Modeling delamination migration: quasi-static and fatigue loading

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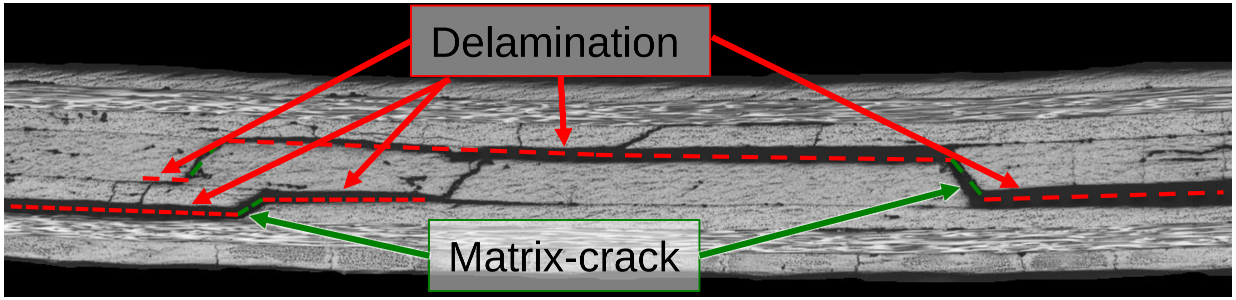
Motivation

Migration: **The process by which a propagating delamination relocates to a new ply interface via matrix cracking**

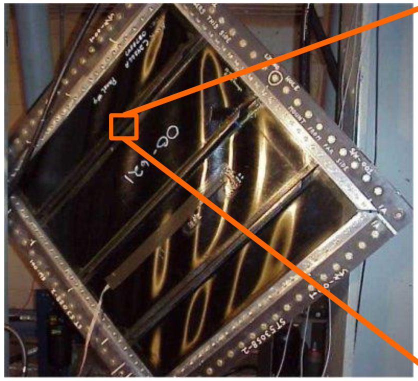
Impact

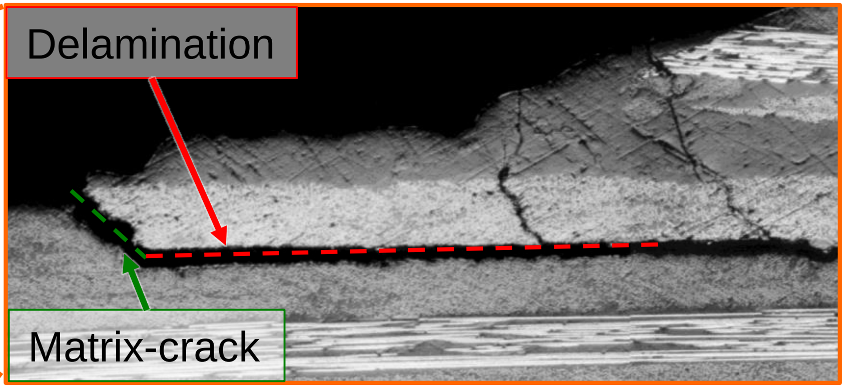


M. McElroy et al. A numerical and experimental study of damage growth in a composite laminate. in proceedings of the ASC 29th Technical Conference, San Diego, CA, USA, 2014.

Skin-stringer pull off

R. Krueger et al. Fatigue Life Methodology for Bonded Composite Skin/Stringer Configurations. NASA/TM-2001-210842, 2001.





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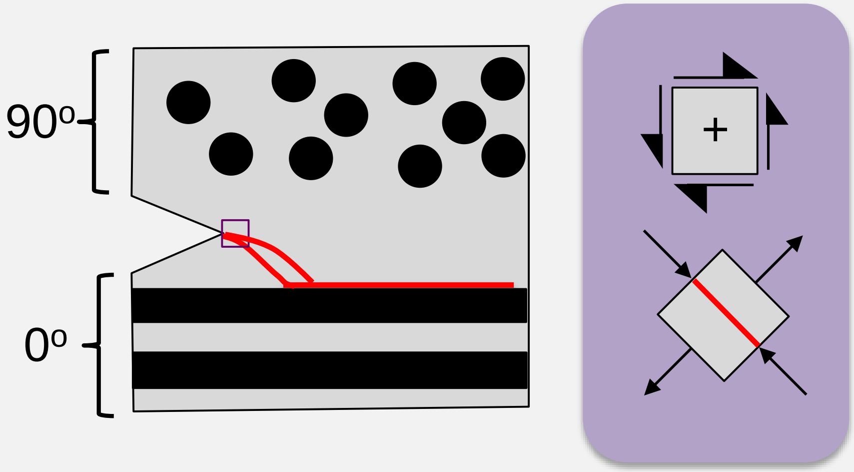
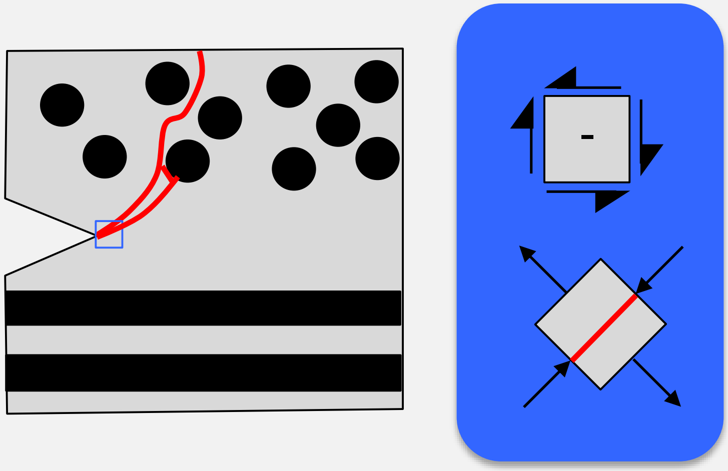
Experiments: delamination migration
Test Setup - Premise

Delamination
("positive" shear stress)



*adapted from Greenhalgh, 2009

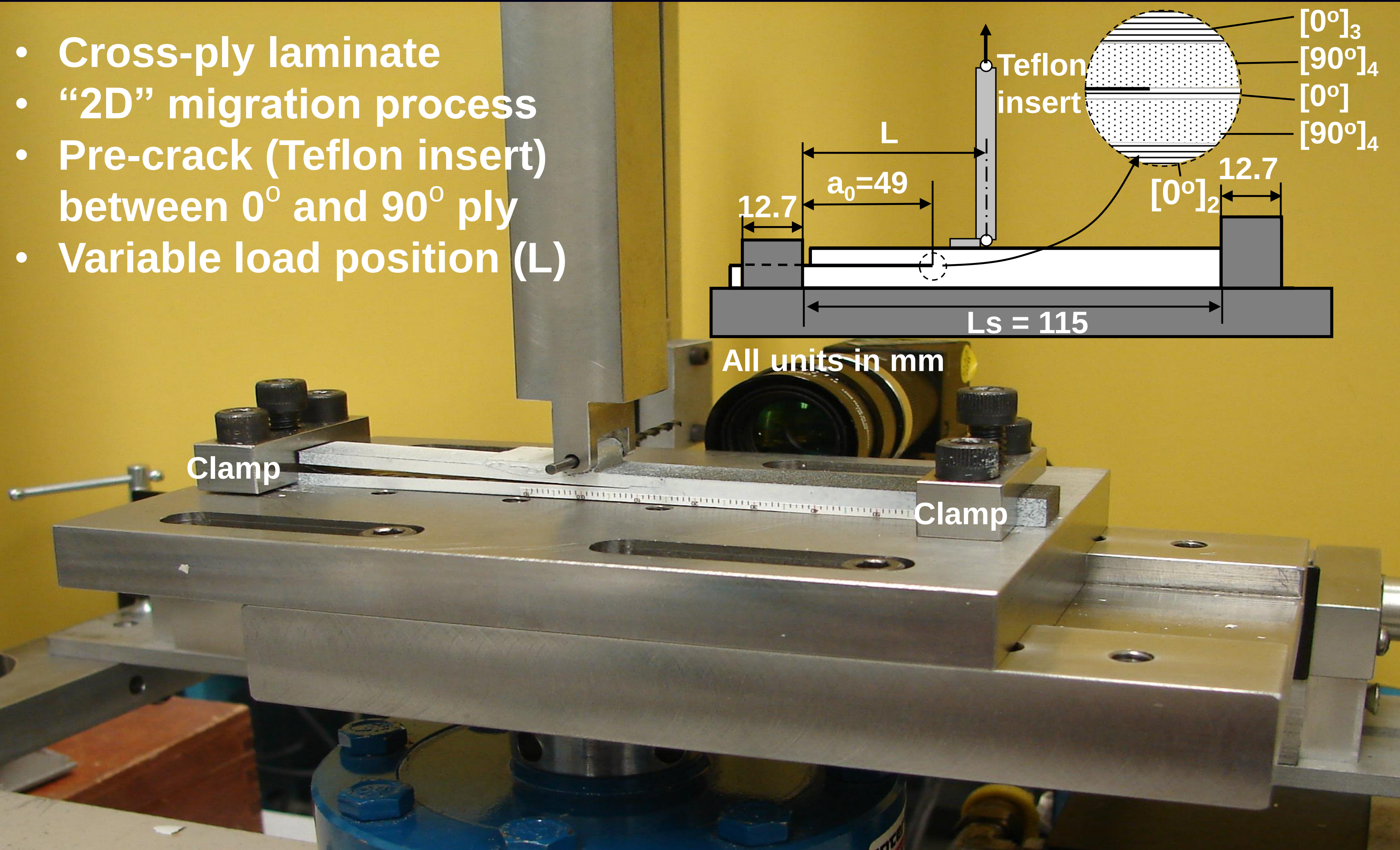
Migration
("negative" shear stress)



*E.S. Greenhalgh, C. Rogers, P. Robinson. Fractographic observations on delamination growth and the subsequent migration through the laminate. Composites Science and Technology, 69:2345-2351, 2009.

Experiments: delamination migration test
Test setup

- **Cross-ply laminate**
- **"2D" migration process**
- **Pre-crack (Teflon insert) between 0^{o} and 90^{o} ply**
- **Variable load position (L)**

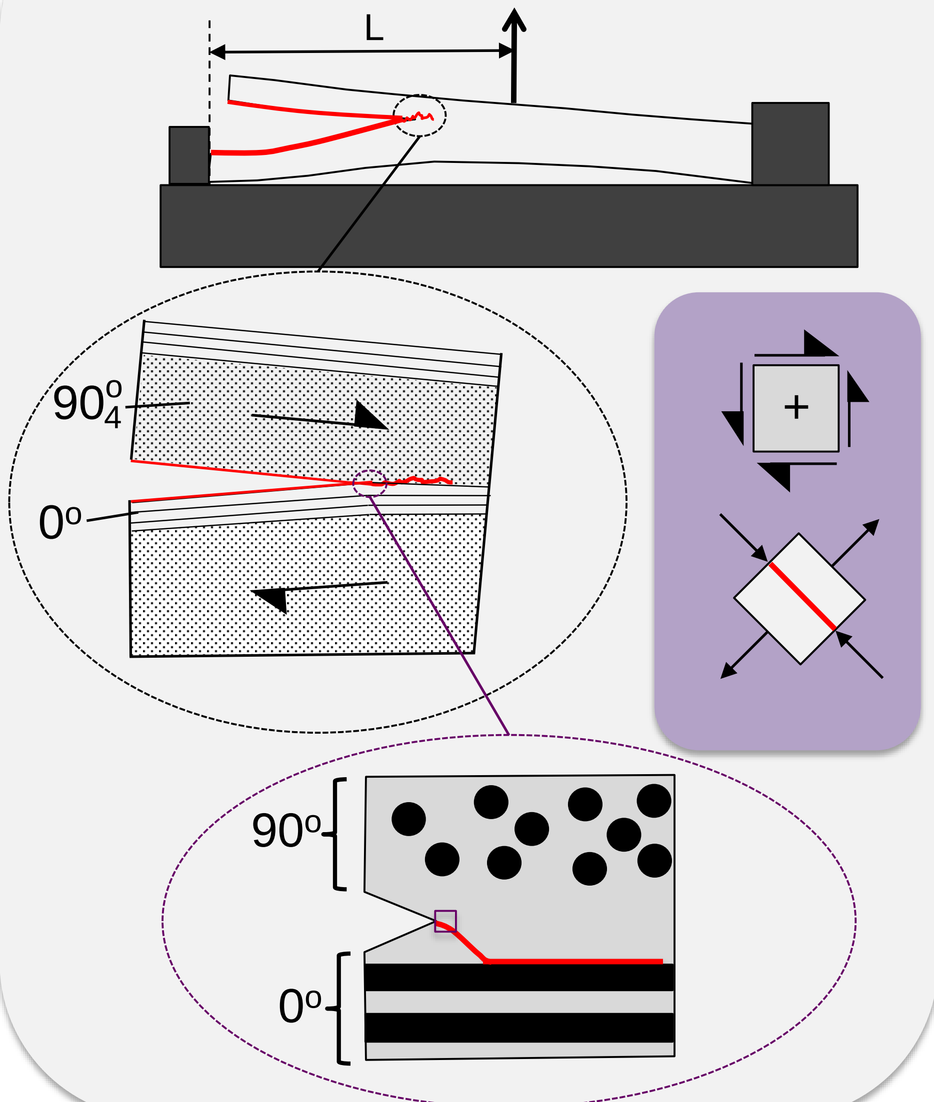


J.G. Ratcliffe, M.W. Czabaj and T.K. O'Brien. A test for characterizing delamination migration in carbon/epoxy tape laminates. NASA/TM-2013-218028, 2014.

Experiments: delamination migration test

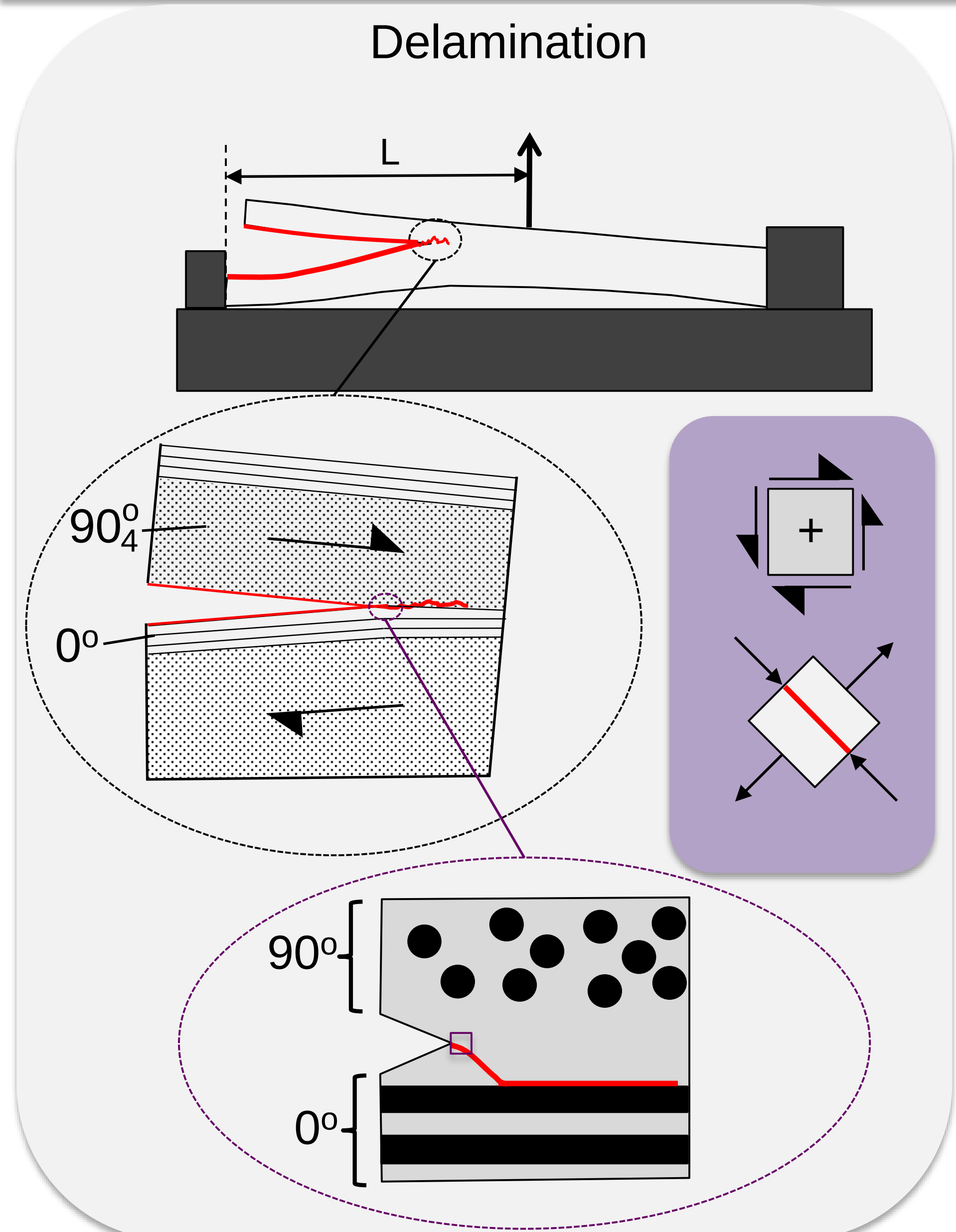
Test setup - overview

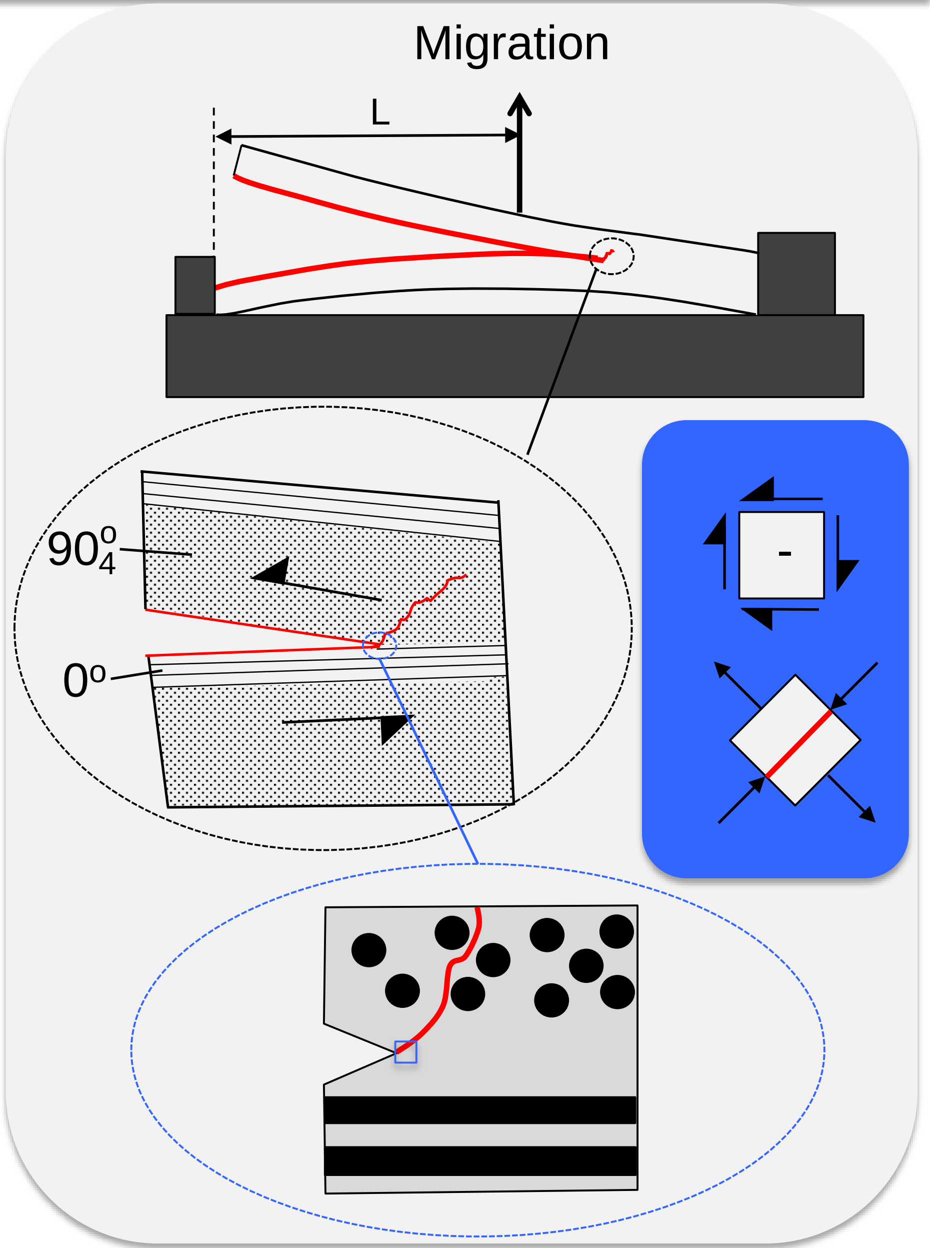
Delamination



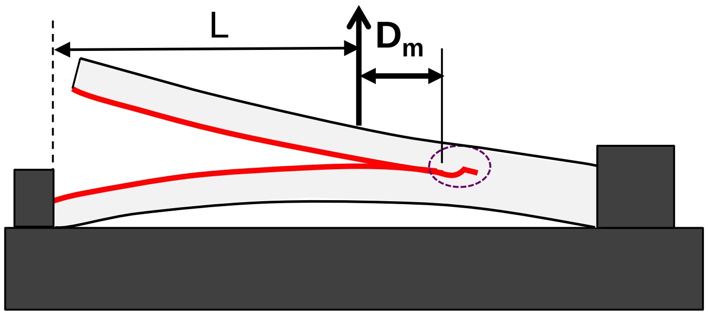
Experiments: delamination migration test

Test setup - overview

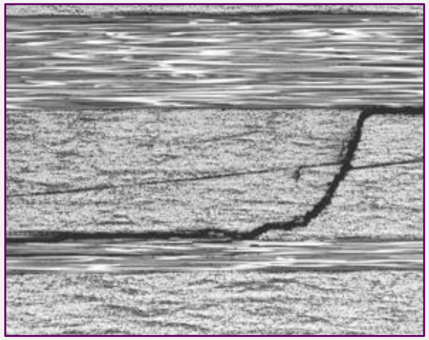




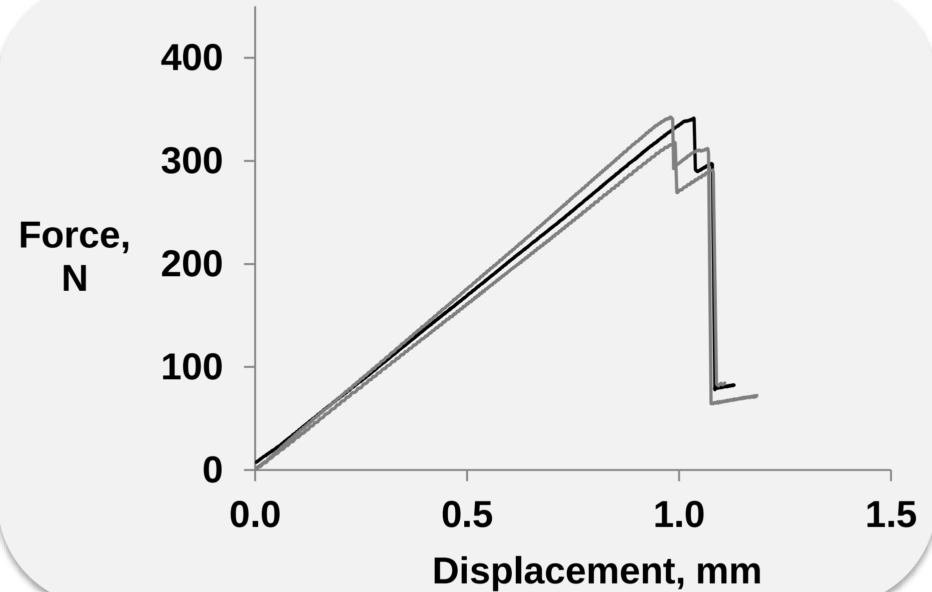
Experiments: delamination migration test
Test setup – validation data



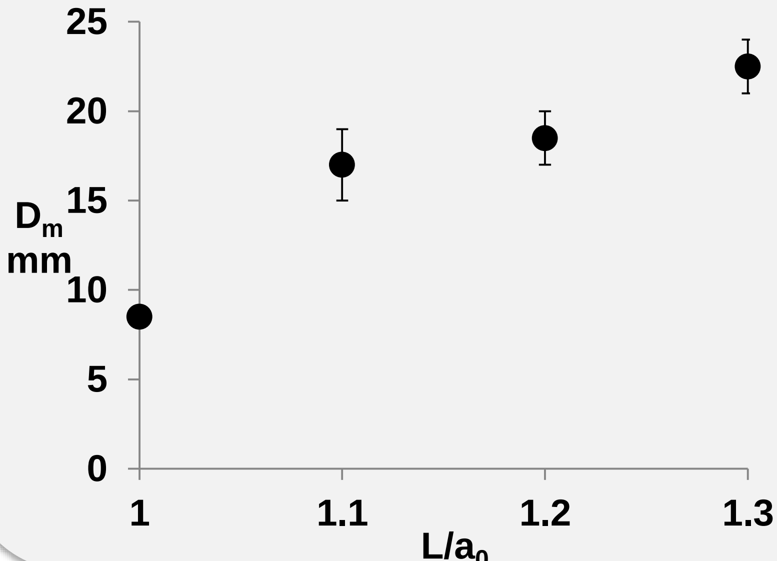
Damage morphology



Load - displacement



Migration location



Contents

Floating Node Method

Same implementation strategy suitable for standard finite element architecture

X-FEM

Phantom Node Method (PNM)

Floating Node Method (FNM)

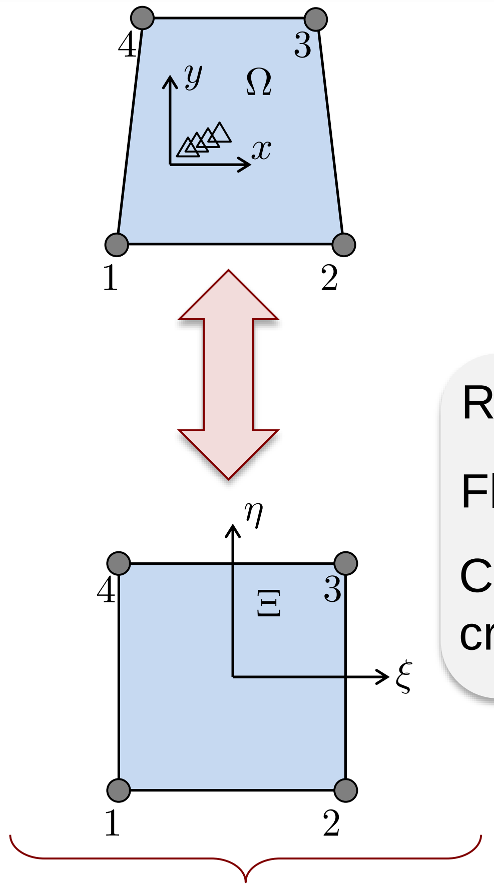
Remeshing

Same solution

Same solution

B.Y. Chen, S.T. Pinho, N.V. De Carvalho, P.M. Baiz, T.E. Tay, A floating node method for the modelling of discontinuities in composites, Engineering Fracture Mechanics, Vol. 127:104-134, 2014.

Floating Node Method (FNM)



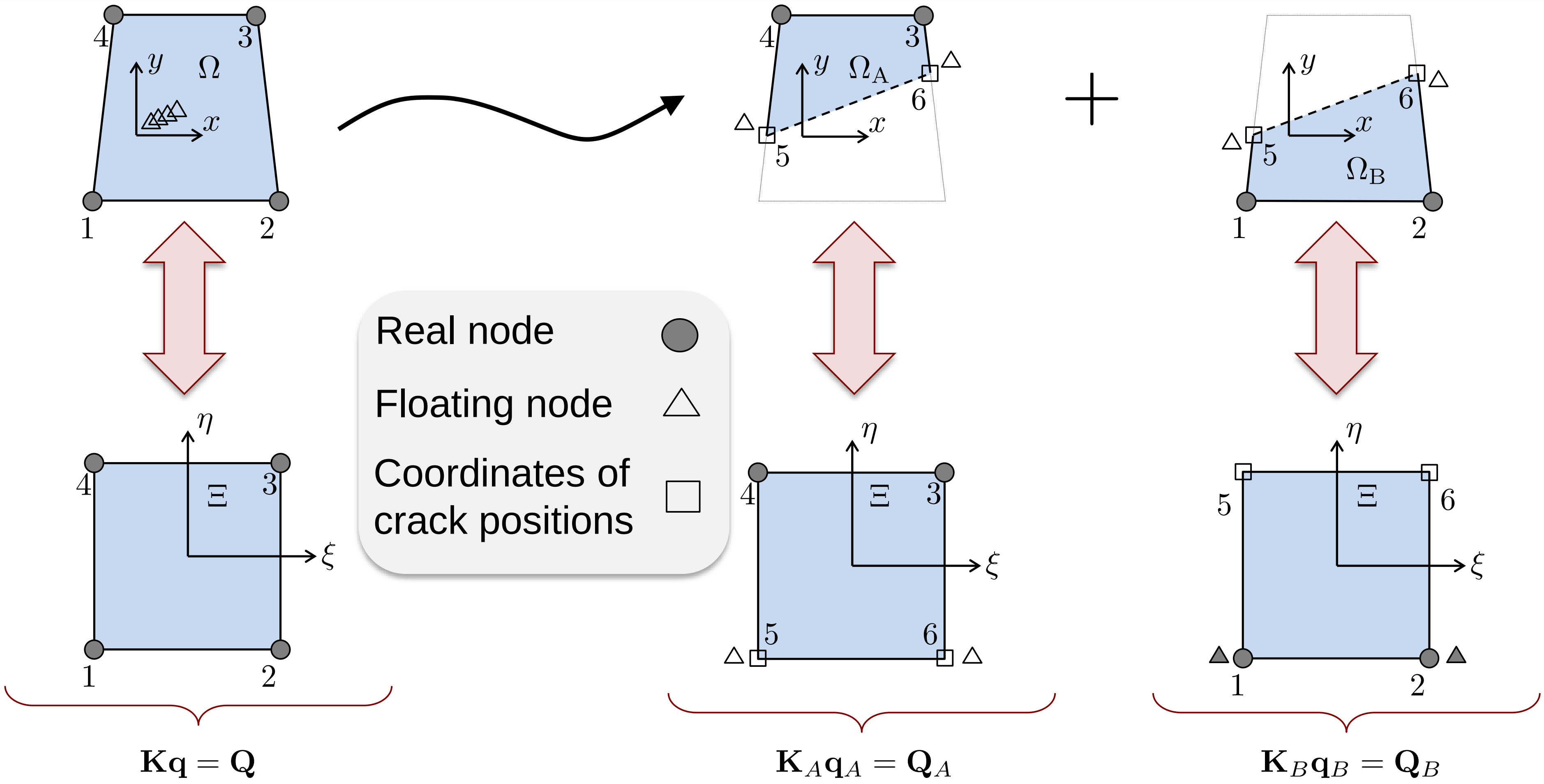
Real node

Floating node

Coordinates of crack positions

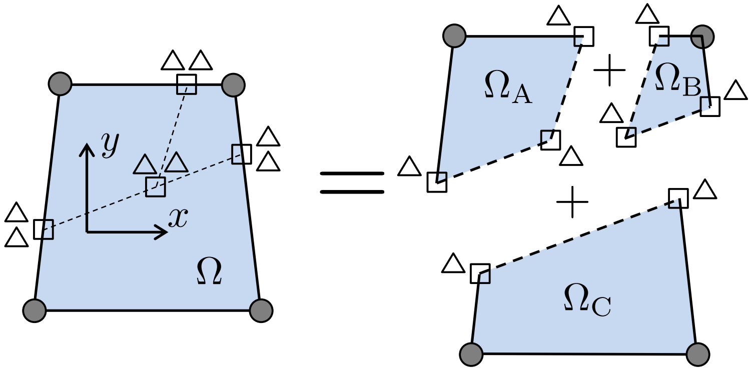
$$\mathbf{Kq} = \mathbf{Q}$$

Floating Node Method (FNM)

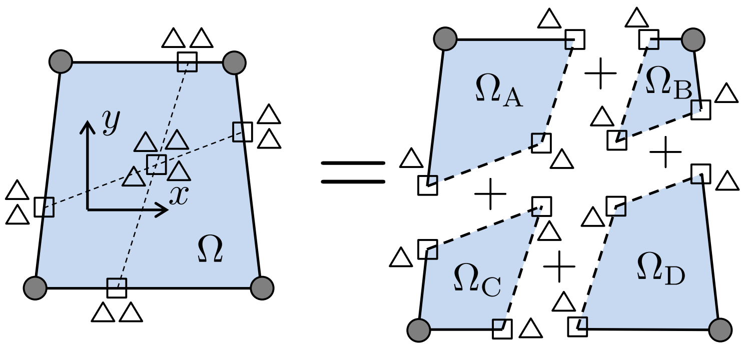


Floating Node Method (FNM)

T crack



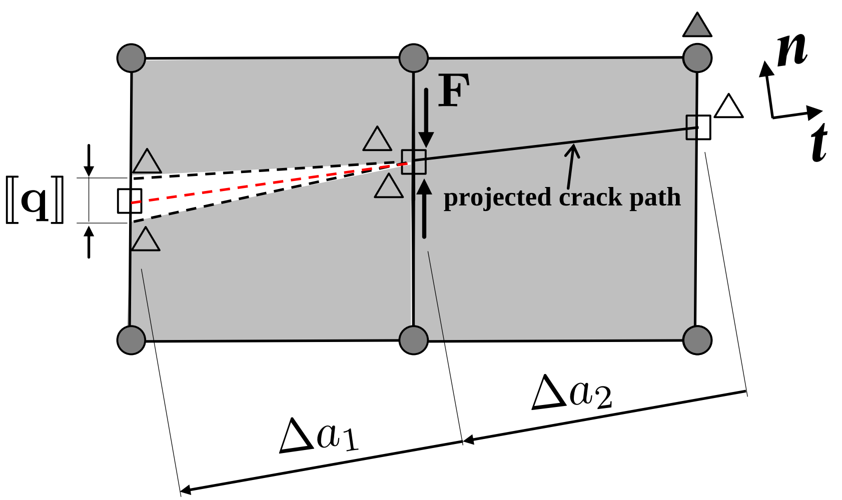
Intersecting cracks



Key Characteristics:

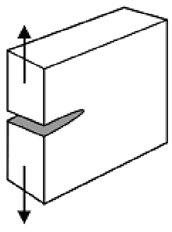
- Floating Nodes are topologically related to each element with no initial position assigned
- The position of the floating nodes is assigned only after the crack path is determined
- The floating nodes are used to form sub-elements within the original element and accommodate crack networks
- Ideally suited to represent multiple cracks and their intersection
- Can be coupled with **Virtual Crack Closure Technique (VCCT)** and <u>cohesive zone crack formulations</u> to model crack propagation

Virtual Crack Closure Technique (VCCT):



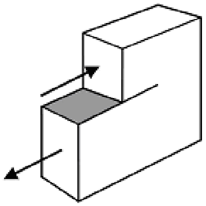
Mode I

$$G_I = \frac{1}{2\Delta a_1} F_n [\![q_\mathrm{n}]\!] \left(\frac{\Delta a_1}{\Delta a_2} \right)^{\frac{1}{2}}$$



Mode II

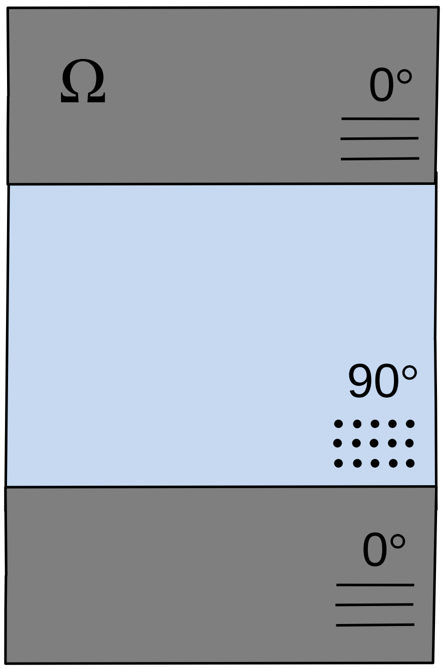
$$G_{II} = \frac{1}{2\Delta a_1} F_t [\![q_\mathrm{t}]\!] \left(\frac{\Delta a_1}{\Delta a_2} \right)^{\frac{1}{2}}$$



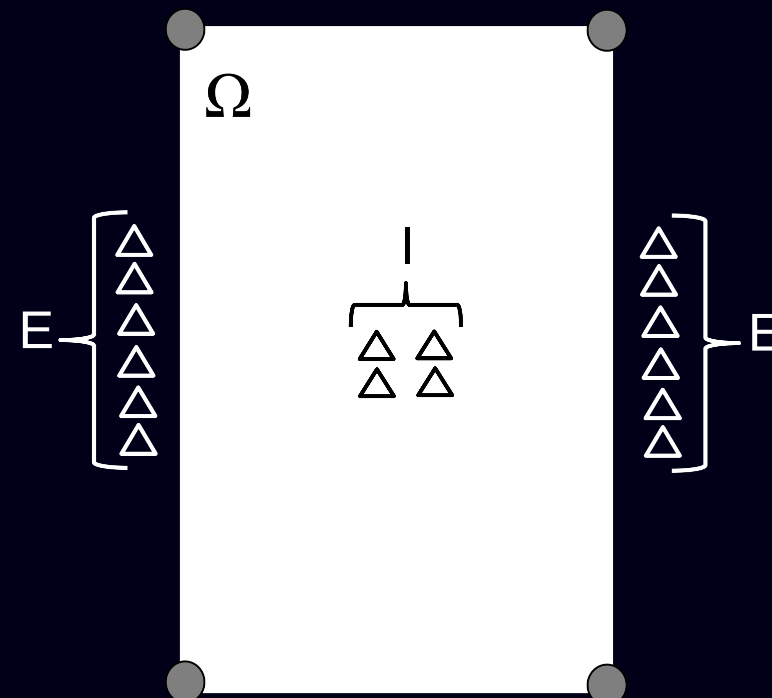
FNM & VCCT applied to cross-ply laminates:

Laminate

[0°/90°$_2$/0°]



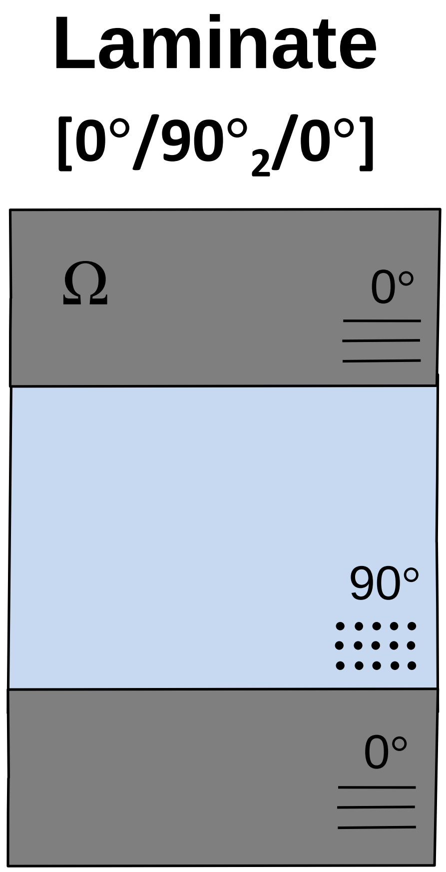
1 FNM Element (multiple plies)

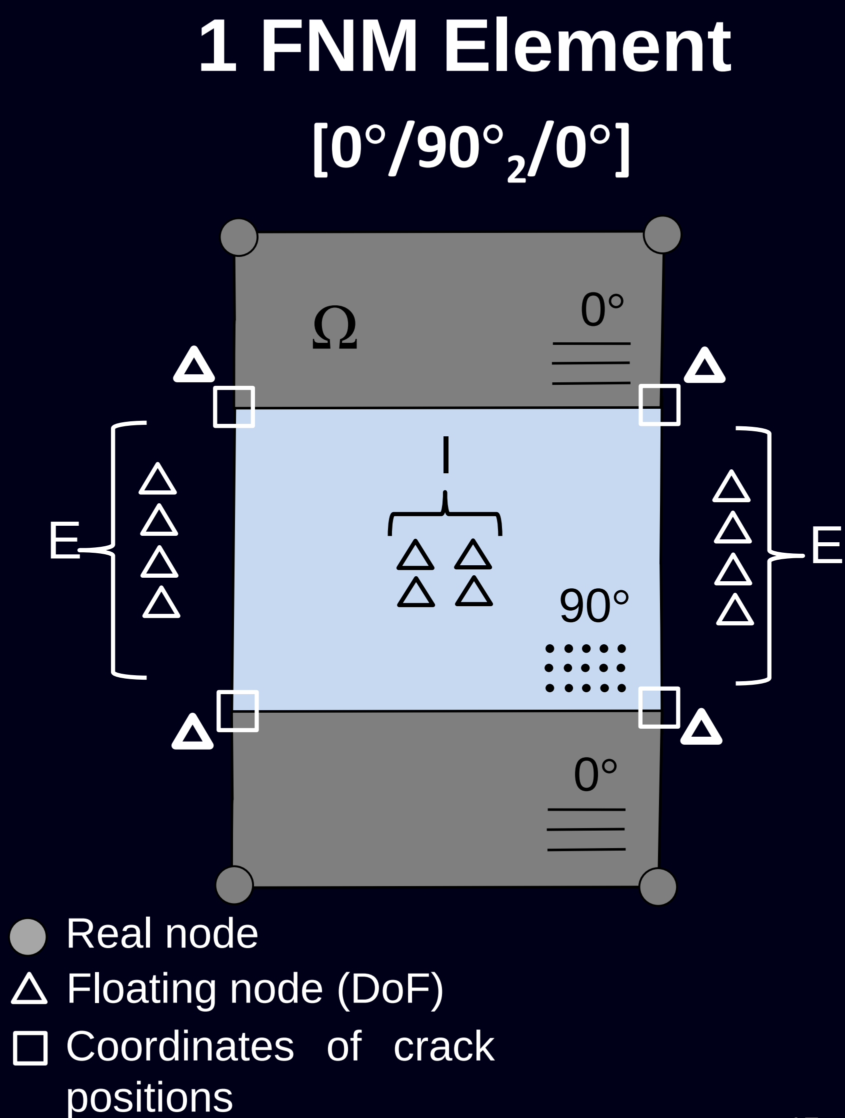


● Real node
△ Floating node (DoF)
□ Coordinates of crack positions

N.V. De Carvalho et al, Modeling delamination migration in cross-ply tape laminates, Composites Part A: Applied Science and Manufacturing, 71, 192-203, 2015.

FNM & VCCT applied to cross-ply laminates:





FNM & VCCT applied to cross-ply laminates:

Quasi-static

- **Fracture Criterion:**

$$f\left(G_I, G_{II}\right) = \frac{G_T}{G_c^{Int}} - 1 = 0$$

- **Mixed Mode exponential law:**

$$G_c^{Int} = G_{Ic} + \left(G_{IIc} - G_{Ic}\right)\left(\frac{G_{II}}{G_T}\right)^{\eta}$$

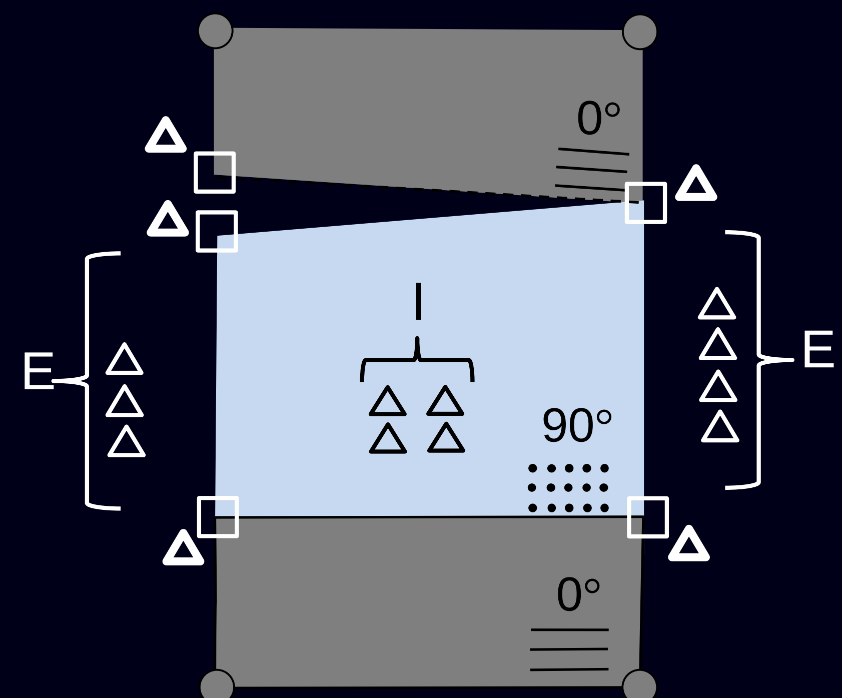
Fatigue

$$\frac{\mathrm{d}a}{\mathrm{d}N} = A\left(G_{Tmax}\right)^{n}$$

$$n = n_I + \left(n_{II} - n_I\right)\left(\frac{G_{IImax}}{G_T}\right)$$

$$A = A_I + \left(A_{II} - A_I\right)\left(\frac{G_{IImax}}{G_T}\right)$$

Delamination



- Real node
- Floating node (DoF)
- Coordinates of crack positions

FNM & VCCT applied to cross-ply laminates: Migration onset

Quasi-static

$$\frac{G_T}{G_c^i\left(F_t\right)} > \frac{G_T}{G_c^{Inter}} \geq 1$$

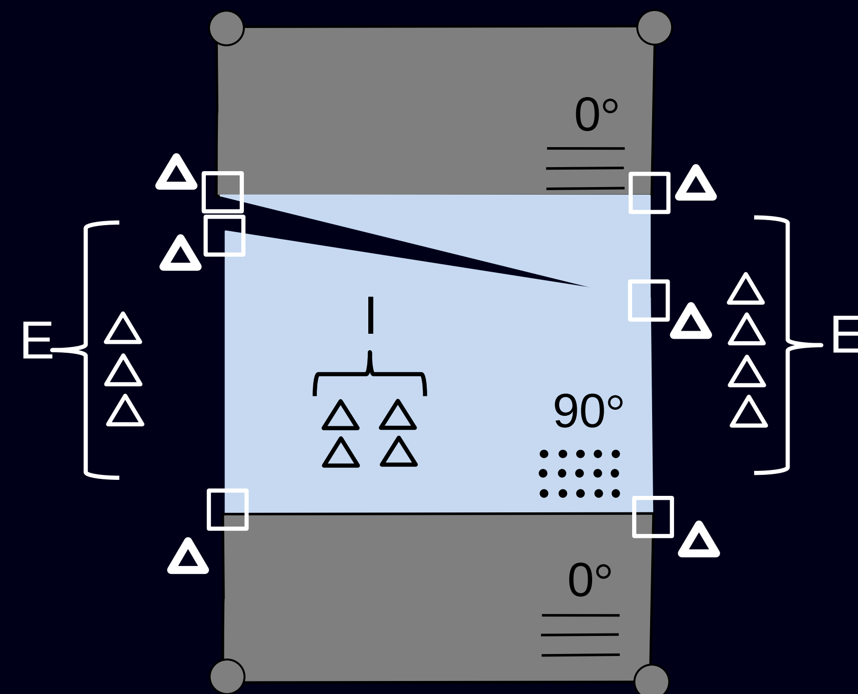
$$G_c^i = \begin{cases} G_c^A, & F_t < 0 \\ G_c^B, & F_t > 0 \end{cases}$$

Fatigue

$$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\left(F_t\right)\right)_i > \left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{Inter}$$

$$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_i = \begin{cases} \left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_A, & F_t < 0 \\ \left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_B, & F_t > 0 \end{cases}$$

Migration onset (delamination to matrix crack)

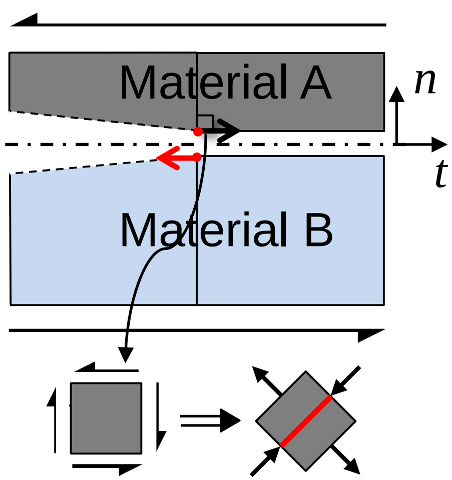


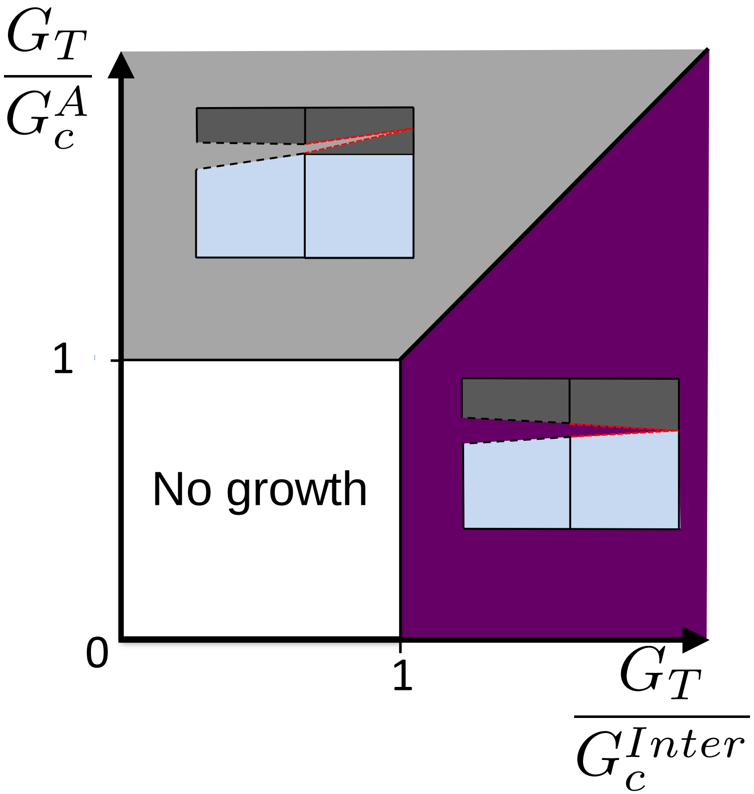
- Real node
- Floating node (DoF)
- Coordinates of crack positions

FNM & VCCT applied to cross-ply laminates: Migration onset – quasi-static

$$\boxed{\frac{G_T}{G_c^i\left(F_t\right)}} > \boxed{\frac{G_T}{G_c^{Inter}}} \geq 1$$

$$G_c^i = \begin{cases} \boxed{G_c^A, \quad F_t < 0} \\ G_c^B, \quad F_t > 0 \end{cases}$$

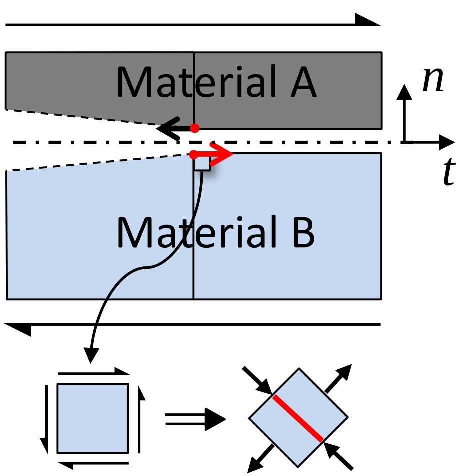


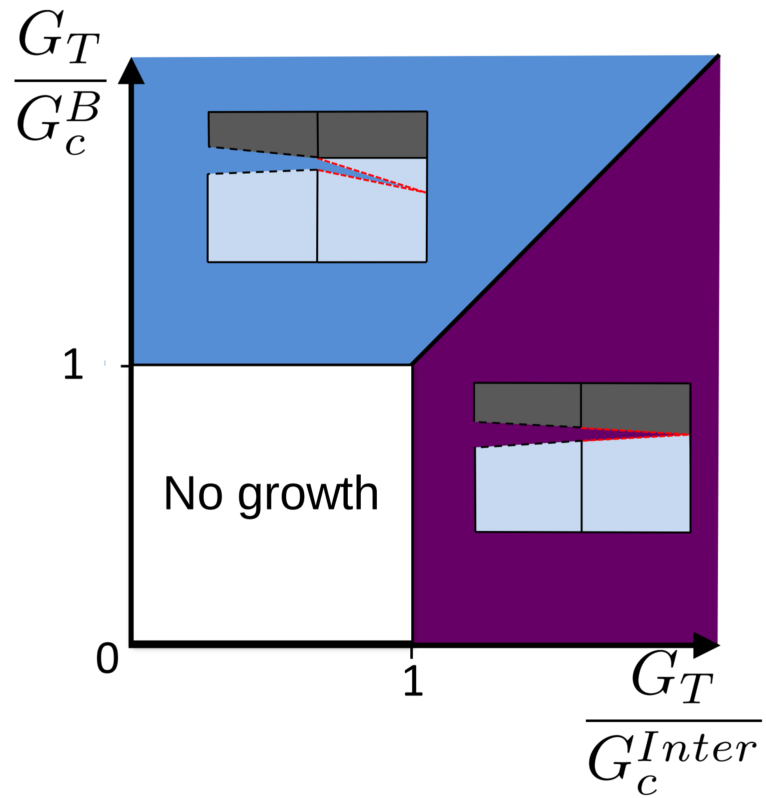


FNM & VCCT applied to cross-ply laminates: Migration onset – quasi-static

$$\boxed{\frac{G_T}{G_c^i\left(F_t\right)}} > \boxed{\frac{G_T}{G_c^{Inter}}} \geq 1$$

$$G_c^i = \begin{cases} G_c^A, & F_t < 0 \\ \boxed{G_c^B, \quad F_t > 0} \end{cases}$$

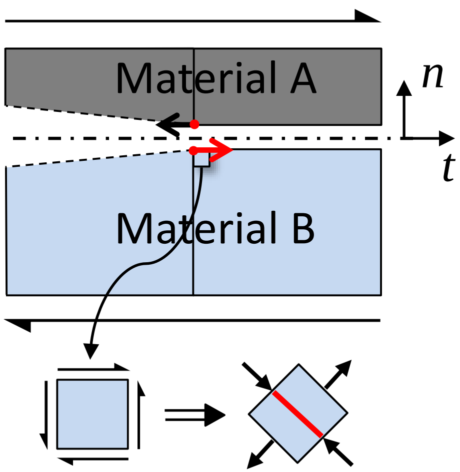


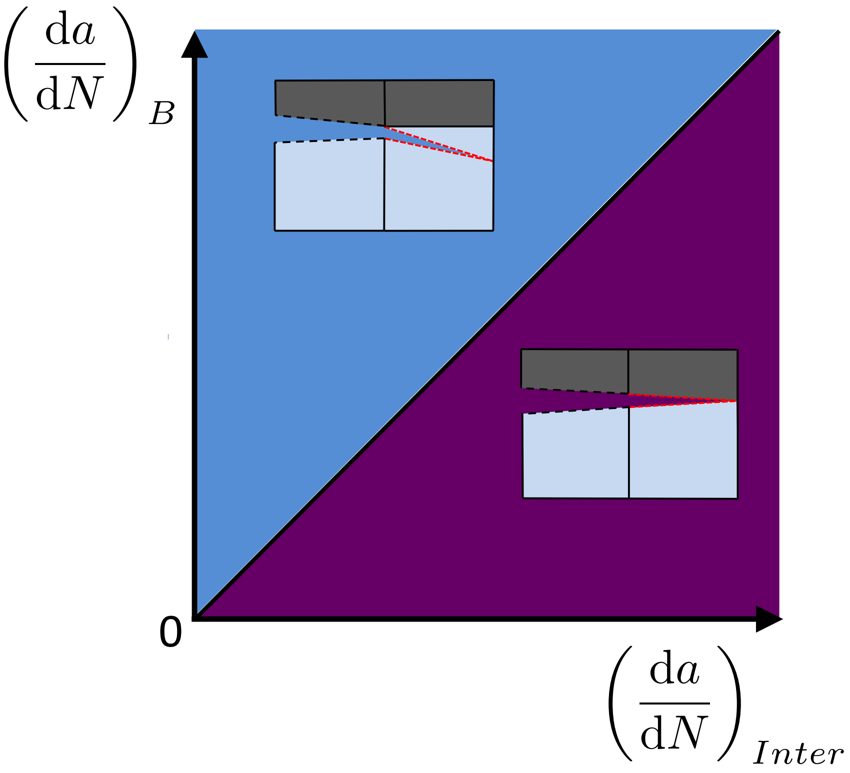


FNM & VCCT - application to composites: Migration onset - fatigue

$$\boxed{\left(\frac{\mathrm{d}a}{\mathrm{d}N}(F_t)\right)_i} > \boxed{\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_{Inter}}$$

$$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_i = \begin{cases} \left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_A, & F_t < 0 \\ \boxed{\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)_B, \quad F_t > 0} \end{cases}$$





FNM & VCCT applied to cross-ply laminates:

Quasi-static

$$f\left(G_I, G_{II}\right) = \frac{G_T}{G_{Ic}} - 1 = 0$$

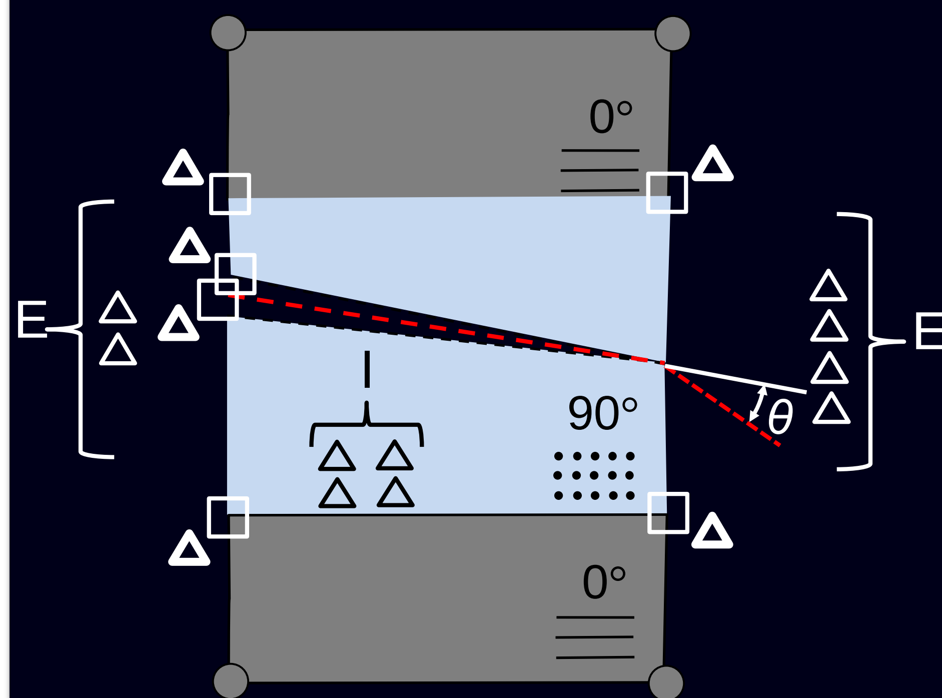
Fatigue

$$\frac{\mathrm{d}a}{\mathrm{d}N} = A_I \left(G_{Tmax}\right)^{n_I}$$

Maximum tangential stress criterion:

$$\theta = 2\tan^{-1}\left(\frac{1}{4}\left[\left(\frac{G_I}{G_{II}}\right) \pm \sqrt{\left(\frac{G_I}{G_{II}}\right)^2 + 8}\right]\right)$$

Matrix Crack

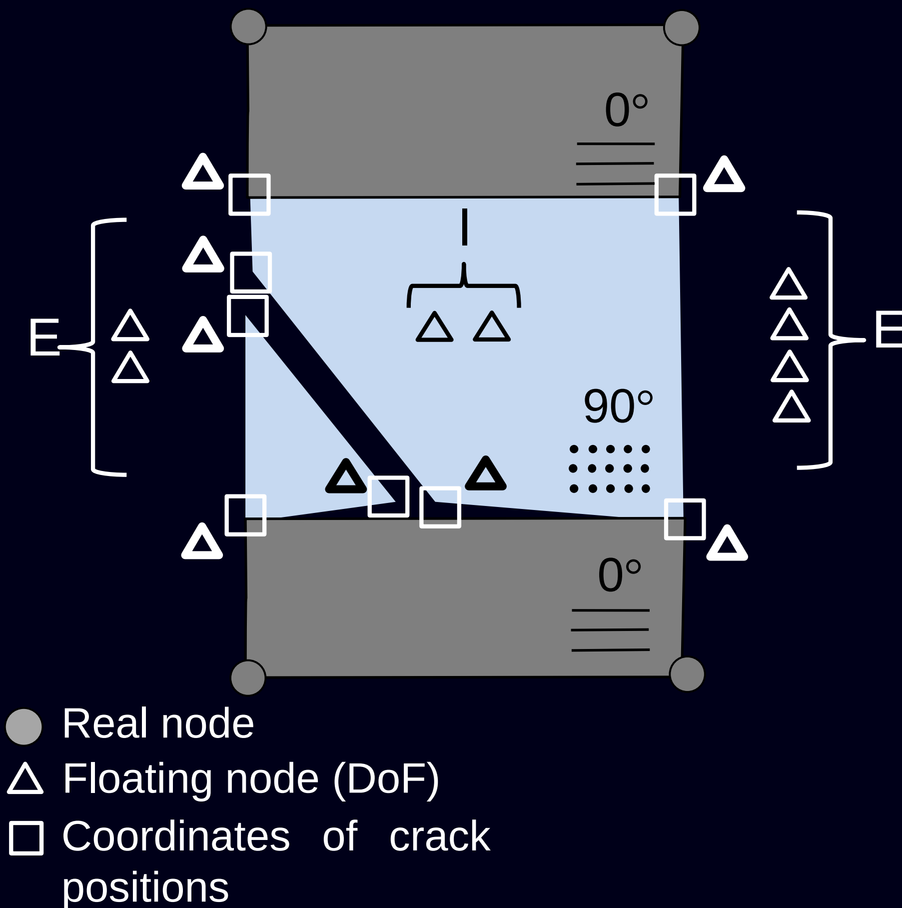


- Real node
- Floating node (DoF)
- Coordinates of crack positions

FNM & VCCT - application to composites: migration matrix crack to delamination interaction

- **Topological criterion**
  - **local delamination is onset when matrix crack reaches interface**

Migration
(matrix crack to delamination)



Fatigue algorithm

$$G_{Imax}\big|^{i},\ G_{IImax}\big|^{i}$$

$$\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)\Bigg|^{i}$$

❶ DETERMINE THE GROWTH RATE FOR EACH CRACK

$$\delta N\big|^{i}_{inc} = \frac{\delta a\big|^{i}_{1el}}{\left(\frac{\mathrm{d}a}{\mathrm{d}N}\right)\Big|^{i}} - \delta N\big|^{i}_{acc}$$

$$\delta N\big|^{n}_{inc} = \min\left\{ \delta N\big|^{i}_{inc} \right\}$$

❷ DETERMINE THE NUMBER OF CYCLES NEEDED TO PROPAGATE EACH CRACK BY ONE ELEMENT, AND THE CRACK WHICH PROPAGATES IN FEWEST CYCLES

$$a\big|^{n} = a\big|^{n} + \delta a\big|^{n}_{1el}$$

❸ PROPAGATE THE CRACK

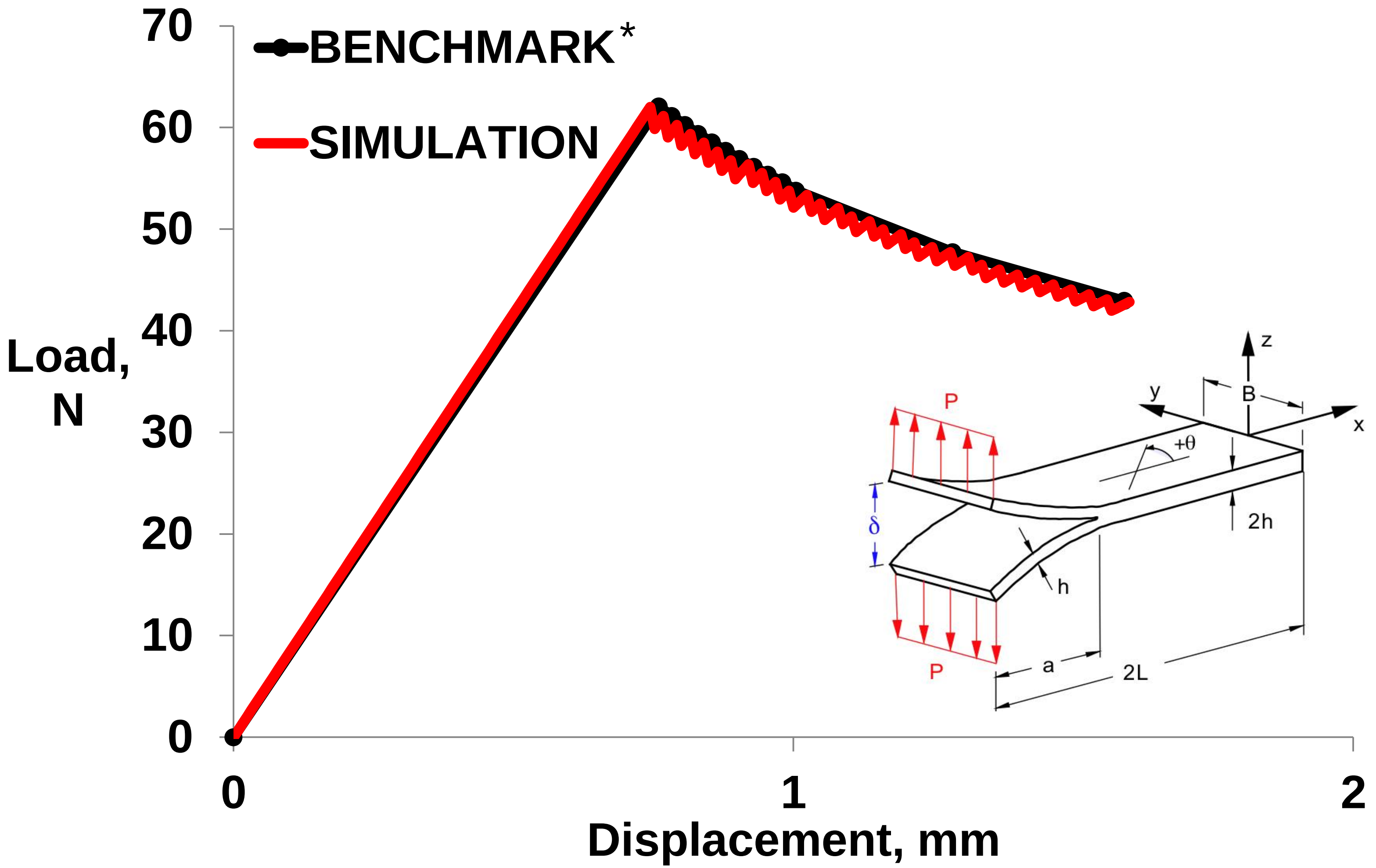
$$N = N + \delta N\big|^{n}_{inc}$$

$$\delta N\big|^{i}_{acc} = \delta N\big|^{i}_{acc} + \delta N\big|^{n}_{inc}$$

$$\delta N\big|^{n}_{acc} = 0$$

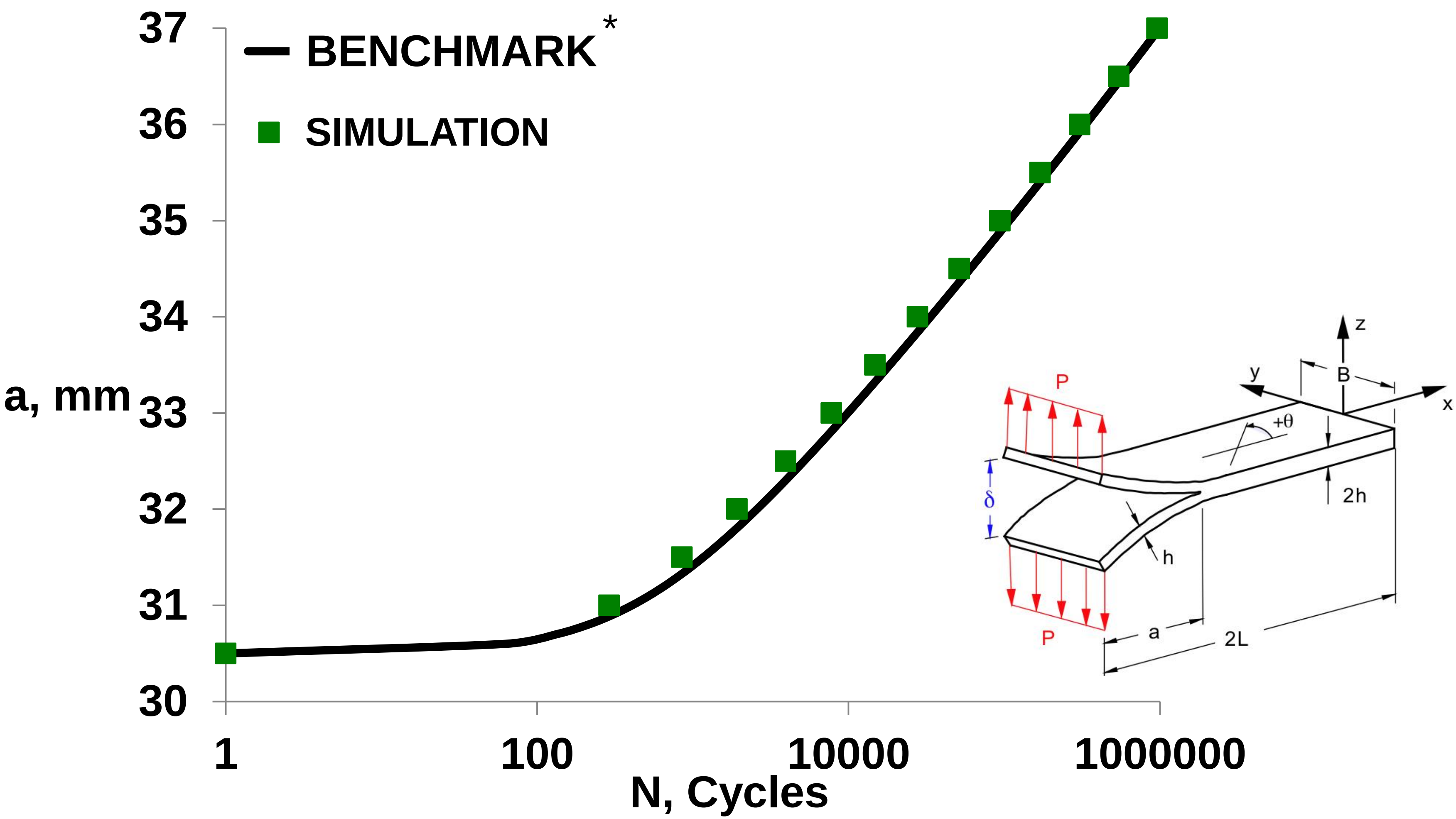
❹ ACCUMULATE THE CYCLES

Verification – Static: DCB



* R. Krueger. An Approach to Assess Delamination Propagation Simulation Capabilities in Commercial Finite Element Codes. NASA/TM-2008-215123, 2008

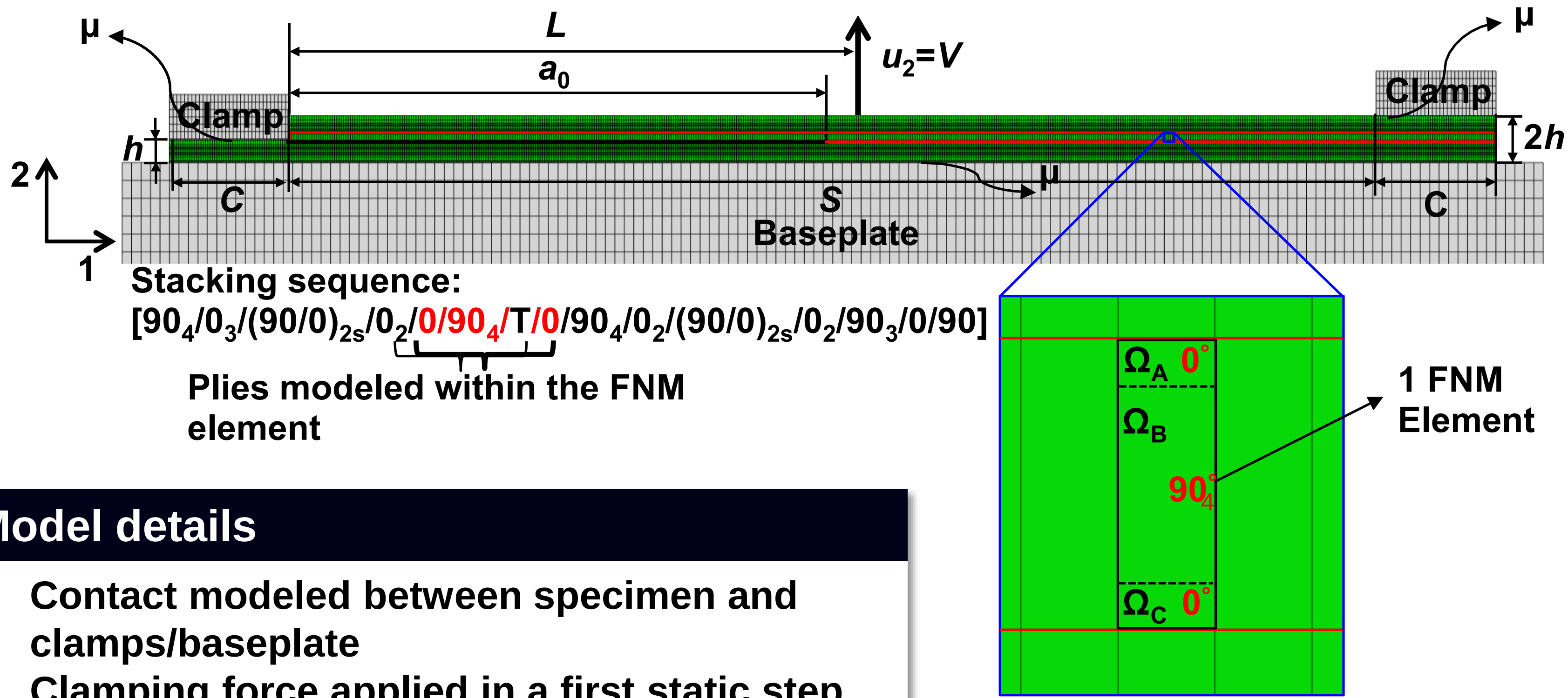
Verification – Fatigue: DCB benchmark



* R. Krueger. Development of a Benchmark Example for Delamination Fatigue Growth Prediction. NASA/CR-2010-216723

Contents

Numerical model



Model details

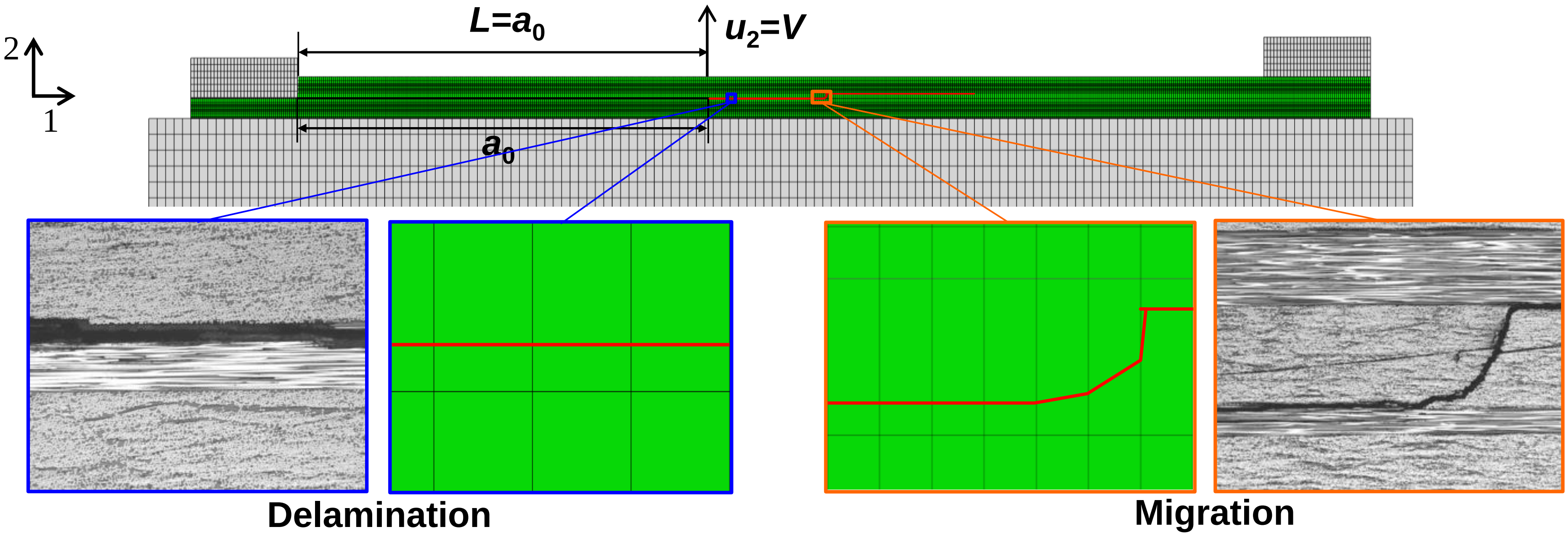
- Contact modeled between specimen and clamps/baseplate
- Clamping force applied in a first static step
- Abaqus/Standard (Implicit) + UEL
- All material properties obtained using standard/recommended test methods

Dimensions (mm)				
B^*	$2h$	C	S	a_0
12.7	5.25	12.7	115	49

*B is the width of the specimen (out-of-the page);
90° - specimen width direction; 0° - specimen span direction

Validation: delamination migration test

Results - migration process

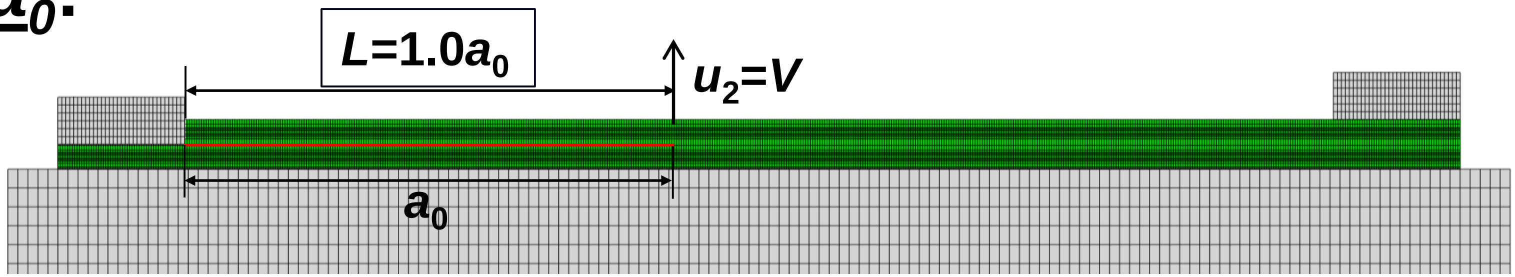


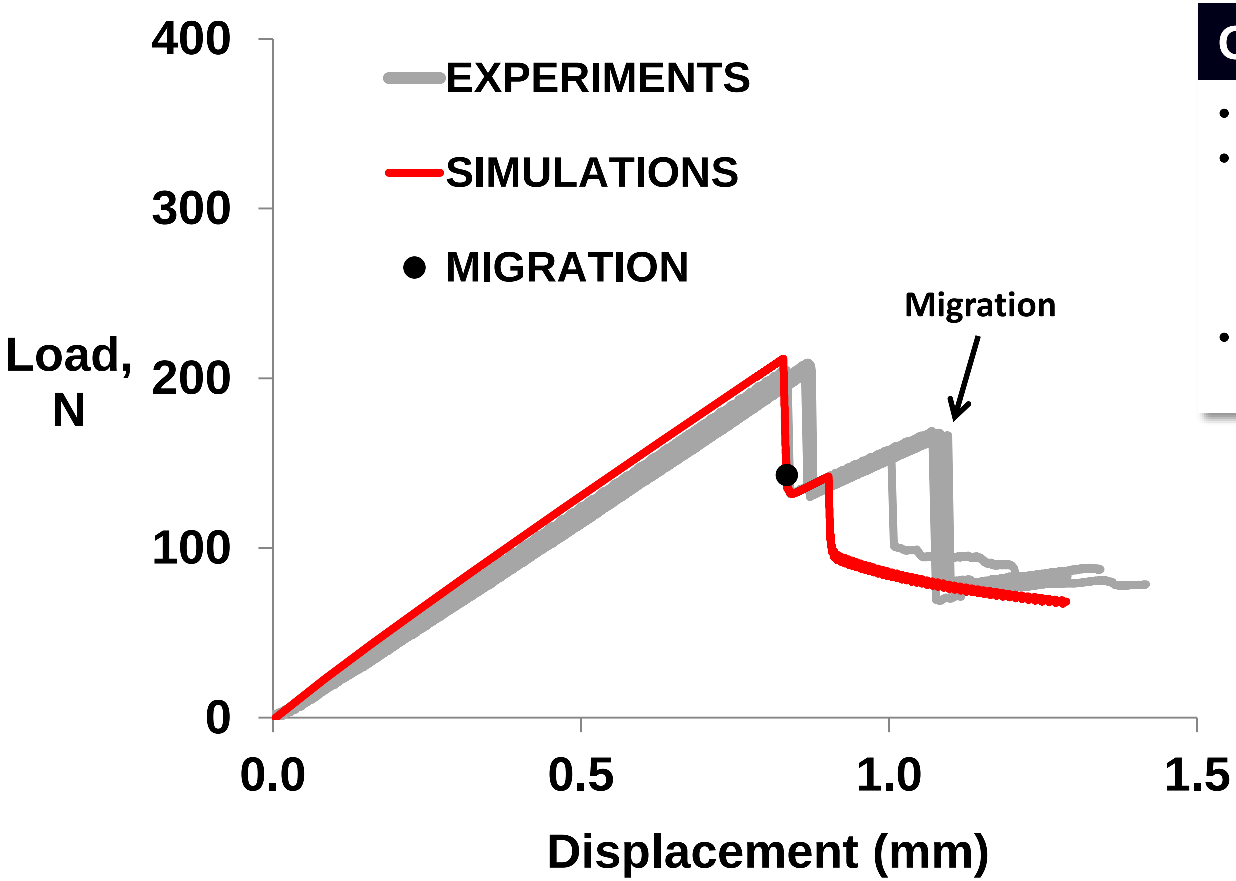
Observations

- Correct sequence of events: delamination followed by migration
- Failure morphology well captured – including crack path through-thickness

Validation: delamination migration test
Results – load vs displacement

L=1.0a_0:



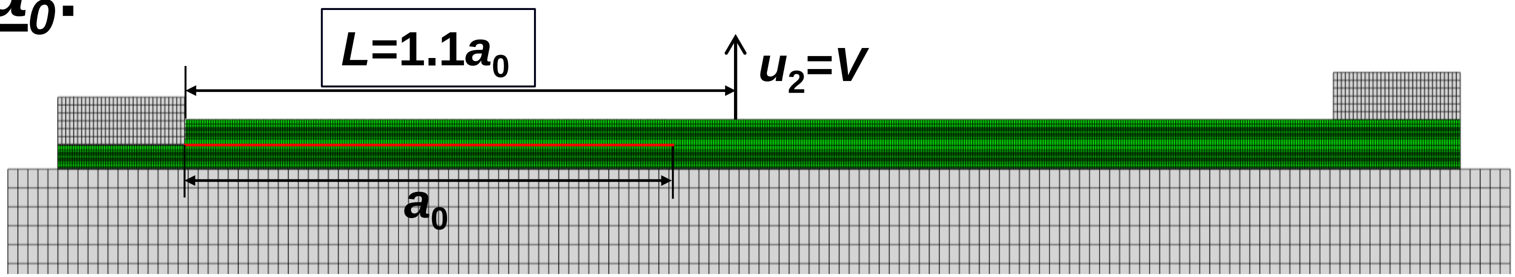


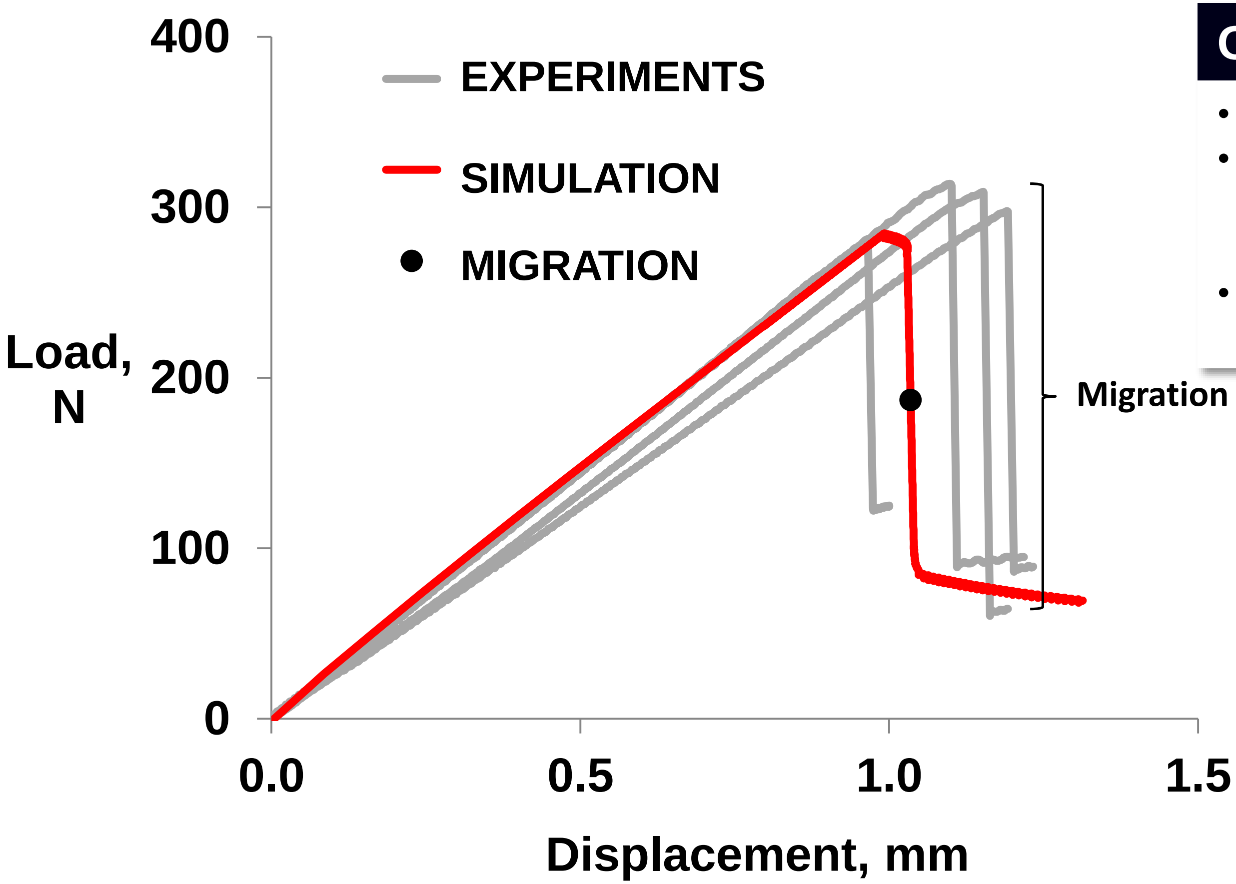
Observations

- Max load: good agreement
- Delamination: unstable growth followed by arrest and subsequent unstable and stable growth
- Migration: predicted before delamination arrest

Validation: delamination migration test
Results – load vs displacement

$\underline{L=1.1a_0}$:



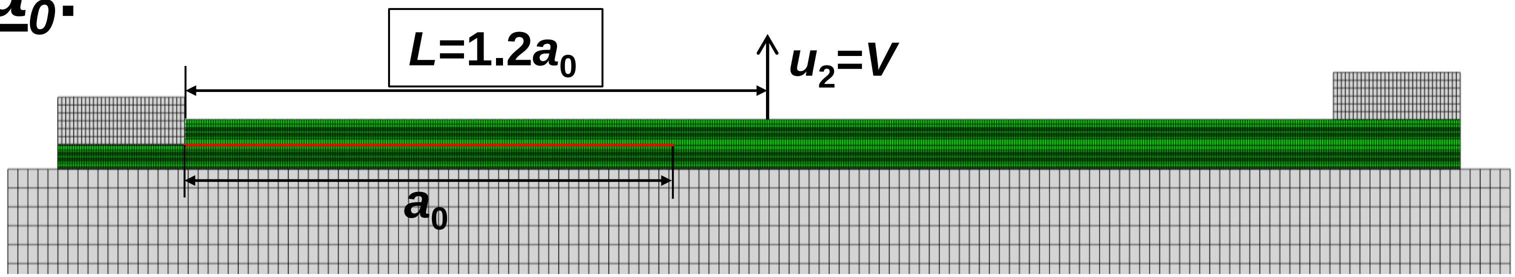


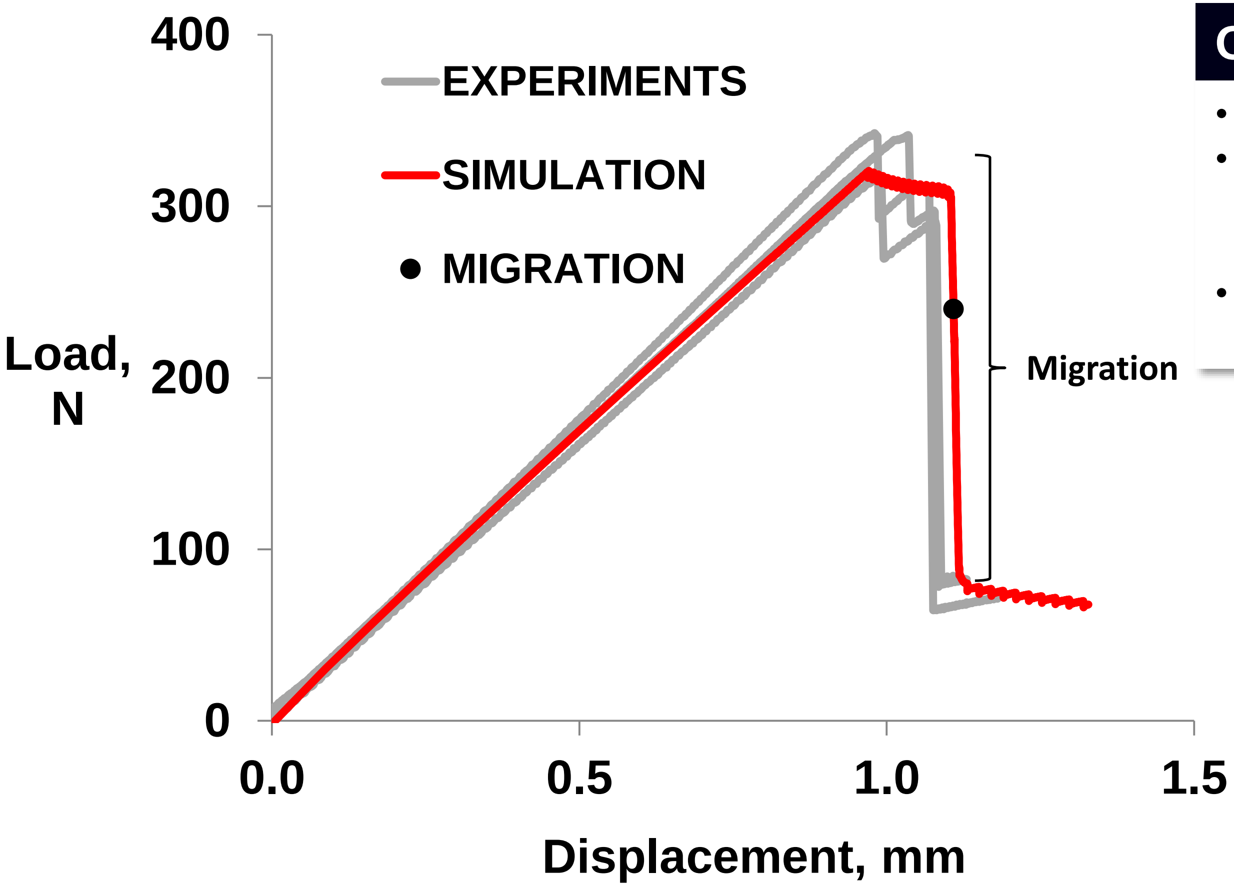
Observations

- Max load: good agreement
- Delamination: small region of stable growth prior to main load-drop
- Migration: predicted within the main load drop

Validation: delamination migration test
Results – load vs displacement

L=1.2a_0:

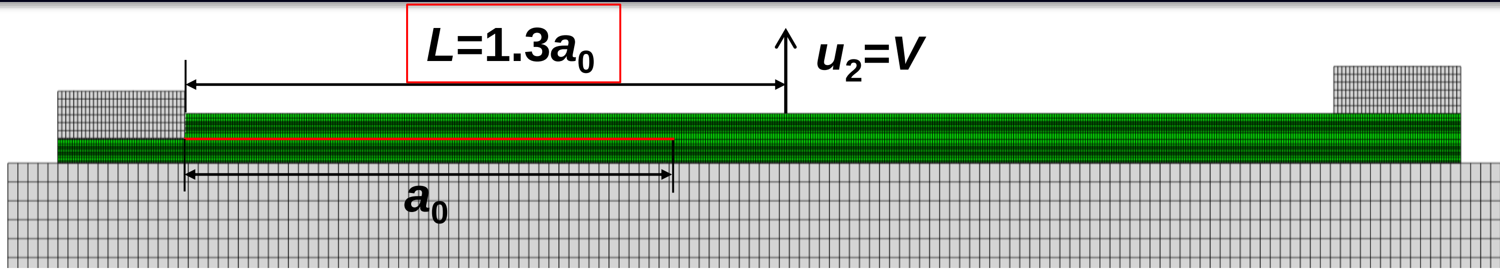


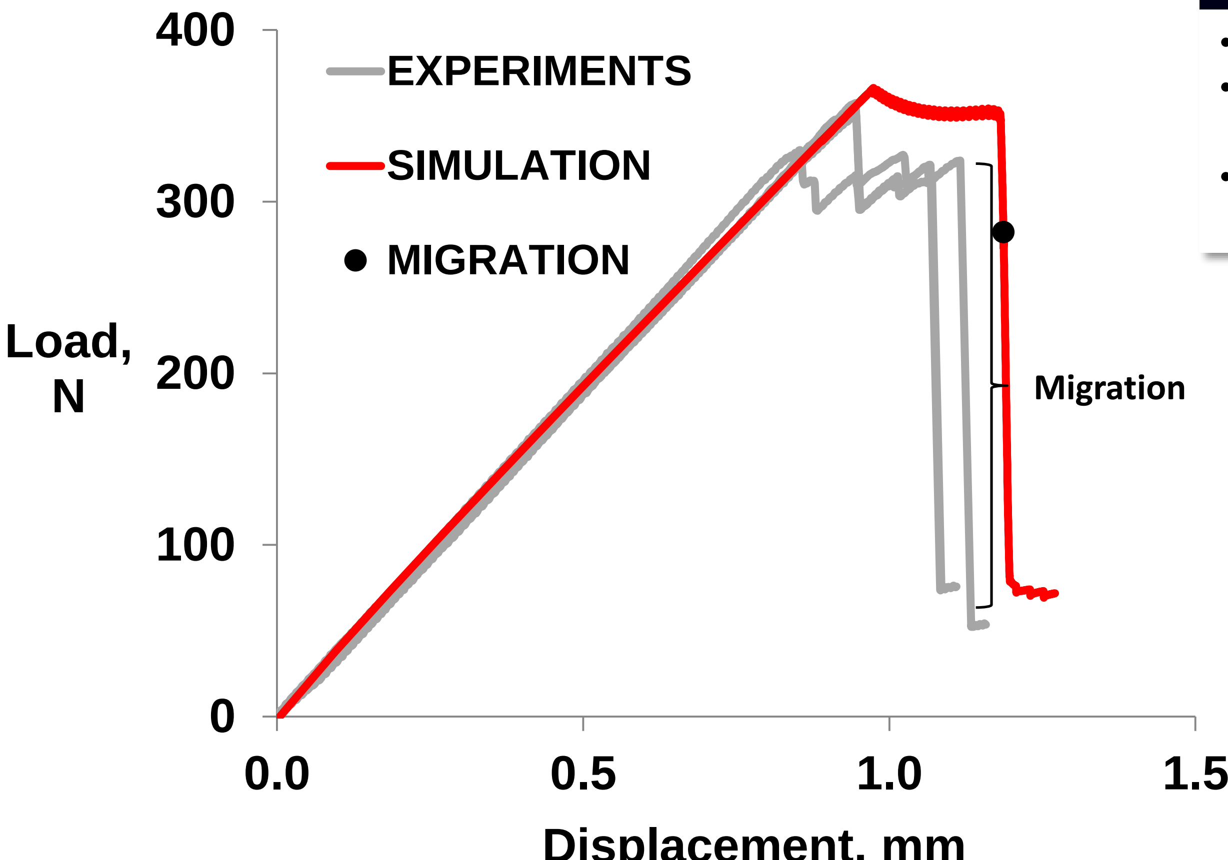


Observations

- Max load: good agreement
- Delamination: stable delamination growth prior to main load-drop
- Migration: predicted within the main load drop

Validation: delamination migration test
Results – load vs displacement



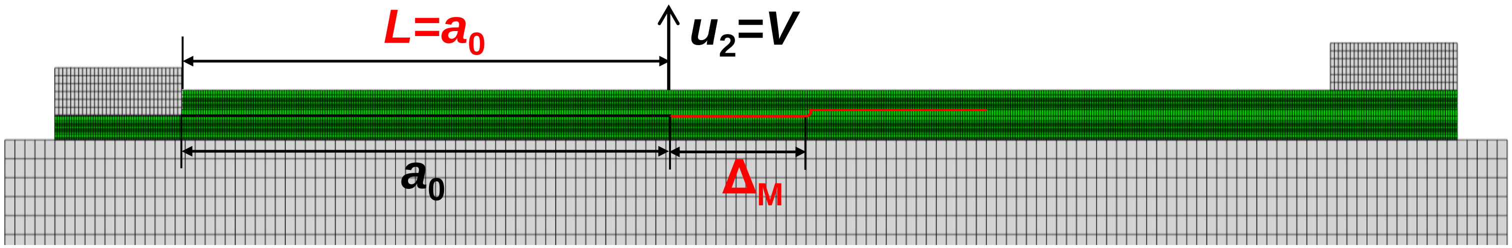


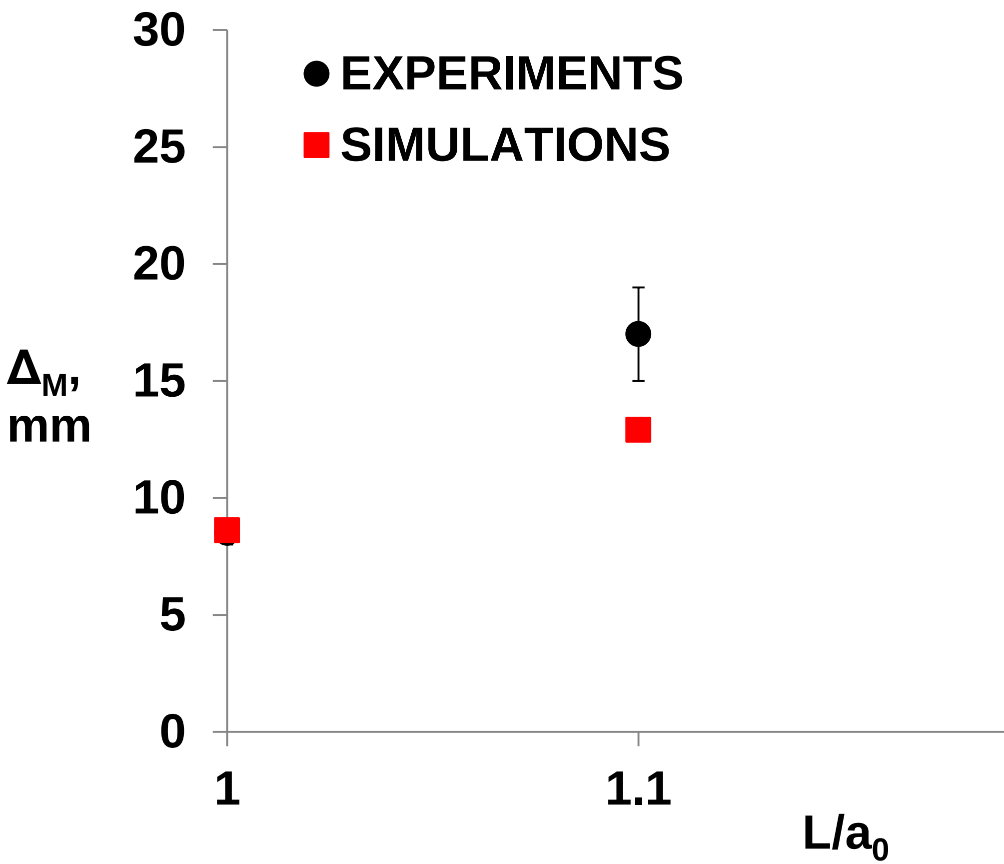
Observations

- Max load: good agreement
- Delamination: stable growth prior to main load-drop
- Migration: predicted within the main load drop

Validation: delamination migration test

Results – Migration location



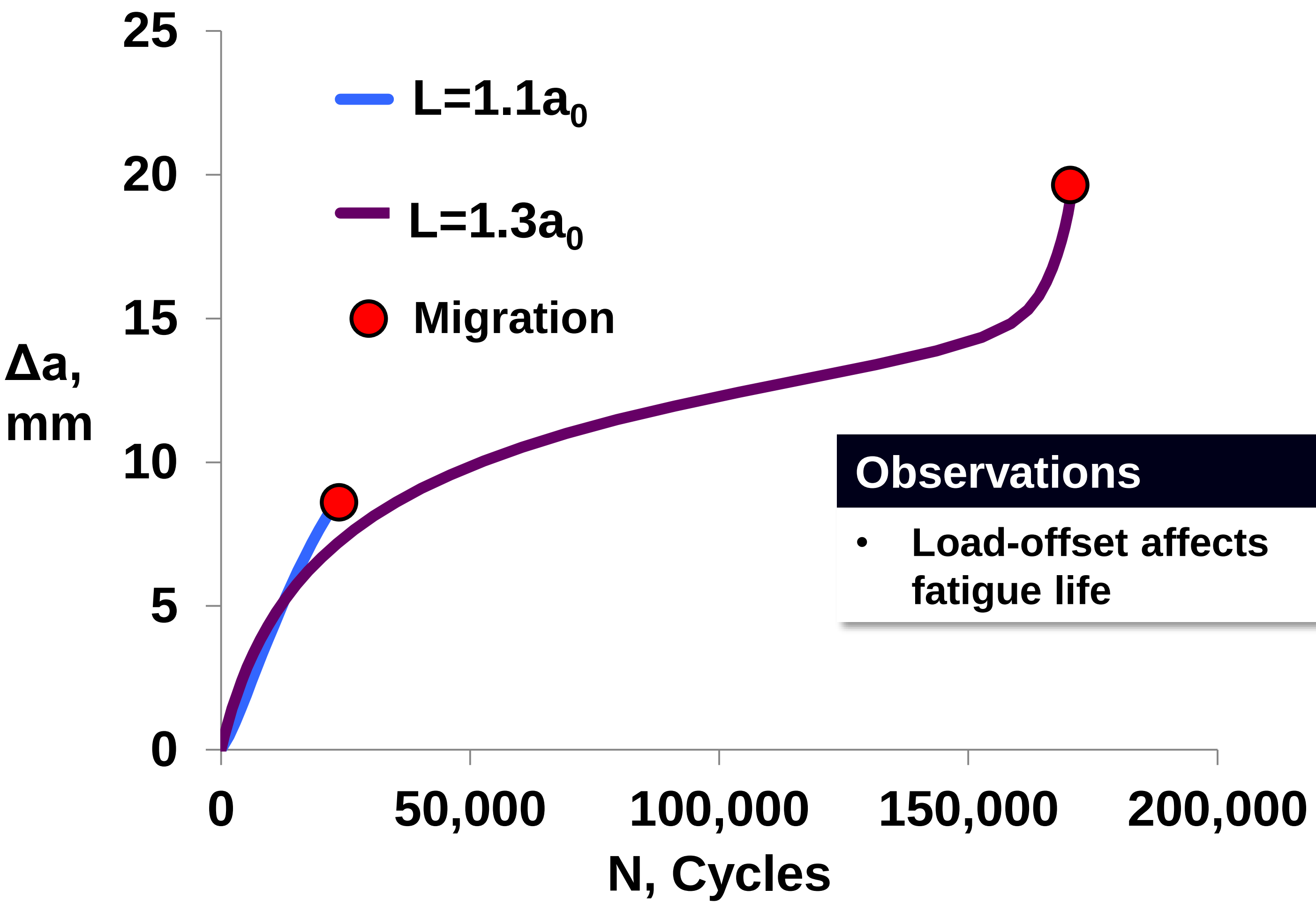


Observations

- Trend well captured
- Conservative predictions

Fatigue - Preliminary results
Delamination growth and cycles to migration

Constant amplitude, R = 0.1 and f = 5 Hz:



Observations
• Load-offset affects fatigue life

Contents

Summary

- Developed a **finite element** model based on the **Floating Node Method** combined with the **Virtual Crack Closure Technique** to capture the interaction between **delamination and matrix-cracking**

- Identified and applied **migration criteria** for both **quasi-static and fatigue loading**

- **Compared simulations** and **experiments**.
  - **Good agreement** observed for **load-displacement, migration location** and **path**

- **Validation** of the **fatigue simulations are in progress**

Modeling delamination migration: quasi-static and fatigue loading

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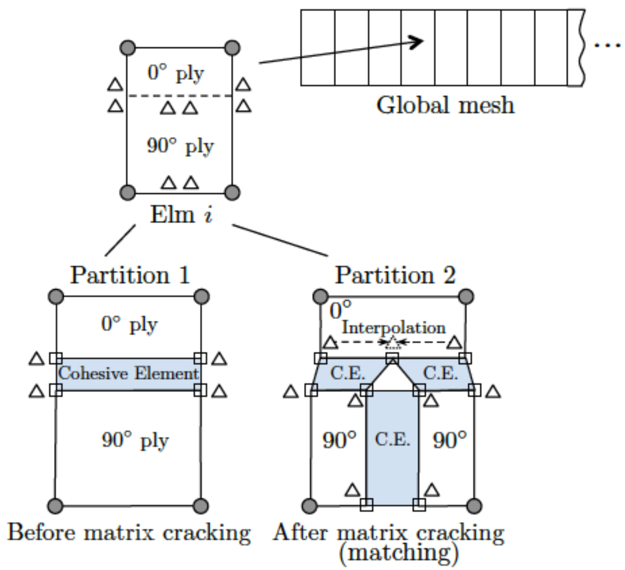
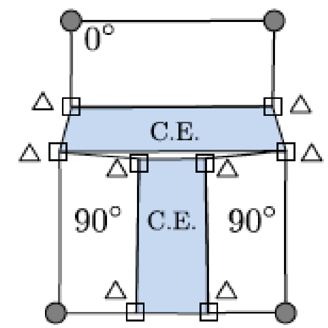
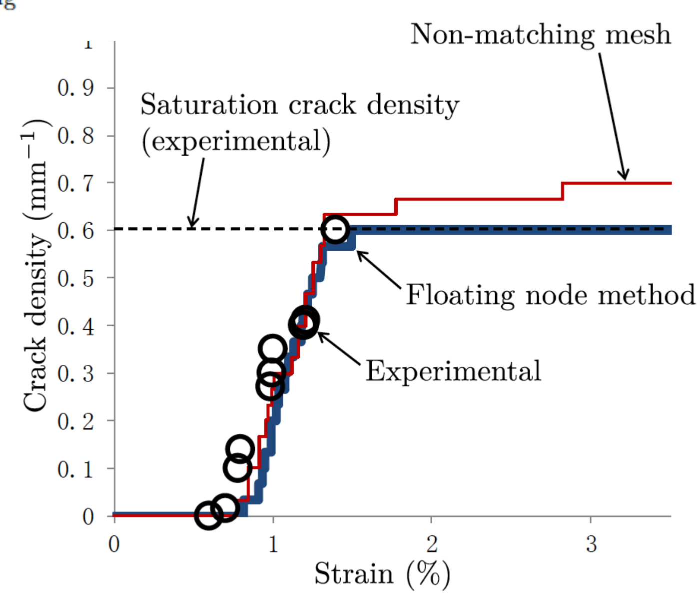
Backup Slides: cohesive zone elements

FNM

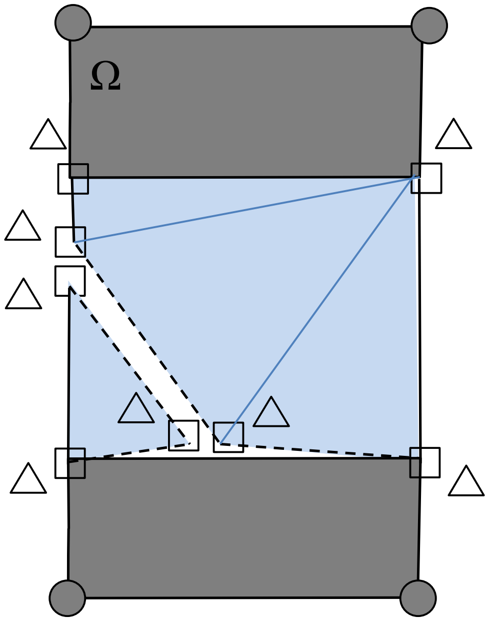


"Non-matching mesh"





Backup Slides: element integration



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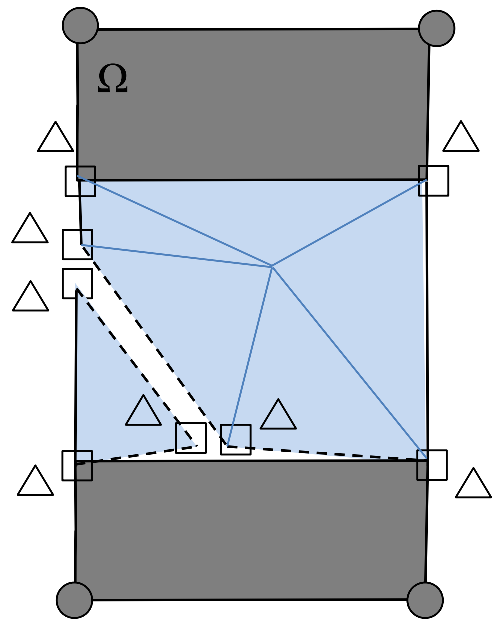
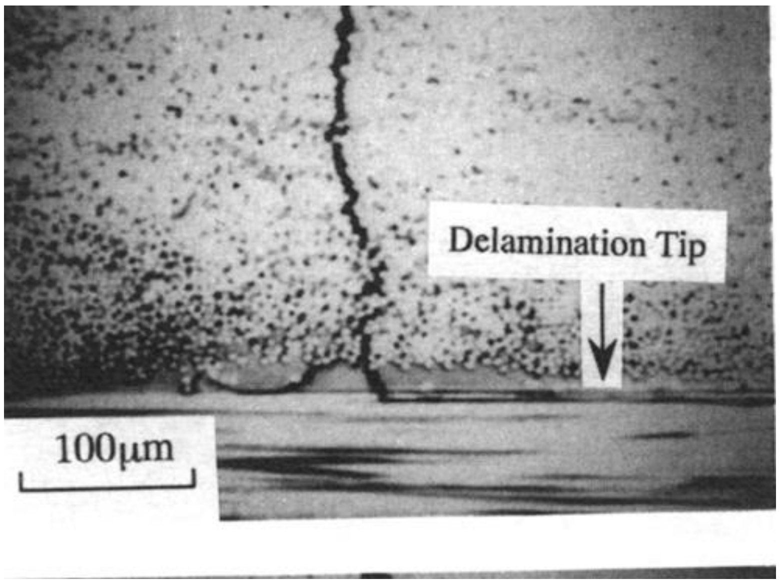
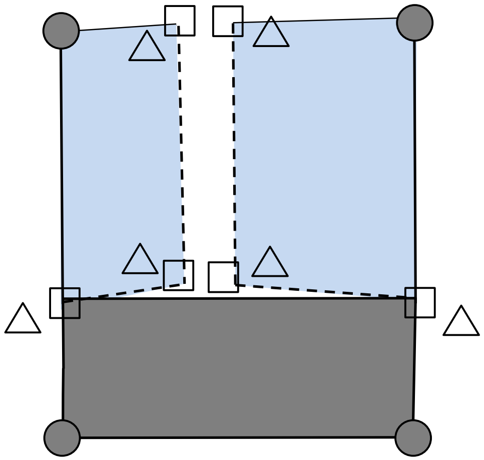


or

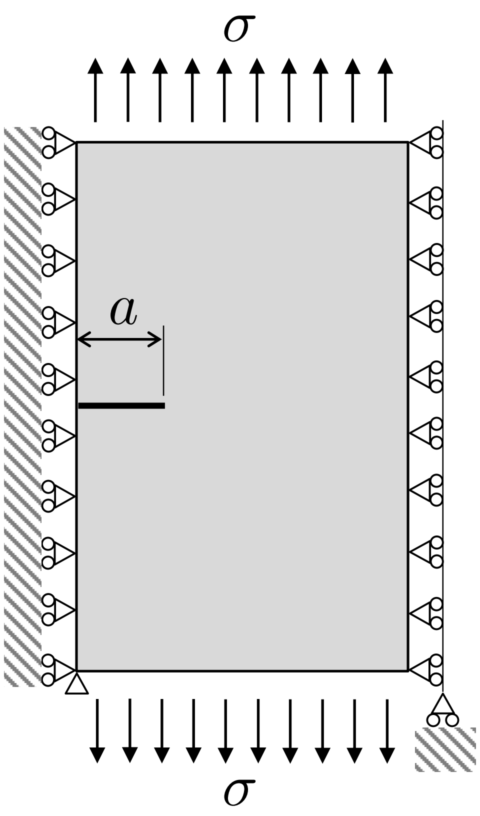
…

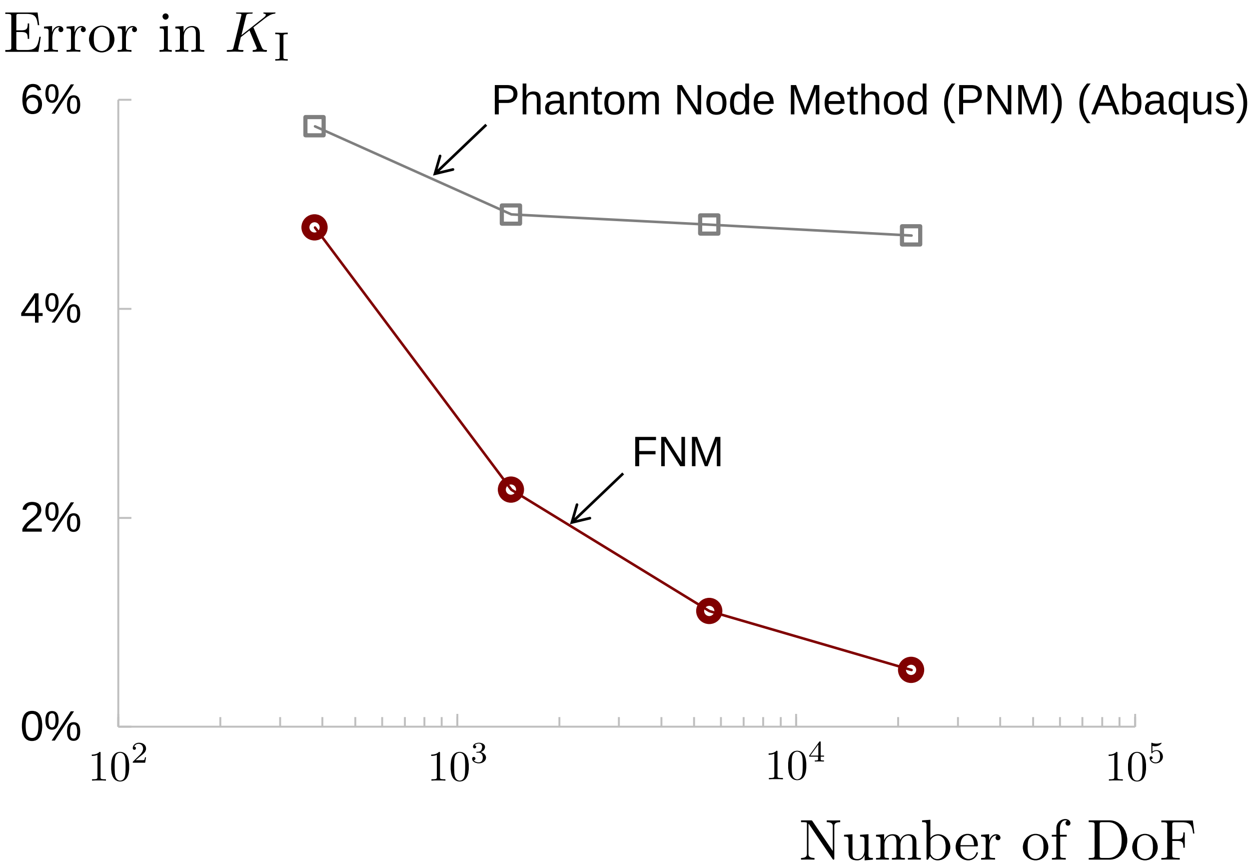
Backup Slides: Topological migration criterion, experimental evidence



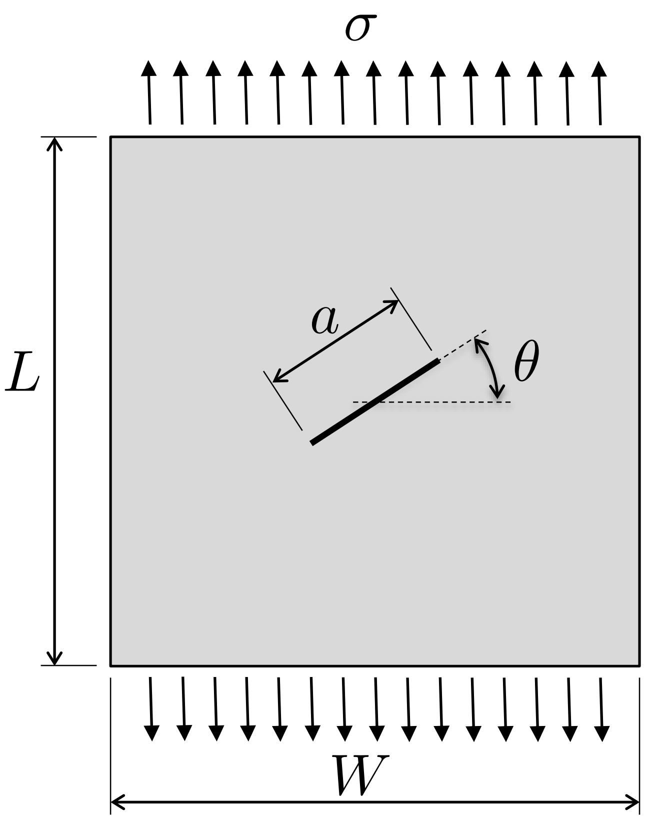


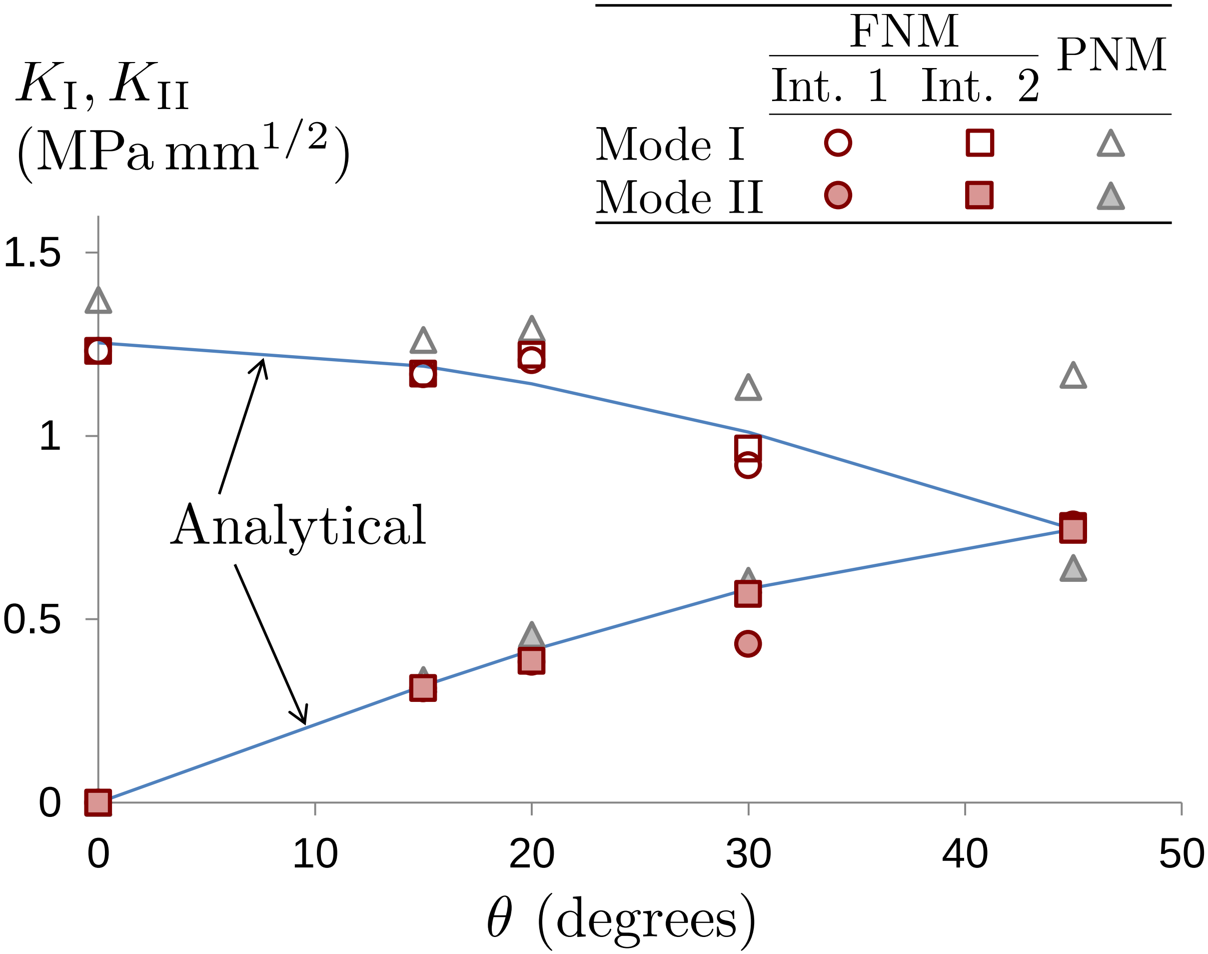
Backup Slides: FNM vs PNM, convergence: K_I



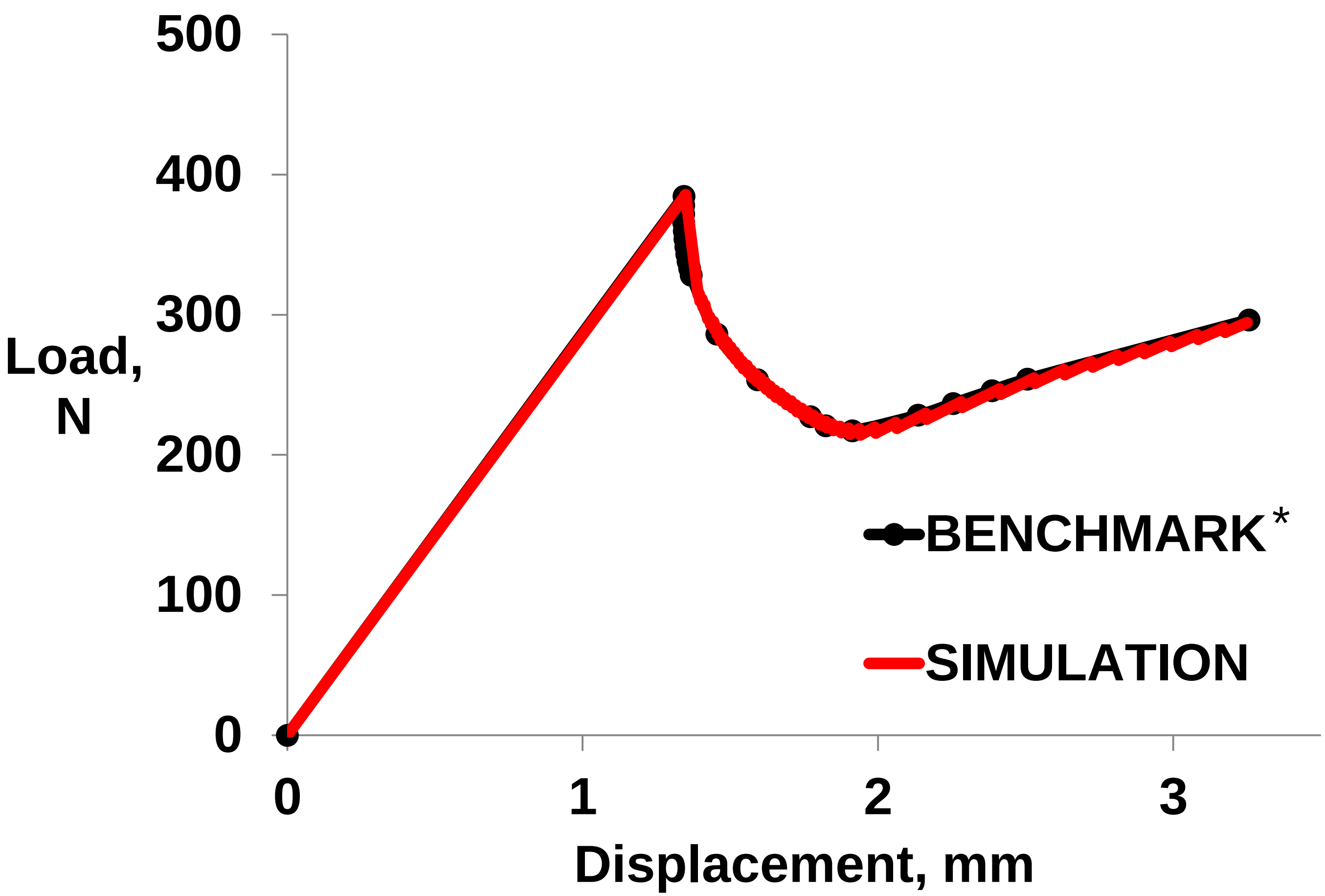


Backup Slides: FNM vs PNM, accuracy: K_I, K_{II}





Backup slides: MMB benchmark



*R. Krueger. Development of and application of benchmark examples for mixed-mode I/II quasistatic delamination propagation predictions. NASA-CR-2012-217562, 2012.