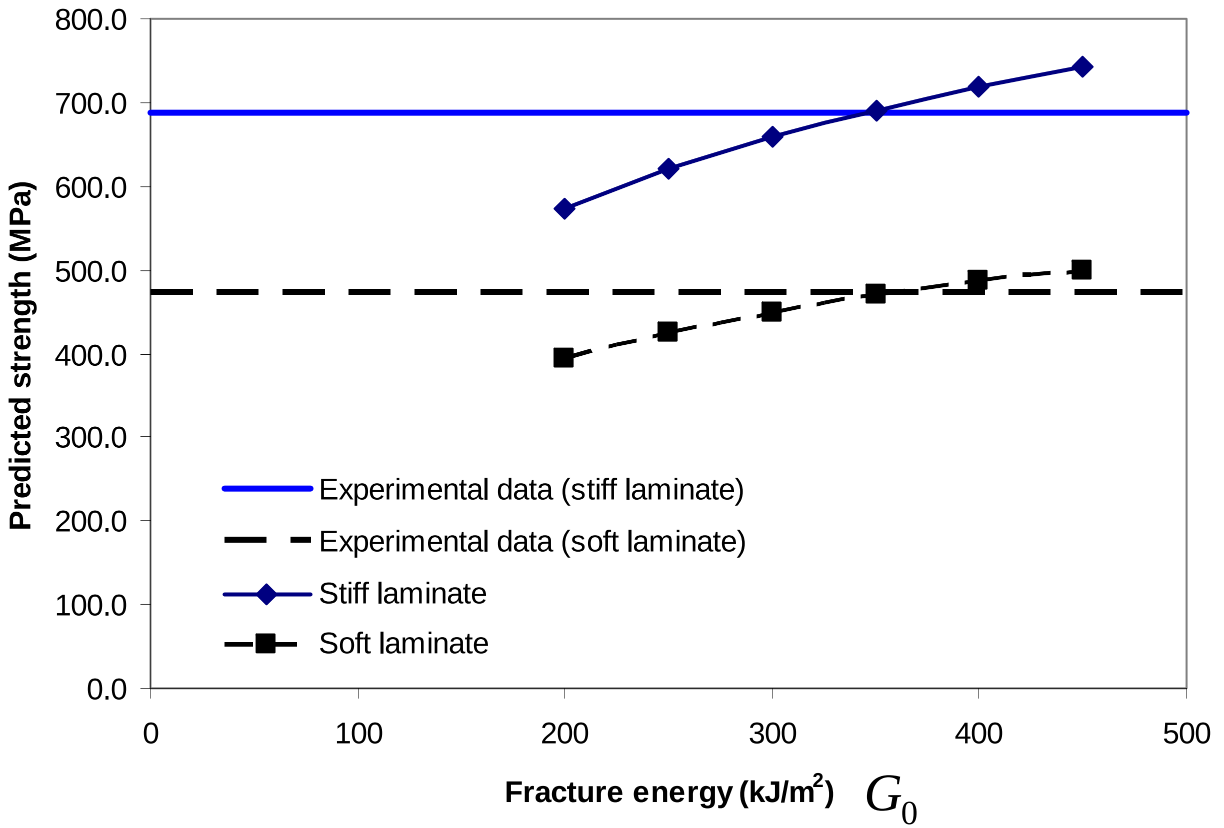
Assume: $G_{45} = \frac{1}{5} G_0 \quad G_{90} = \frac{1}{5} G_{45}$



Predictions

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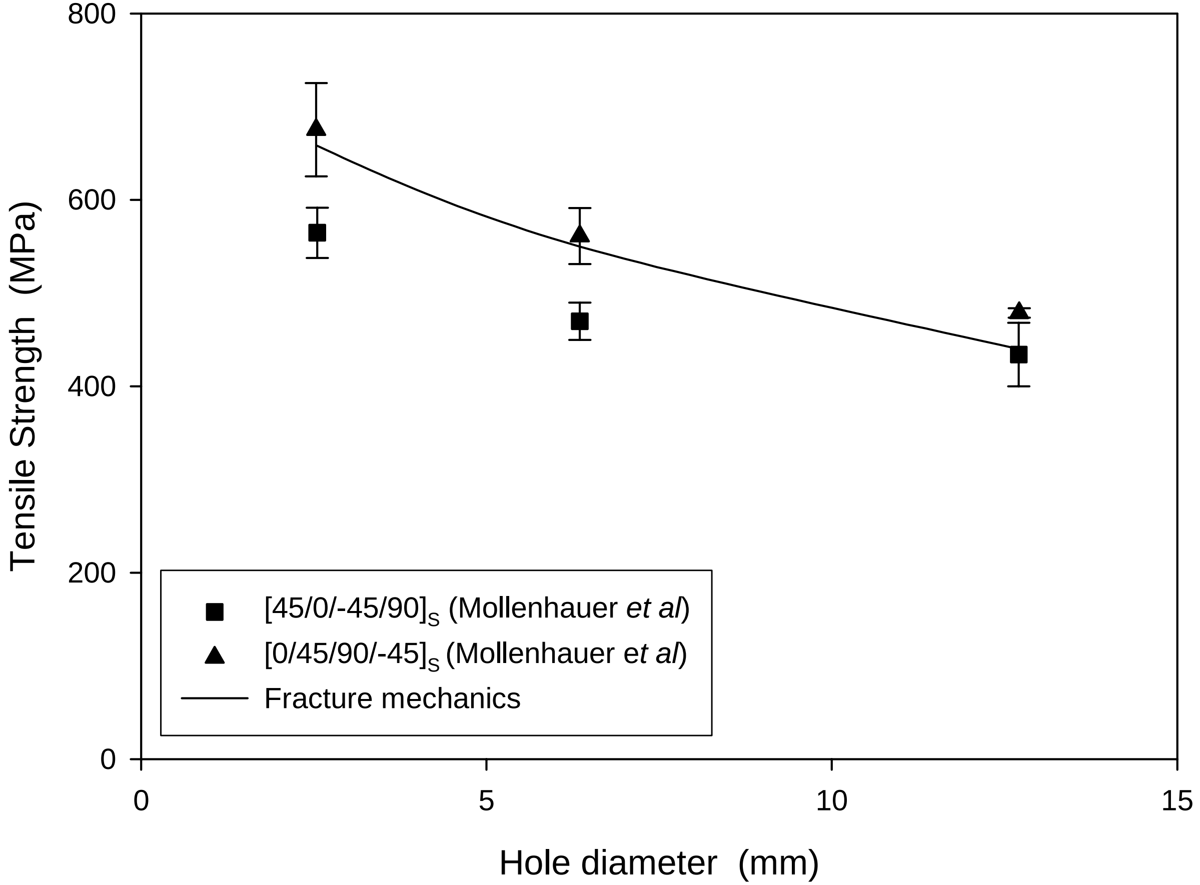
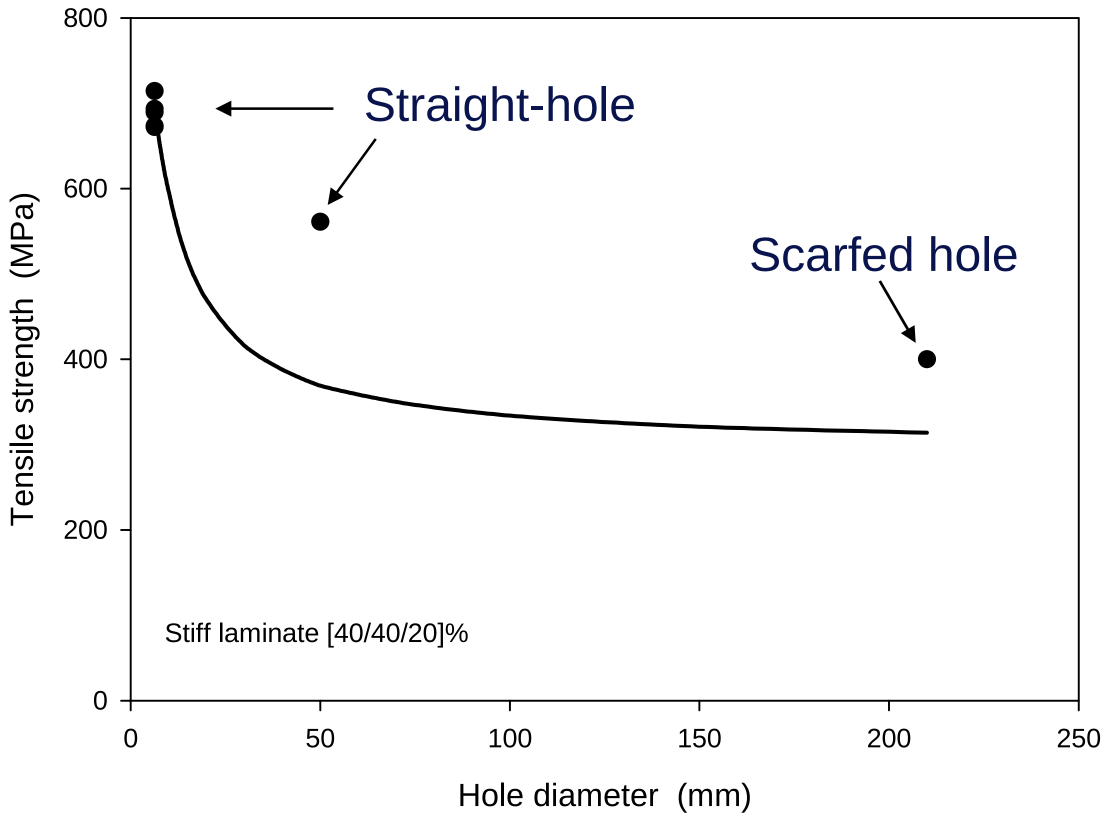
- Open hole tension strength of quasi-isotropic laminate
- Data by Mollenhauer *et al* (CompTest 2006)
- Model does not predict layup effects



Predictions

- Large straight-hole and tapered hole
  - Significant under-prediction of strength
  - Need greater critical flaw size



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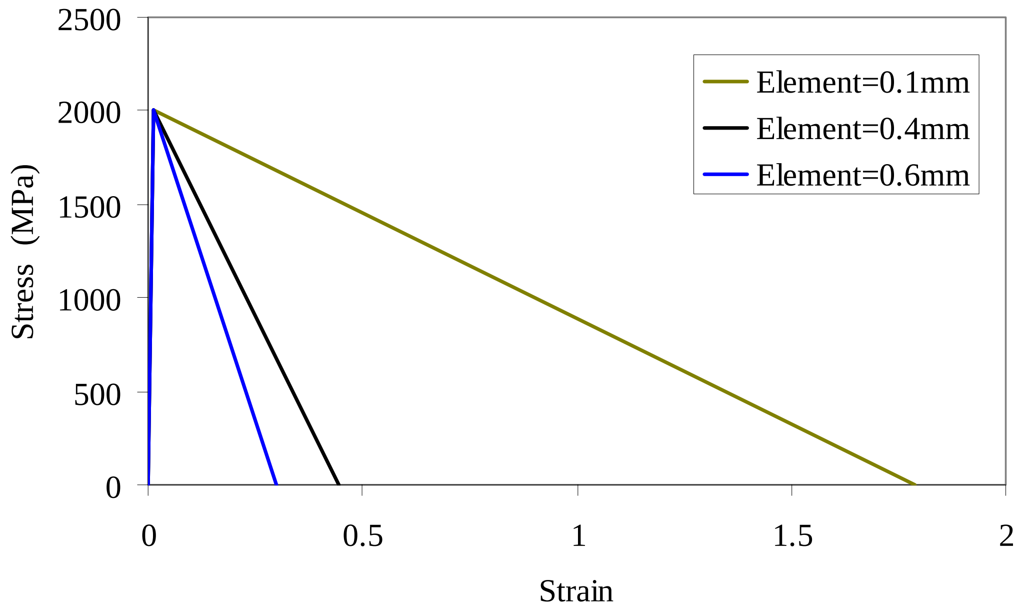
Abaqus Damage Model

Strain-softening model:

- Bazant's crack band model
- Best for square elements



- Shell elements: all plies have identical strains at any time.
- Scarfed region is modelled as multi-stepped (one step per ply). No bending.

Issues:

- Mesh refinement
- Identification of fracture energies
- Predictions of through-thickness geometry variation

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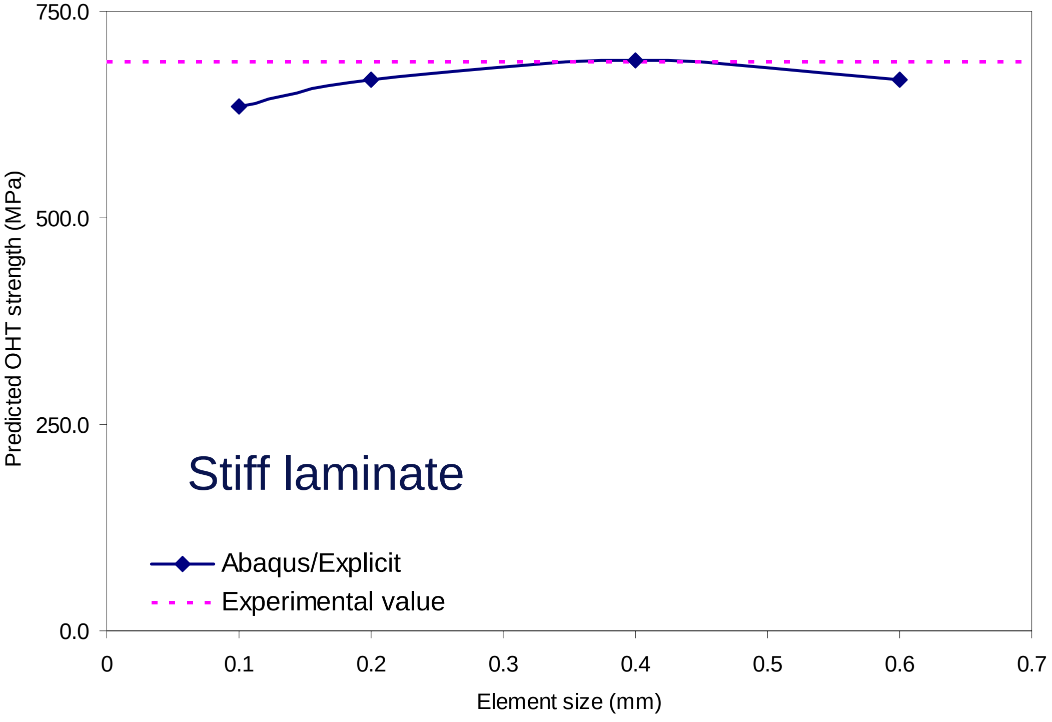
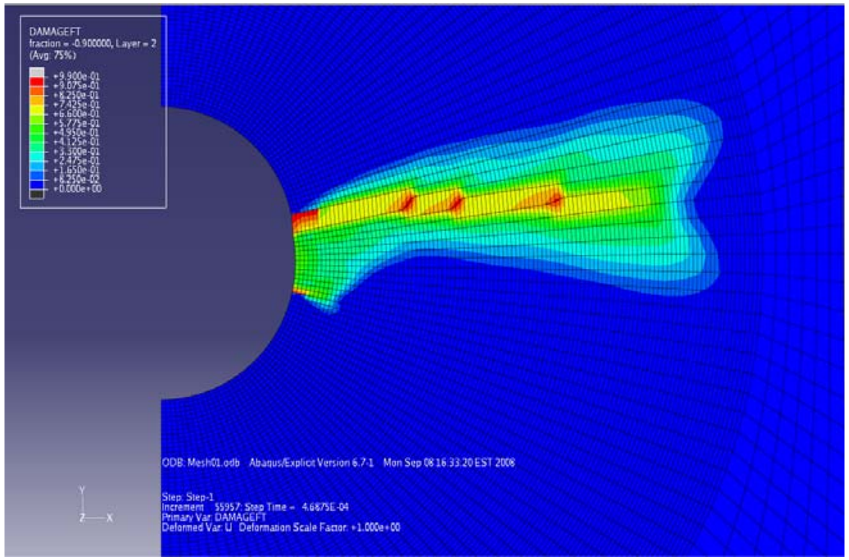
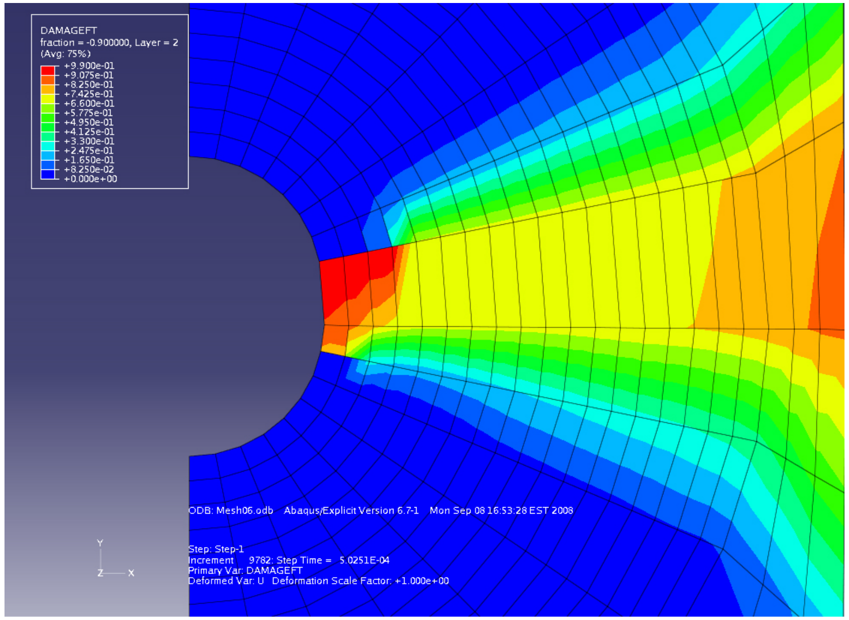
Mesh refinement

Straight-hole of 6.35mm diameter

Relative insensitivity to mesh refinement







Identification of Fracture Energies

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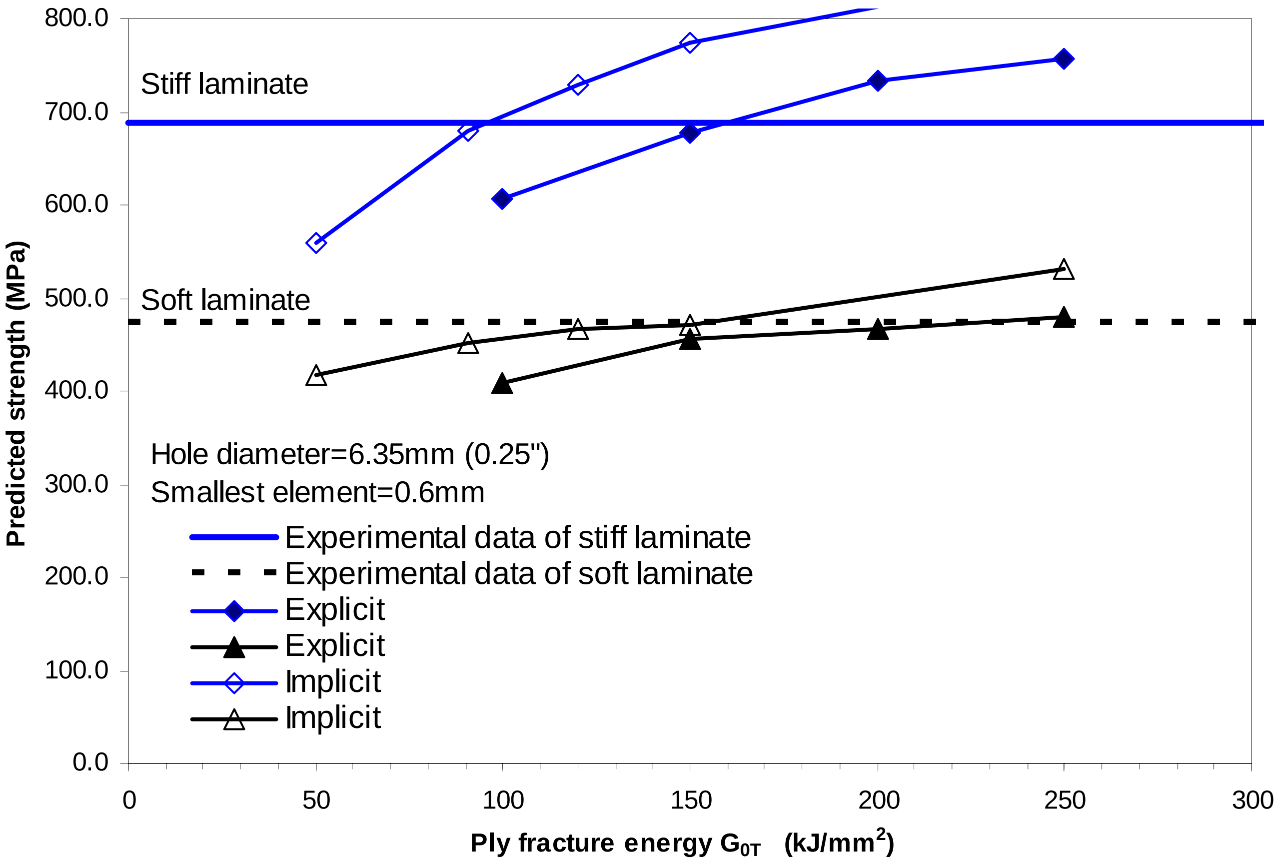
- Ply fracture energies depend on solver
- Consistency between two stacking sequences



$$G_{0C} = 0.8G_{0T} \qquad G_{90T} = G_{90C} = 0.003G_{0T}$$

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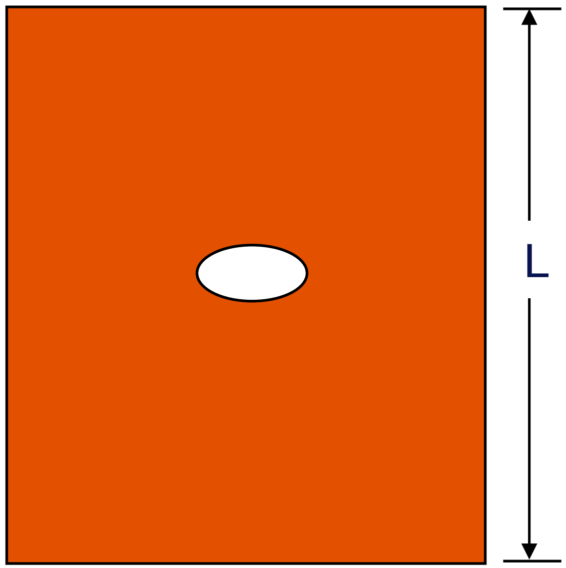
Explicit versus Implicit

- Implicit code suffered convergence problems and required damping
- Explicit code more robust, damping not required, but requires large time increments to avoid inertia effect

Fundamental resonant (in-plane) period $$T_0 = 2L\sqrt{\frac{\rho}{E}}$$

Time increment: $$\Delta T = h\sqrt{\frac{\rho}{E}}$$



Total time: many times of the fundamental period

Number of increments: $$N\frac{T_0}{\Delta T} \approx \frac{2L}{h}N$$

- Independent of density
- Element size h needs to be small fraction of critical flaw size (e.g., h = 0.1 a)
- N=?

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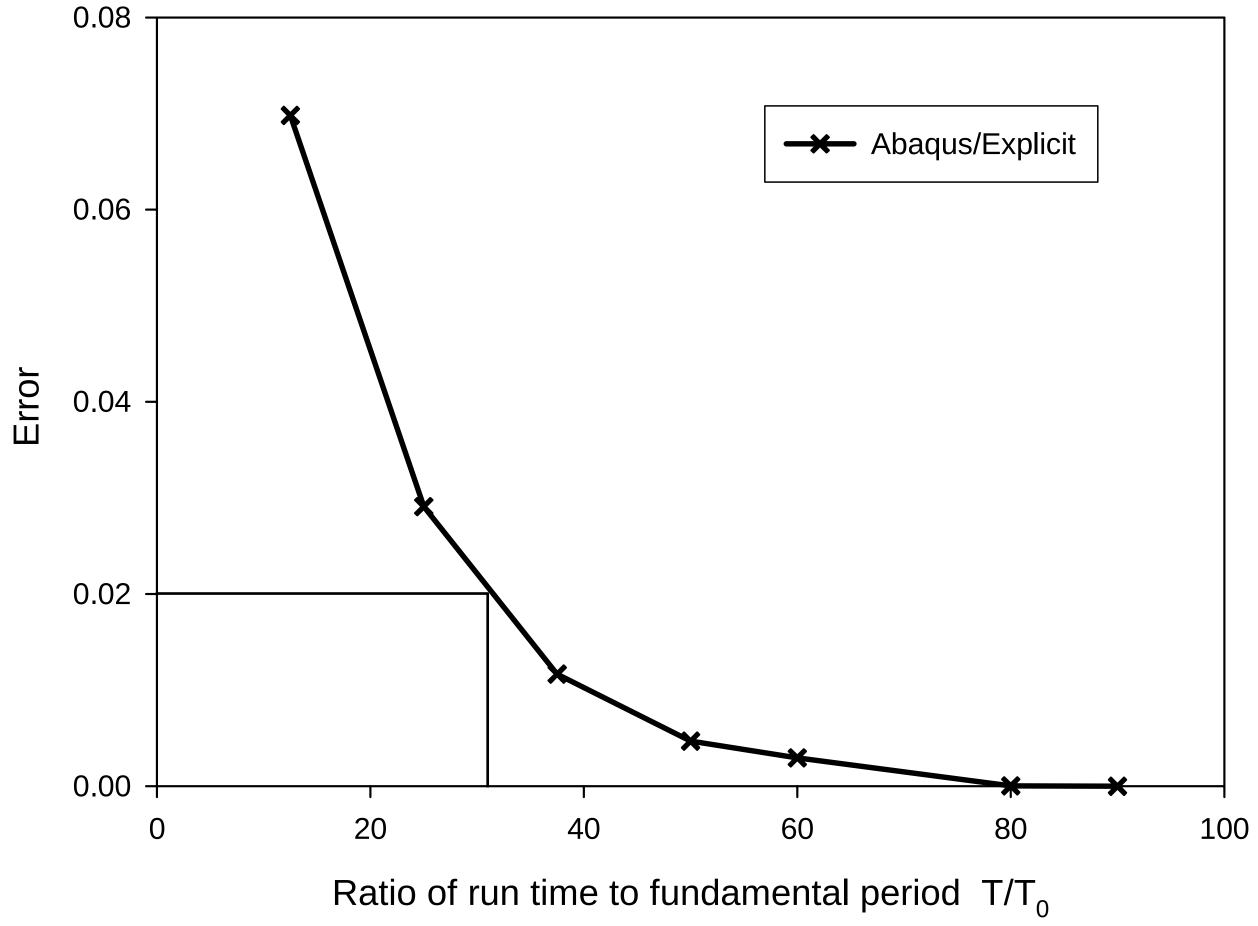
Abaqus/Explicit

- Run time versus error due to inertia effect
  - Error less than 2% requires loading duration about 30 times the fundamental period
  - ➢ Any disturbance resulting from damage progression reverberates 60 times



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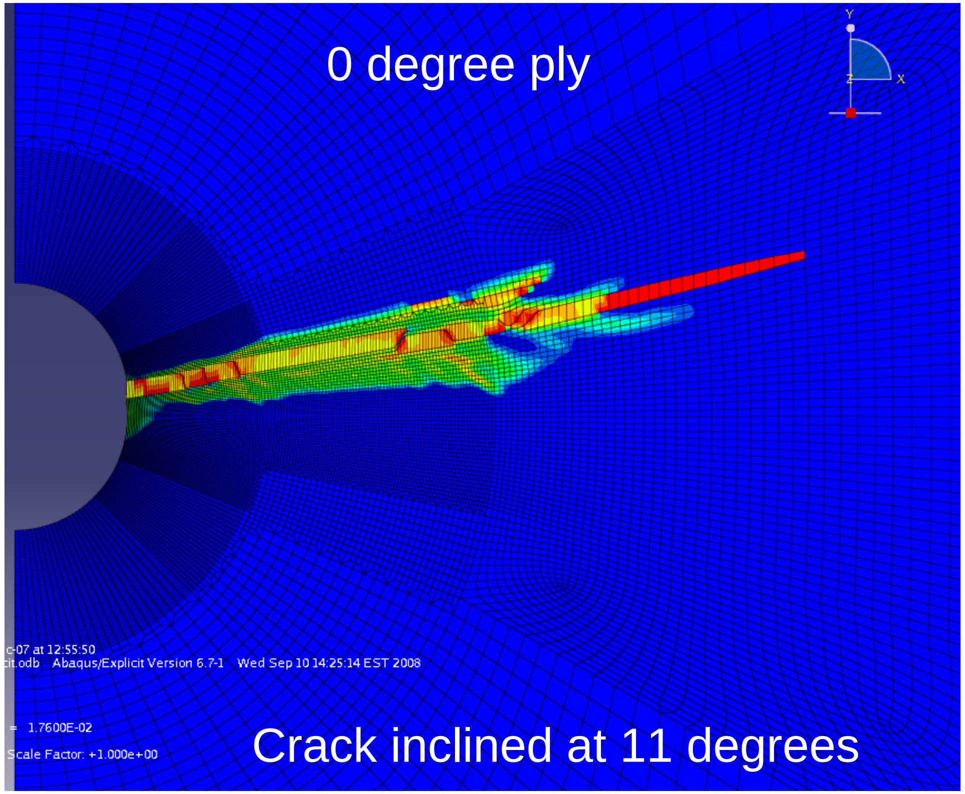
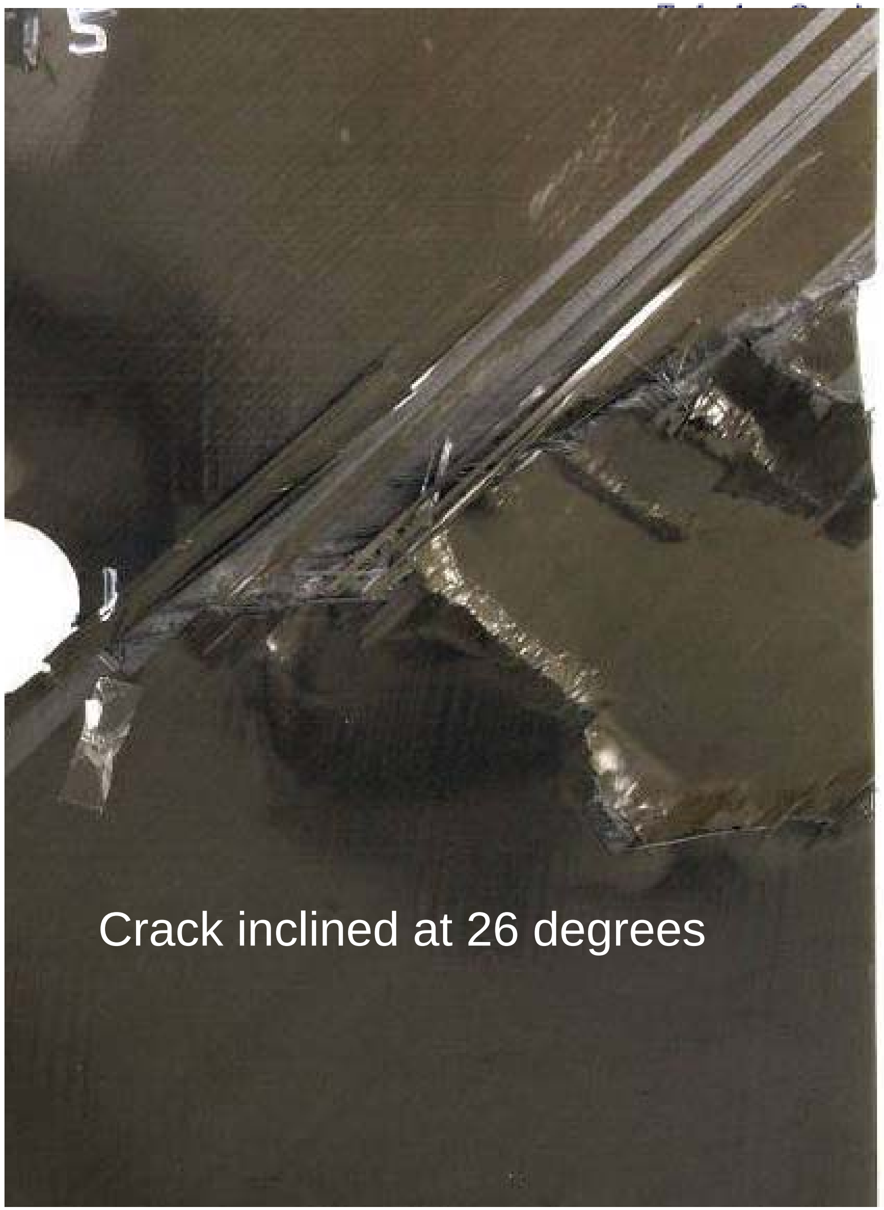
Failure path

- Straight hole





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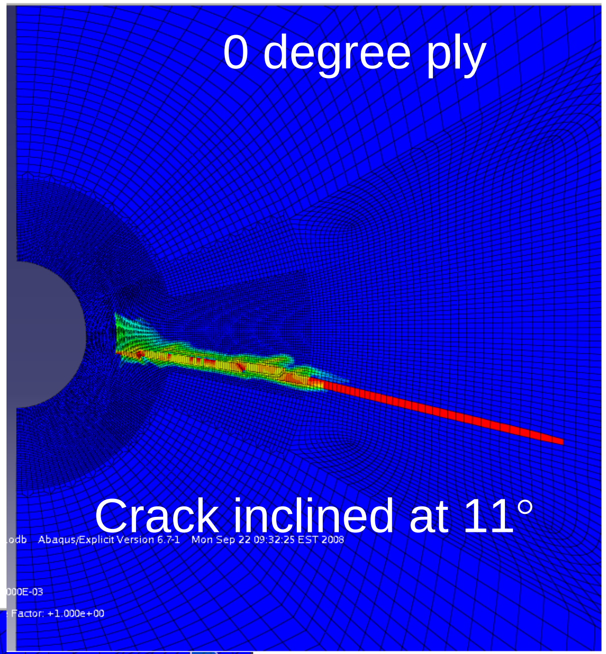
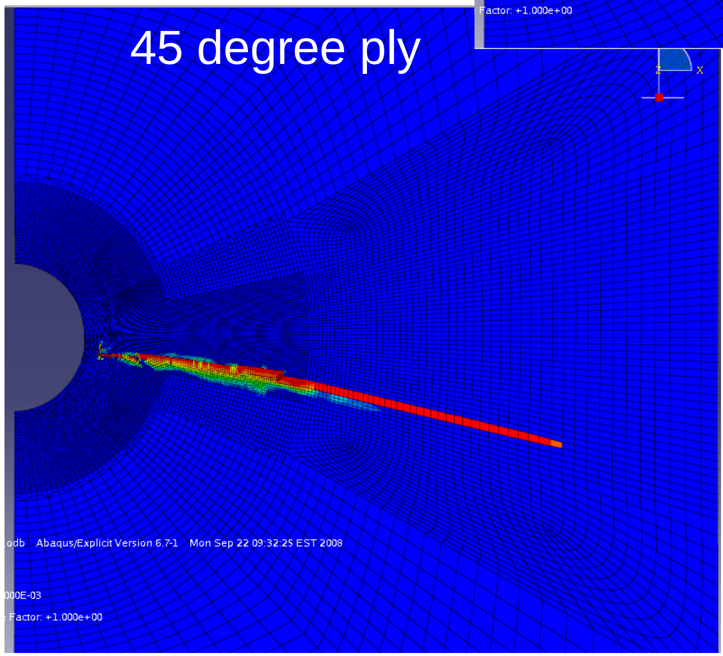
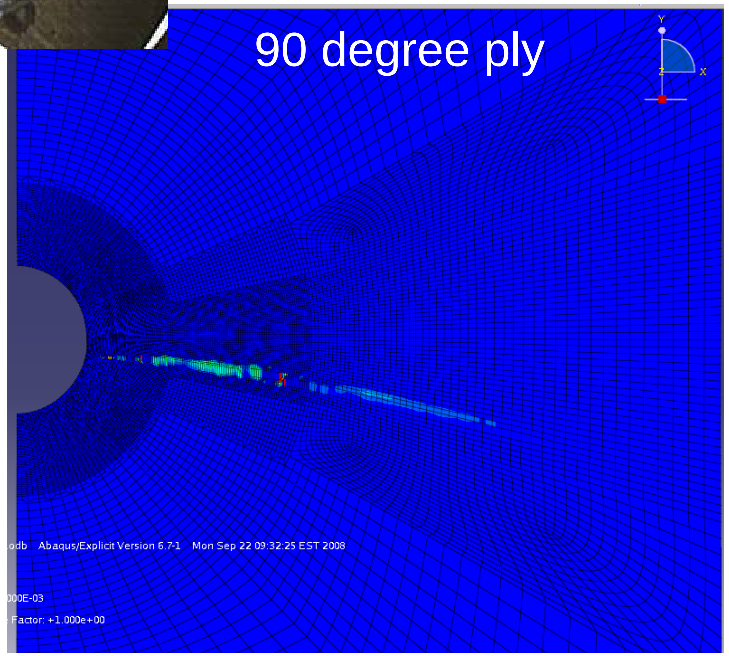
Failure path

- Scarfed hole







Scarfed and straight-hole panels

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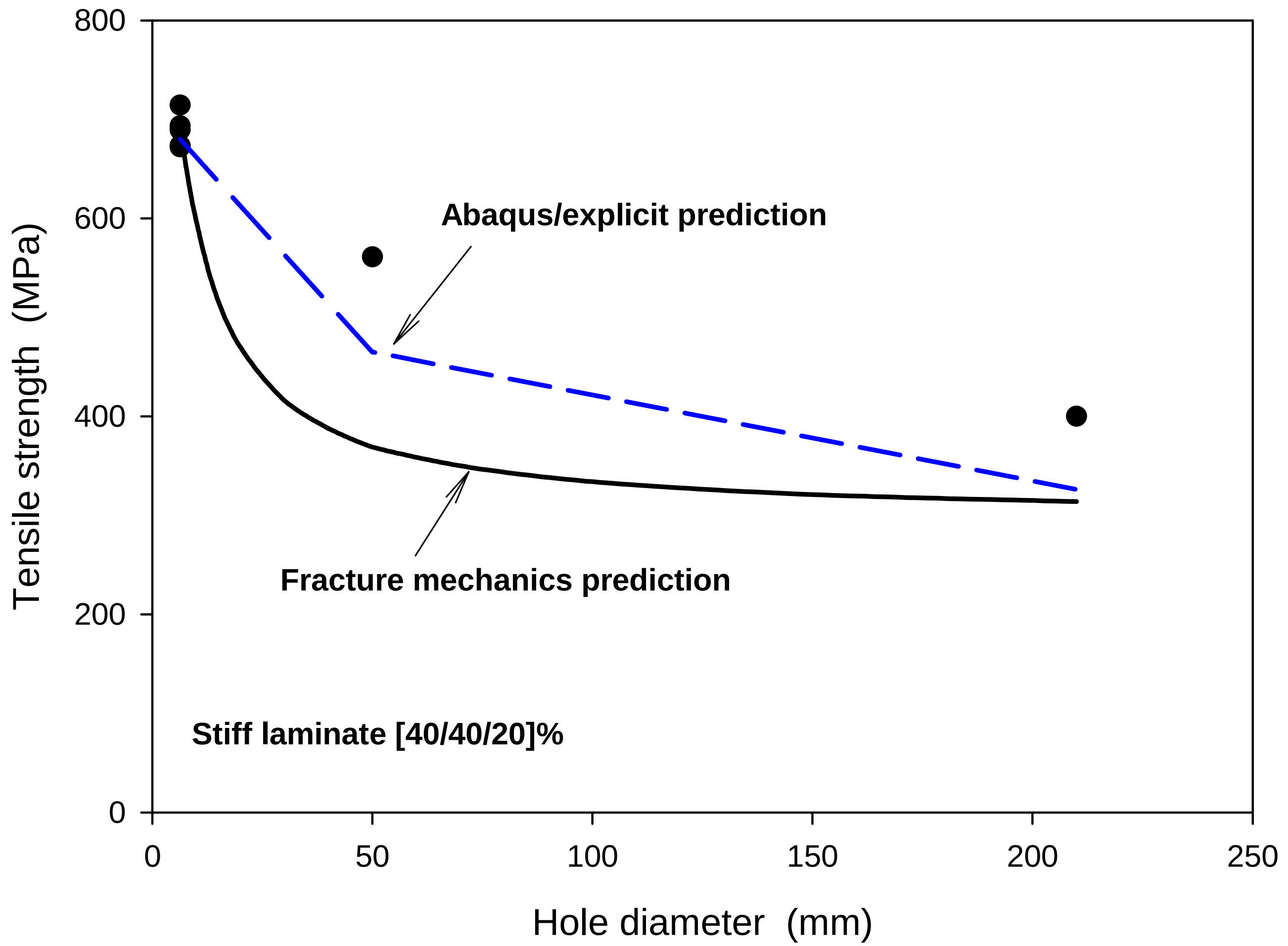
- Abaqus model provided an improvement but under-predicted strength by 20% and the angle of fracture path.



Quasi-isotropic laminates

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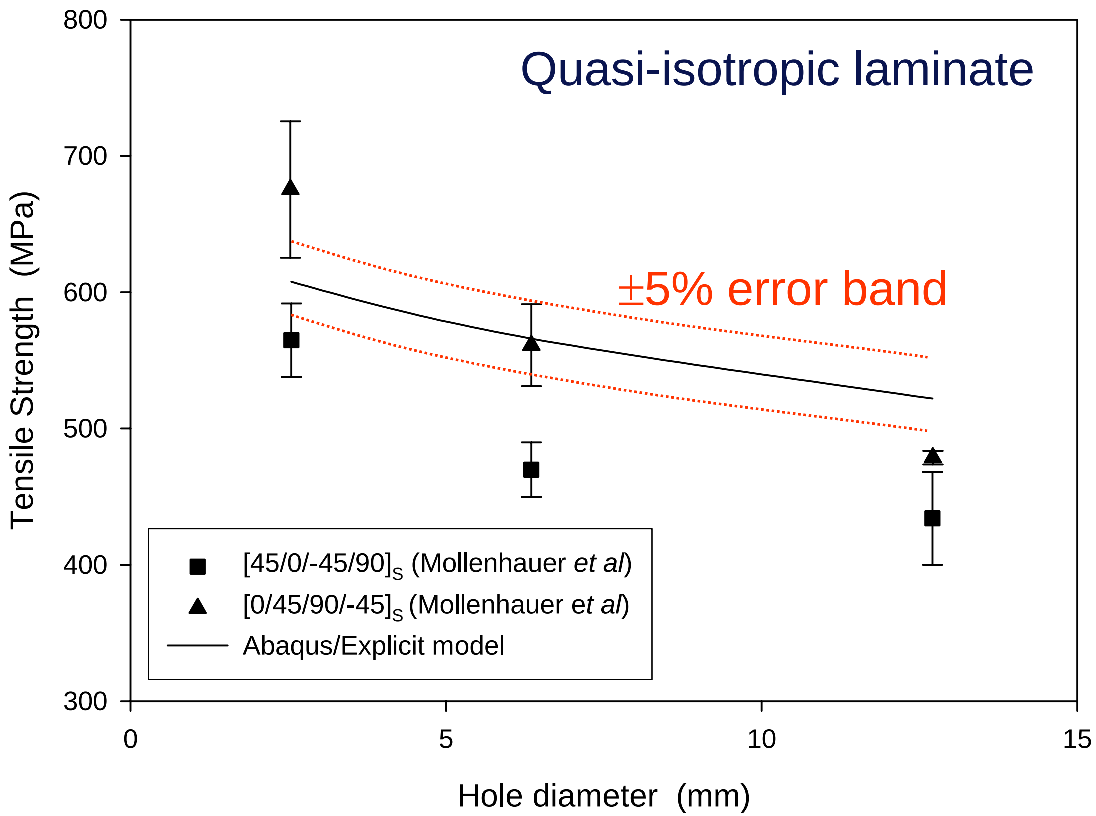
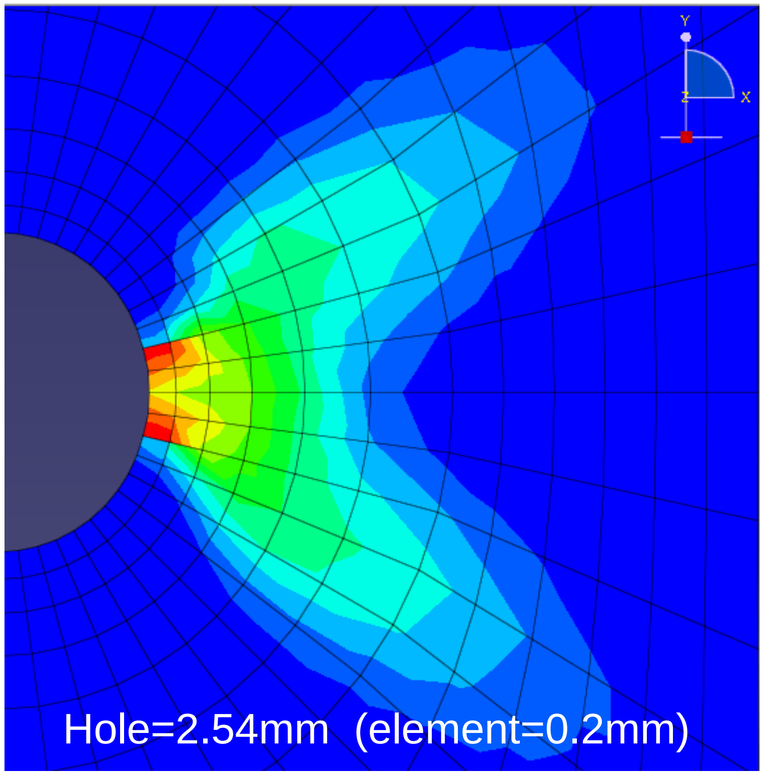
- Over-prediction of strength for large holes
  - Using fracture energies "backed-out" from stiff laminate data
- Stacking sequence effect not predicted





Damage Initiation Model

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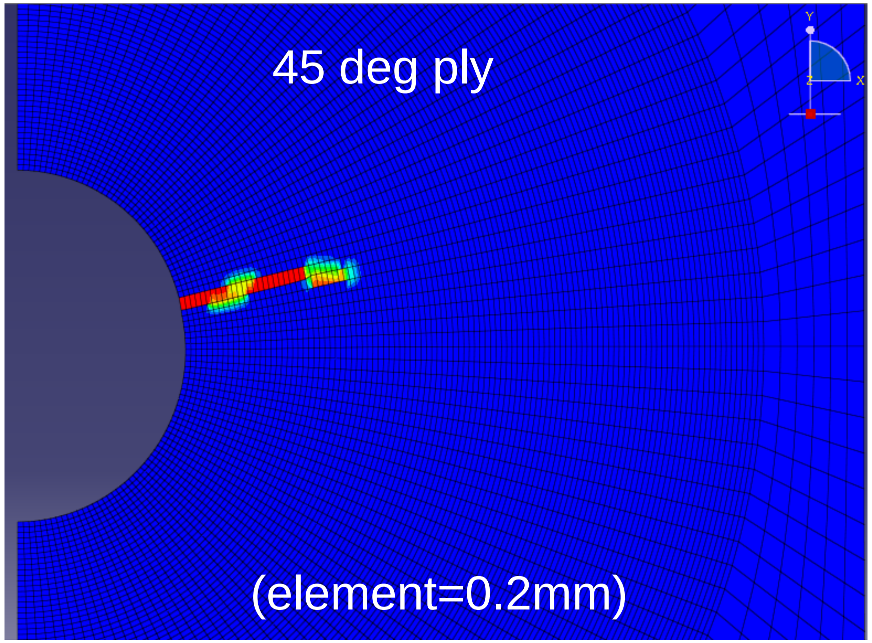
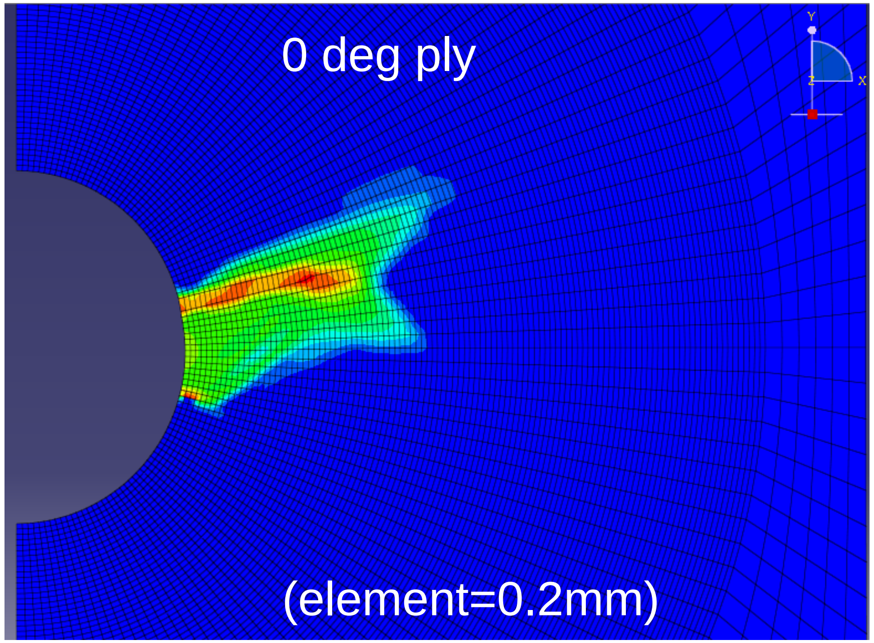
Difference in fracture path due to incorrect damage initiation model?

- Need alternative failure criterion to model off-axis plies

Hole=12.7mm (G_{0t}=160 kJ/m^2)





Alternative Failure Criteria

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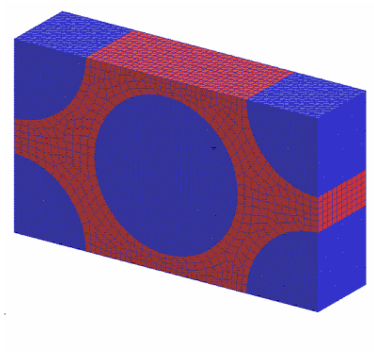
- Modified strain-invariant (Wang, C.H., Chapter 8, Multi-scale Modelling of Composite Material Systems, 2005)
  - Fibre tensile fracture (shear failure)
  - Fibre compression failure (micro-buckling)
  - Matrix shear failure
  - Matrix dilatation fracture

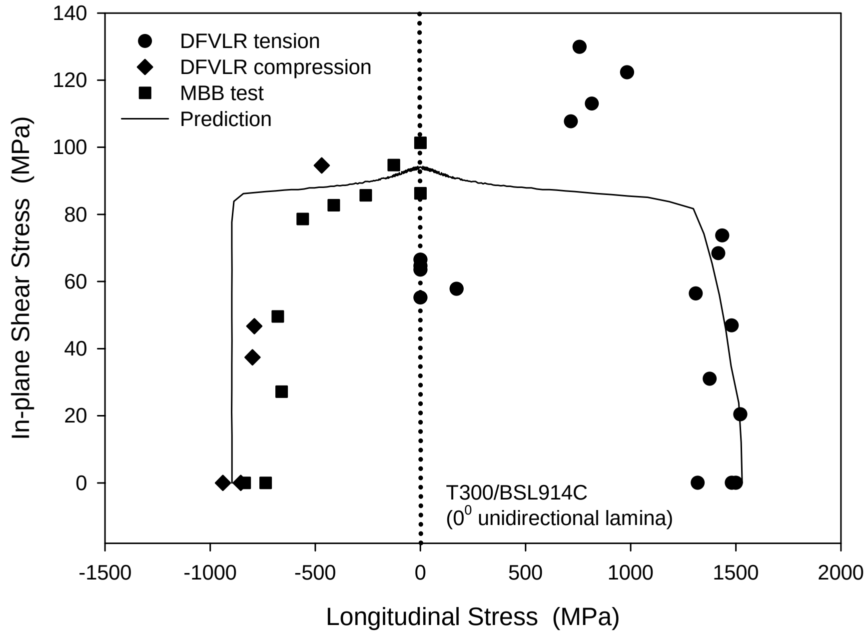
$$\varepsilon_{vM}^{(f)} \geq \varepsilon_{c}^{(f)}$$

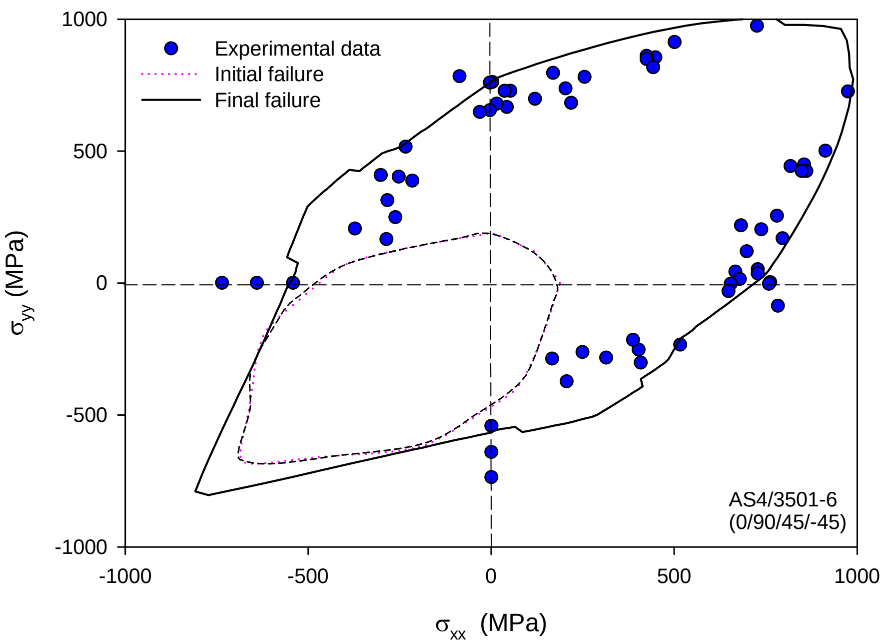
$$\sigma_{1}^{(f)} \leq \sigma_{c}^{(f)}$$

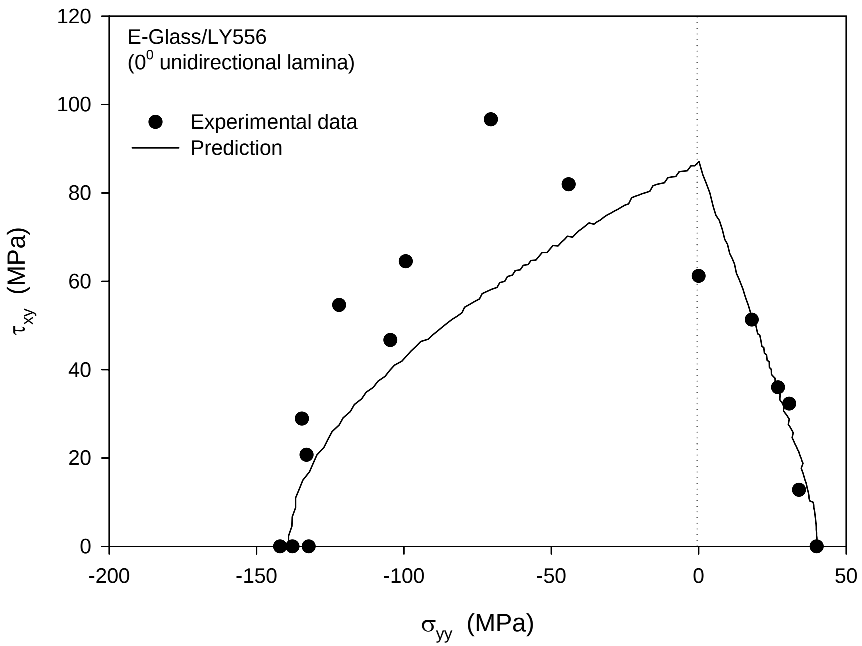


Stress-invariant theory

- Comparison with published data
  (Wang 2005)







Damage Progression Model

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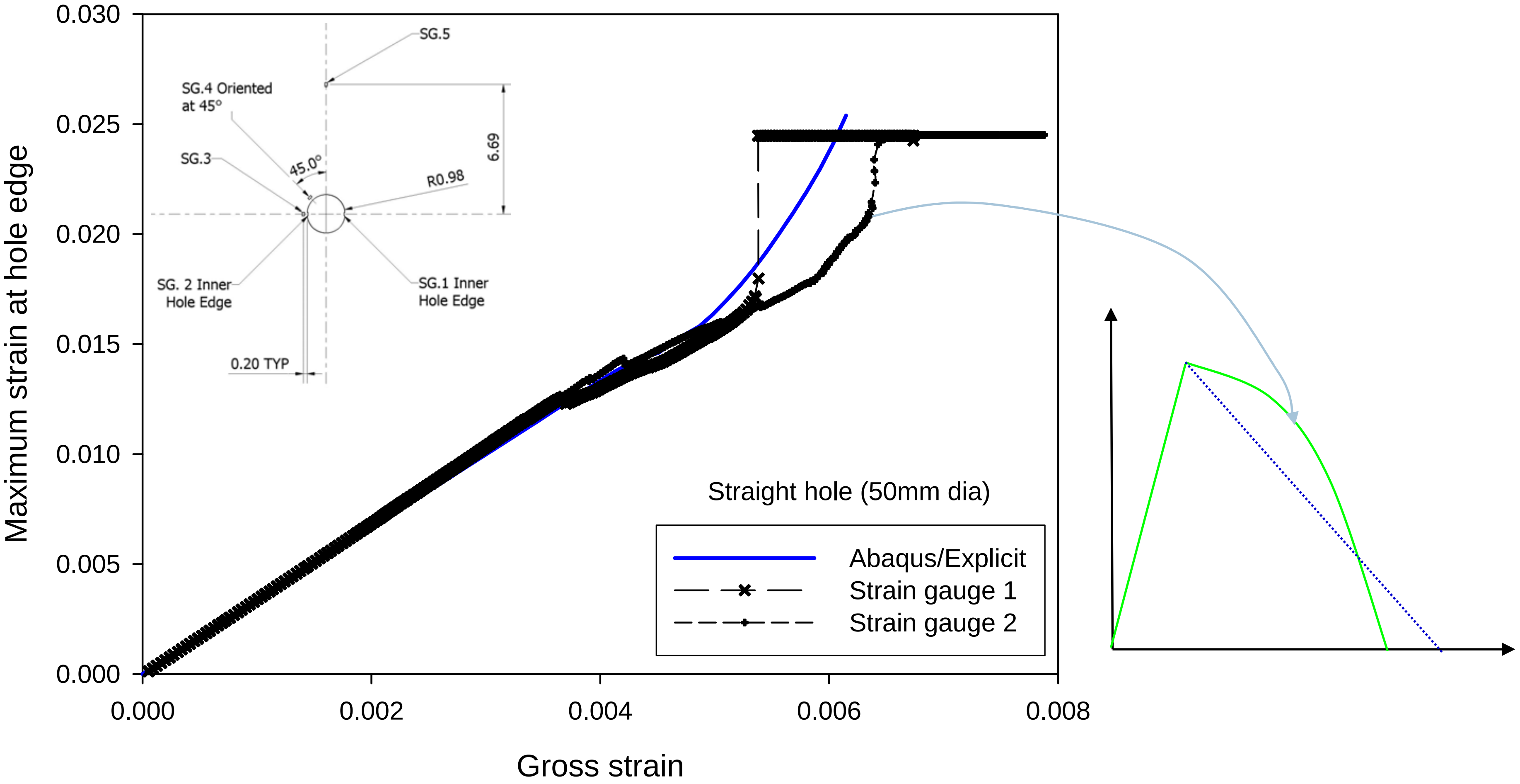
- Predicted maximum strain is less than measurement
  - Stress-softening law may need modification



Conclusions

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- Fracture mechanics (inherent-flaw) showed promises at dealing with stacking sequence, but failed to predict effects of hole size and through-thickness tapering.
- Abaqus damage model under-predicted strength of cutouts larger than those in calibration coupons.
- Comparison of prediction with experimental data suggests alternative damage initiation model and damage progression model.
- Optimisation techniques may be required to back-out material properties.
- Improved solution method needs to be developed to improve computational efficiency.