Modeling delamination migration: quasi-static and fatigue loading

N. V. De Carvalho
nelson.carvalho@nasa.gov
National Institute of Aerospace

B.Y. Chen
Imperial College London
National University of Singapore

J.G. Ratcliffe
NASA Langley

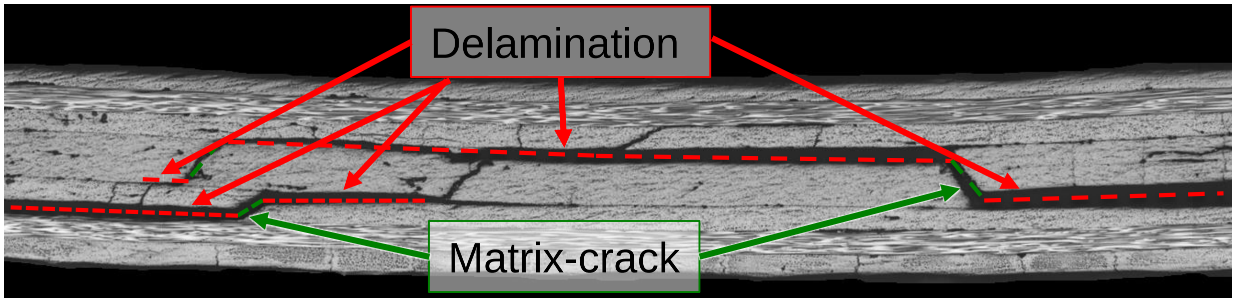
S. T. Pinho, P. Baiz
Imperial College London

T. E. Tay
National University Singapore

Motivation

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

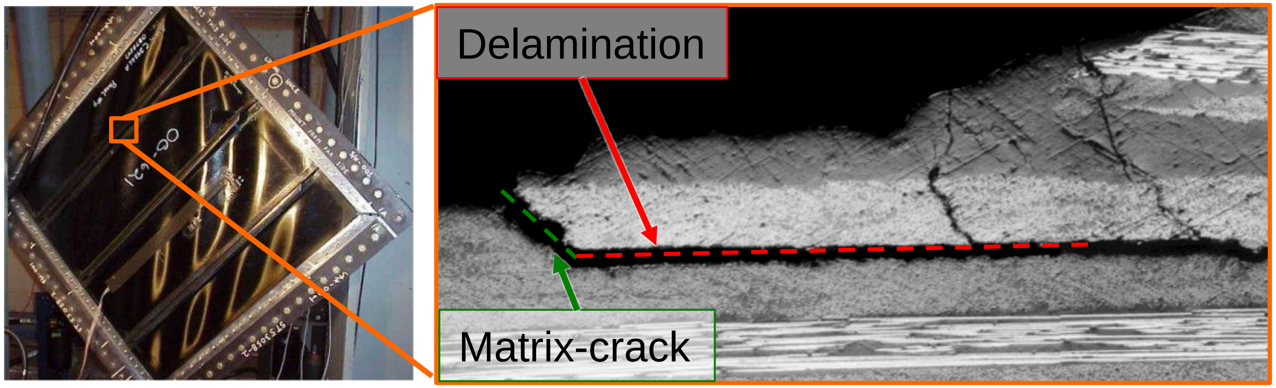
Impact



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.

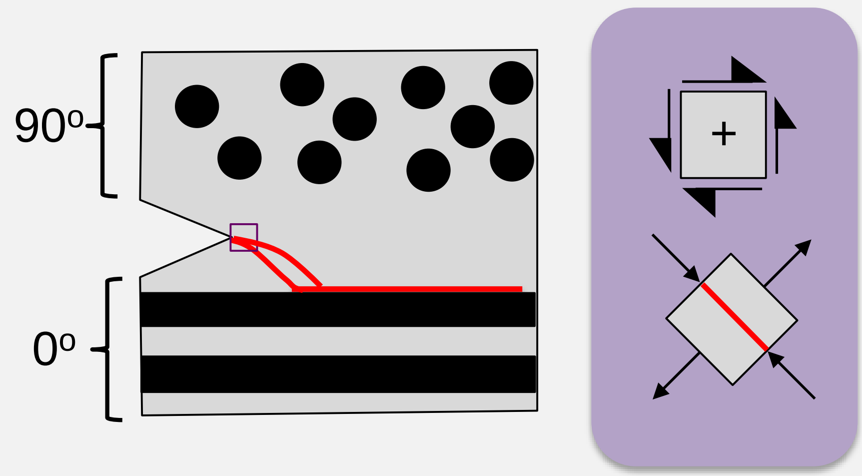


Contents

Contents

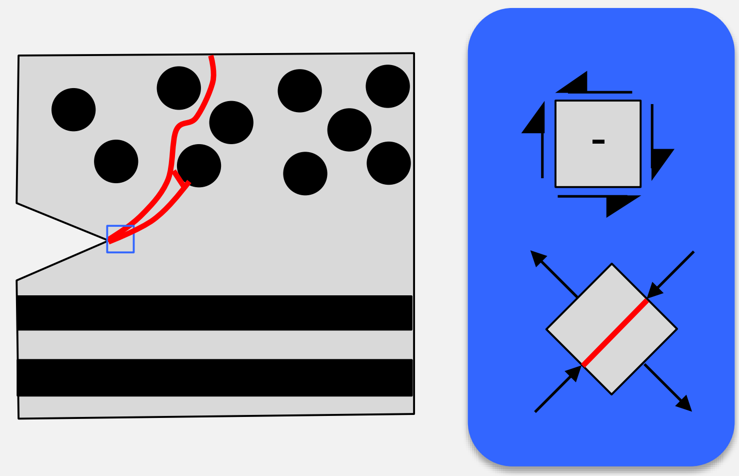
Experiments: delamination migration
Test Setup - Premise

Delamination
("positive" shear stress)



*adapted from Greenhalgh, 2009

Migration
("negative" shear stress)

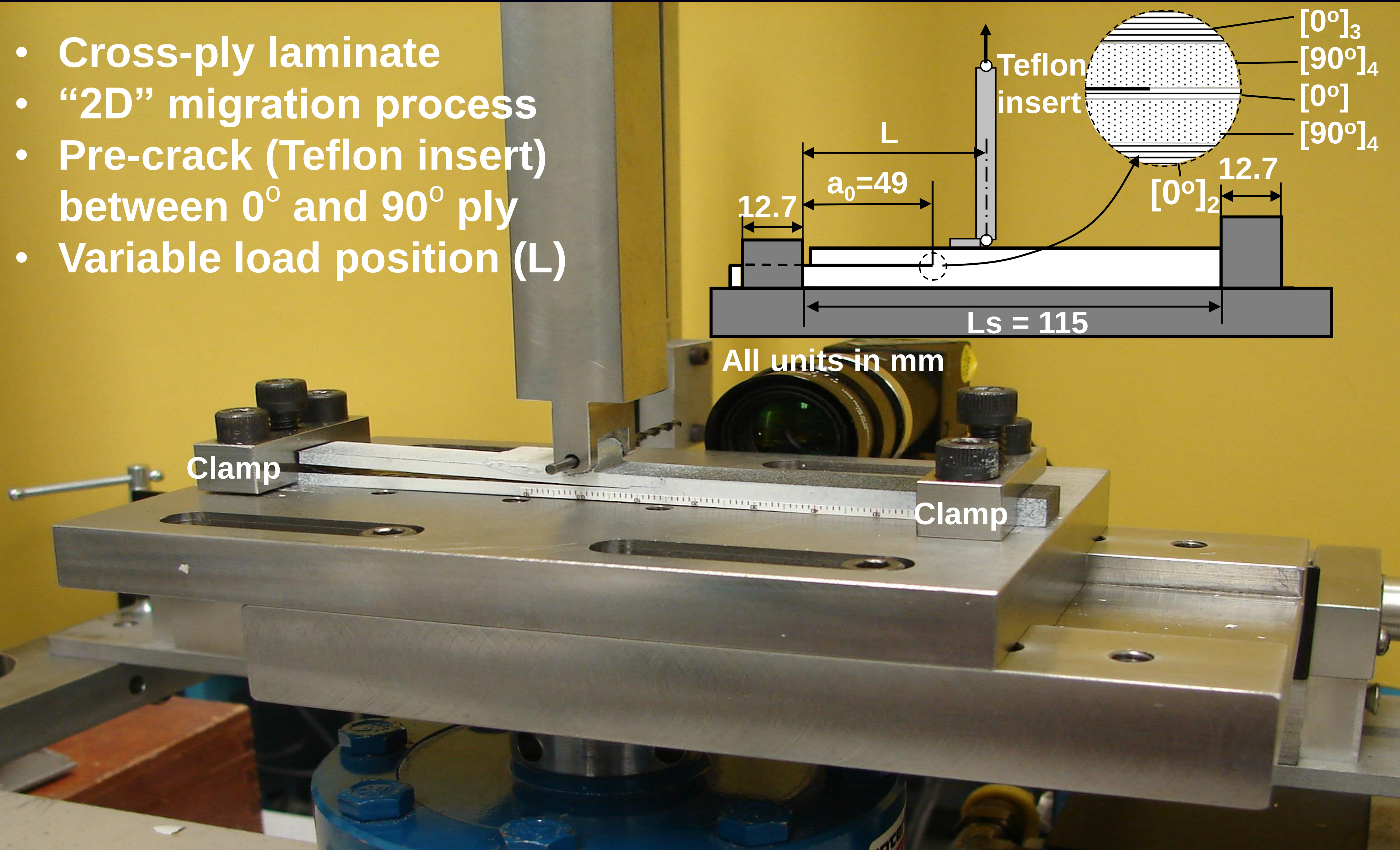


*E.S. Greenhalgh, C. Rogers, P. Robinson. Fractographic observations on delamination growth and the subsequent migration through the laminate. Composites Science and Technology, 69:2345-2351, 2009.

Experiments: delamination migration test

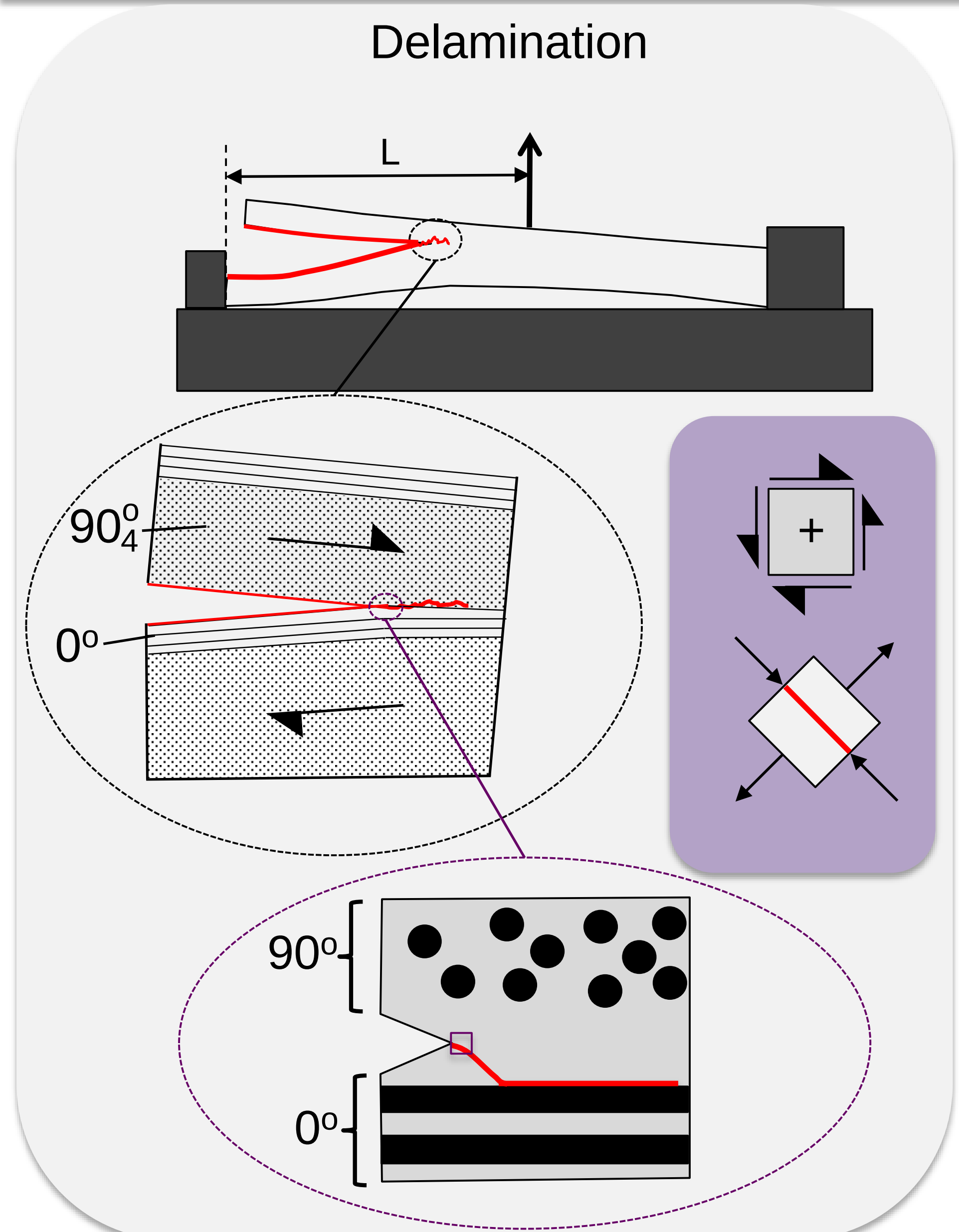
Test setup

- **Cross-ply laminate**
- **"2D" migration process**
- **Pre-crack (Teflon insert) between 0° and 90° 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.

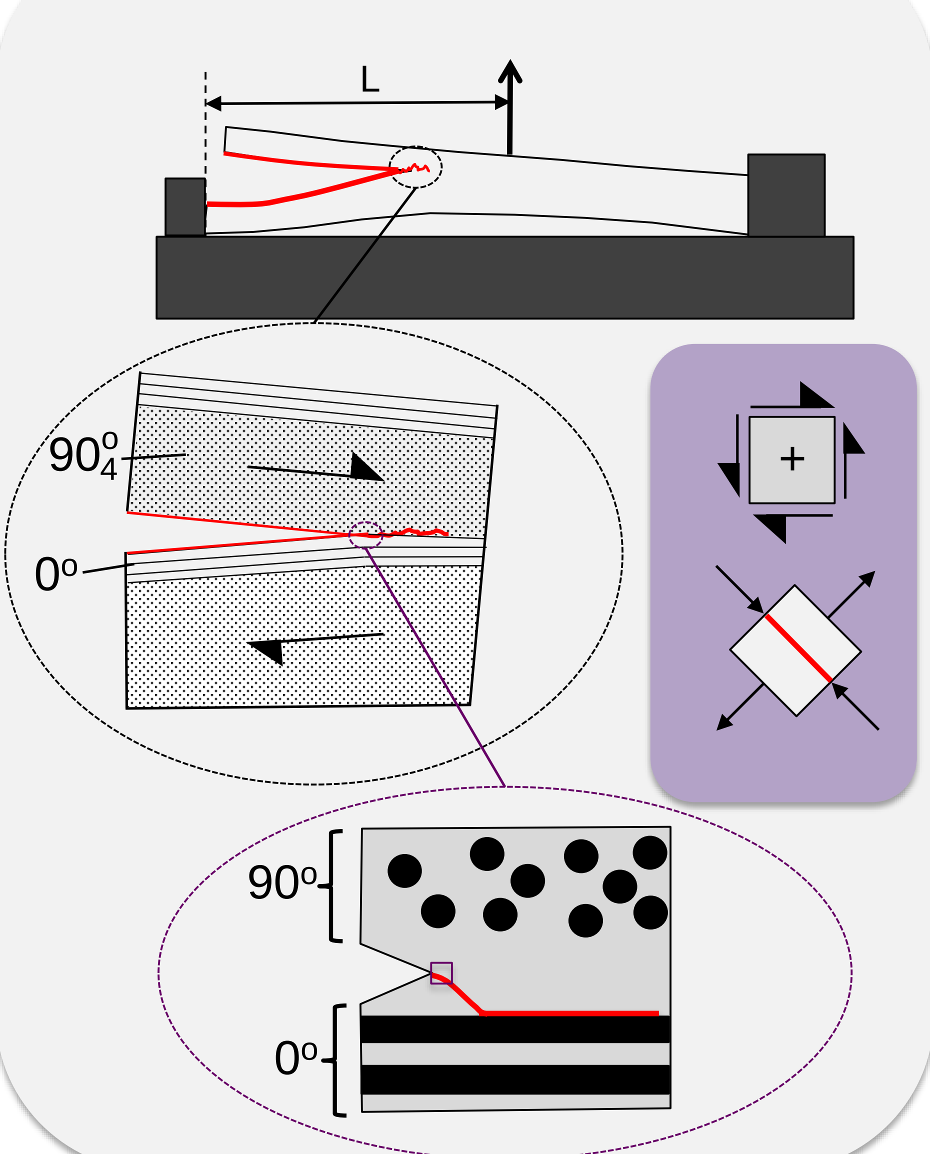
Experiments: delamination migration test
Test setup - overview



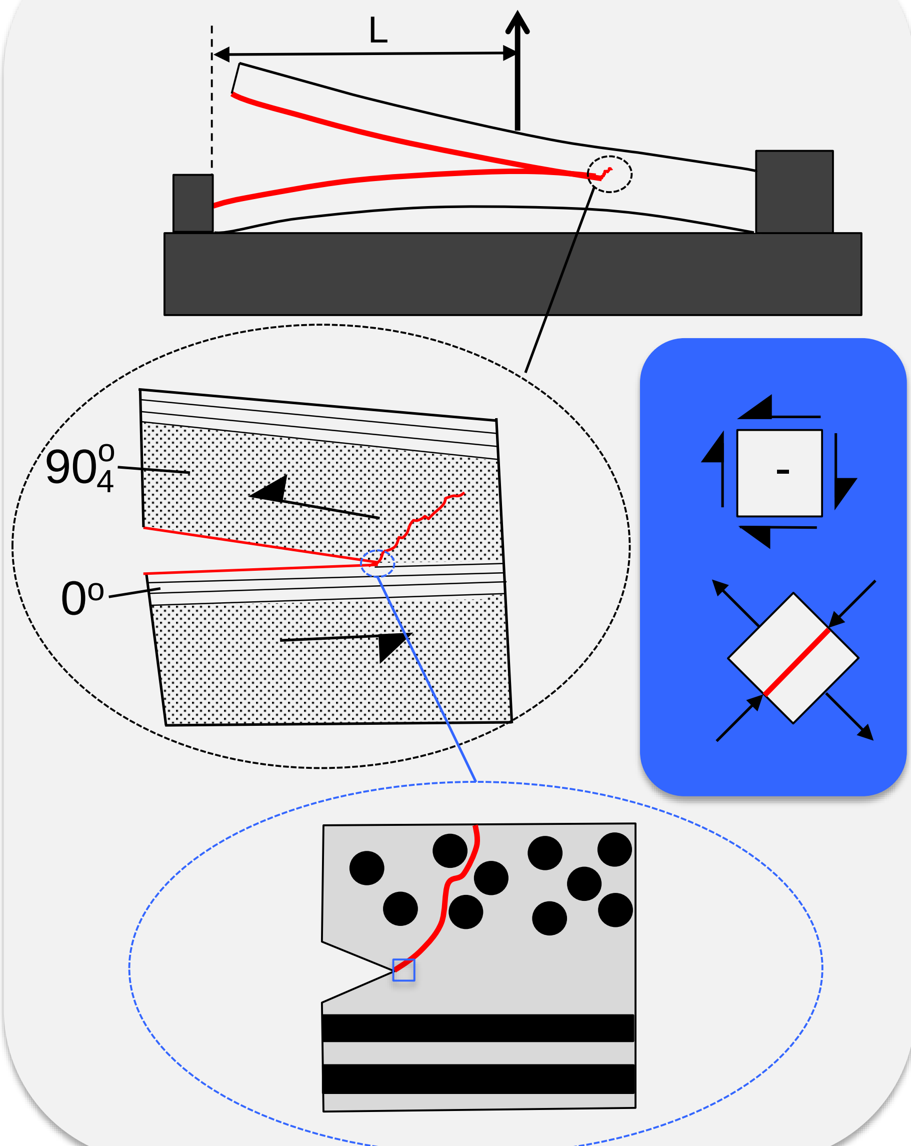
Experiments: delamination migration test

Test setup - overview

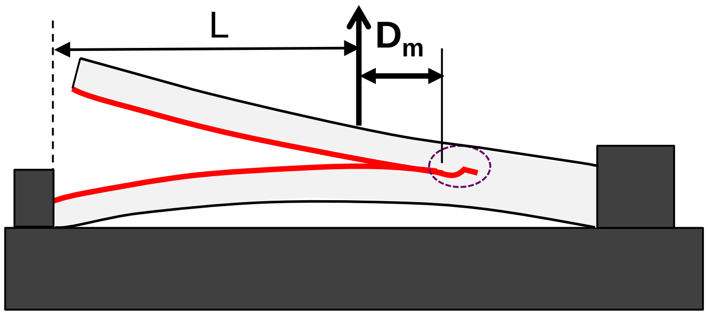
Delamination



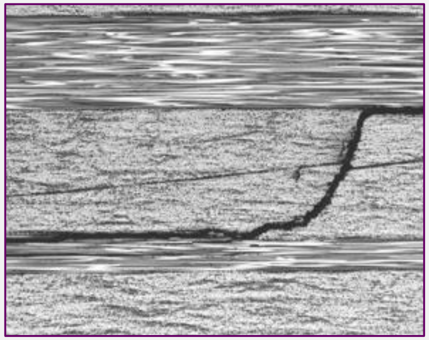
Migration



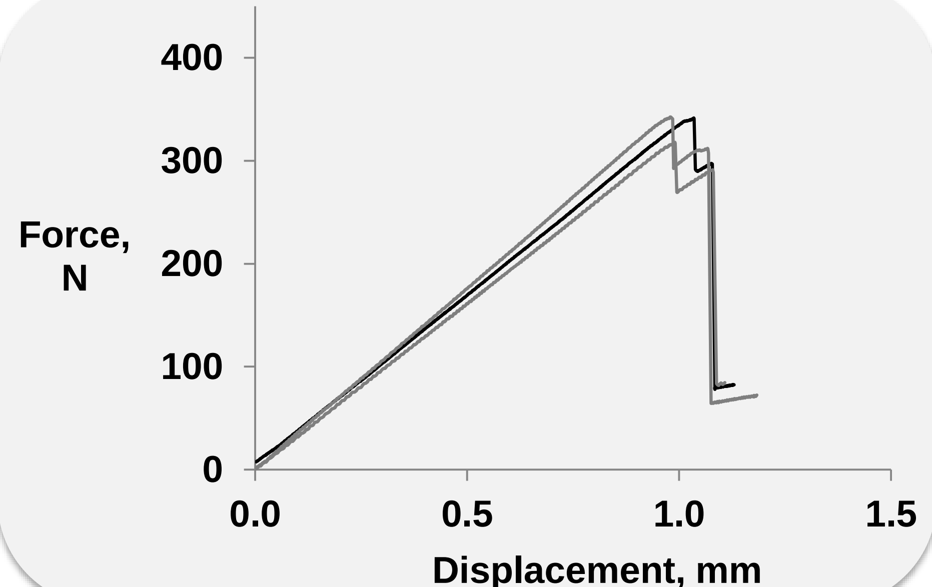
Experiments: delamination migration test
Test setup – validation data



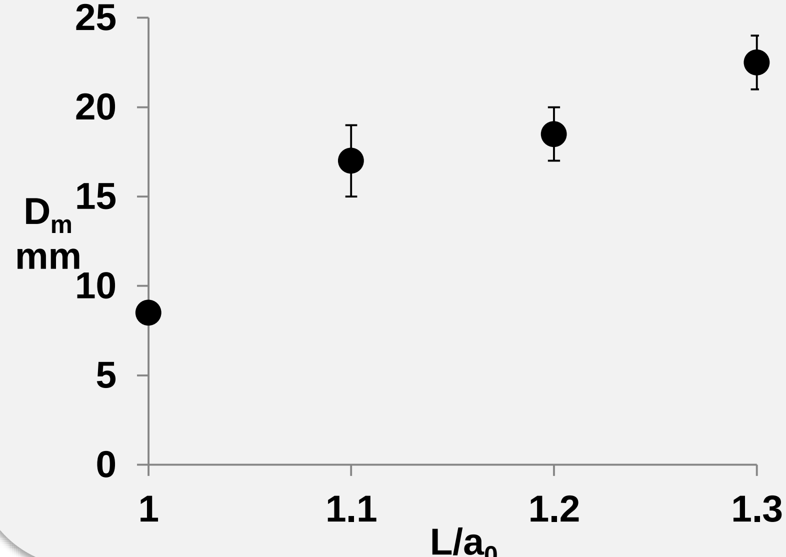
Damage morphology



Load - displacement

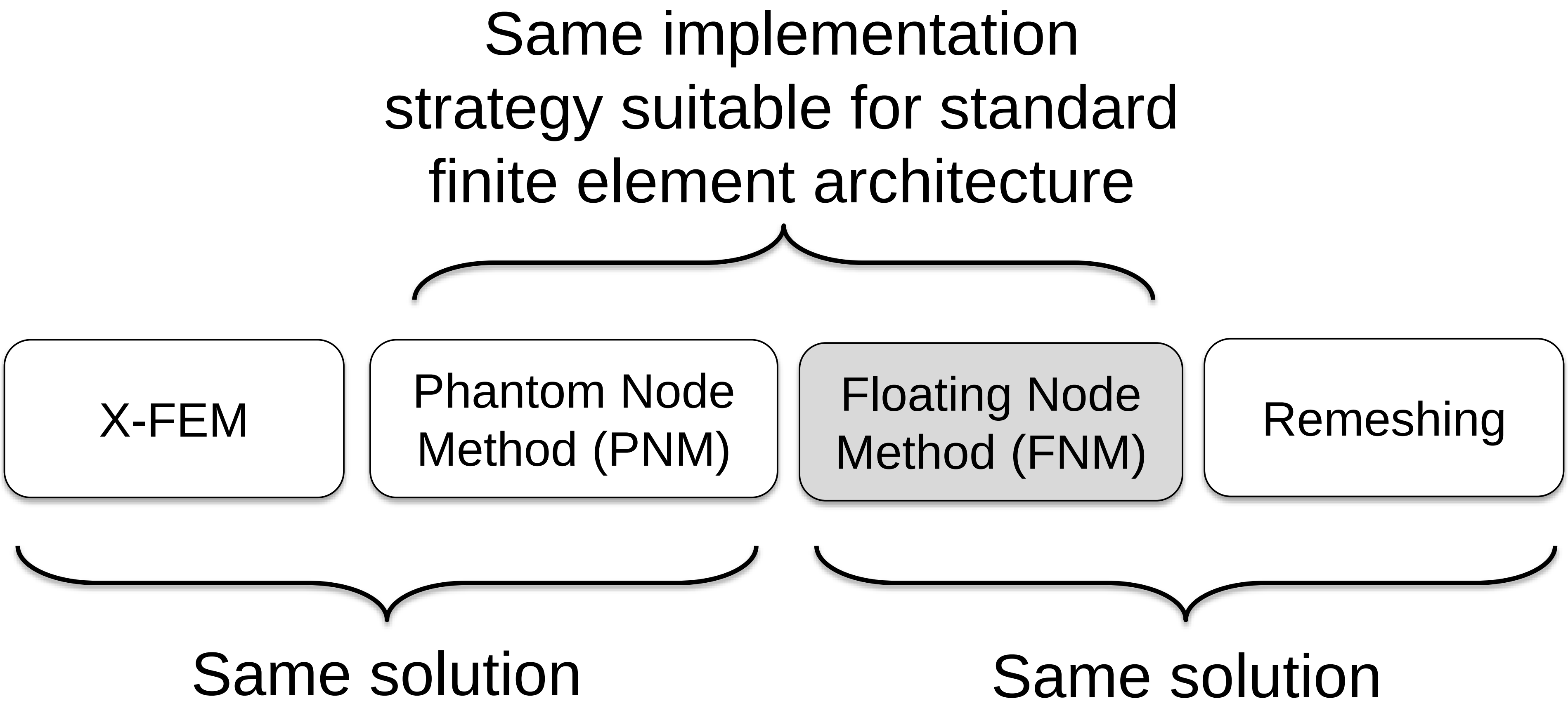


Migration location



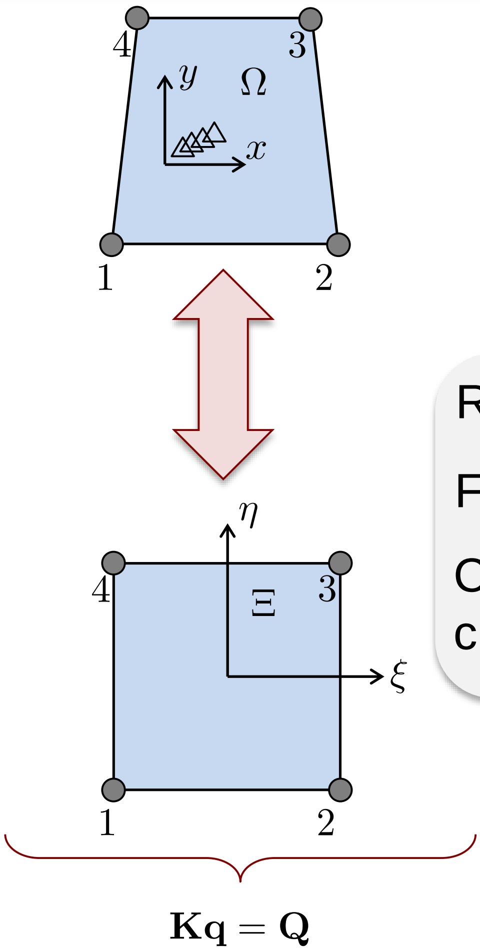
Contents

Floating Node Method



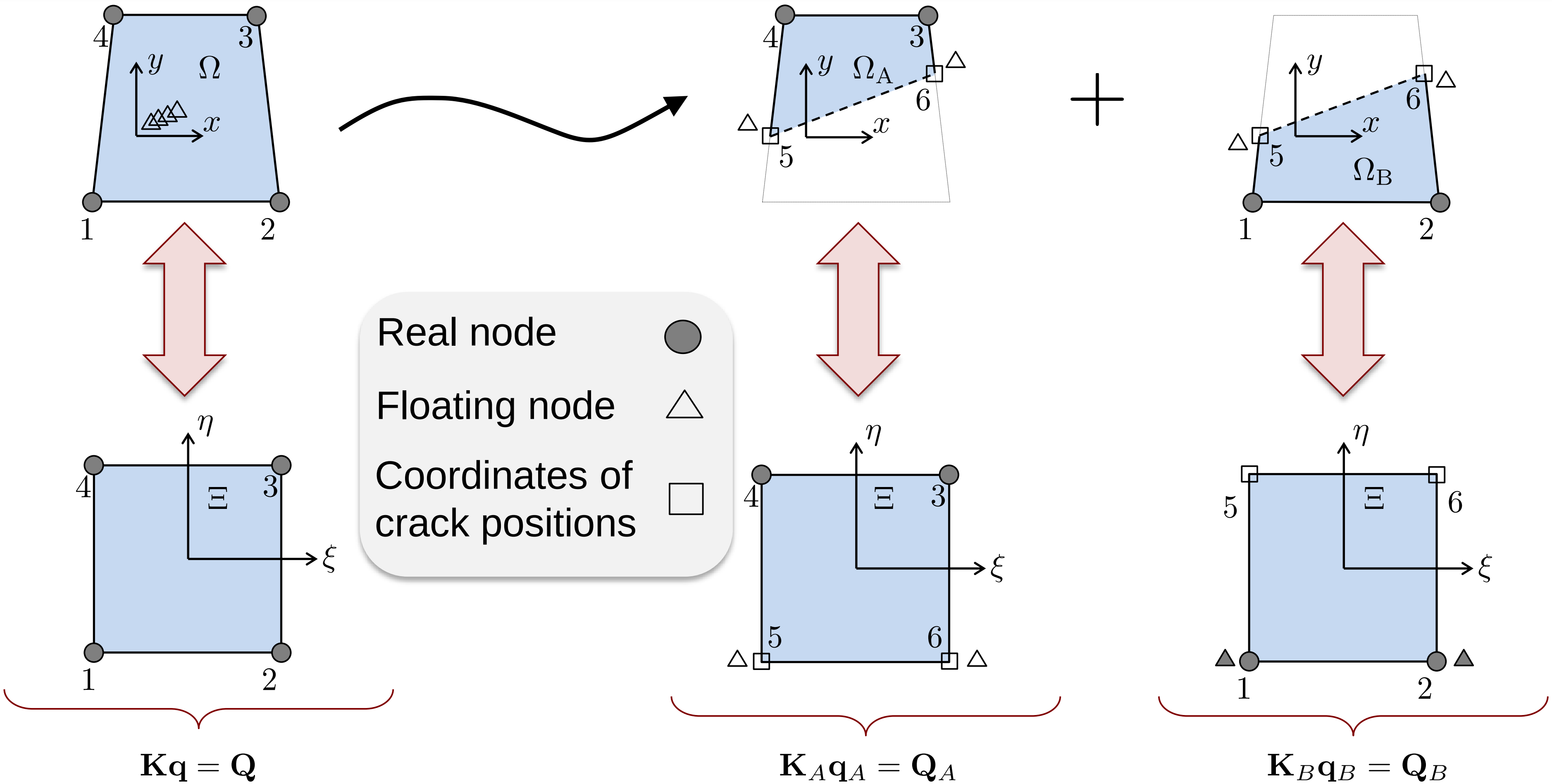
B.Y. Chen, S.T. Pinho, N.V. De Carvalho, P.M. Baiz, T.E. Tay, A floating node method for the modelling of discontinuities in composites, Engineering Fracture Mechanics, Vol. 127:104-134, 2014.

Floating Node Method (FNM)



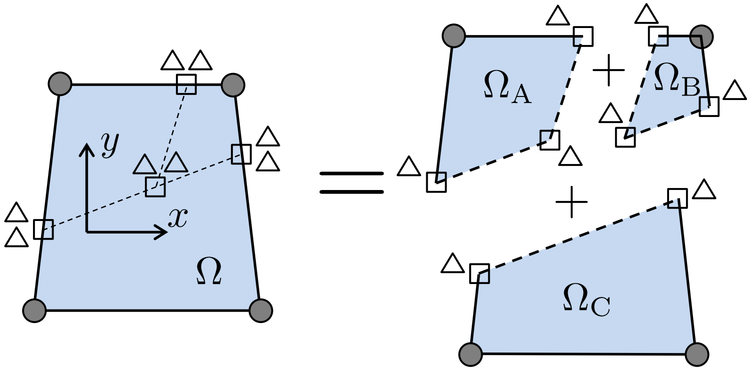
Real node	●
Floating node	△
Coordinates of crack positions	□

Floating Node Method (FNM)

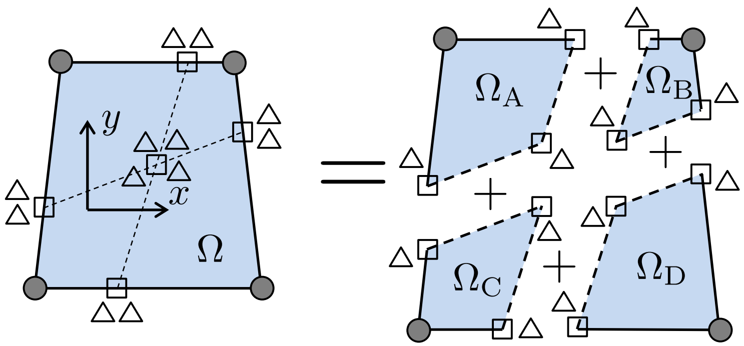


Floating Node Method (FNM)

T crack



Intersecting cracks

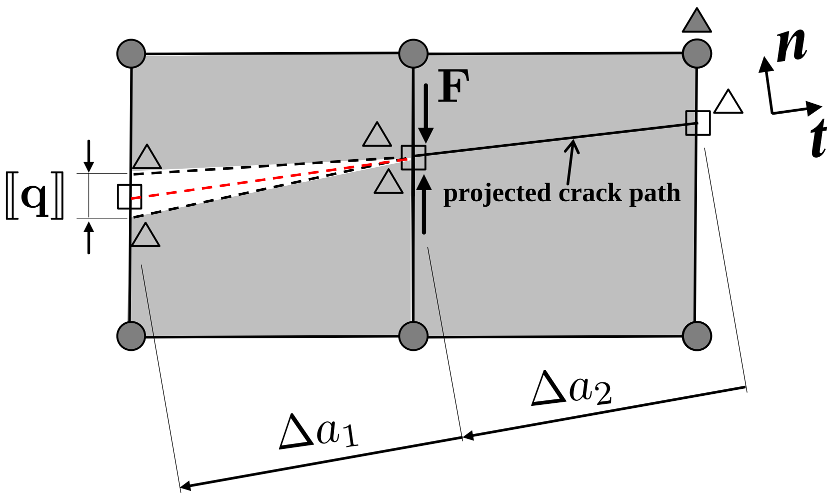


Key Characteristics:

- 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

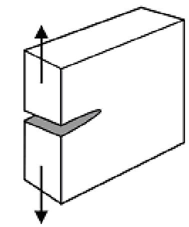
Floating Node Method & Virtual Crack Closure Technique

Virtual Crack Closure Technique (VCCT):



Mode I

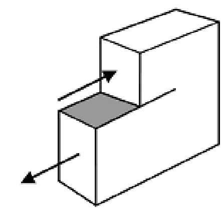
$$G_I = \frac{1}{2\Delta a_1} F_n [\![q_{\mathrm{n}}]\!] \left(\frac{\Delta a_1}{\Delta a_2} \right)^{\frac{1}{2}}$$



I

Mode II

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

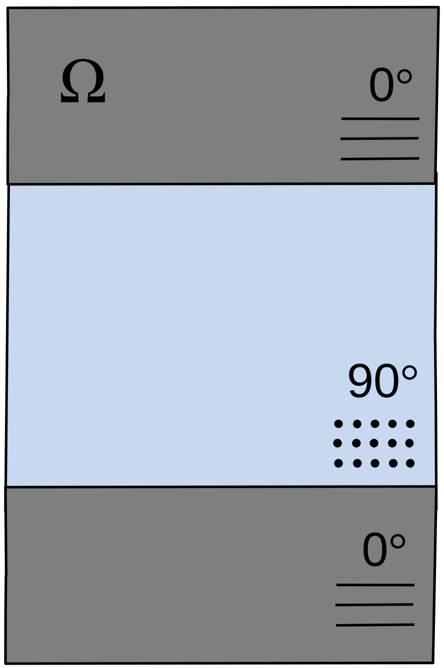


II

FNM & VCCT applied to cross-ply laminates:

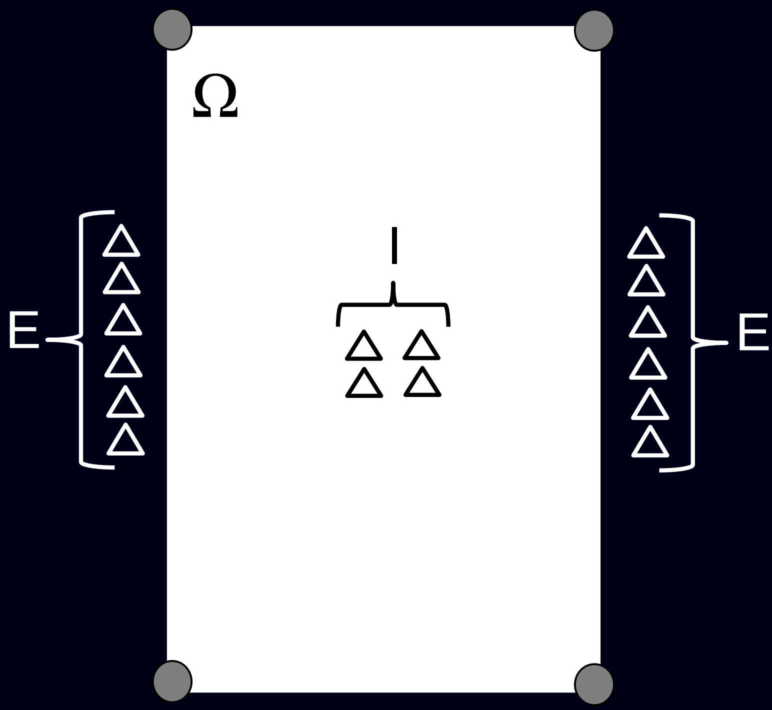
Laminate

[0°/90°$_2$/0°]



1 FNM Element

(multiple plies)



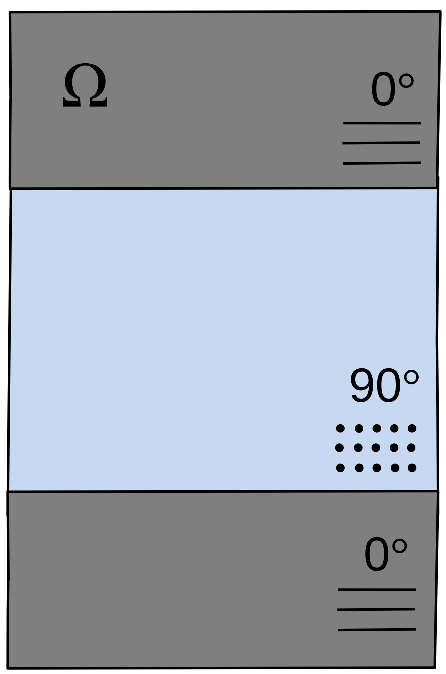
- Real node
- Floating node (DoF)
- Coordinates of crack positions

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:

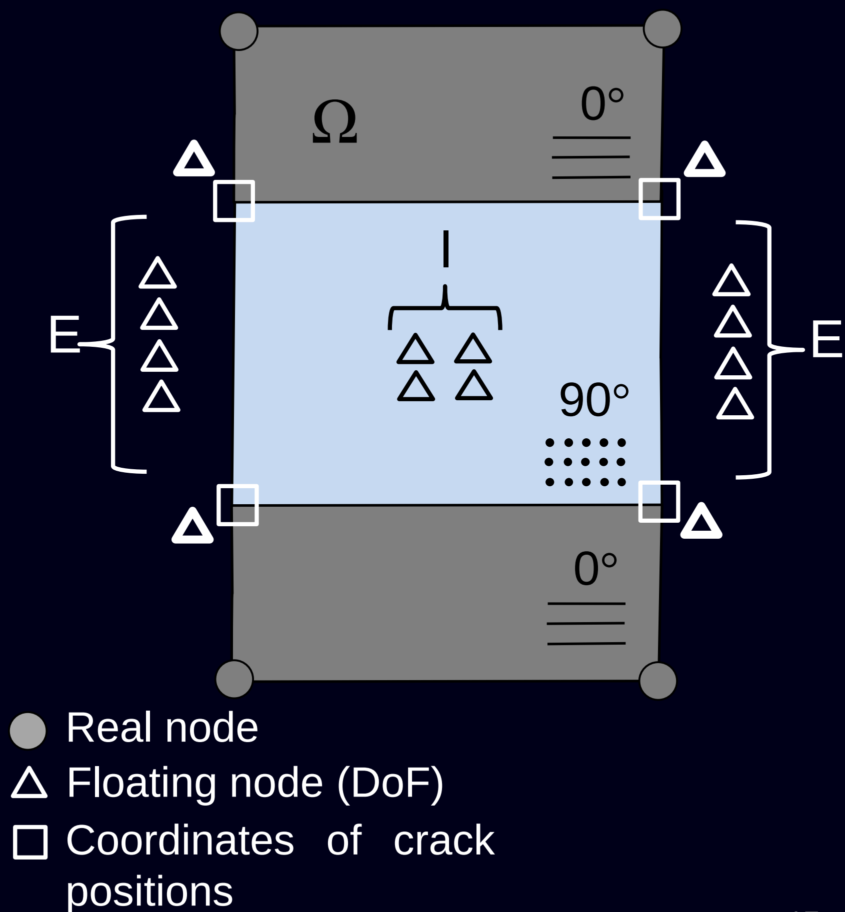
Laminate

[0°/90°$_2$/0°]



1 FNM Element

[0°/90°$_2$/0°]



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:**

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

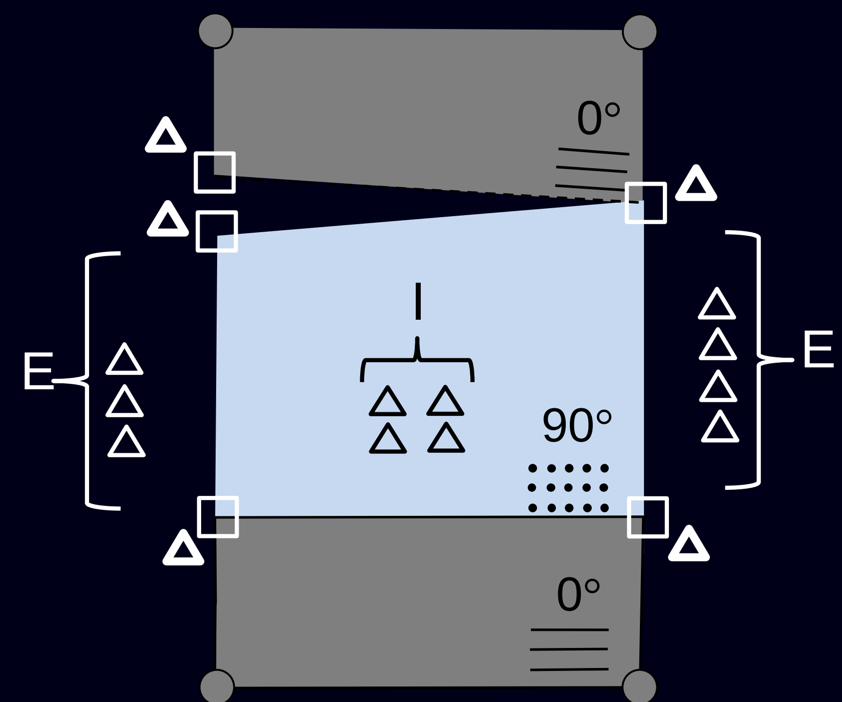
Fatigue

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

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

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

Delamination



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

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

Quasi-static

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

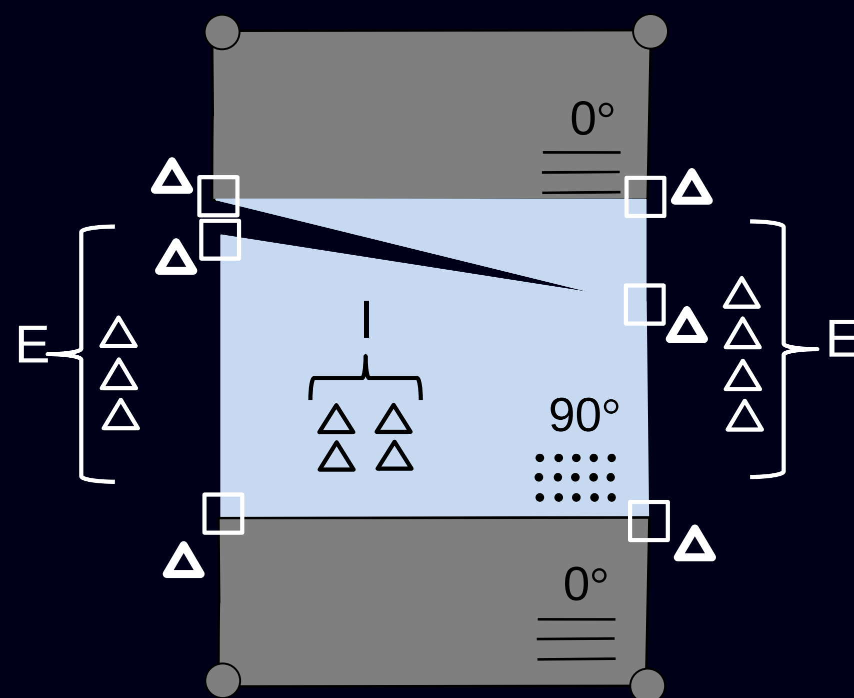
$$G_c^i = \begin{cases} G_c^A, & F_t < 0 \\ G_c^B, & F_t > 0 \end{cases}$$

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)

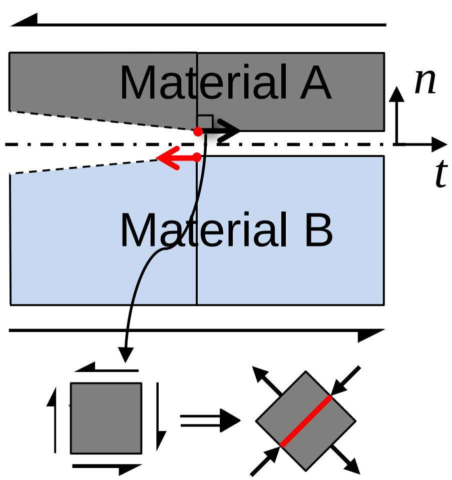


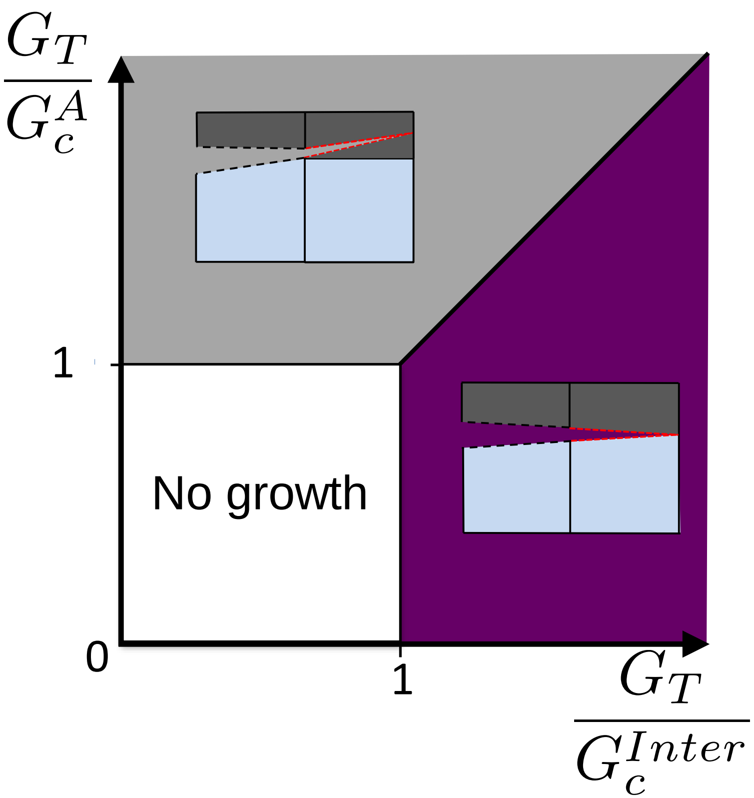
- Real node
- Floating node (DoF)
- Coordinates of crack positions

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

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

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

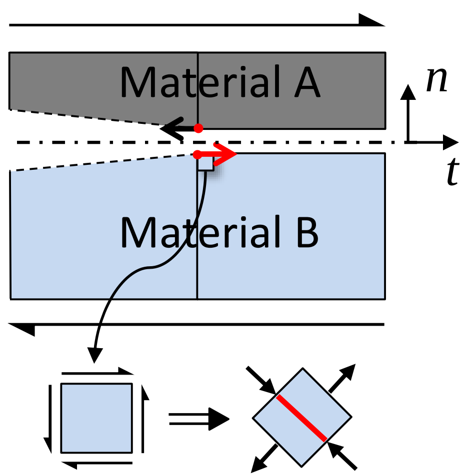


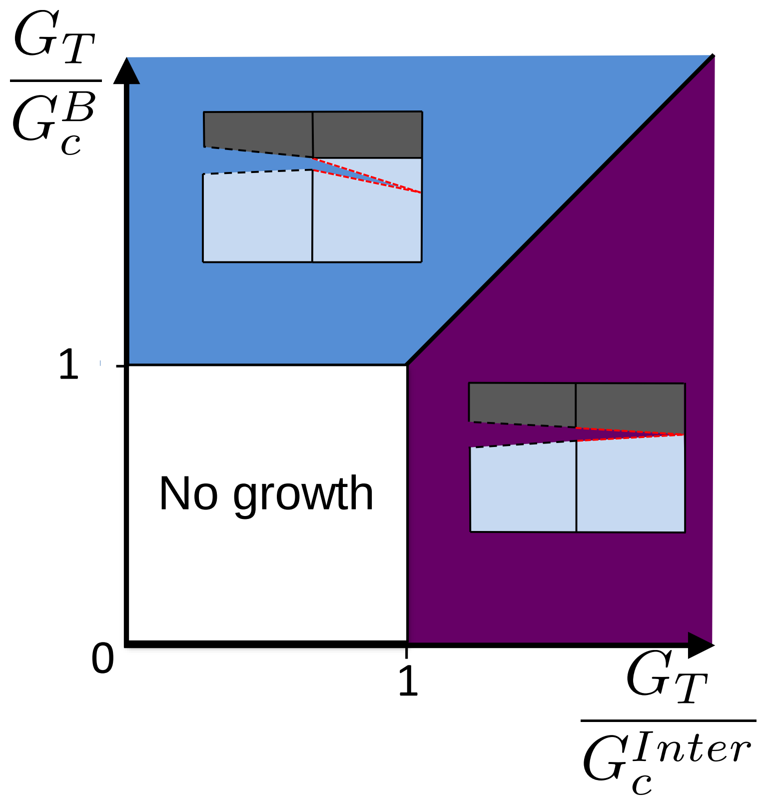


FNM & VCCT applied to cross-ply laminates: Migration onset – quasi-static

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

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

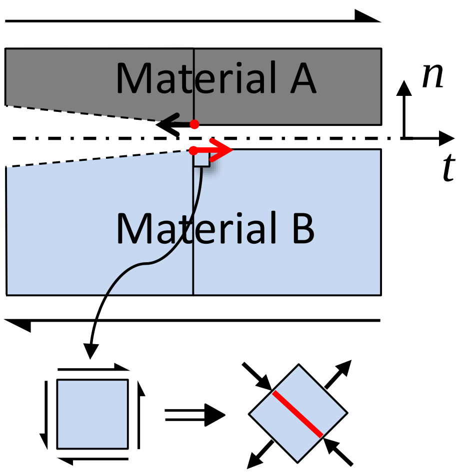


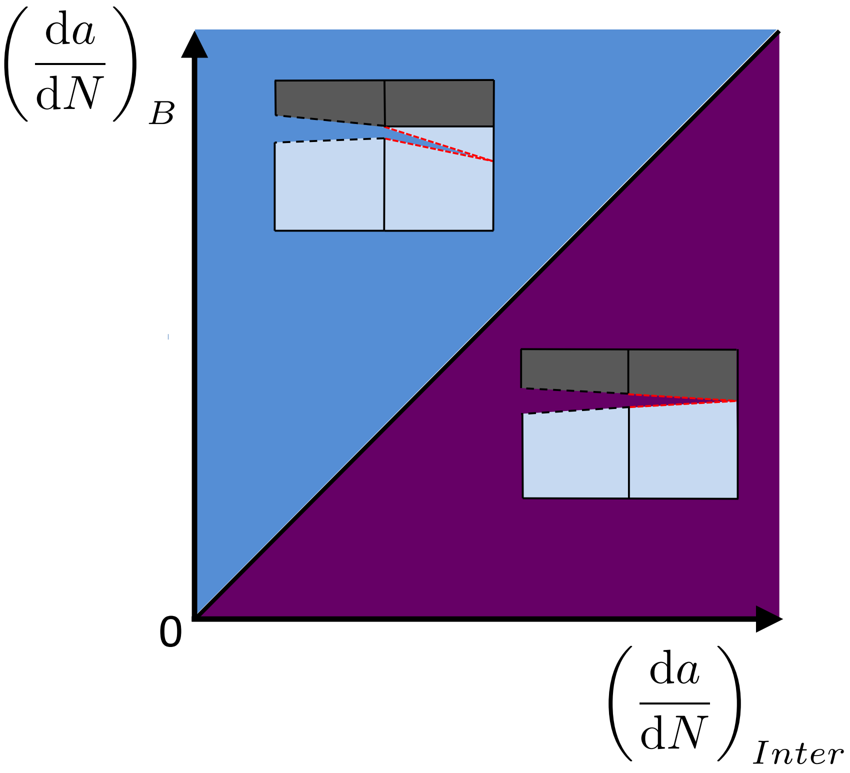


FNM & VCCT - application to composites: Migration onset - fatigue

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

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





FNM & VCCT applied to cross-ply laminates:

Quasi-static

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

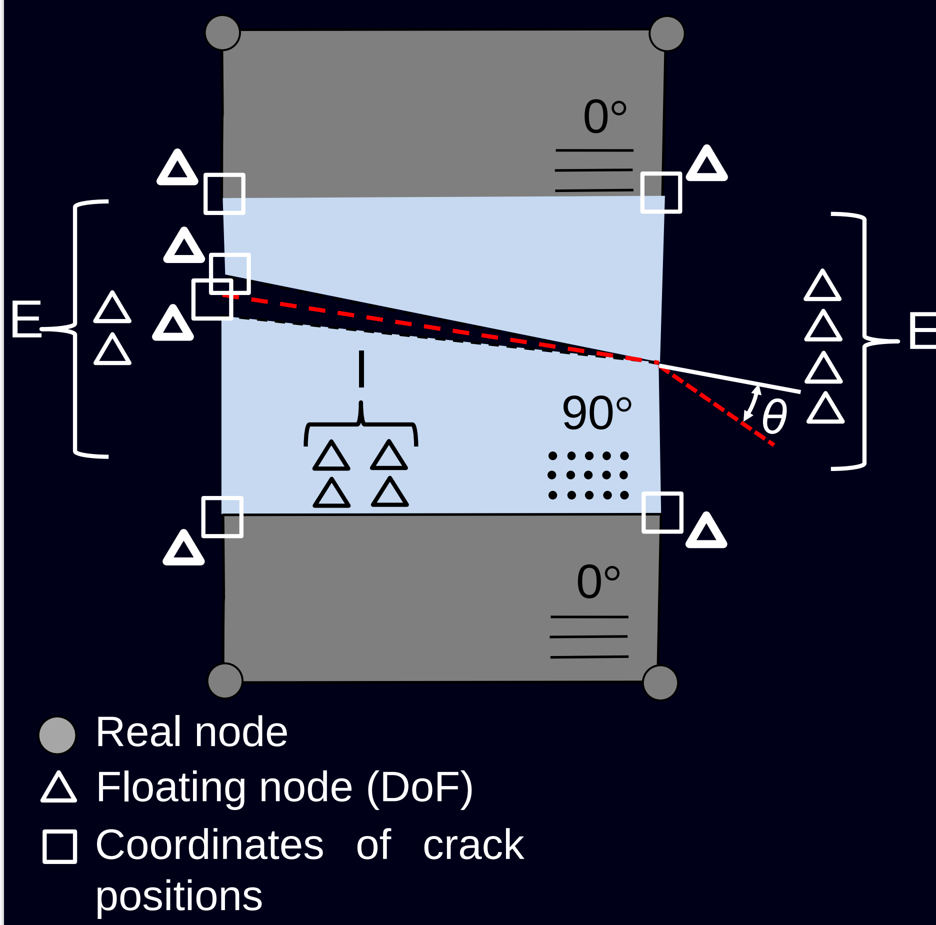
Fatigue

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

Maximum tangential stress criterion:

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

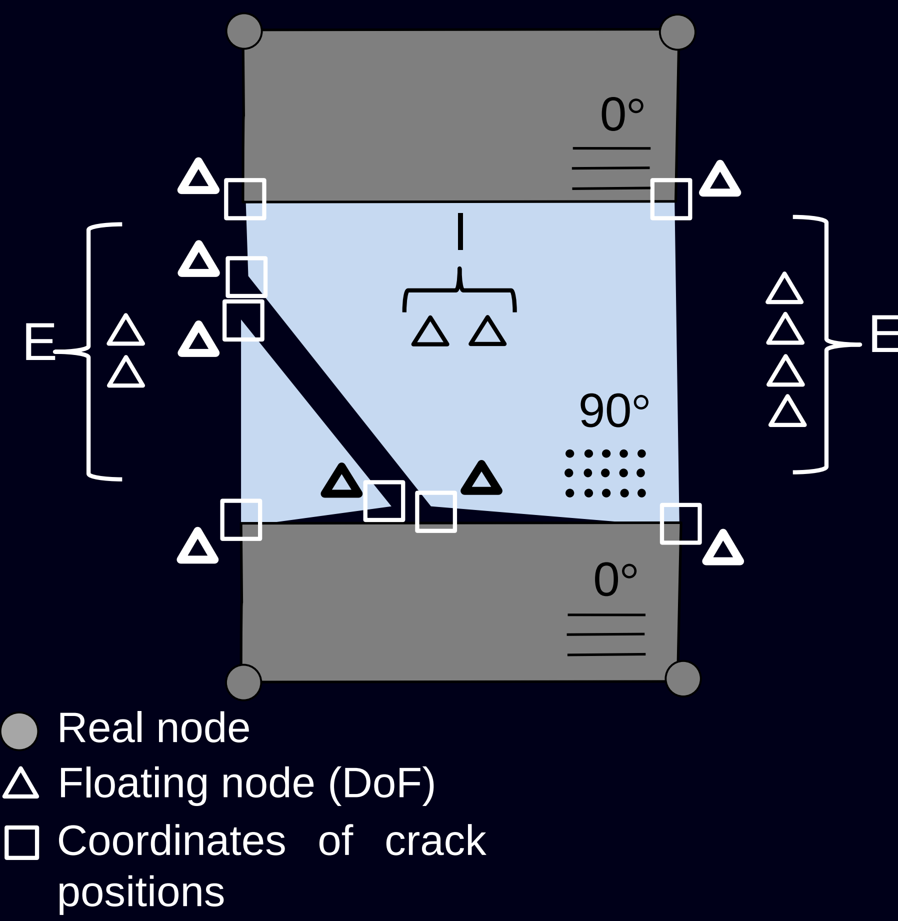
Matrix Crack



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

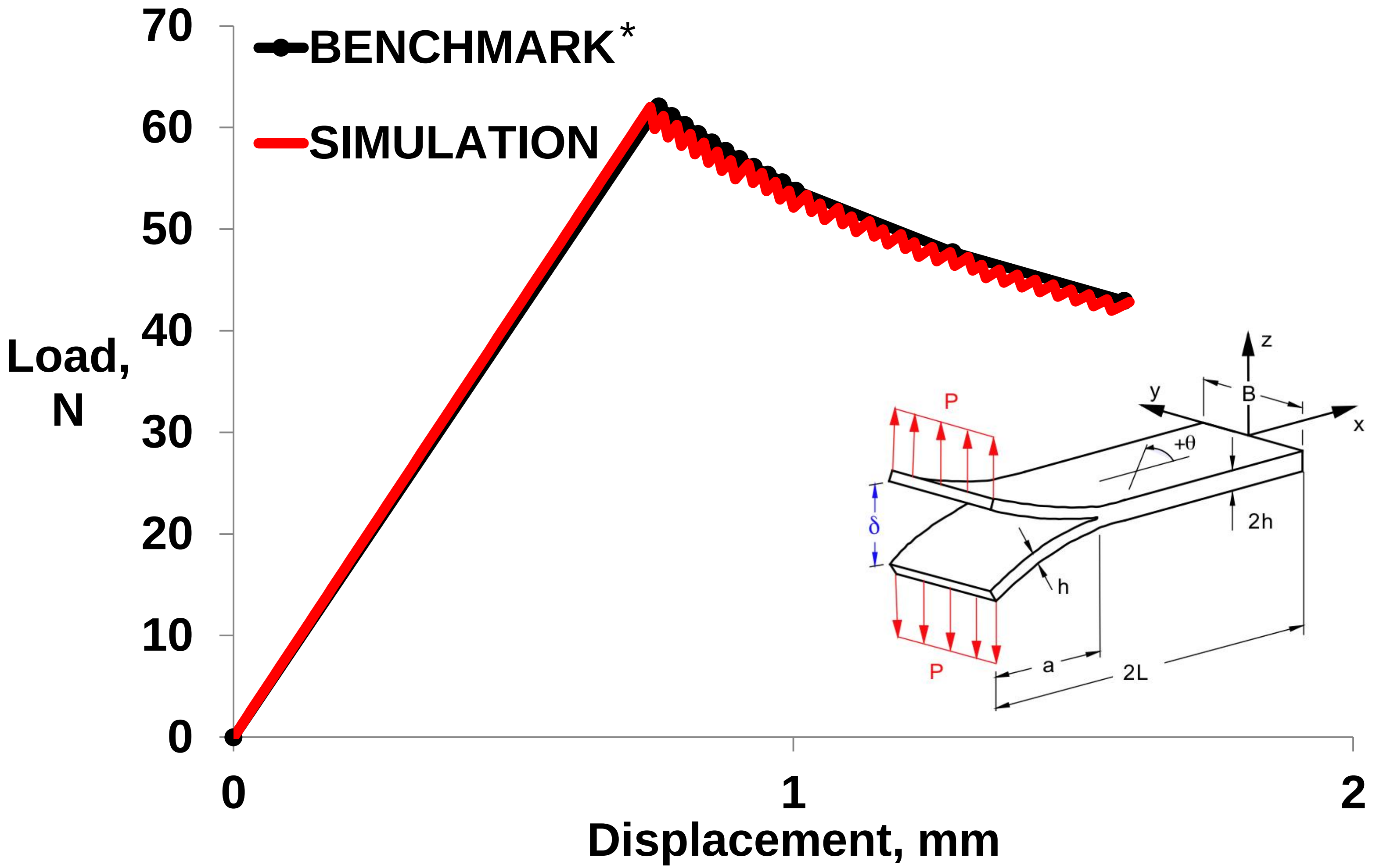
$$a\big|^{n} = a\big|^{n} + \delta a\big|^{n}_{1el}$$

❸ PROPAGATE THE CRACK

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

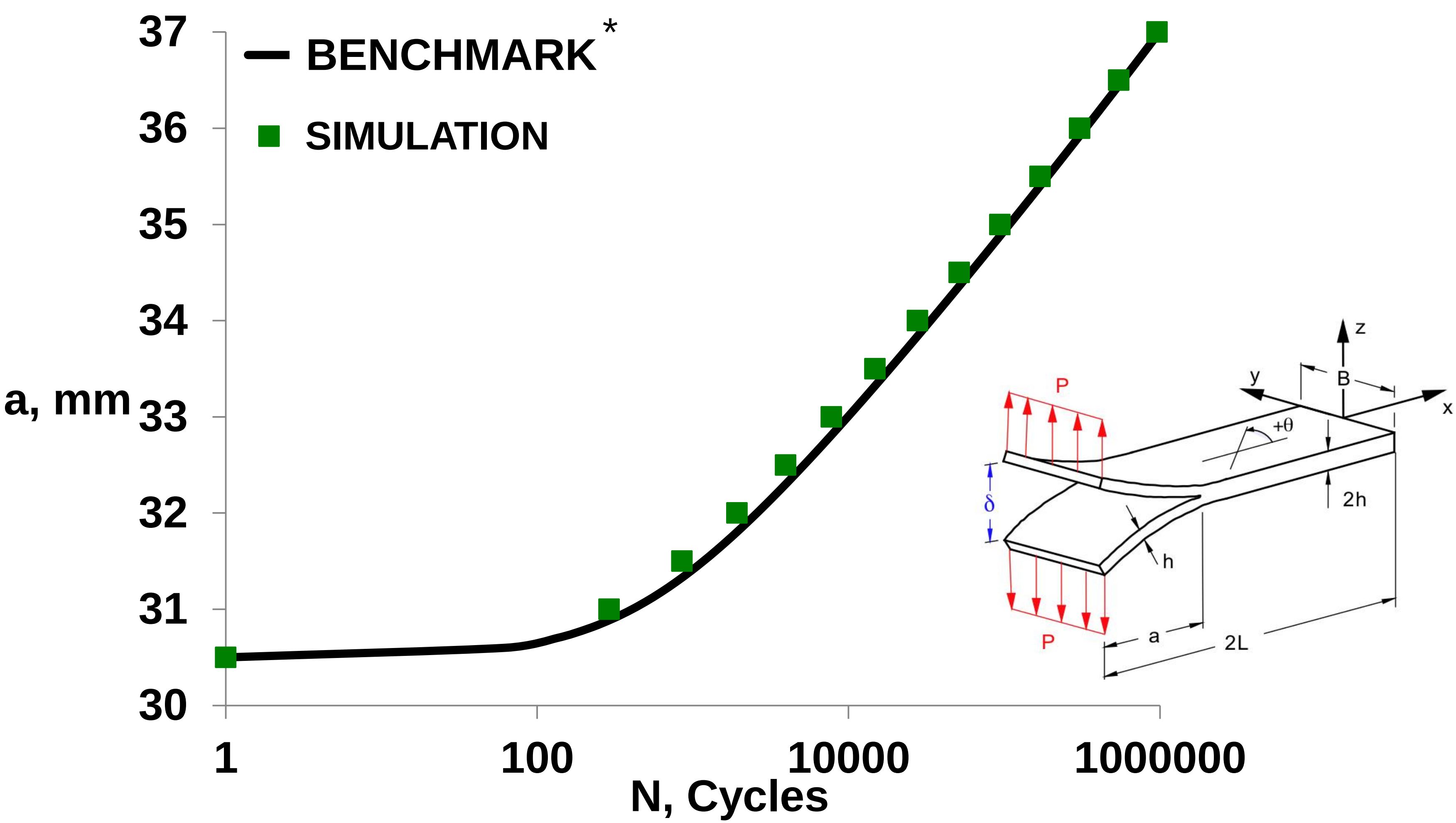
❹ ACCUMULATE THE CYCLES

Verification – Static: DCB



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

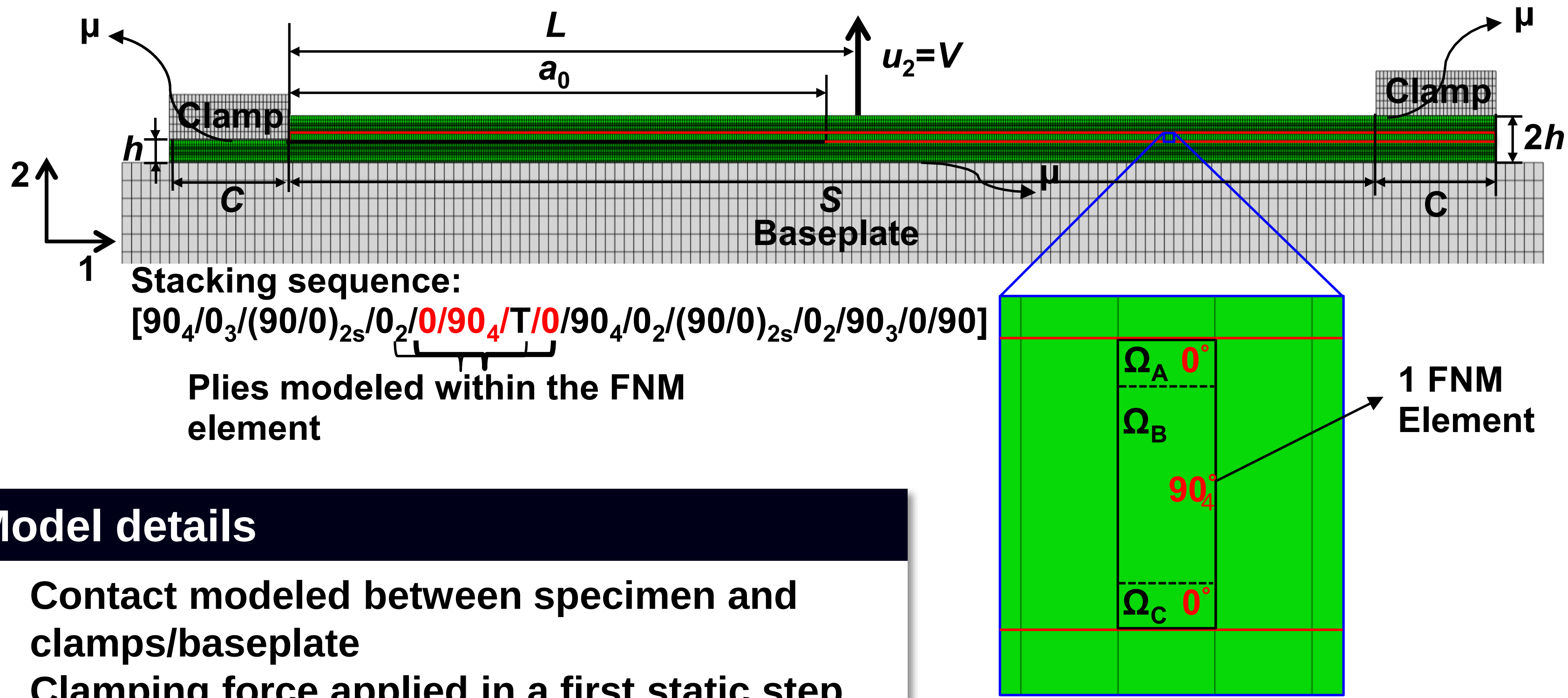
Verification – Fatigue: DCB benchmark



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

Contents

Validation: Delamination migration test
Numerical model



Stacking sequence:
$[90_4/0_3/(90/0)_{2s}/0_2/0/90_4/T/0/90_4/0_2/(90/0)_{2s}/0_2/90_3/0/90]$

Plies modeled within the FNM element

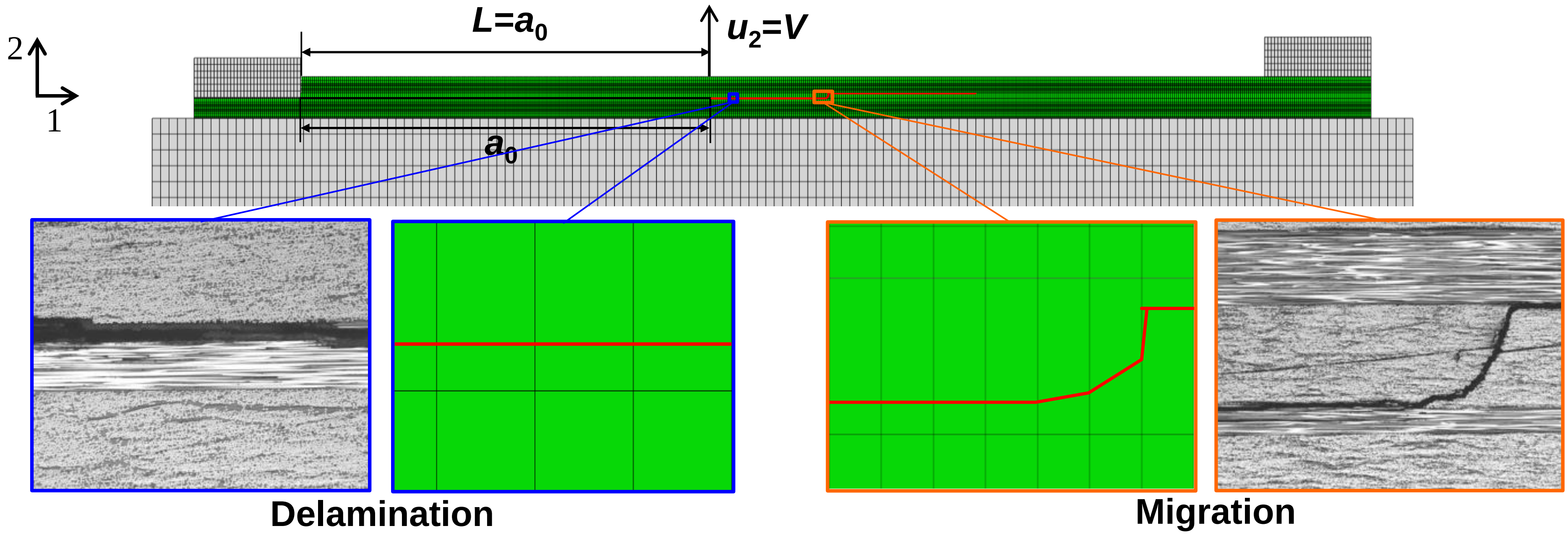
Model details

- 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

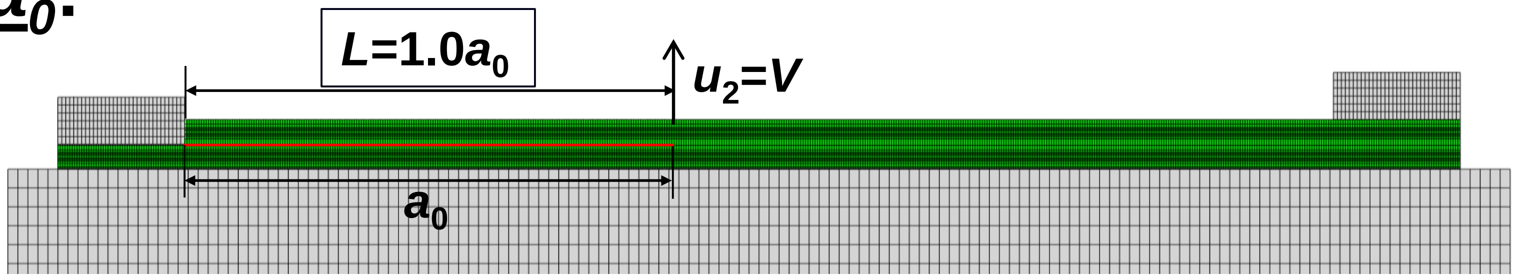


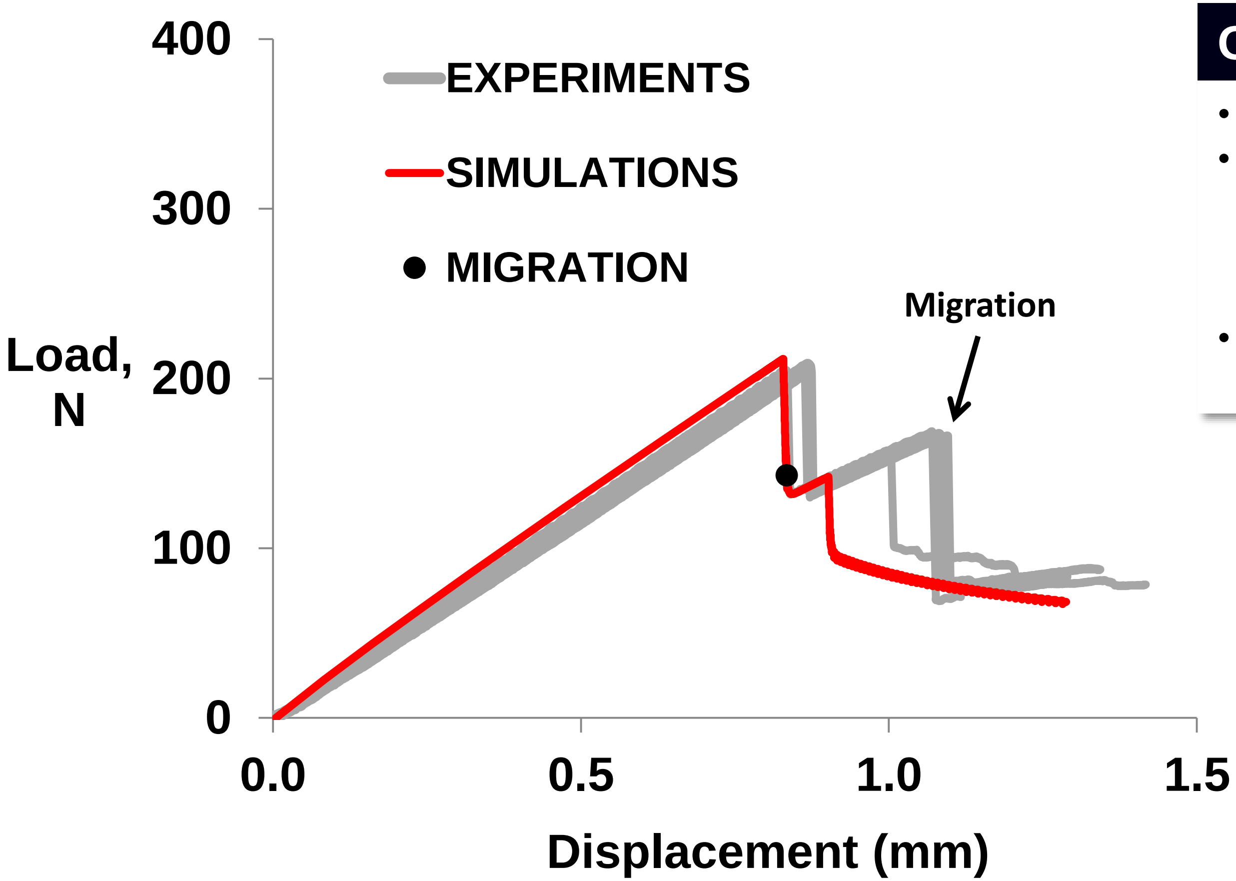
Observations

- **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:



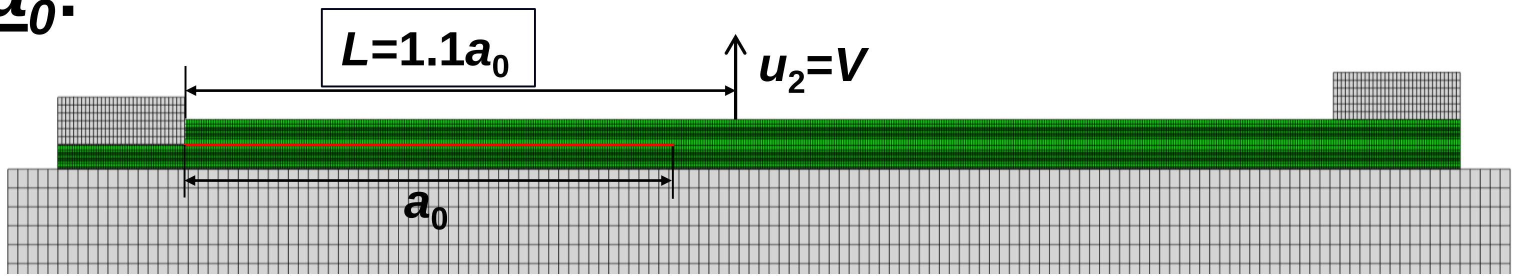


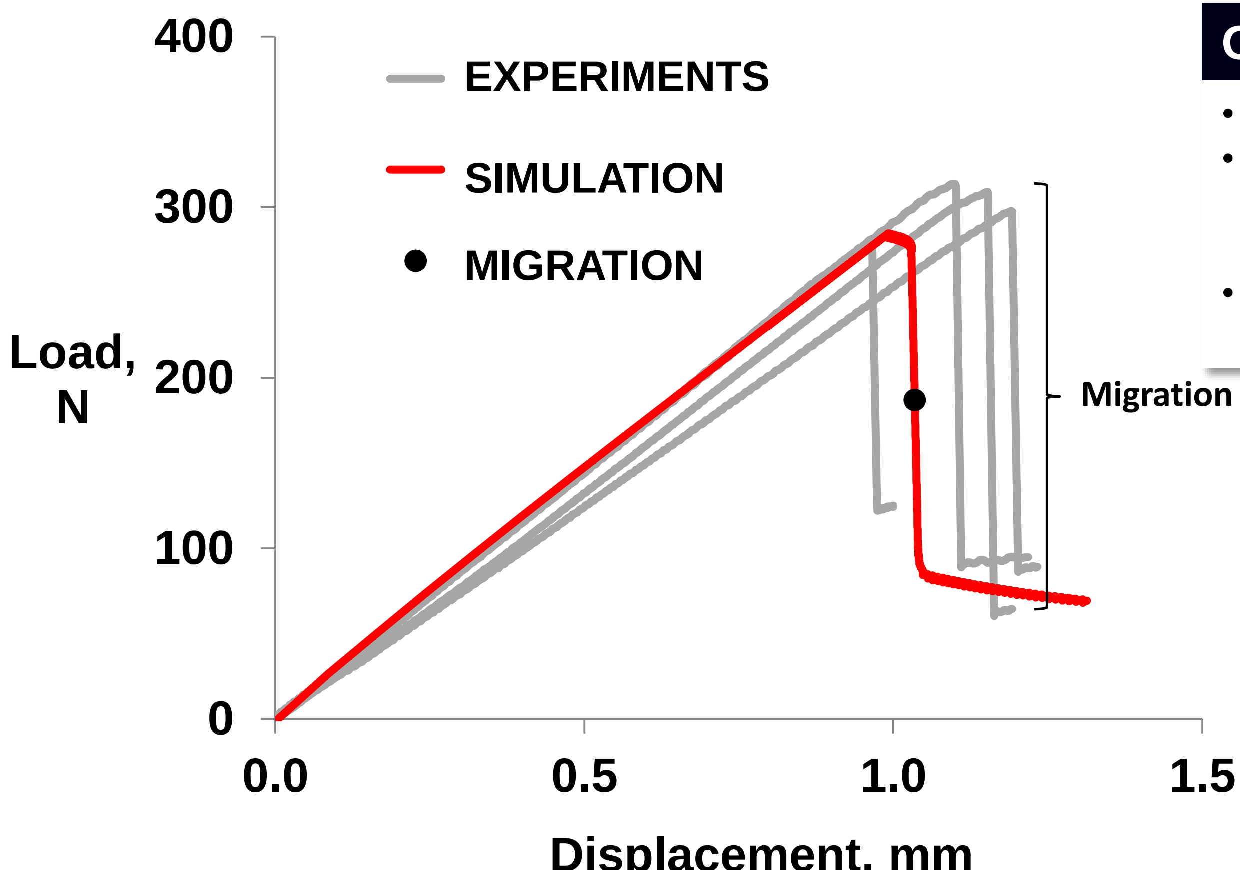
Observations

- 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

$L=1.1a_0$:



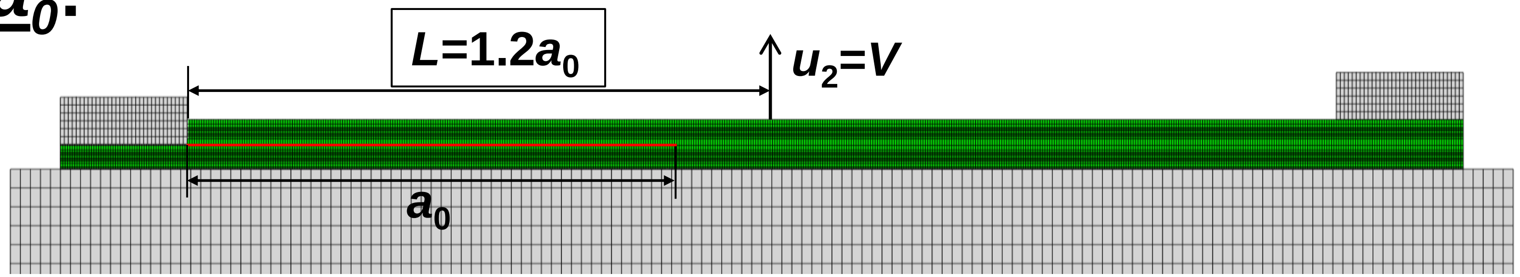


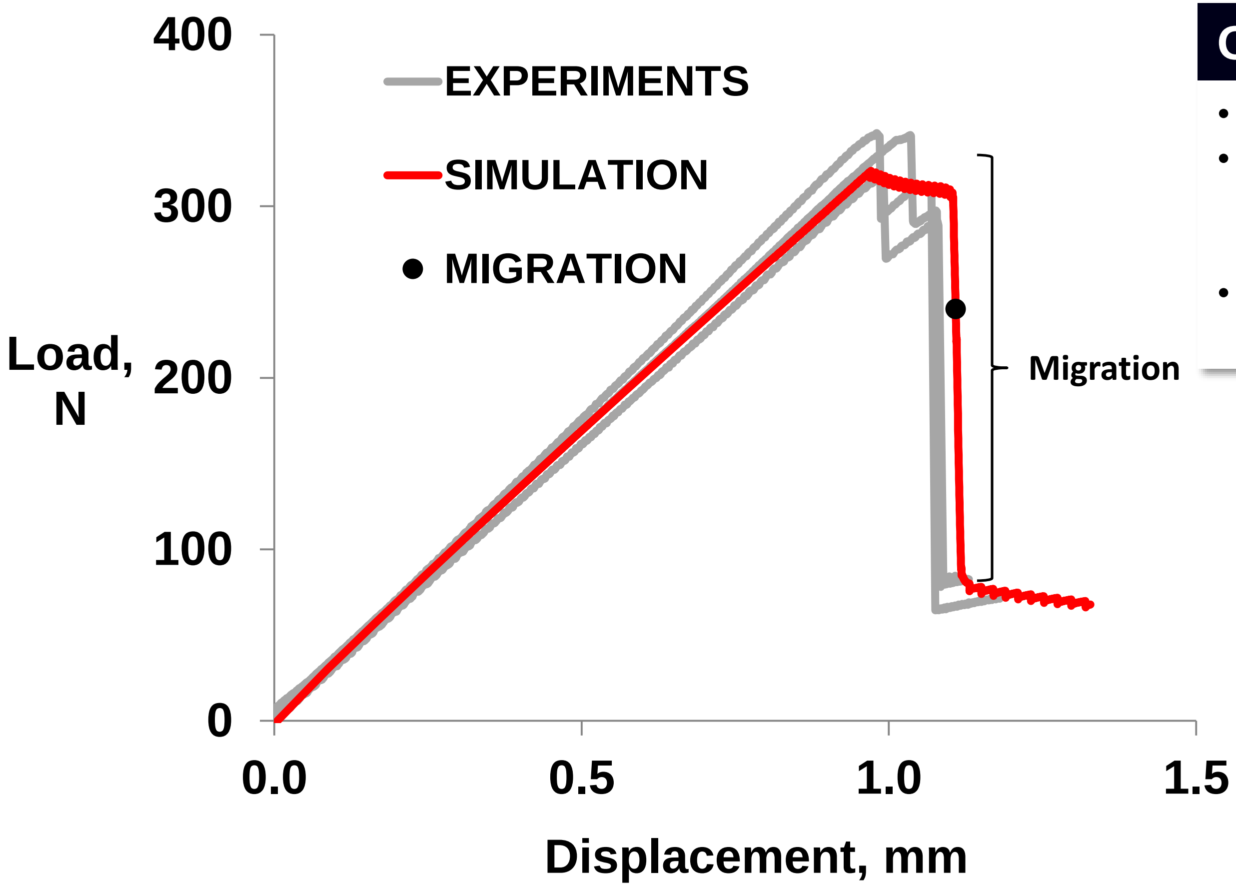
Observations

- 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

$L=1.2a_0$:

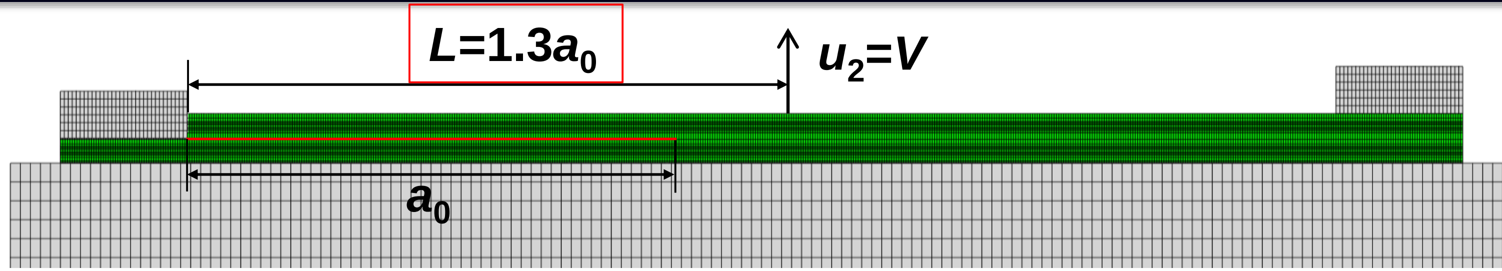


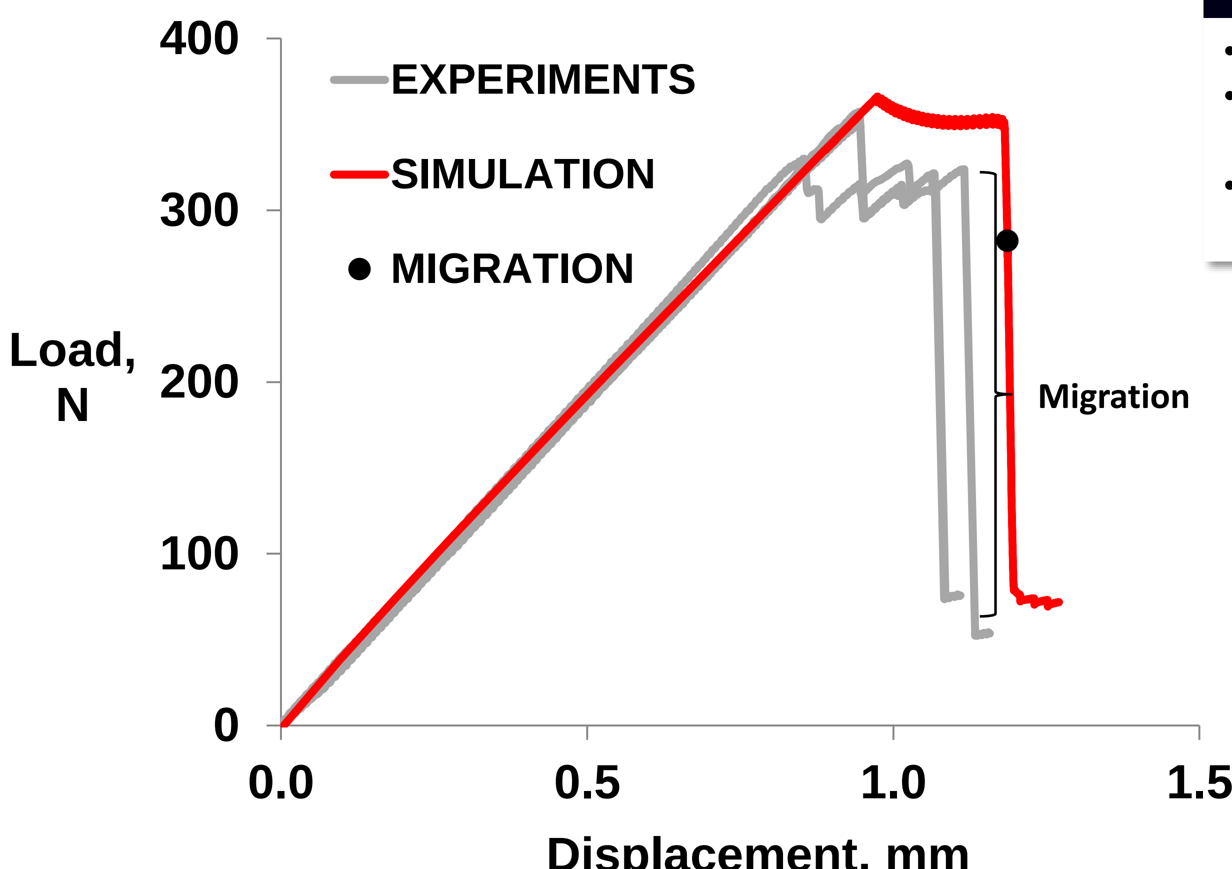


Observations

- 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

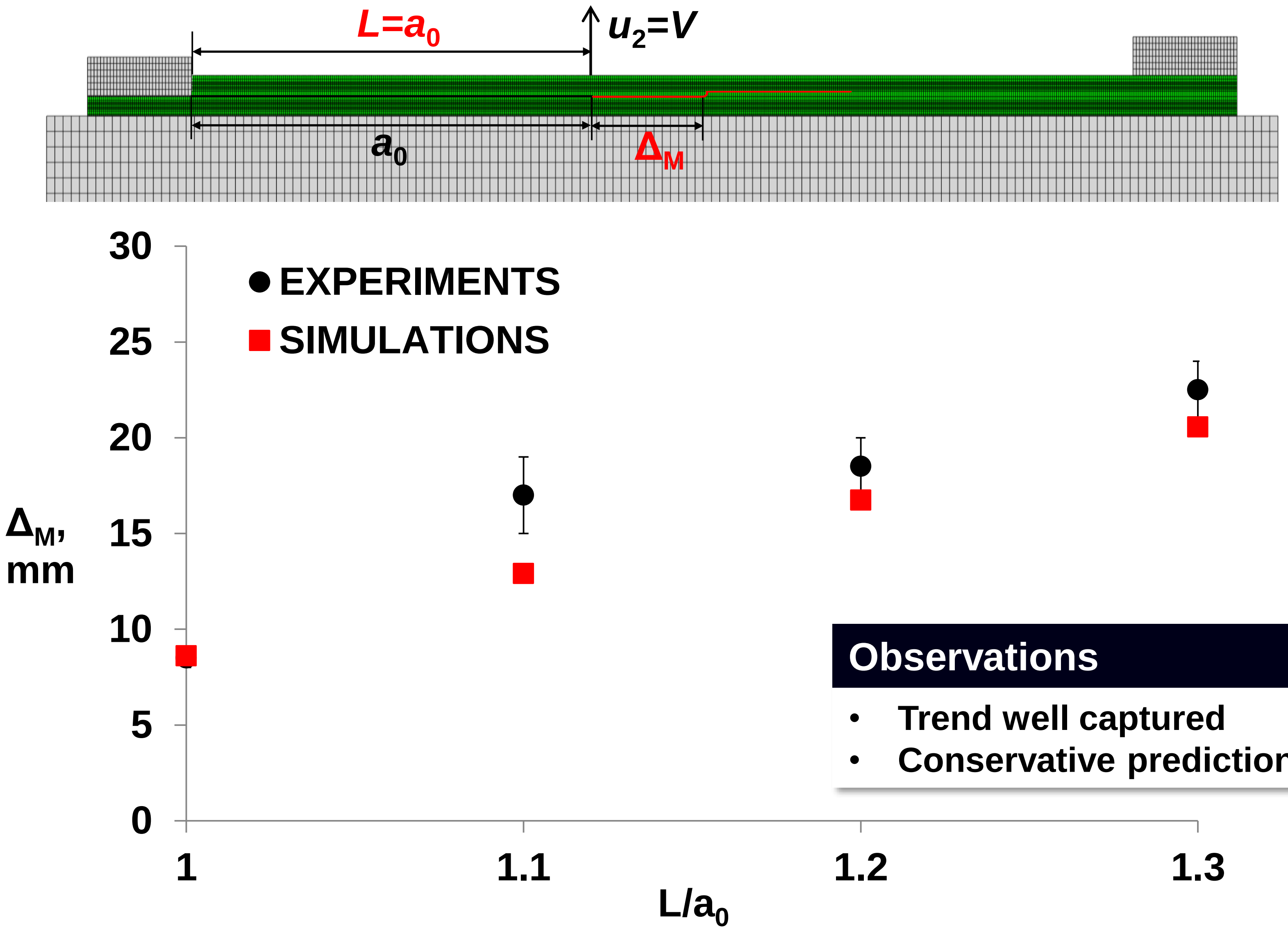




Observations

- 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

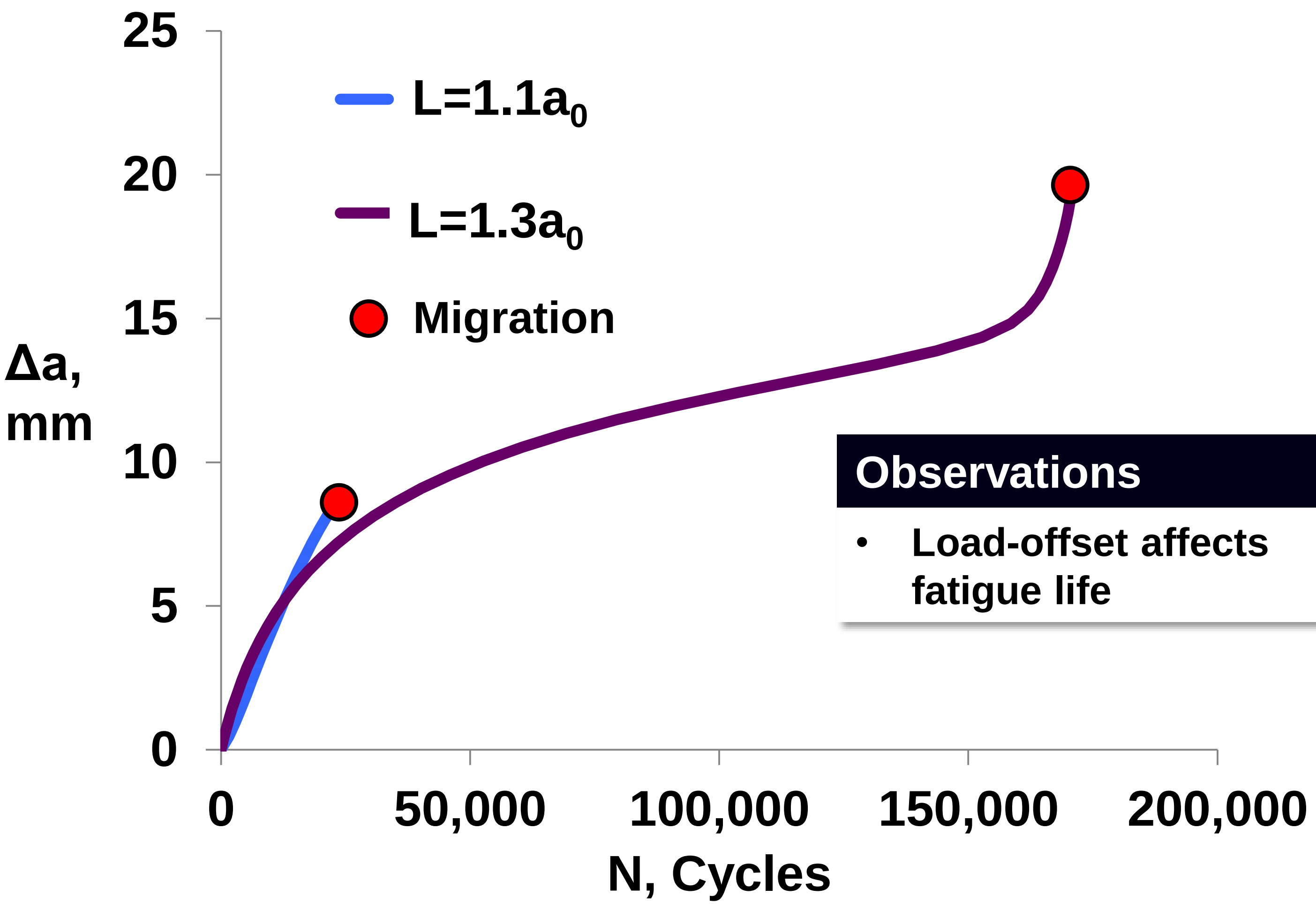


Observations

- 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

1 **Experiments:** delamination migration test

2 **Modeling approach:** Floating Node Method (FNM) and Virtual Crack Closure Technique (VCCT)

3 **Validation:** modeling delamination migration

4 **Summary**

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

N. V. De Carvalho
nelson.carvalho@nasa.gov
National Institute of Aerospace

B.Y. Chen
Imperial College London
National University of Singapore

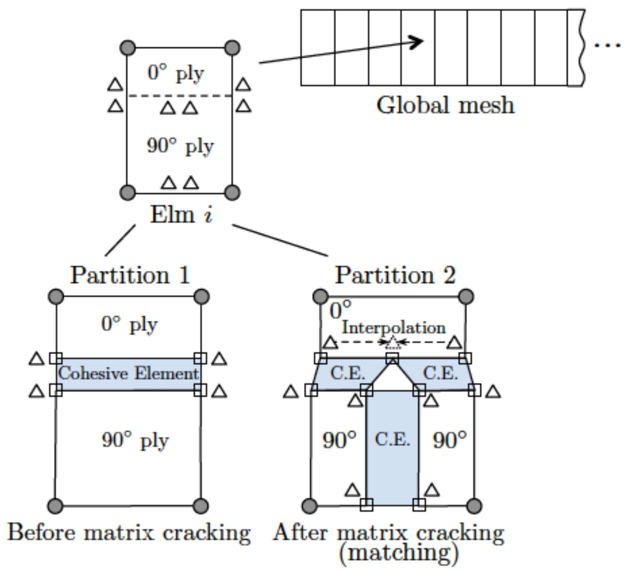
J.G. Ratcliffe
NASA Langley

S. T. Pinho, P. Baiz
Imperial College London

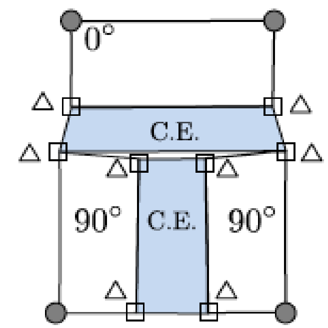
T. E. Tay
National University Singapore

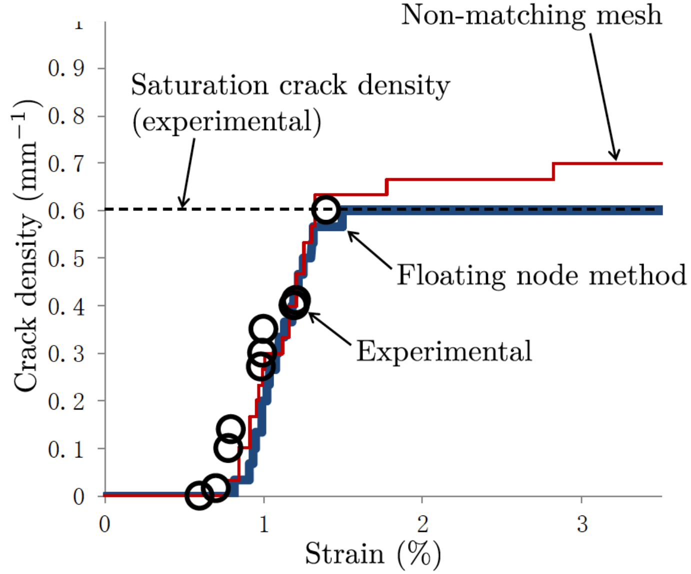
Backup Slides: cohesive zone elements

FNM

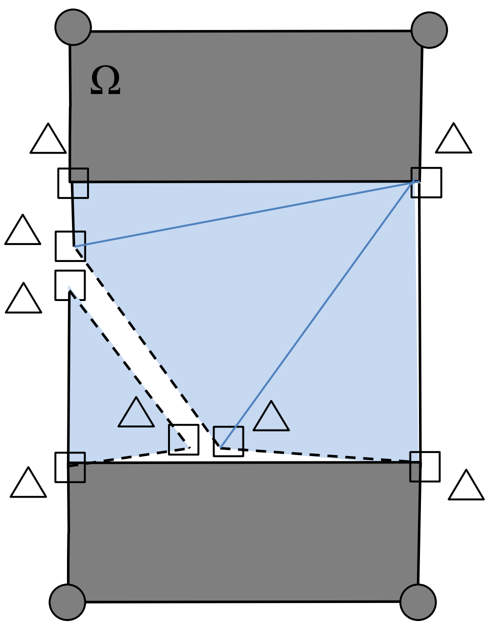


"Non-matching mesh"

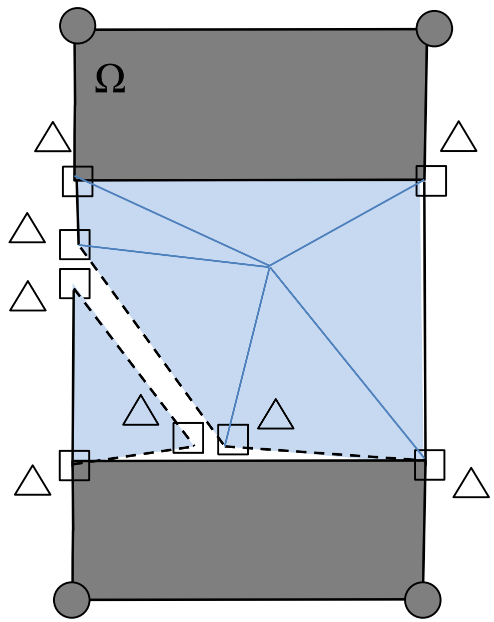




Backup Slides: element integration



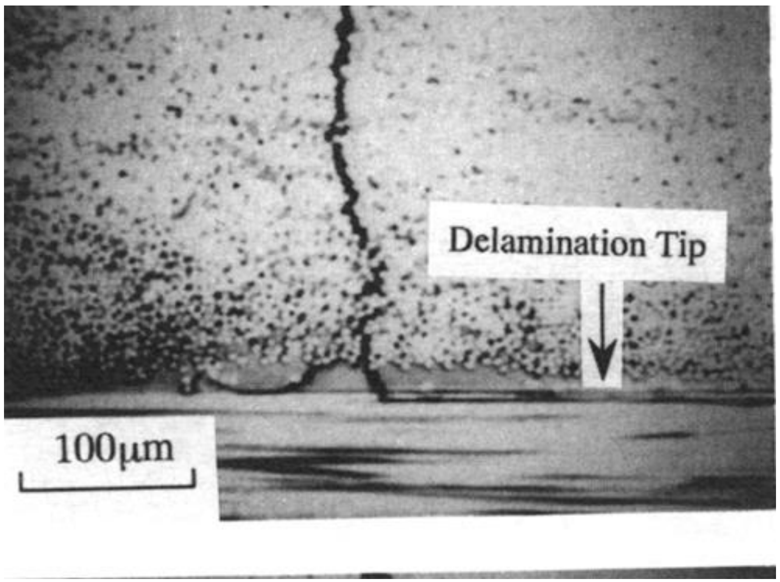
or

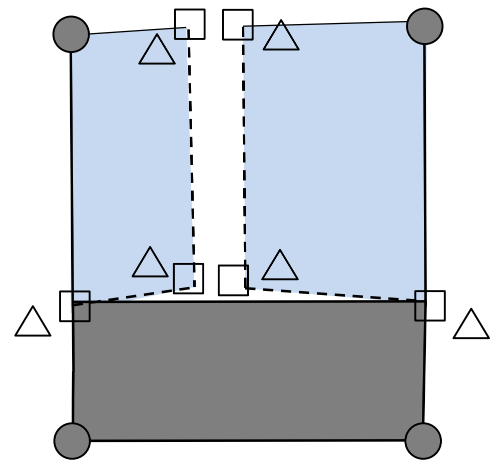


or

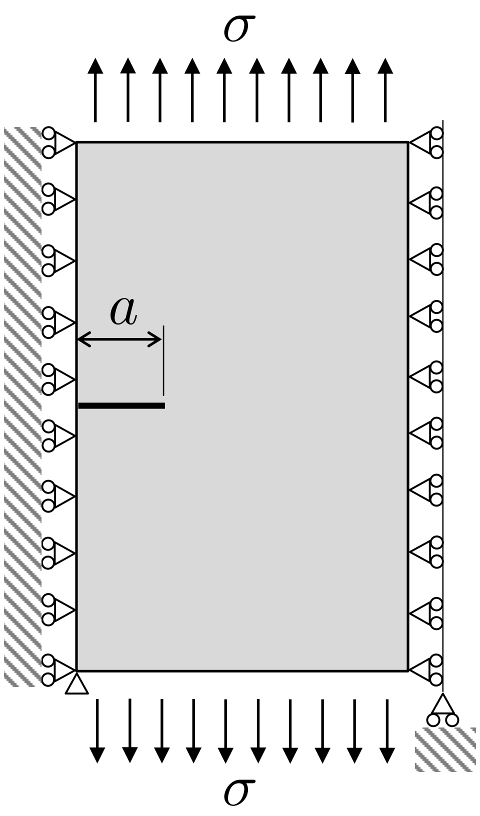
…

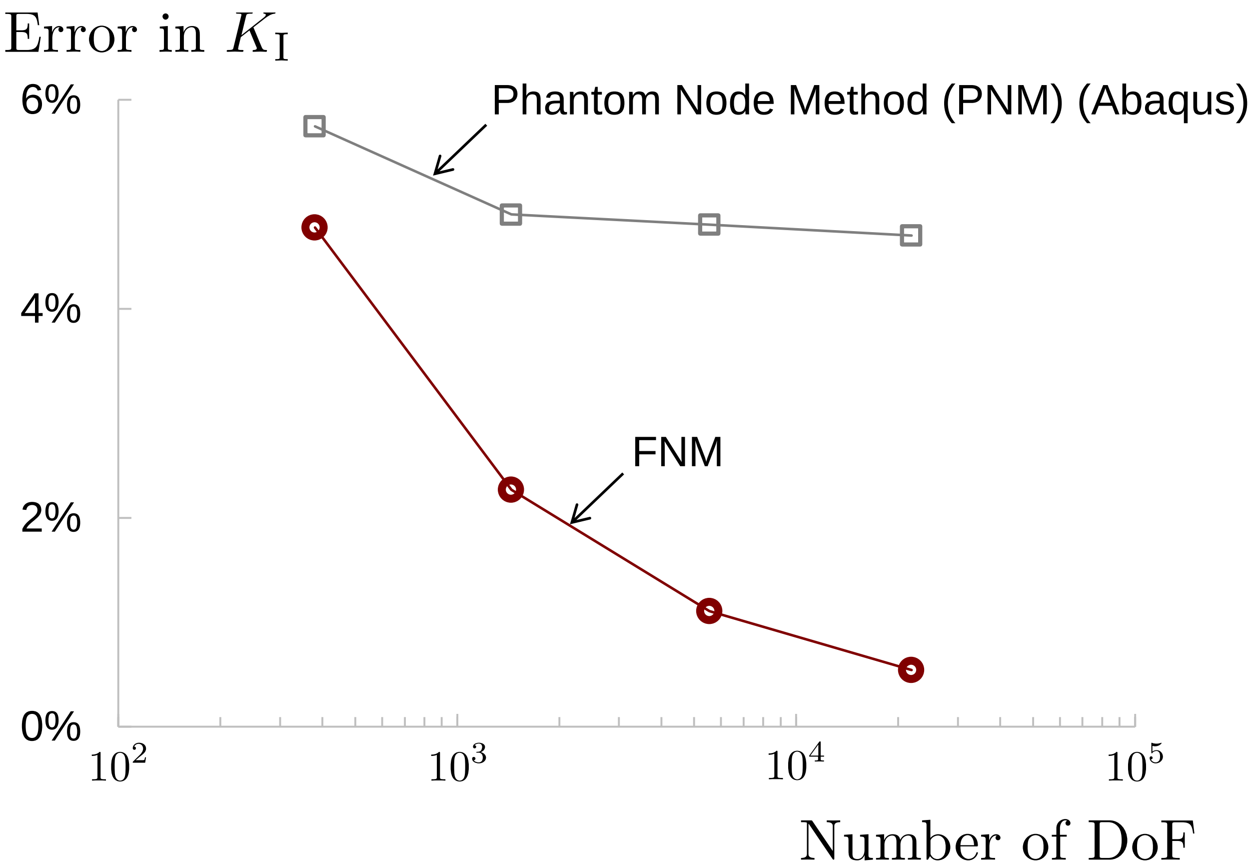
Backup Slides: Topological migration criterion, experimental evidence



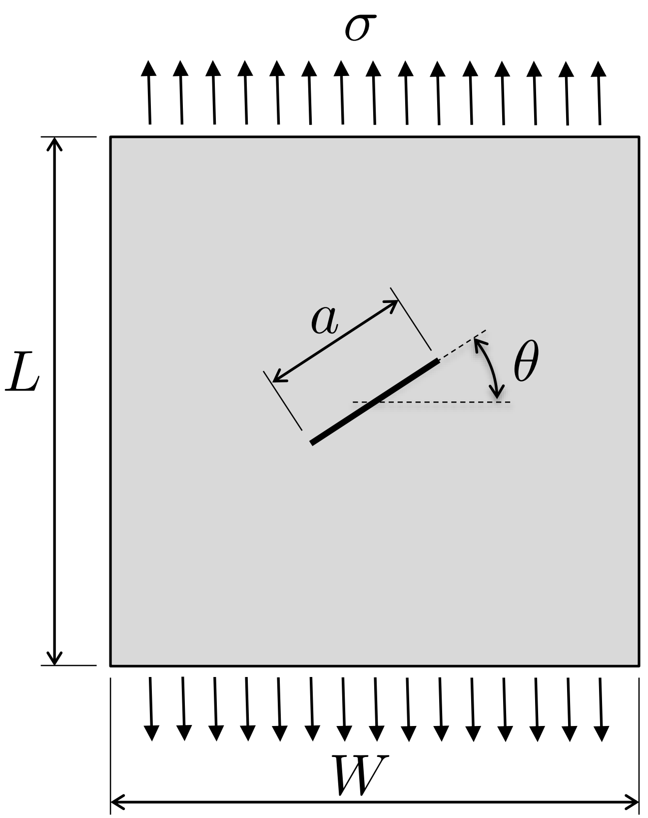


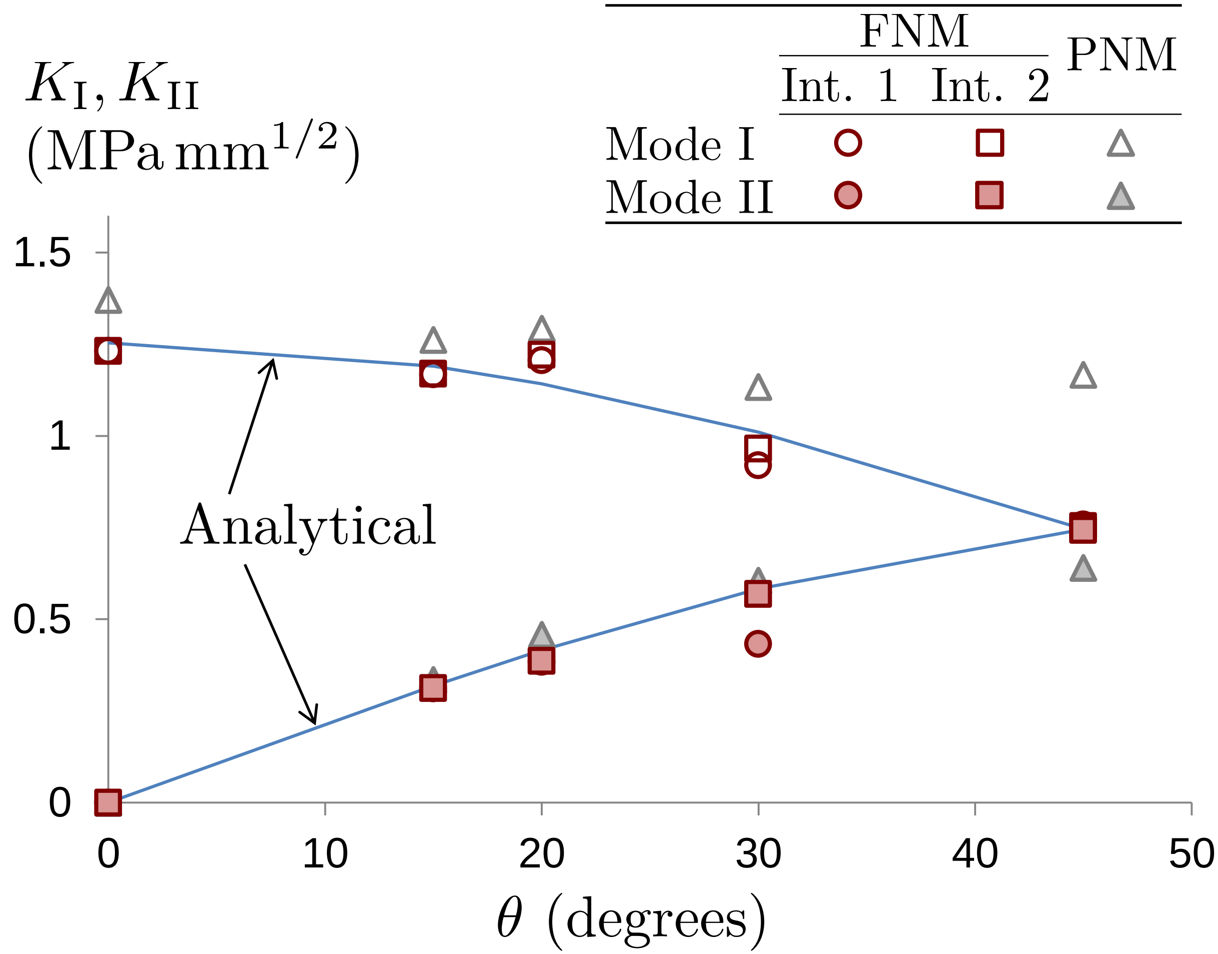
Backup Slides: FNM vs PNM, convergence: K_I



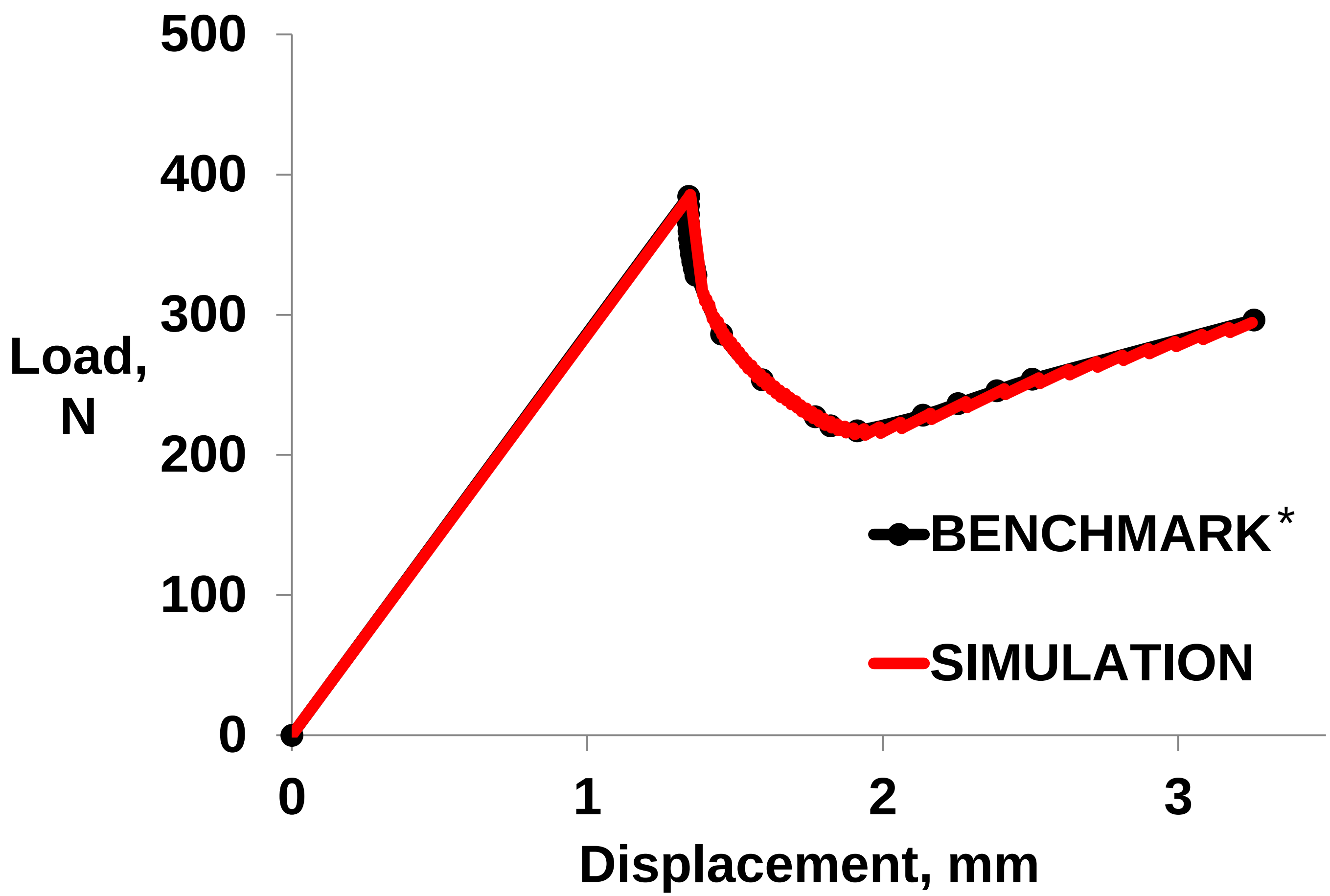


Backup Slides: FNM vs PNM, accuracy: K_I, K_{II}





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.