Baylor University

Friday, September 7, 2023
Session: Modeling of Composites

Fatigue crack propagation of carbon fiber-reinforced composite laminates

Modeling strategies

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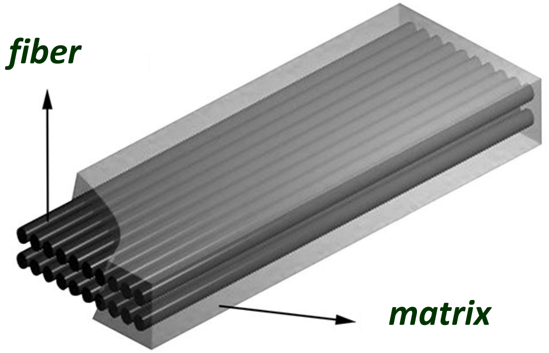
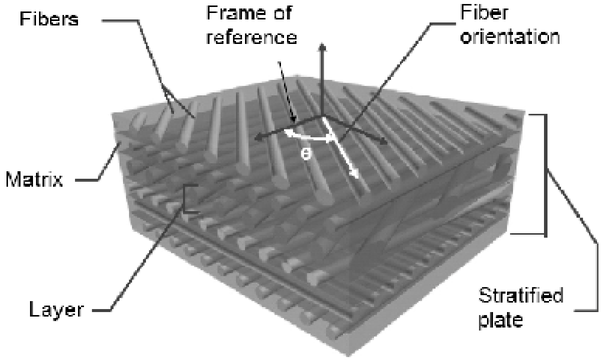
Introduction – fiber-reinforced composites in automotive industry

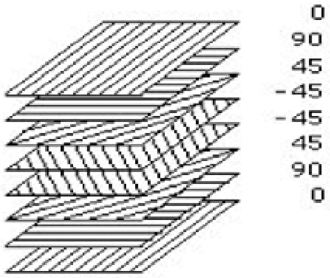
- **Advanced composite materials** – high-performance <u>matrix</u> reinforced with continuous <u>fibers</u>
  - Fiber – carbon, glass, aramid, natural fiber
  - Matrix – thermoset (epoxy, polyester, phenolics), thermoset (PA, PP, PE, PS, ABS, PC/ABS, PEEK)

unidirectional ply (lamina)



stack of laminae (laminates)





tailorable *freedom to define ply orientations*

- **Composites in automotive industry** – popular for producing primary and secondary parts
  - Lightweight
  - High specific stiffness (or strength)
  - Tailorable

<u>primary part</u>

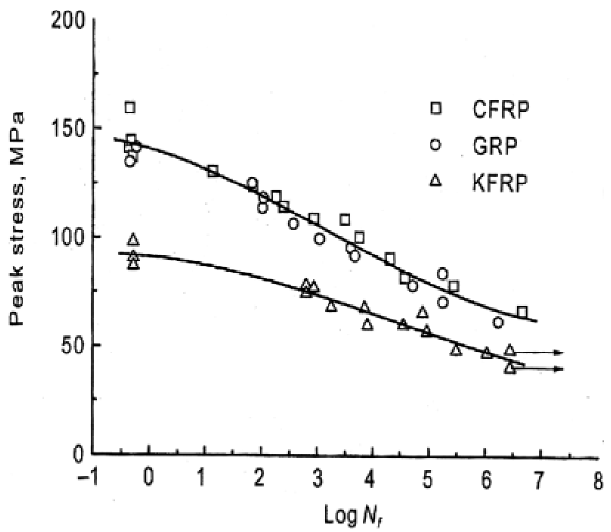
BMW i3 (330 lbs)

<u>secondary part</u>

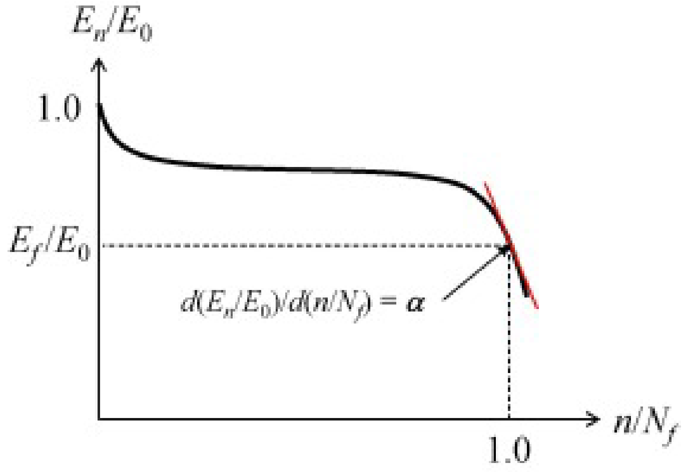
Introduction – fatigue phenomena in fiber-reinforced composites

- **Composites in operational condition → fatigue**
  - Failure in materials due to repeated/cyclic loading applied below static limit
  - Progressive (initiation and propagation), multiple (transverse crack, delamination, fiber fracture)
- **Diagrams to characterize fatigue behavior**

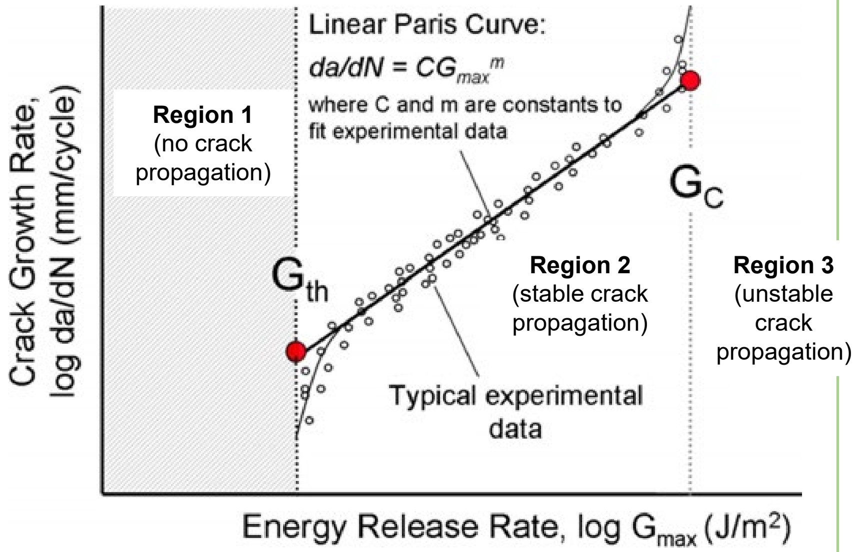
Fatigue life (S-N curve)



Stiffness degradation



Fatigue crack propagation



- **Above quantities provide thresholds, but they remain phenomenological (degradation mechanism causing fatigue failure are not physically understood)**
- **Experiment is expensive and time consuming**
- **Modeling can be cost effective, but fatigue damage modeling is very challenging**

Introduction – fatigue damage modeling approaches

- **Modeling approaches**

Our focus

Empirical/phenomenological

Fatigue life model (failure onset, stress-based or strain-based vs. cycle-to-failure)

Stiffness degradation (mesoscale continuum damage mechanics)

Numerical

Virtual crack closure technique (VCCT) (linear elastic fracture mechanics; force and displacement at nodes; mesh refinement required)

Extended finite element method (X-FEM) (discontinuous function needed to “enrich” elements around the crack; no mesh refinement)

Cohesive zone element (interlaminar/intralaminar damage represented by thin cohesive layer with embedded traction-separation law coupled with fatigue)

Property degradation coupled with failure theory (mesoscale continuum damage mechanics; ply failure criterion based on physics-based failure theory)

Objectives

- Developing **finite-element based modeling strategies** for simulating **fatigue crack propagation** in composites
- Demonstrating the capability of our strategies by studying two cases:

(i) end-notch flexure under 4-point bending (interlaminar mode II crack)

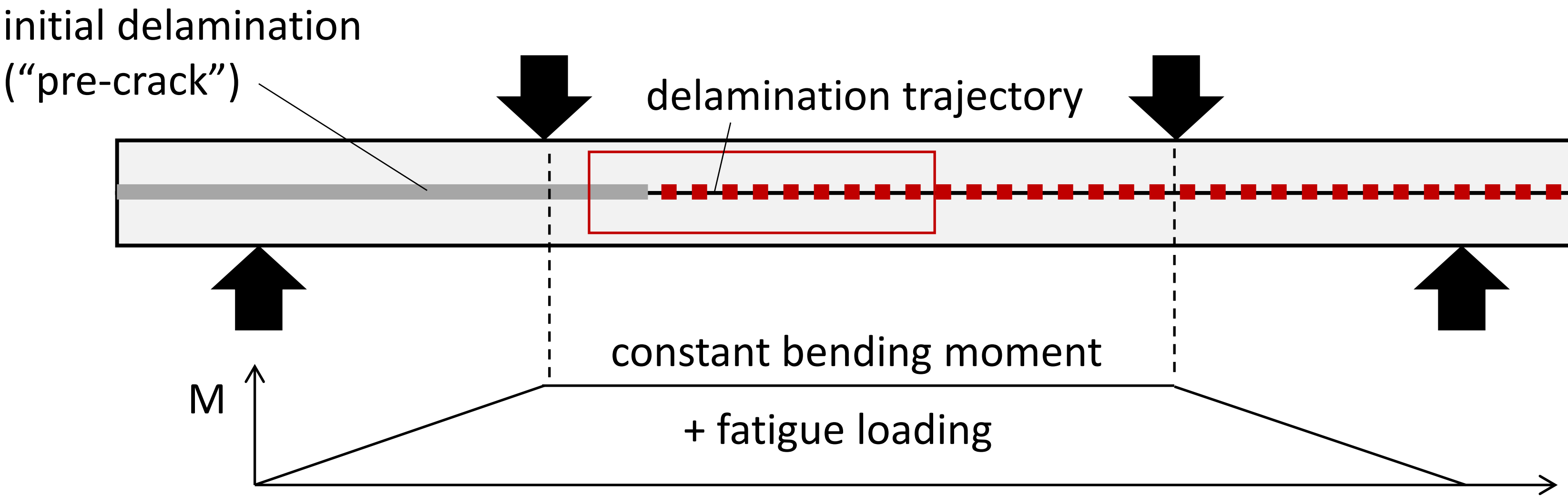
(ii) open hole under tension-tension fatigue (intralaminar)

Fatigue crack propagation in composites under mode II loading

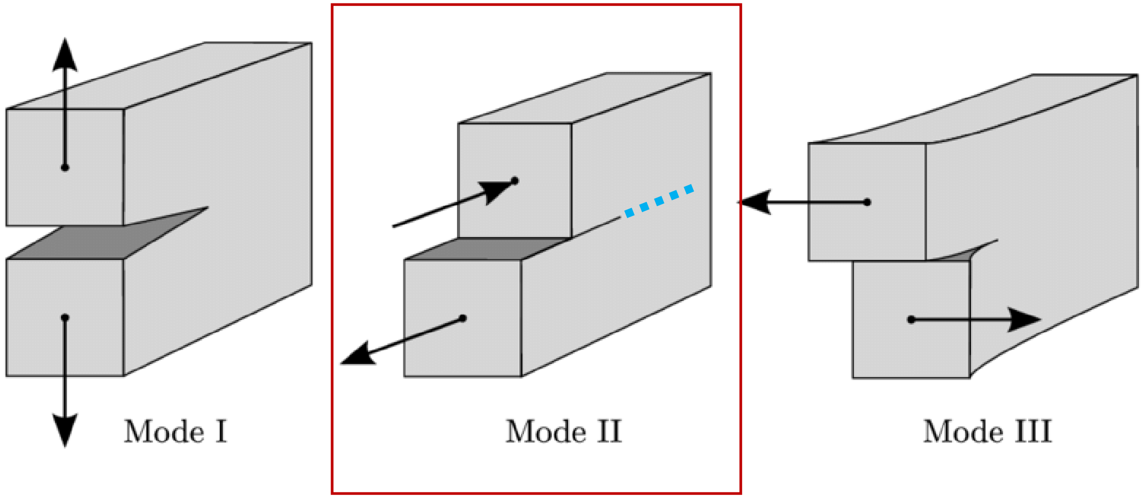
interlaminar damage (delamination)

Introduction – model overview

Trajectory of delamination in end-notch flexure laminates under 4-point bending fatigue (mode II fatigue)

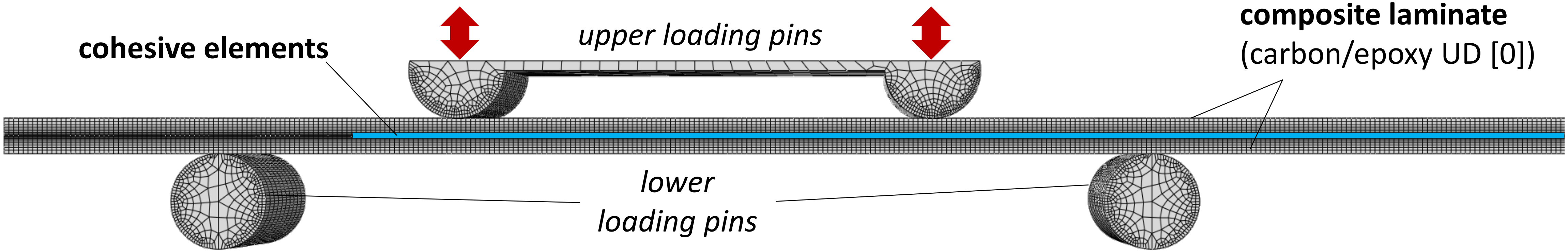


recall mode of fracture
- Mode I (opening)
- **Mode II (in-plane shear)**
- Mode III (out-of-plane shear)



Methods – overview of finite element procedure

Finite element mesh – ABAQUS/Explicit



Key ingredients

(1)
Cohesive constitutive law

(2)
Fatigue degradation rule

(3)
Loading envelope strategy

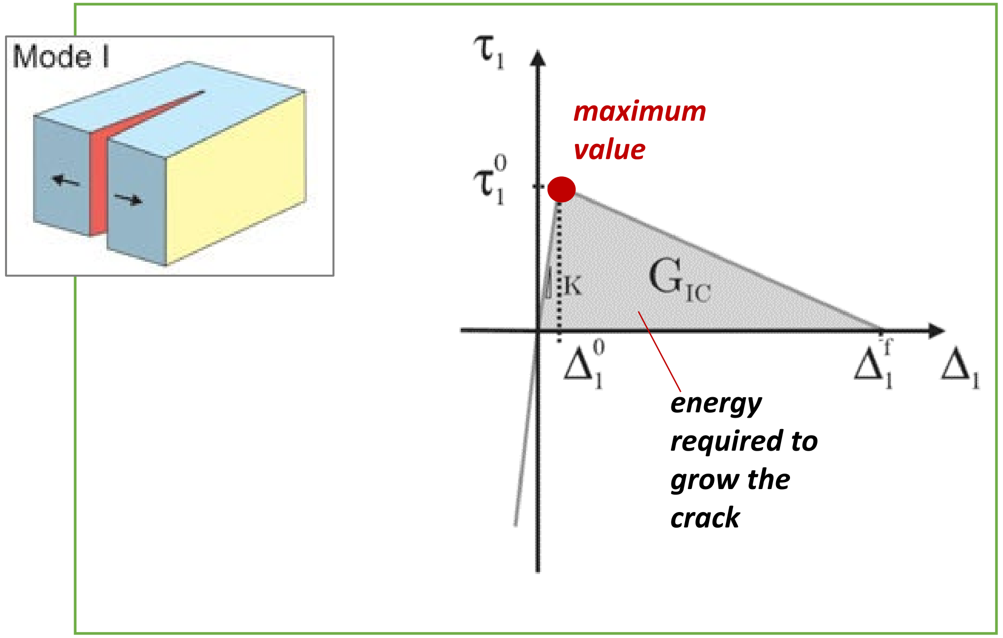
Technical implementation

- **Python script** – to access ABAQUS database (part, assembly, elements, element connectivity array)
- **VUMAT script (user subroutine interface)** – to define (1) cohesive constitutive law (incl. crack tip tracking algorithm in using four integration points), (2) fatigue degradation rule, (3) loading envelope strategy

Methods – (1) cohesive constitutive law

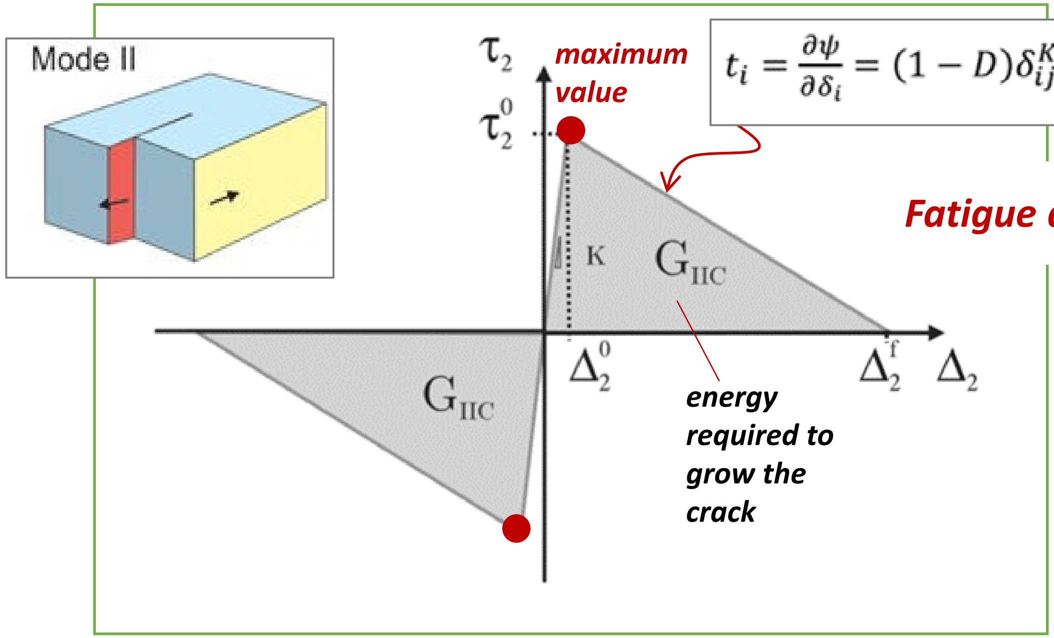
Cohesive element → representation of interlaminar damage

- Theoretically zero-thickness element enriched with a **traction-separation law (e.g., bi-linear)**
- Inserted at the interface where the interlaminar damage (delamination) will likely occur
- Damage initiates when maximum value is reached



maximum value

energy required to grow the crack



maximum value

energy required to grow the crack

$$t_i = \frac{\partial \psi}{\partial \delta_i} = (1-D)\delta_{ij}^K K \delta_j - D\delta_{ij}^K K \delta_{1j}^K \langle -\delta_1 \rangle$$

⇩

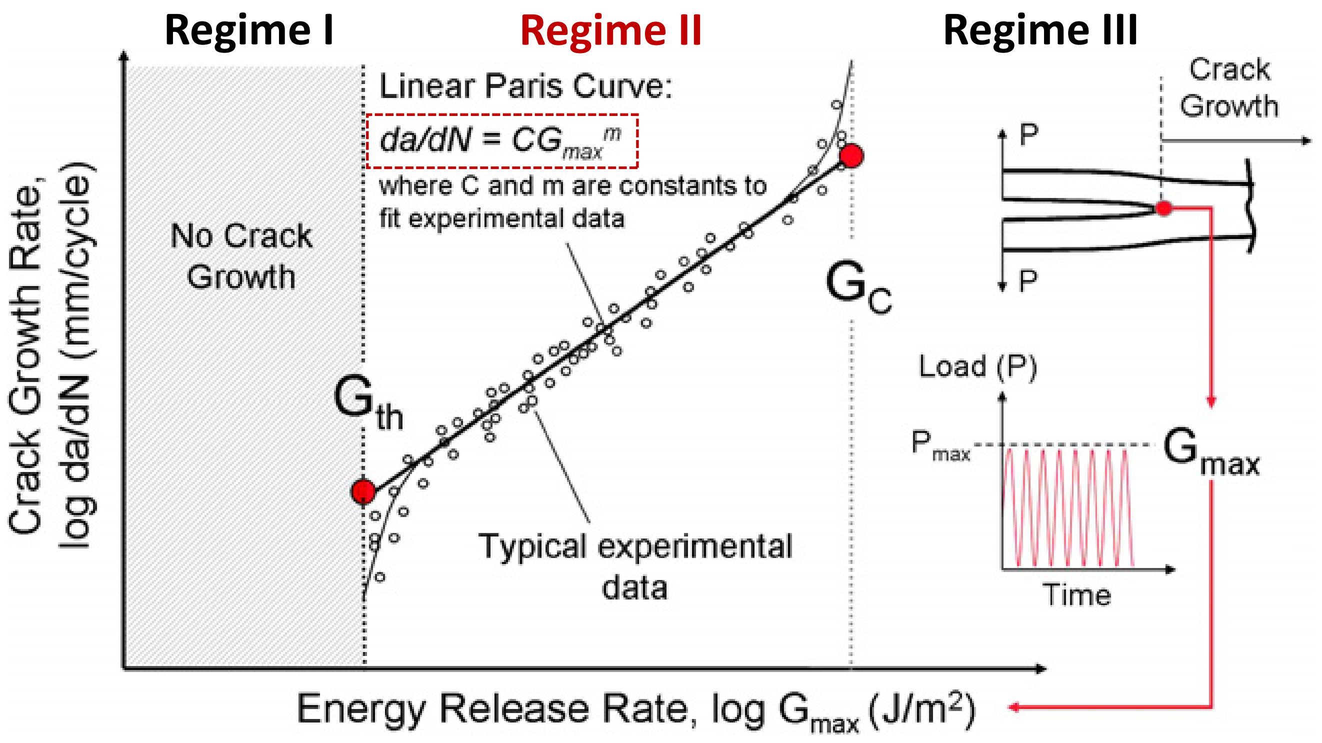
Fatigue degradation rule

Criteria selected and prescribed in ABAQUS/Explicit

- Damage initiation: Maxs damage (others: Maxe damage, Quads damage, Quade damage)
- Damage evolution: Bi-linear (others: trapezoidal, polynomial, exponential)
- Ultimate failure: B-K energy-based mixed-mode criterion (others: displacement)

Methods – (2) fatigue degradation rule

- **Key point:** fatigue crack propagation rate ($\partial a/\partial N$) → fatigue degradation rate ($\partial d_f/\partial N$)



Regime II of fatigue crack growth rate (da/dN) describes a **stable crack propagation**

Identifiable parameters during experiments:

- N
- P_{max}, P_{min}
- d_{max}, d_{min}
- Crack length, a

Calculated parameters based on experiments

- G_{max}, G_{min}

$\partial a/\partial N$ **is** determined purely by the **change in energy release rate** at the **crack tip** and at each cycle

$$\frac{\partial a}{\partial N} = C\left(\frac{\Delta G}{G_c}\right)^{m}$$

constant

constant

change in energy release rate

References

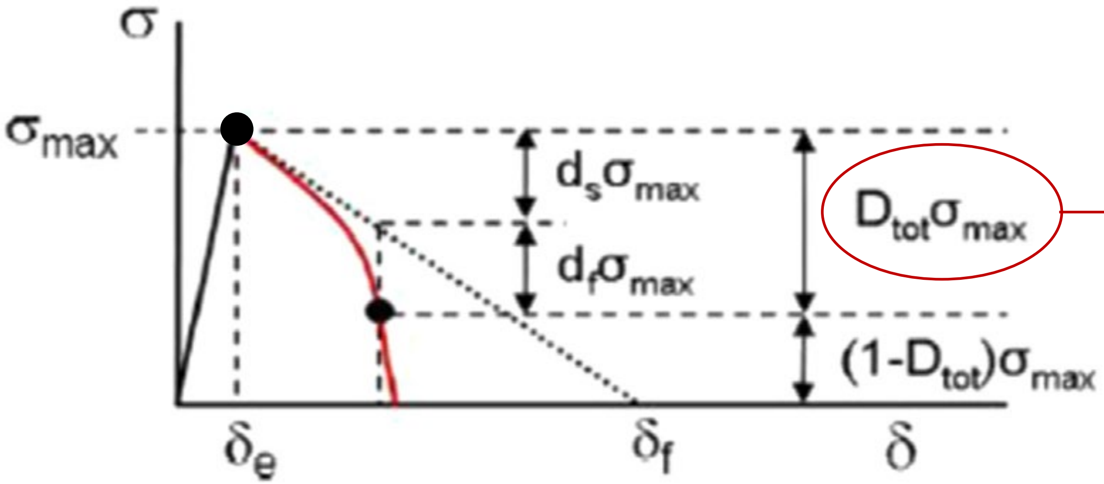
Paris and Erdogan (1963)

Rans, Alderliesten, and Benedictus (2011)

Methods – (2) fatigue degradation rule

- **Implementing fatigue degradation rule into bi-linear traction-separation law**

Bi-linear traction-separation law



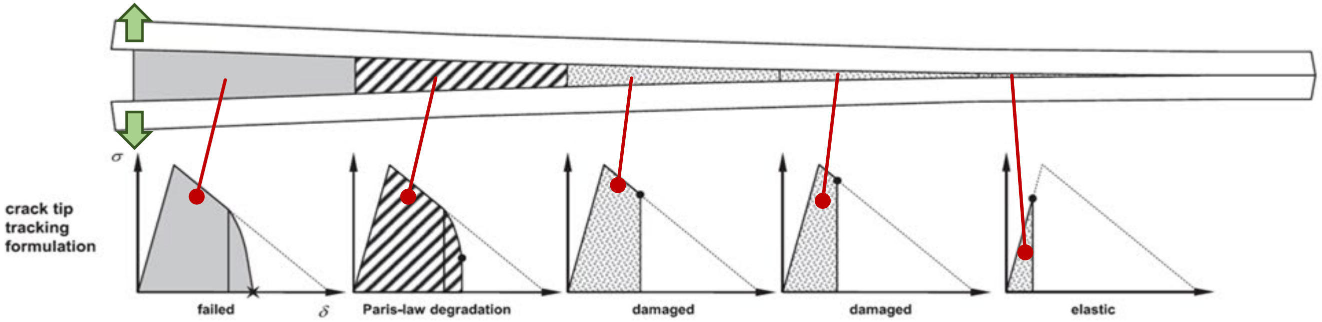
$$D_{tot}\sigma_{max} = (d_s + d_f)\sigma_{max}$$

Damage accumulation rule

$$d_{f,new} = d_{f,old} + \delta N \frac{\partial d_f}{\partial N}$$

$$= d_{f,old} + f\delta t \frac{\partial d_f}{\partial N}$$

"Crack tip tracking algorithm"



Fatigue degradation rate

$$\frac{\partial d_f}{\partial N} = \frac{\Delta D}{\Delta N_e} = \frac{1-d_s}{L_e}\frac{\partial a}{\partial N}$$

$$\frac{dD_f}{\partial N} = \frac{\Delta D}{\Delta N_e} = \frac{1-D_s}{\Delta N_e}$$ *where* $\Delta N_e = \frac{dN}{\partial a} l_e$

References

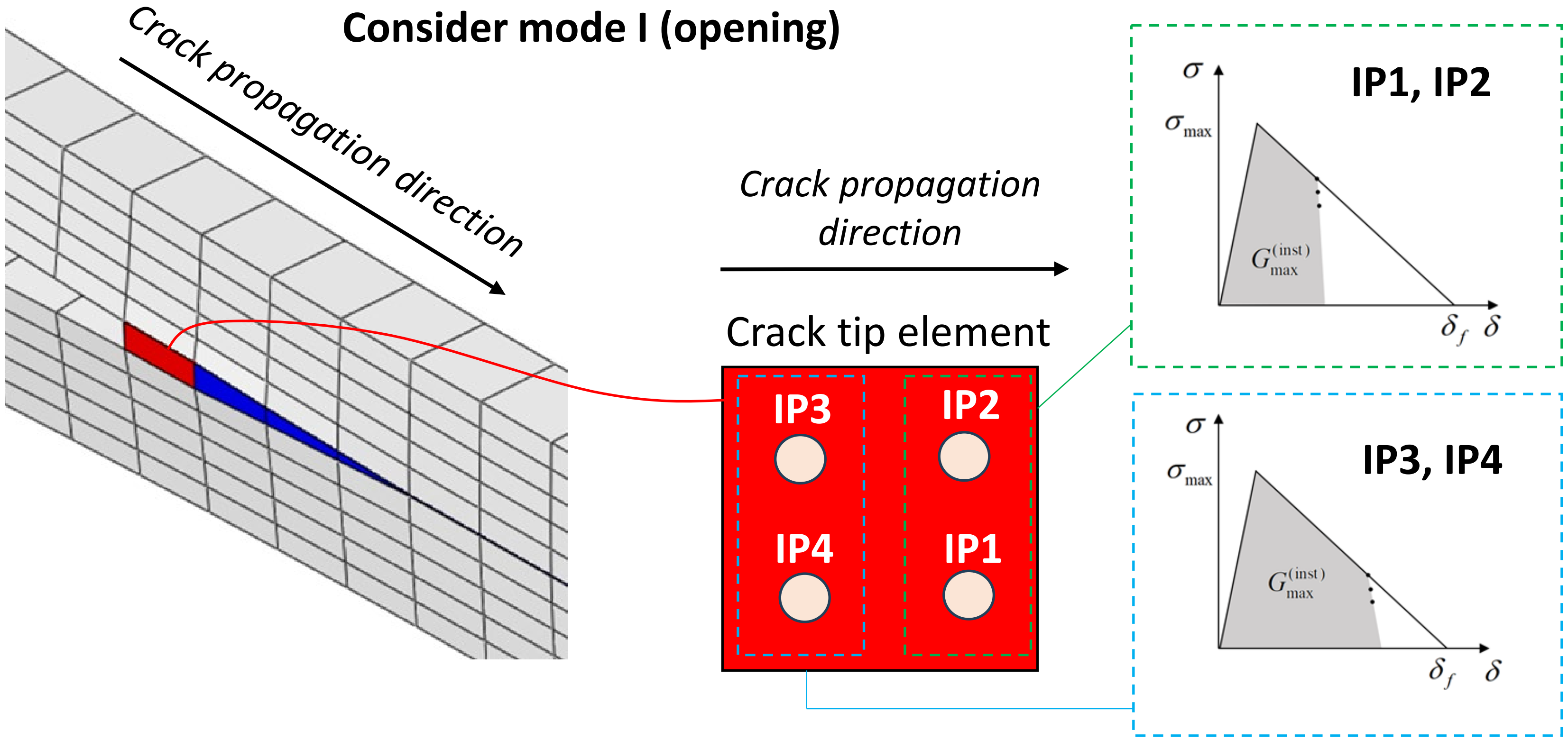
Kawashita & Hallett, IJSS (2012)

Implemented in ABAQUS/Explicit using 4 integration points

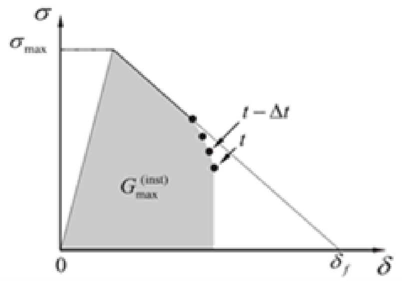
Methods – (2) fatigue degradation rule

"Crack tip tracking algorithm"

Consider mode I (opening)



Instantaneous maximum energy release rate $G_{max}^{(inst)}$ at one integration point is calculated as follows



$$G_{\max}^{(\mathrm{inst})} = \sum_{k=1}^{\mathrm{nstep}(t)} \left(\frac{\sigma_k + \sigma_{k-1}}{2}\right)(\delta_k - \delta_{k-1})$$

Static damage variables Ds are calculated as follows

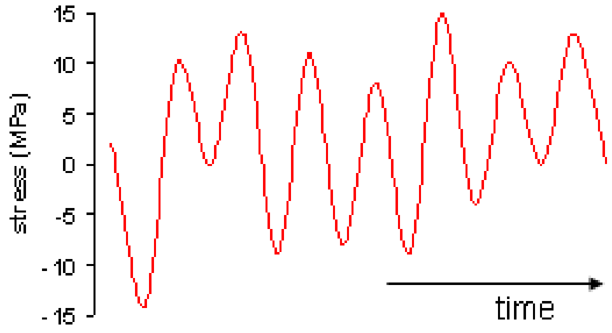
$$D_s = \frac{\delta_m^t - \delta_m^0}{\delta_m^f - \delta_m^0}$$

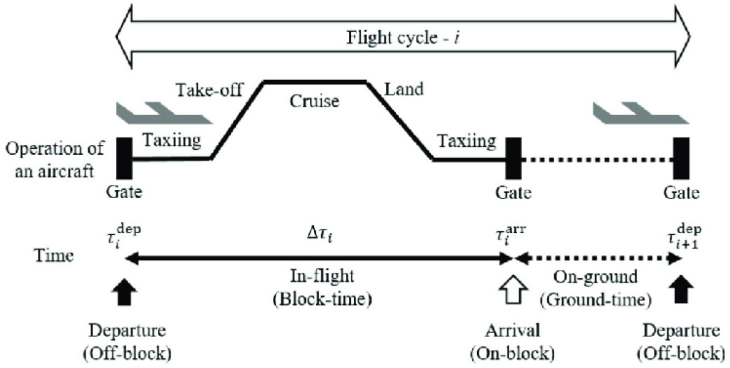
$$d_f^t = d_f^{t-1} + f \cdot dt \cdot \left(\frac{1-d_s}{L_e}\right) C_I \left(\frac{(\sum_{\mathrm{IP}=1}^{4} G_{\mathrm{max,IP}}^{(\mathrm{inst})})/4}{G_{Ic}}\right)^{m_I}$$

Python scripting → VEXTERNALDB → MODULE in VUMAT

Methods – (3) loading envelope strategy

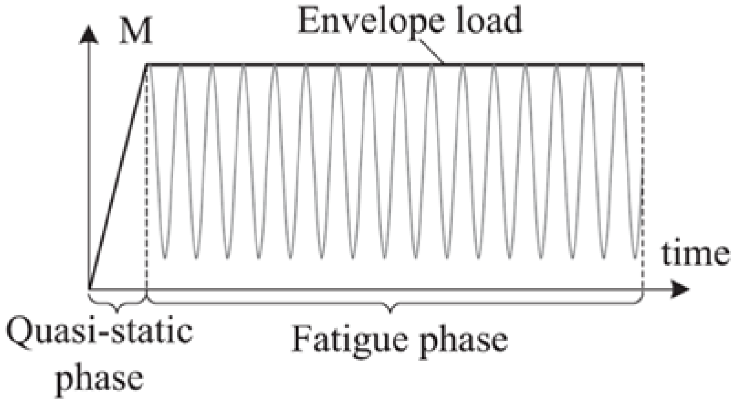
- **Cycle-by-cycle loading** – employed for low-cycle fatigue, computationally inefficient, ductile materials, “variable-amplitude” loading (frequent changes of amplitude)





Present technique

- **Loading envelope strategy** – employed for high-cycle fatigue, computationally efficient, brittle materials/interfaces, “constant-amplitude” loading



Methods – (3) loading envelope strategy

- **Loading envelope strategy**

The number of elapsed cycles in FE model is equal to the product of analysis time in the explicit solution and a pseudo (numerical) fatigue frequency *f*, so the cycles are proportional to the elapsed analysis time

- **Number of cycle (N) → frequency (*f*) x time (*t*)**

$$N = f \cdot t$$

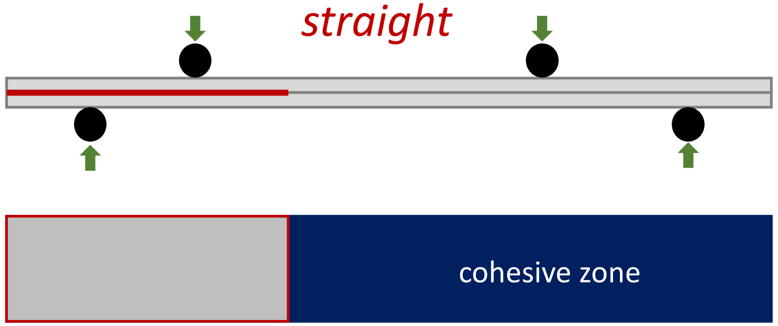
- **Energy release rate Δ*G* → G_{max} and load ratio (R) = P_{min}/P_{max} (or d_{min}/d_{max}) at each cycle**

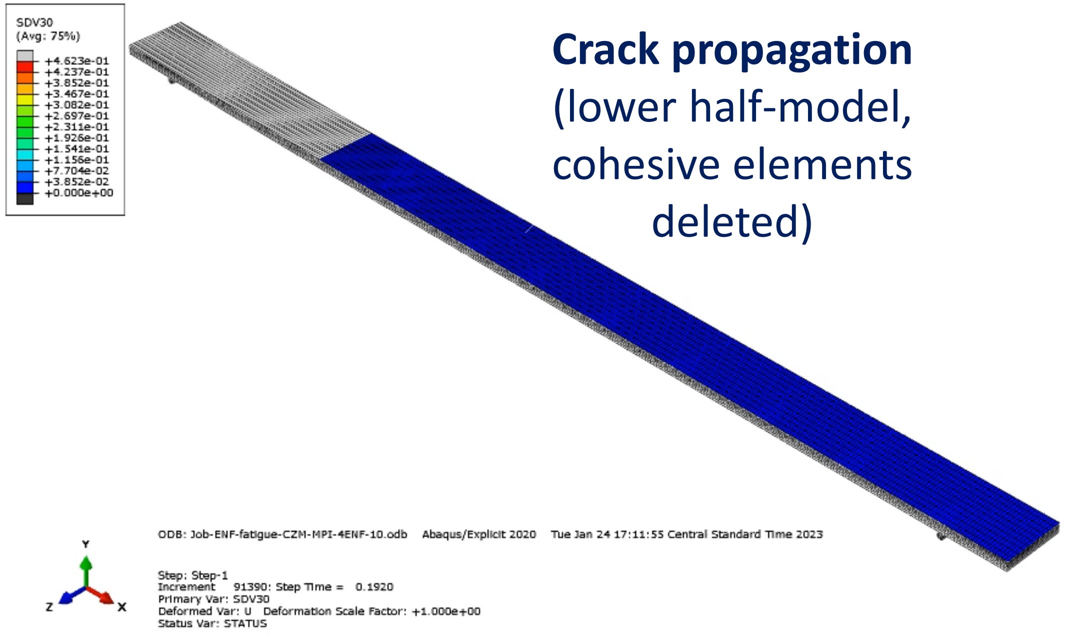
$$\Delta G = G_{max}\left(1 - R^2\right)$$

Results – Validation of model (straight crack front)

Modeling strategy works for simulating fatigue growth of straight crack front

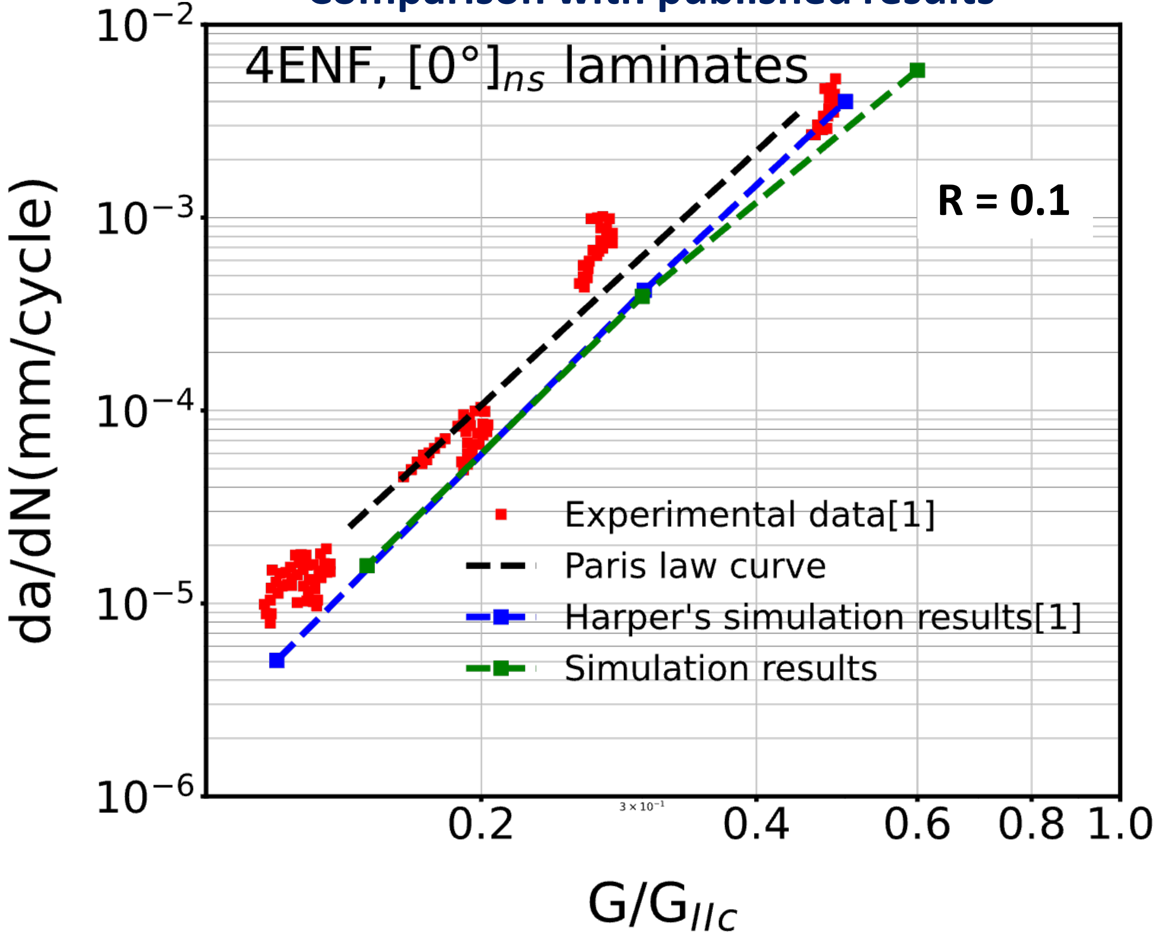
Crack front
straight





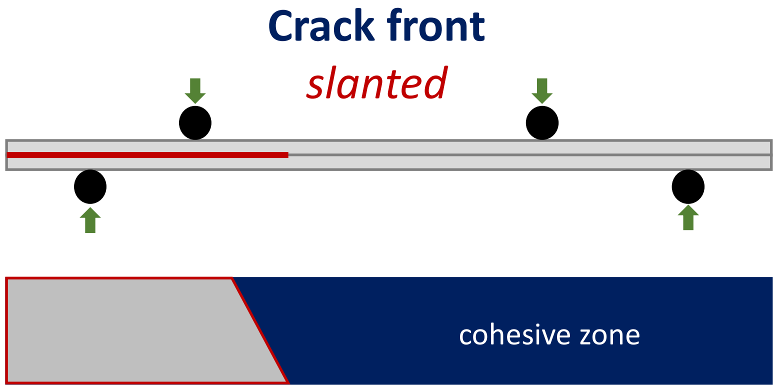
Crack propagation
(lower half-model, cohesive elements deleted)

Comparison with published results



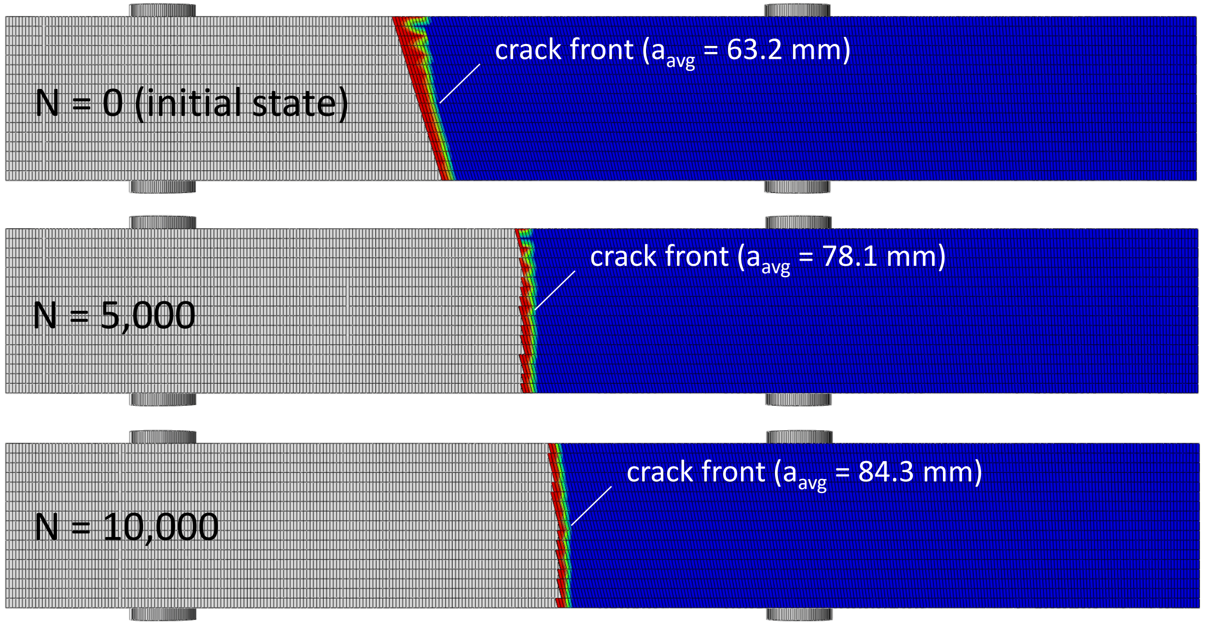
Results – Application of model (slanted crack front) and exp. validation

Modeling strategy works for simulating fatigue growth of slanted crack front

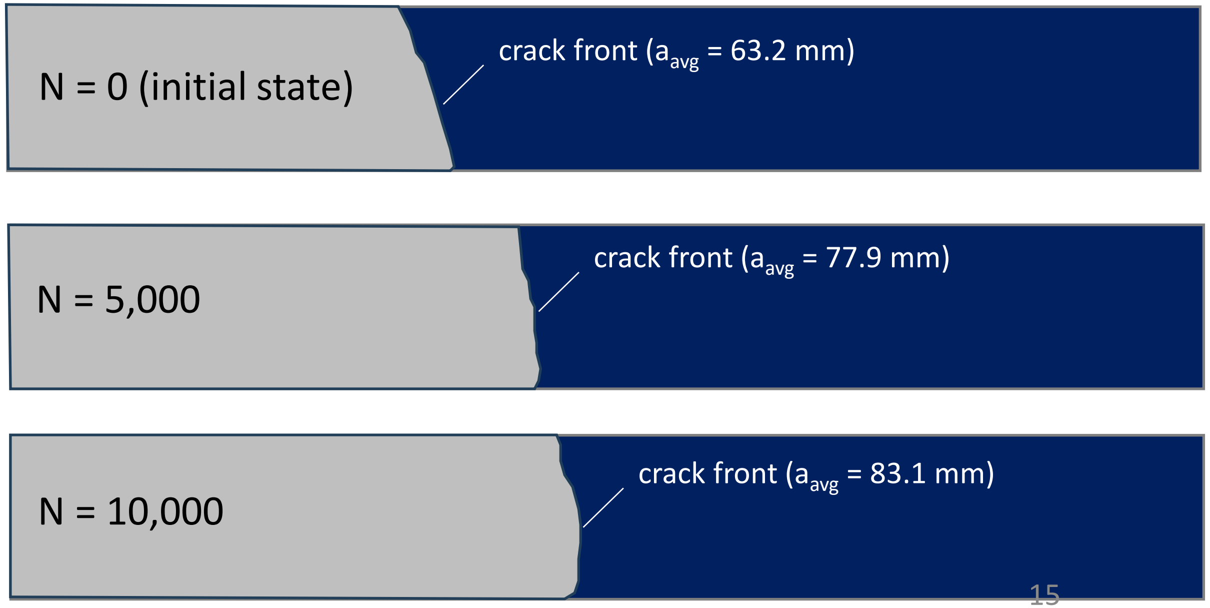


Comparison with in-house experiments

FE simulation



Schematics of NDT scan (experiments)

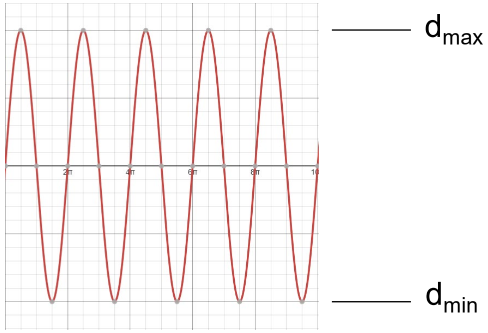


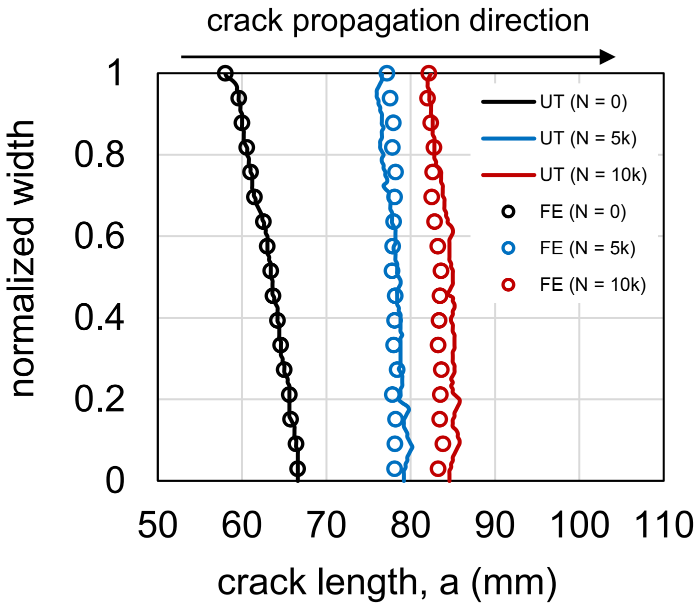
Mode II fatigue crack propagation – results: slanted crack front

Modeling strategy works for slanted crack front at different load ratios (R)

R = 0.1

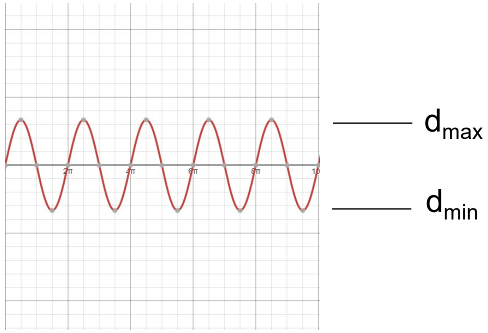
$$R = \frac{d_{min}}{d_{max}} = 0.1$$

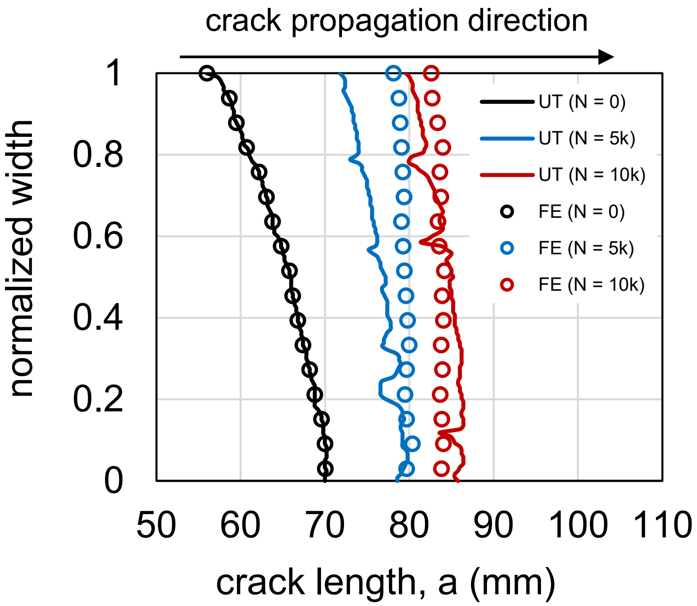




R = 0.3

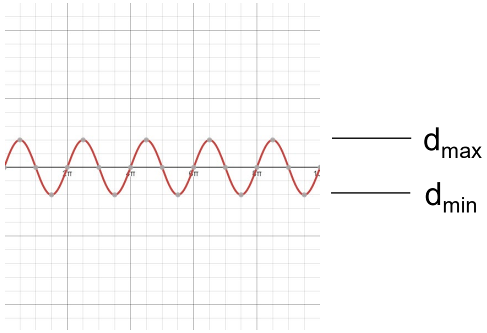
$$R = \frac{d_{min}}{d_{max}} = 0.3$$

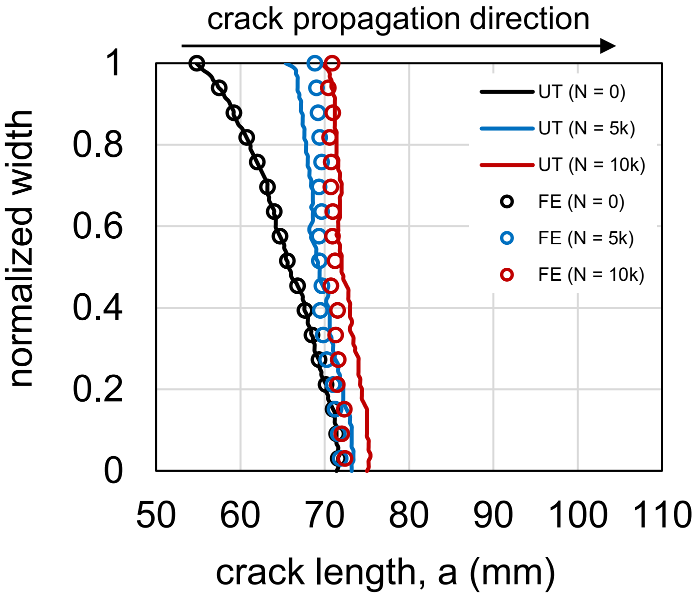




R = 0.5

$$R = \frac{d_{min}}{d_{max}} = 0.5$$



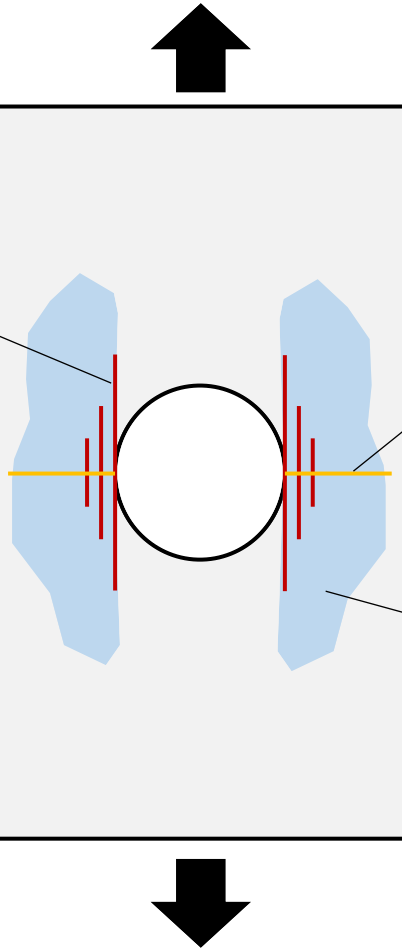


Fatigue crack propagation in composites with circular hole under tension-tension

intralaminar damage

Introduction – damage in open hole tension (OHT) specimen

OHT laminates under tension-tension fatigue → <u>intralaminar and interlaminar</u>



fiber splits in longitudinal direction (intralaminar damage)

fiber splits in transverse direction (intralaminar damage)

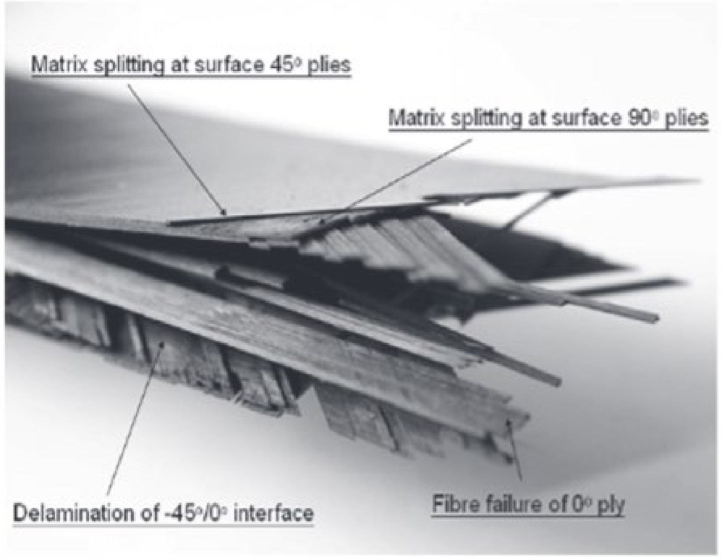
delamination (interlaminar damage)

Open Hole Tension (OHT) laminate

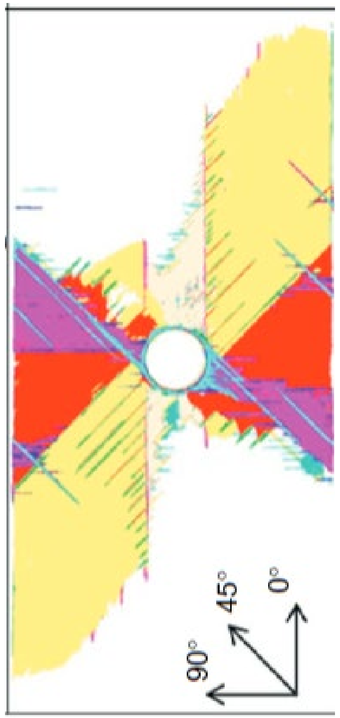
Introduction – damage in open hole tension (OHT) specimen

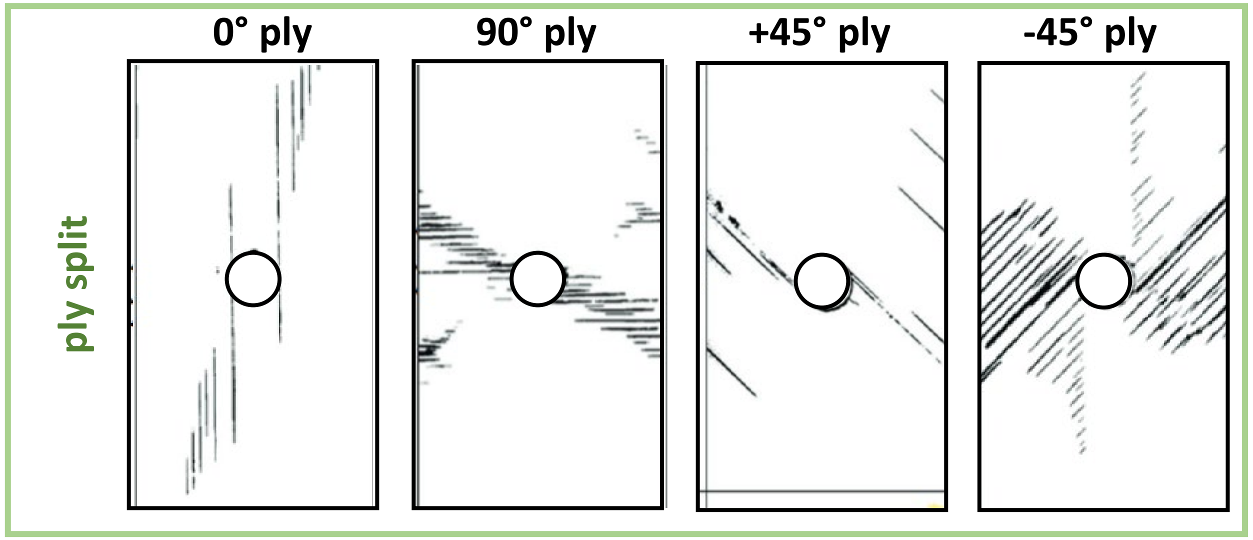
- **Experimental evidence of damage in OHT specimens –** *interlaminar and intralaminar*

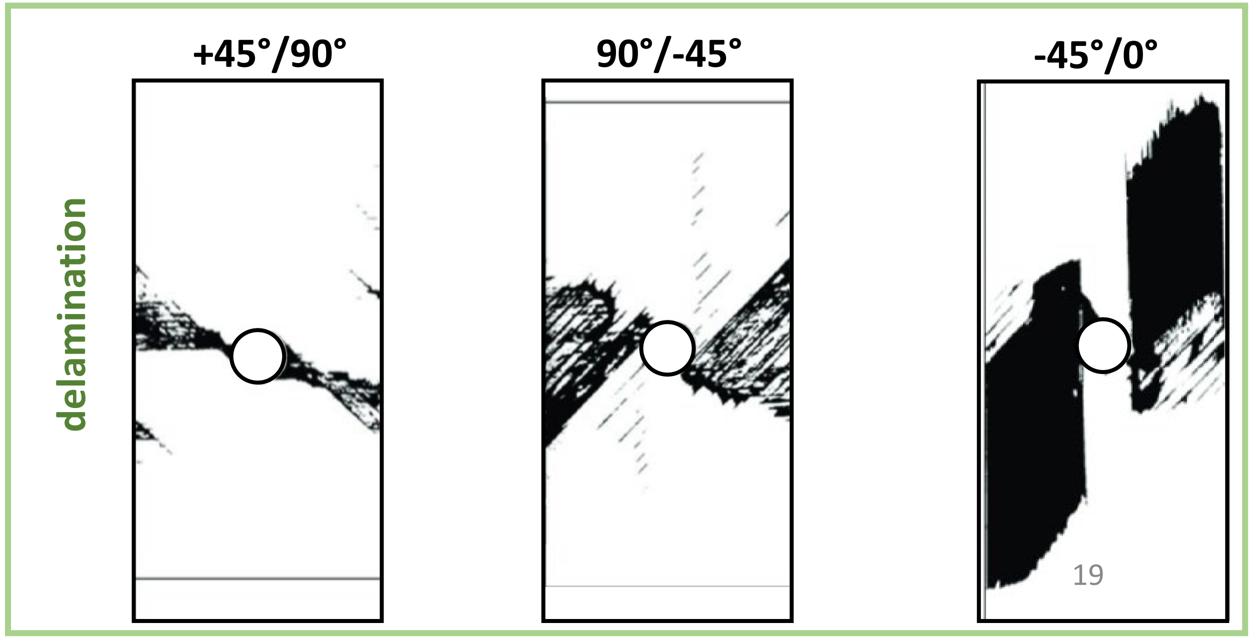
Nixon-Pearson, O. J., et al. *"Damage development in open-hole composite specimens in fatigue. Part 1: Experimental investigation."* ***Composite Structures*** *106 (2013): 882-889.*



overall damage pattern

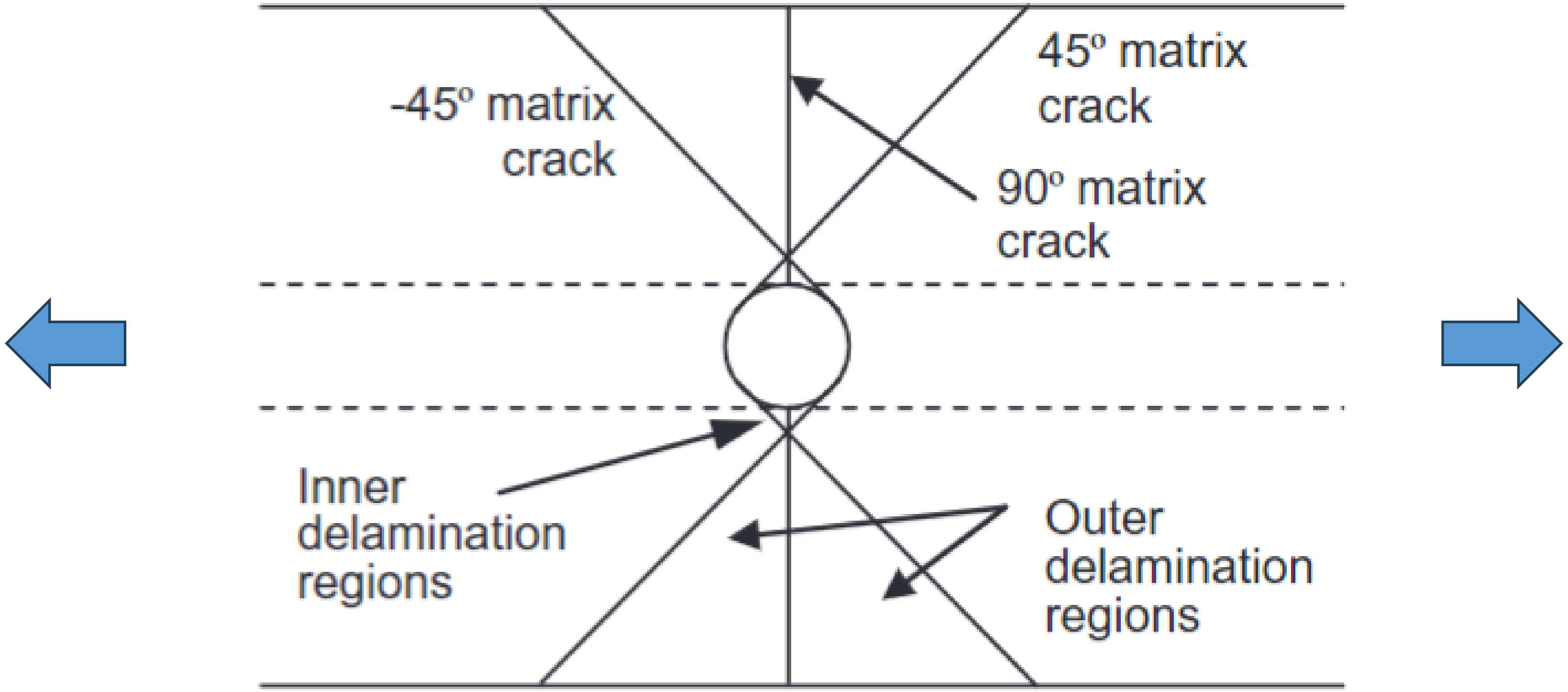






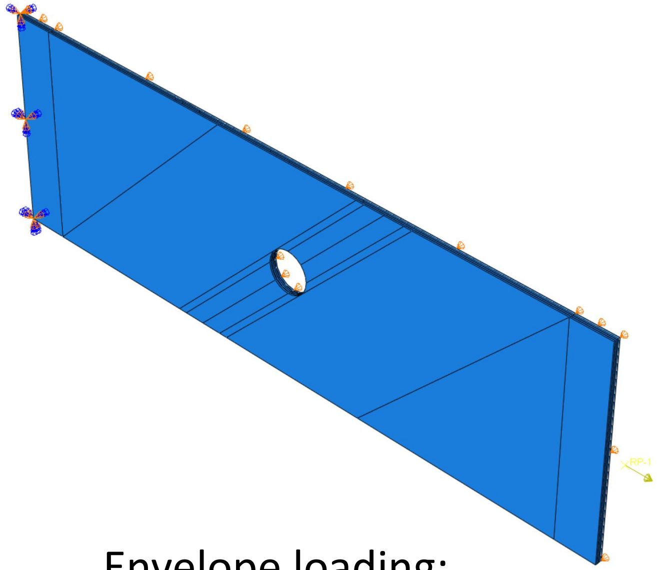
Methods – simplification of damage in OHT specimen

- **Simplification of damage modes –** *a schematic*

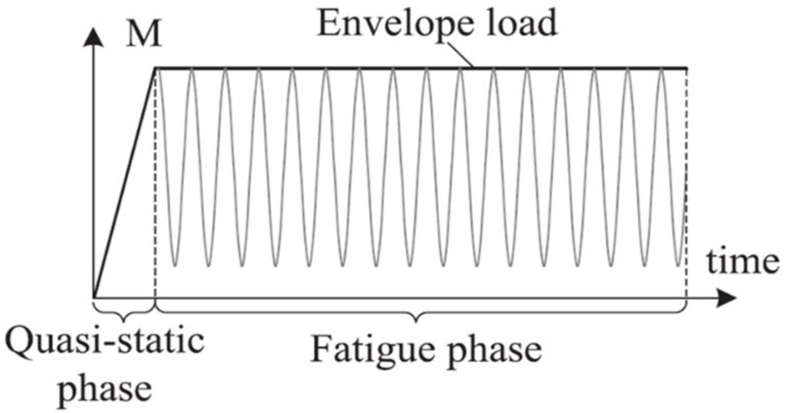


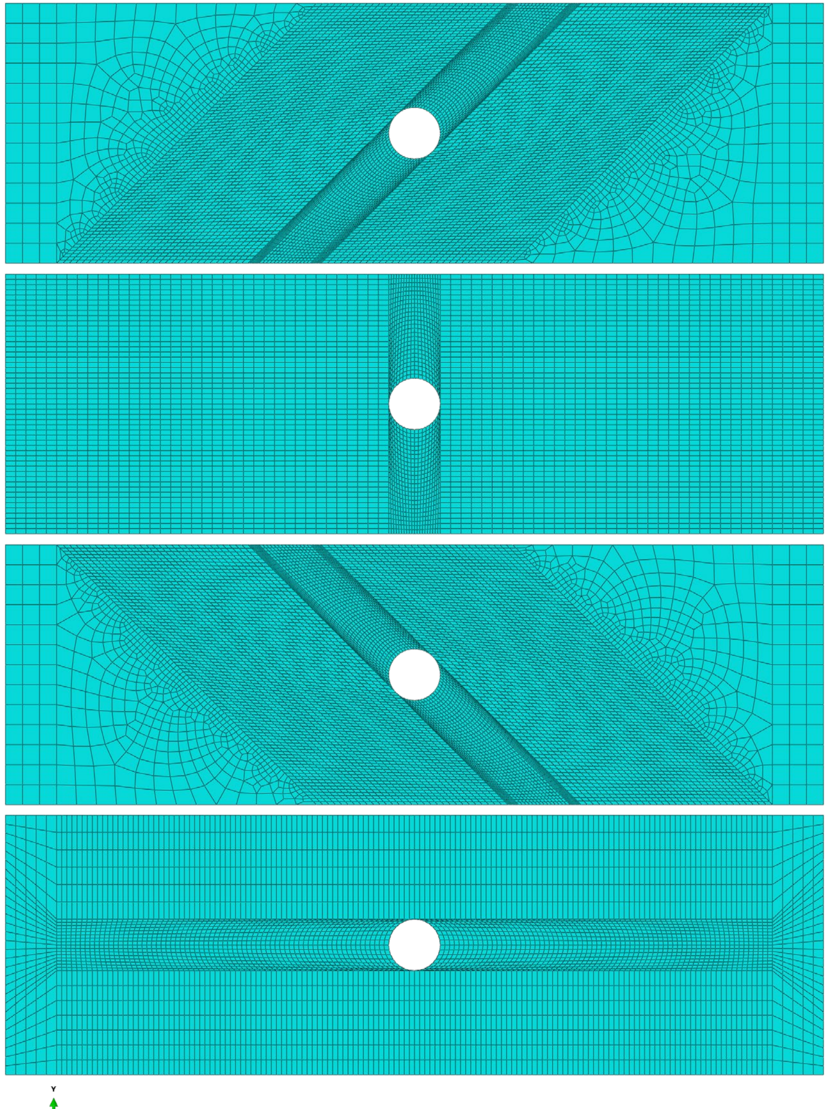
Methods – FE mesh of open hole tension specimen

$[45_2/90_2/-45_2/0_2]_s$ laminates with circular hole under cyclic tension



Envelope loading:

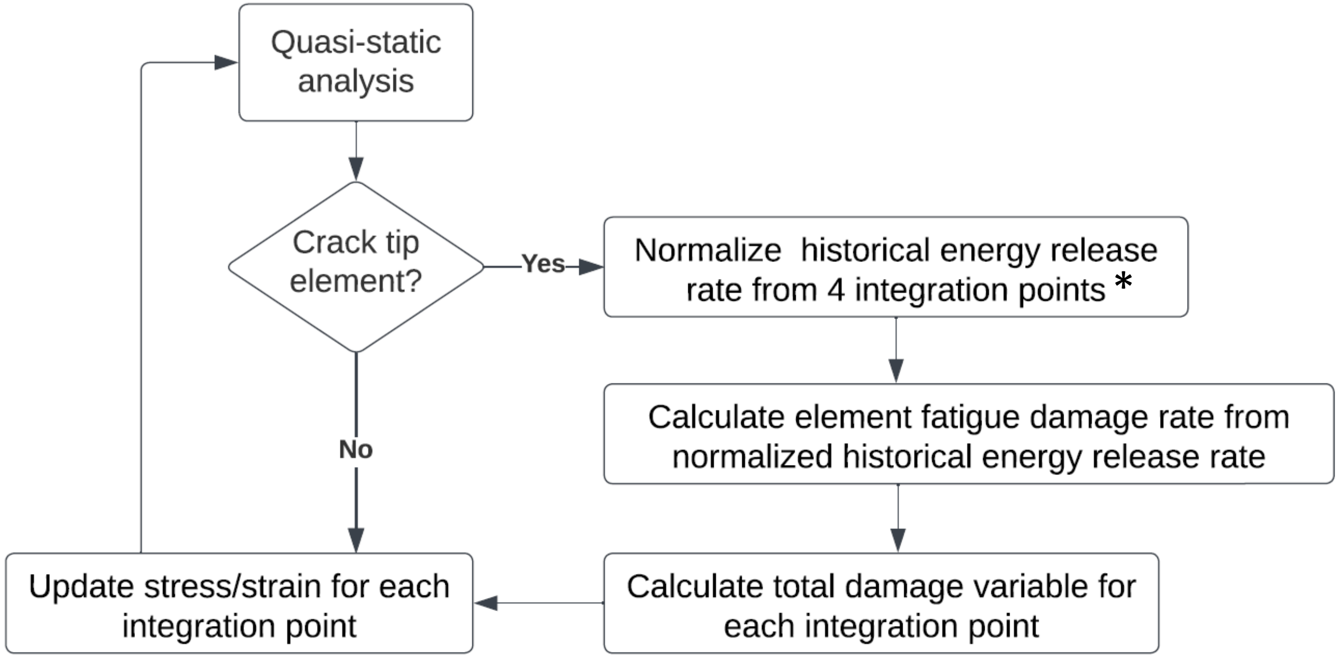




Methods – modeling framework

Key concepts:

- Elements in each ply experience **three stages: (1) quasi-static stage, (2) fatigue stage, (3) final failure stage**
- All elements initially experience **quasi-static stage**. Next, if user-defined initiation time during fatigue (so-called ***t-fatigue***) has been reached, then crack tip element would experience **fatigue stage**. Finally, elements reach the **final failure stage** using pre-defined ***t-final***.


Quasi-static analysis

Crack tip element?

Yes

Normalize historical energy release rate from 4 integration points *

Calculate element fatigue damage rate from normalized historical energy release rate

Calculate total damage variable for each integration point

No

Update stress/strain for each integration point

**We also recommend to use normalized historical energy release rate if the element has multiple integration points*

Three types of crack tip are tracked

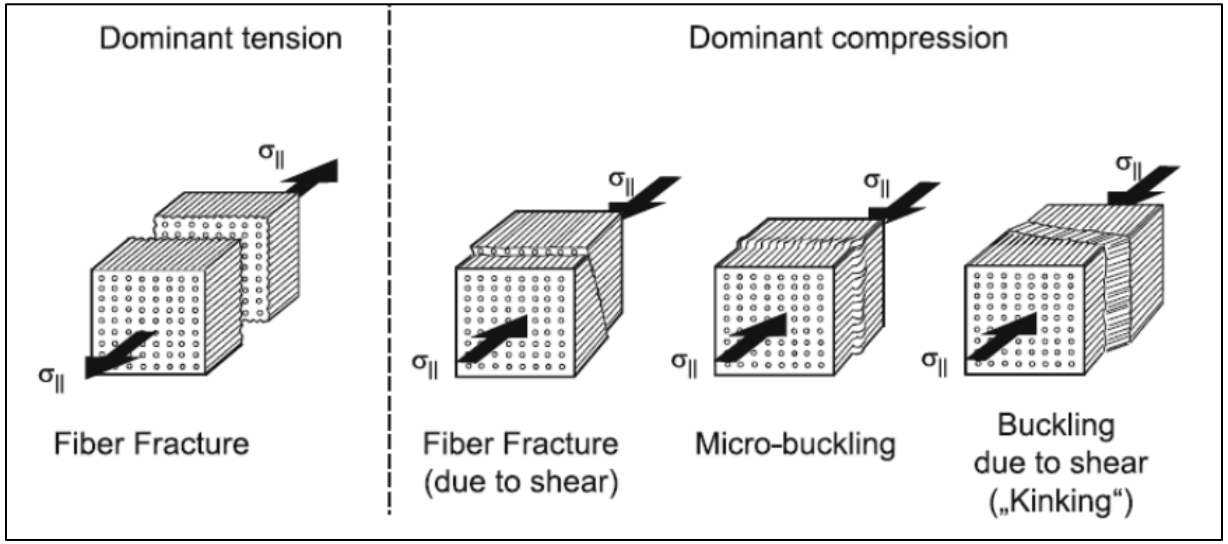
- Pre-set crack front
- Most damaged element after stabilization from static damage analysis
- Direct neighbor elements of failed elements of last time increment along crack propagation path

Methods – failure criteria

- **Puck's criteria –** distinguishing between fiber fracture and interfiber fracture

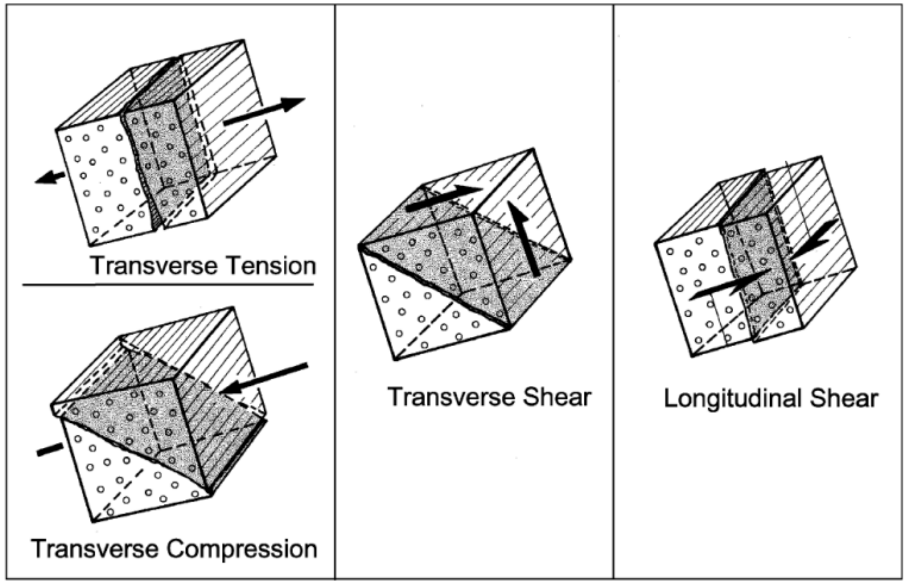
Fiber fracture (FF)

- Taking into account stresses between parallel fibers



Inter-fiber fracture (IFF)

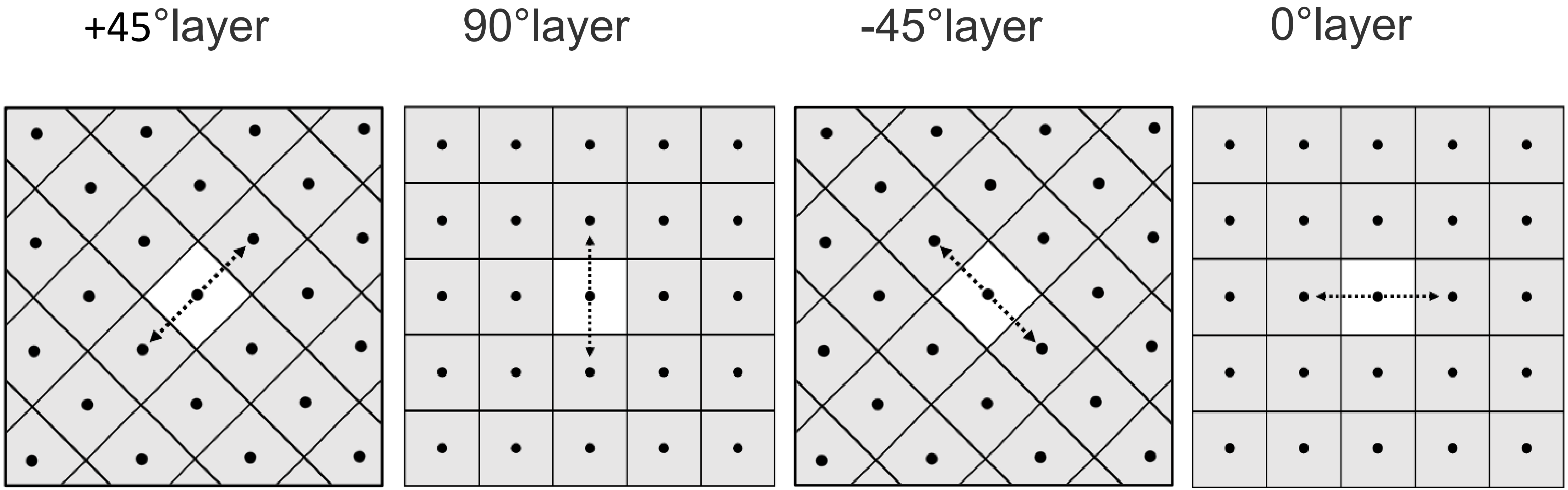
- Taking into account non-fracture plane stresses
- Including both cohesive fracture of the matrix and adhesive failure at fiber/matrix interface – (micromechanics-driven concept)



References: Bek et al. (2021), Kodagali (2017)

Methods – intralaminar crack simulation for each ply

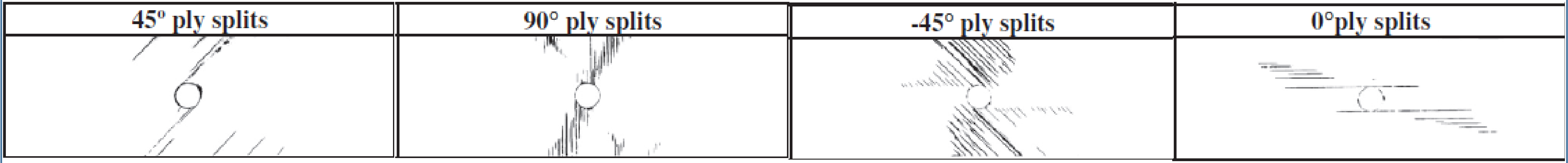
Key: **The characteristic length of crack propagation along the propagation path (l_e) is defined as the length between two integration points of the current crack tip element and crack tip element of previous time increment**



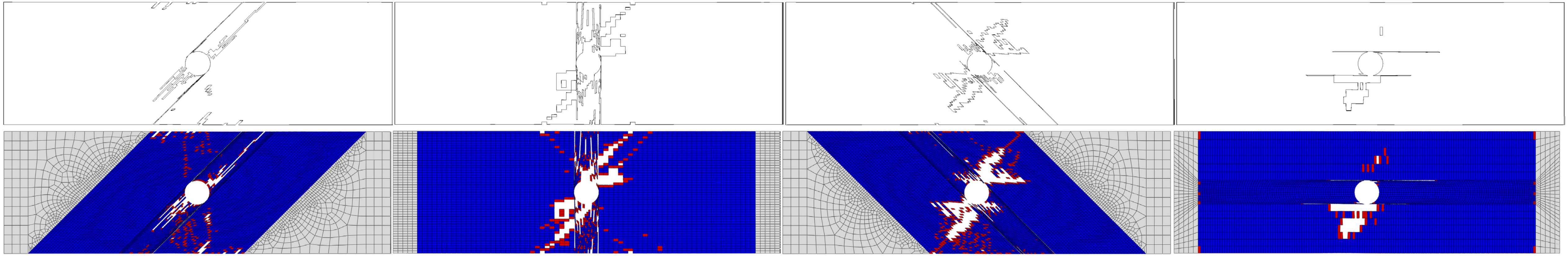
Results – damage pattern at N = 13,000 cycles (ply-by-ply)

Comparison between simulation and published literature [Nixon-Pearson, et al., 2013]

Literature: fatigue damage pattern (schematically drawn from micro-CT) after N = 13,213

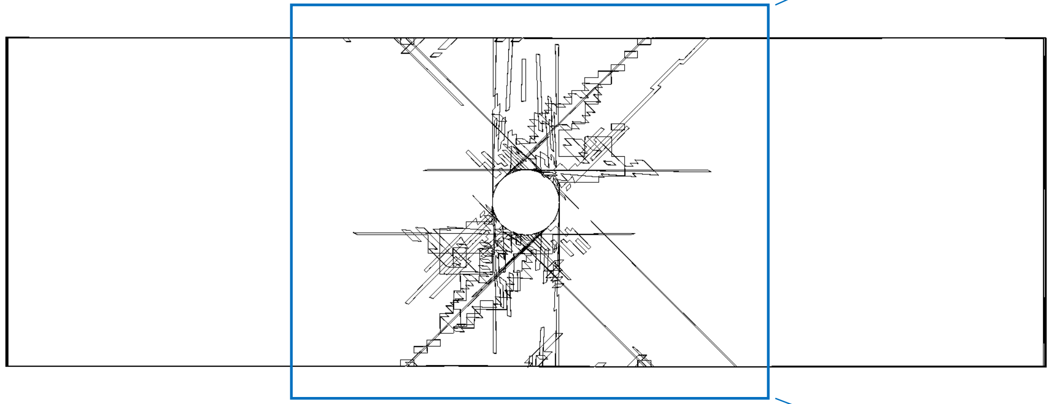


Current simulation: fatigue damage pattern after N = 13,000

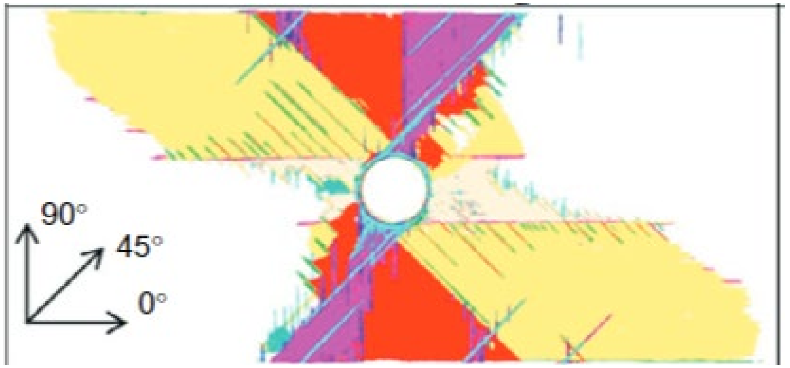


Results – damage pattern at N = 13,000 cycles (superposition)

Present simulation



Nixon-Pearson, et al. Composite Structures (2013)



Future work: implementation of cohesive element at the laminate interfaces for simulating delamination

Conclusions

Modeling strategy for simulating interlaminar fatigue damage in composites

- Crack tip tracking method and Kawashita-Hallett fatigue degradation model was implemented in cohesive zone model in ABAQUS/Explicit
- Simulation results agree well with experiments for different crack fronts and varying load ratio

Modeling strategy for simulating intralaminar fatigue damage in composites

- Crack propagation in quasi-isotropic laminate $[45_2/90_2/-45_2/0_2]_S$ using open hole specimen under T-T fatigue where Puck's criterion is implemented to predict intralaminar cracks
- Simulation results agree well with experiments from published literature
- Delamination between plies will be developed in the future

THANK YOU