EFFECTS OF VARIABLE AMPLITUDE FATIGUE ON DELAMINATION AND CRACK GROWTH RATE MODELS

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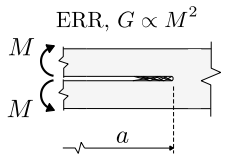
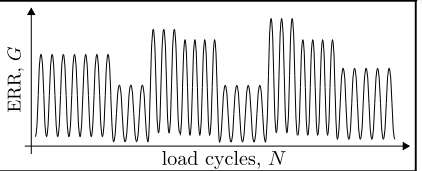
Fatigue-driven delamination

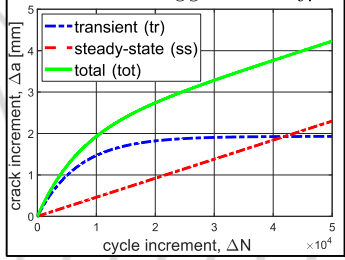




Model

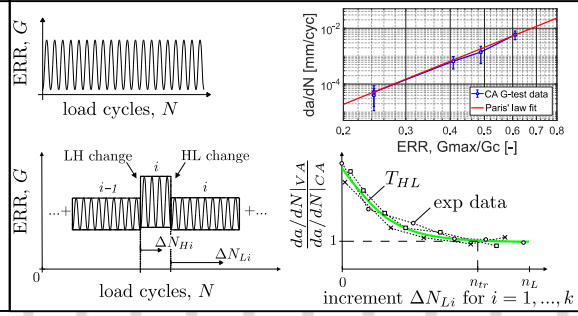
New formulation

$$\frac{da}{dN} = \frac{da}{dN}_{ss} + \frac{da}{dN}_{tr}$$

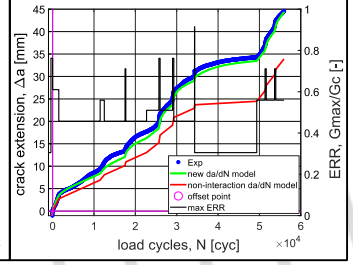


Experimental testing

Characterise $\frac{da}{dN}_{ss}$ and $\frac{da}{dN}_{tr}$



Demonstrate



Jensen SM, Bak BLV, Bender JJ, Carreras L & Lindgaard E (**2021**) *Transient delamination growth in GFRP laminates with fibre bridging under variable amplitude loading in G-control*, **Composites Part B: Engineering** 225: 109296

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Background and research objective

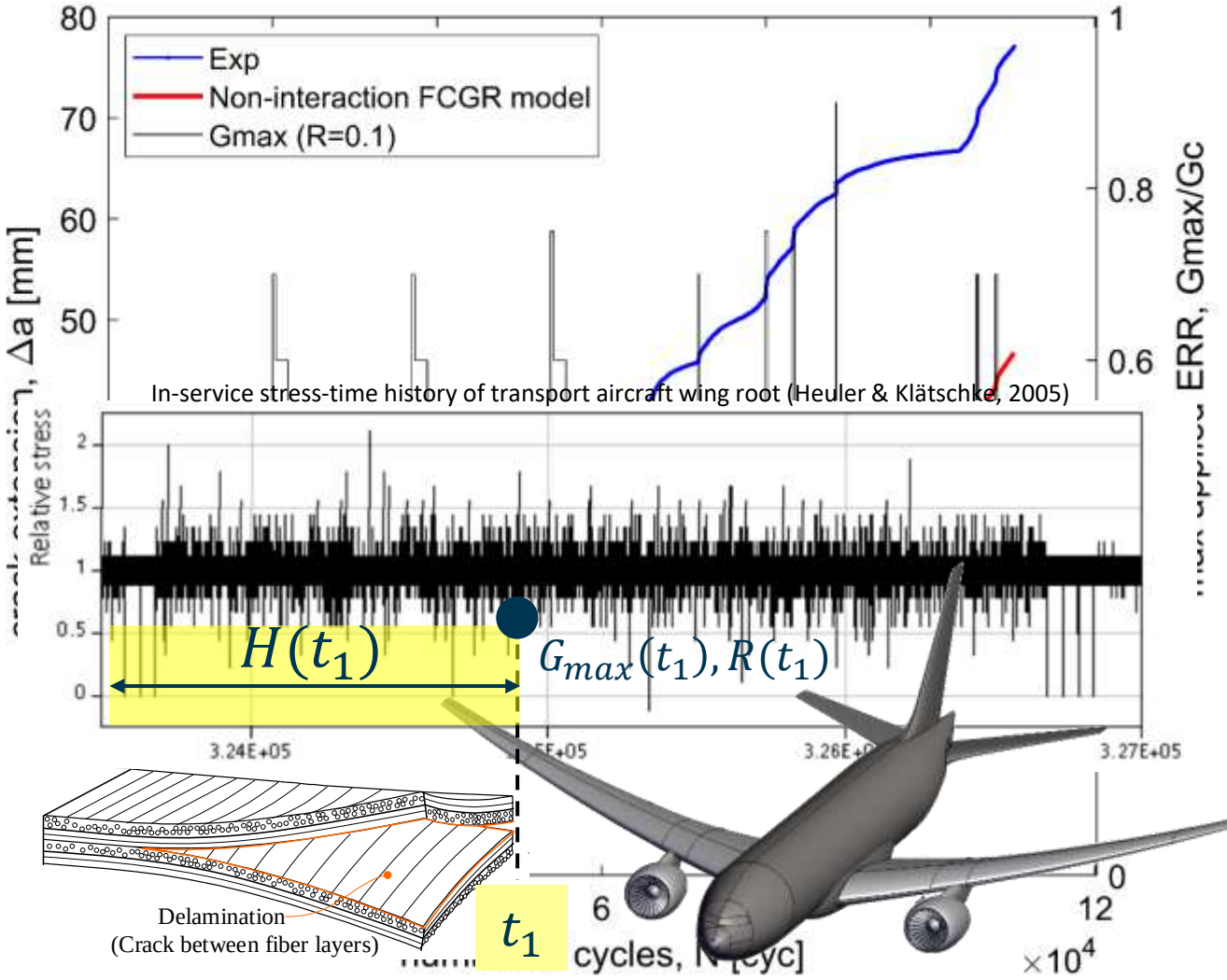
- Delaminations in FRPs may propagate under **VA fatigue** during operation

- In crack growth rate (**CGR**) models the loads are expressed in energy release rate (ERR) values:

$$\frac{da}{dN}(t_1) = \underbrace{f(G_{max}(t_1), R(t_1))}_{\textbf{Non-interaction model}} \overset{?}{H(t_1)}$$

- How is the crack growth rate (da/dN) affected by the load history (H)?

VA example:



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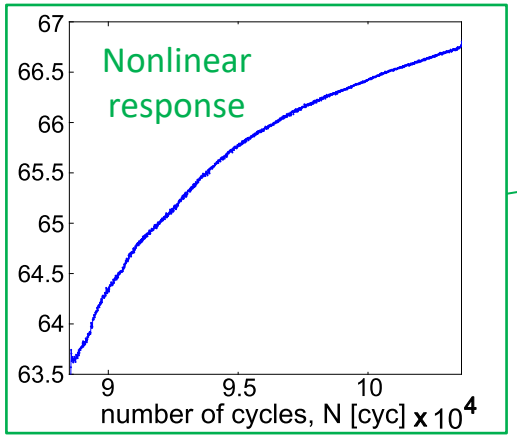
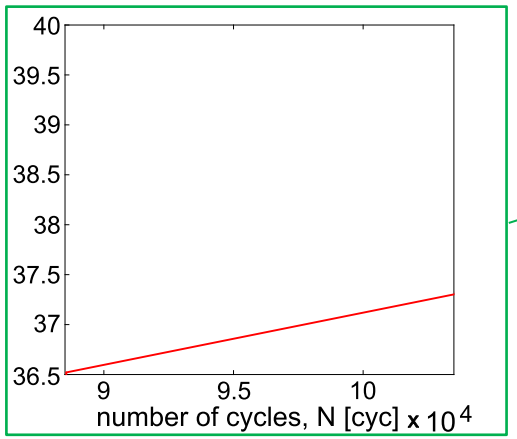
Background and research objective

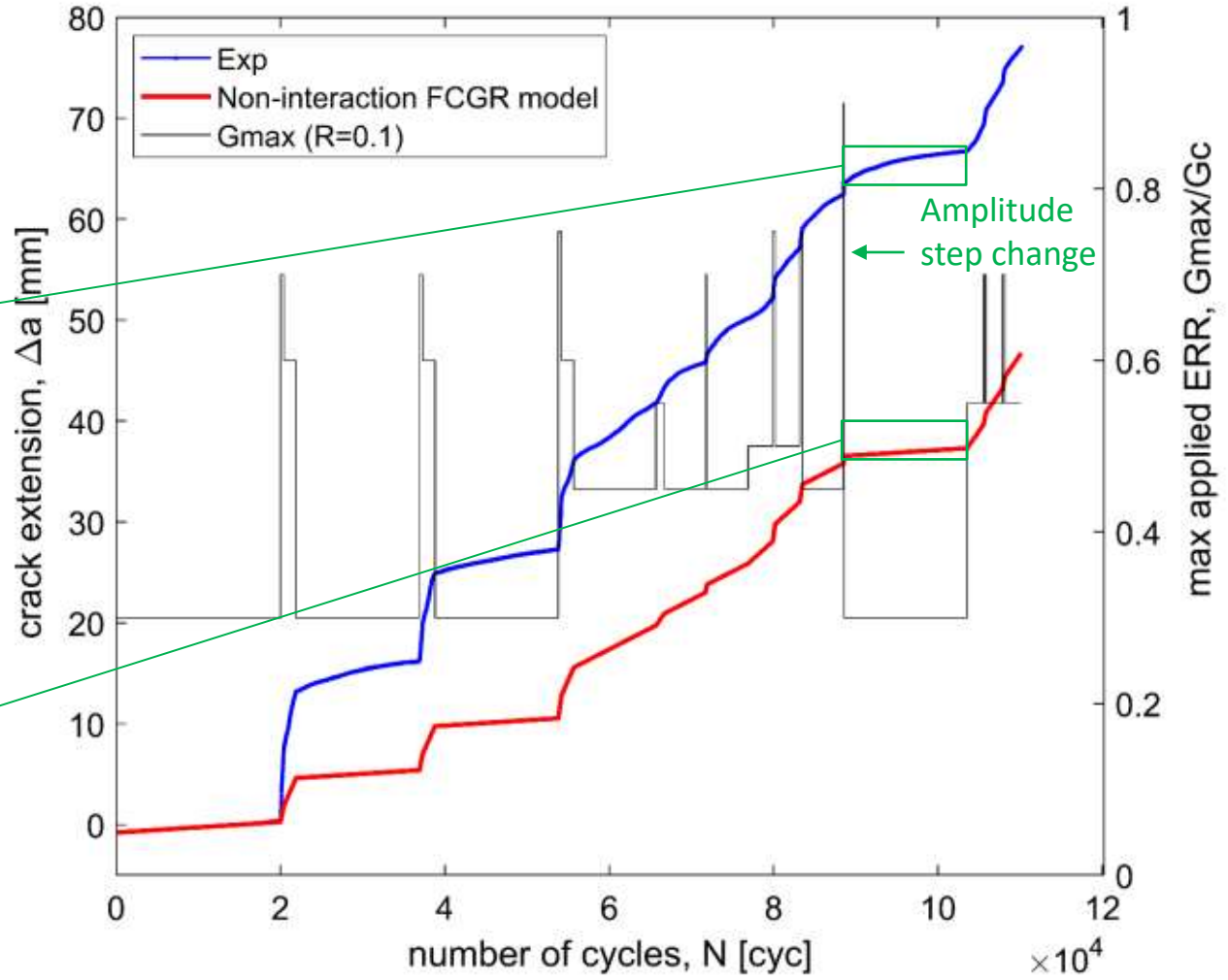
- Concentrate on the crack growth following **amplitude step changes** because of interesting **phenomenological behaviors**

zoom-in



zoom-in





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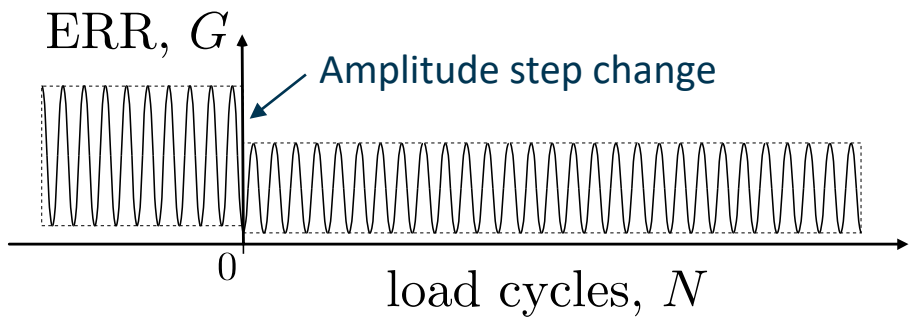
Background and research objective

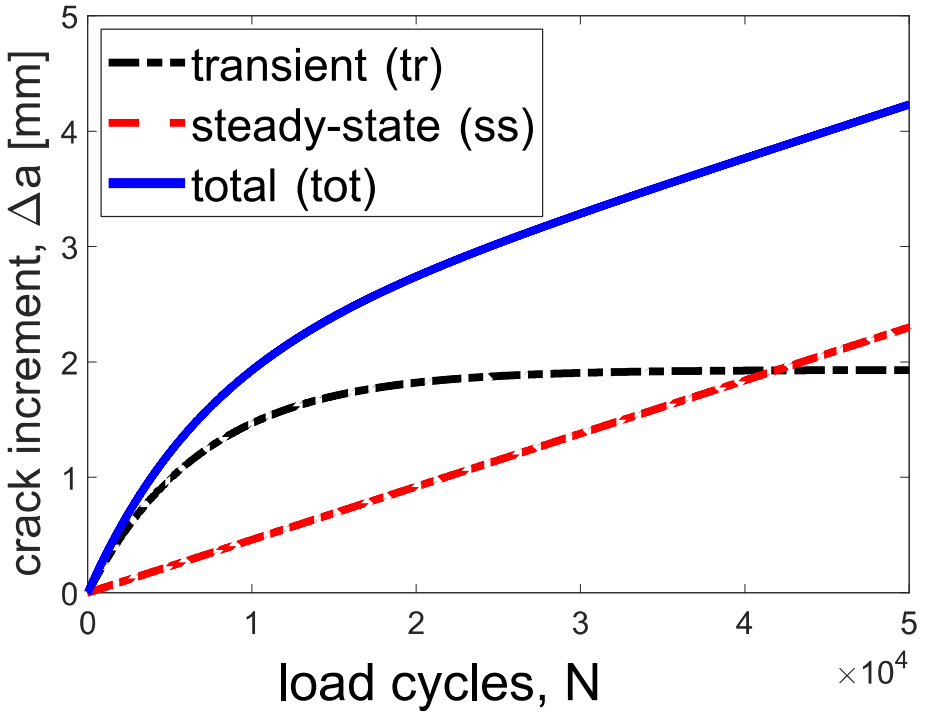
- Can the **nonlinear experimental response** be **decomposed into a steady-state and transient** response?

- A new CGR model:

$$\frac{da}{dN} = \underbrace{\frac{da}{dN_{ss}}}_{\text{Steady-state}} + \underbrace{\frac{da}{dN_{tr}}}_{\text{transient}}$$

- Questions: How…
  - can the responses (ss, tr) be **characterized**?
  - to **formulate** these with CGR functions?
  - will the new model **perform** under VA fatigue?





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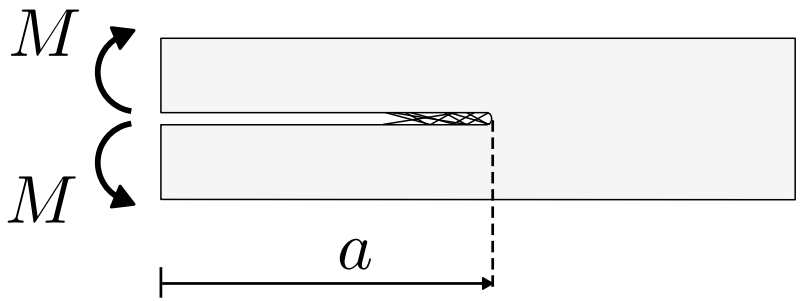
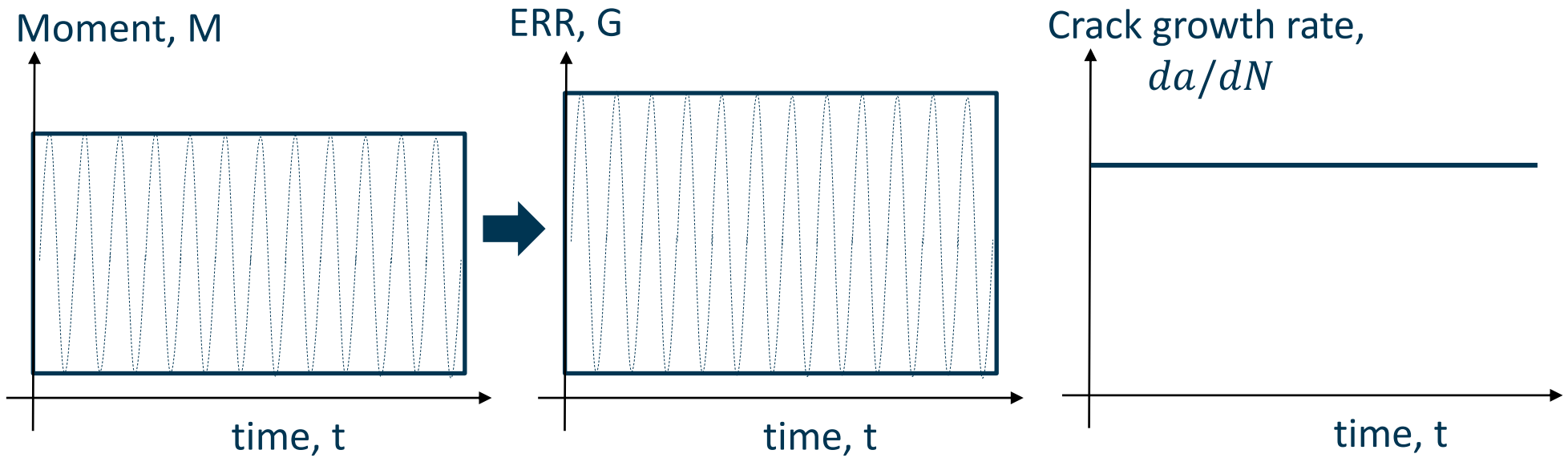
Cyclic steady-state crack growth

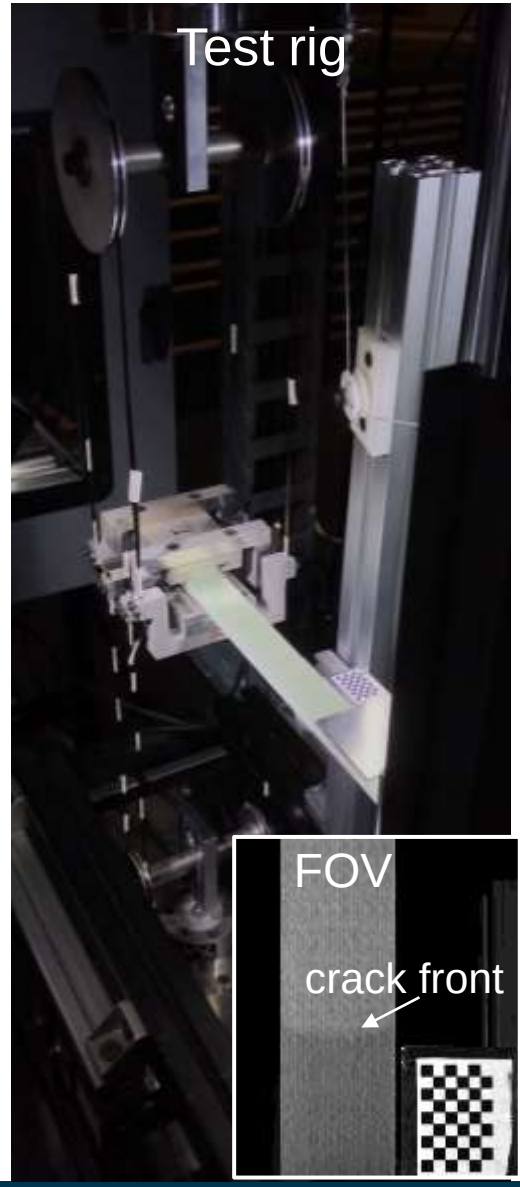
Pure moment loaded DCB specimen:

- ERR-controlled testing is possible
- Constant amplitude (CA) ERR-testing enables “cyclic steady-state crack growth”
- Constant crack growth rate



$$G = \frac{M^2}{bEI}$$





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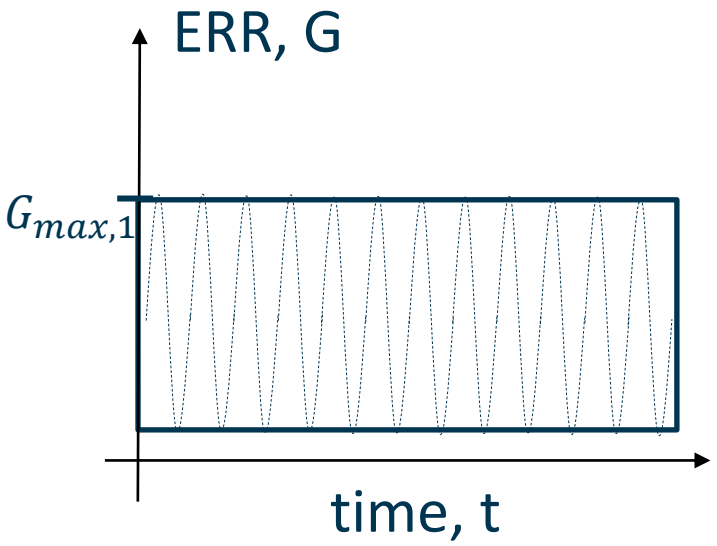
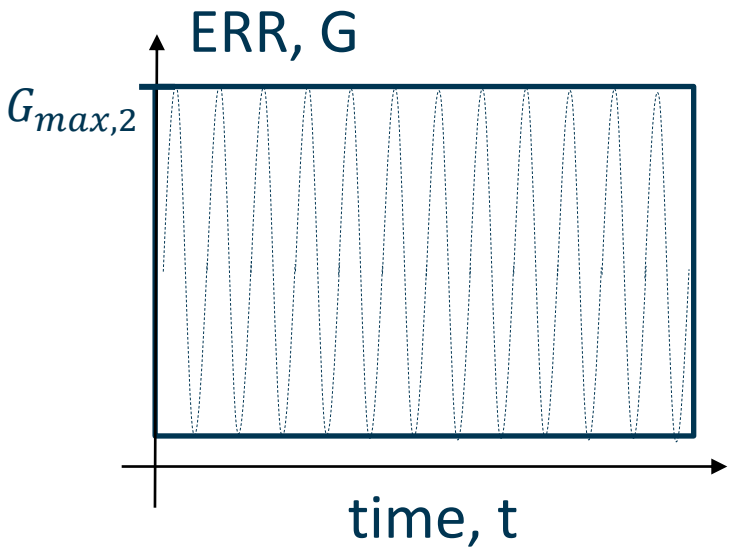
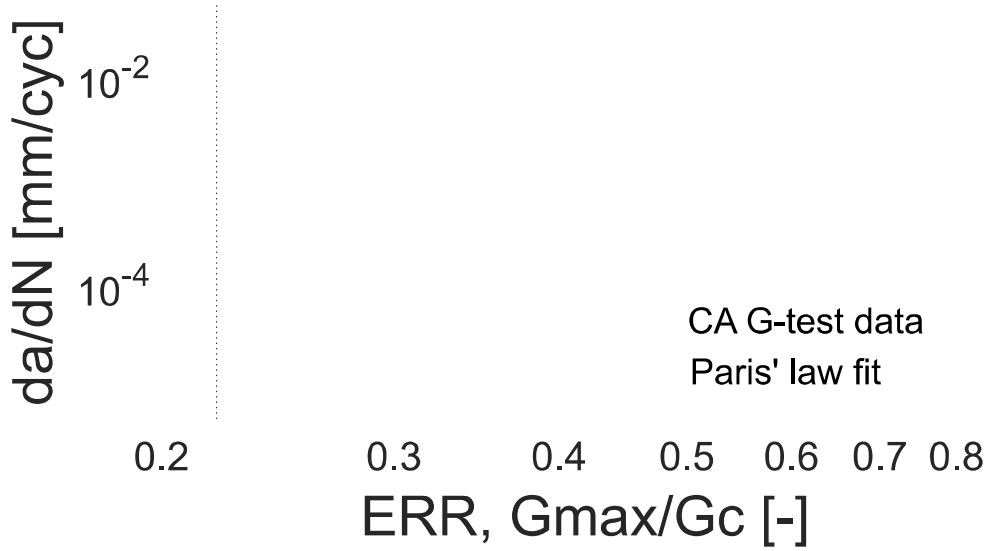
Cyclic steady-state crack growth characterization

- Use the CA ERR-tests to characterize the steady-state term: $\frac{da}{dN} = \boxed{\frac{da}{dN_{ss}}} + \frac{da}{dN_{tr}}$
- Multiple CA tests are conducted at different levels of G_{max}
- A Paris' law like relation: $\frac{da}{dN_{ss}} = F_{ss}(G_{max}, R)$ ← Identical to conventional CGR models and neglects the load history







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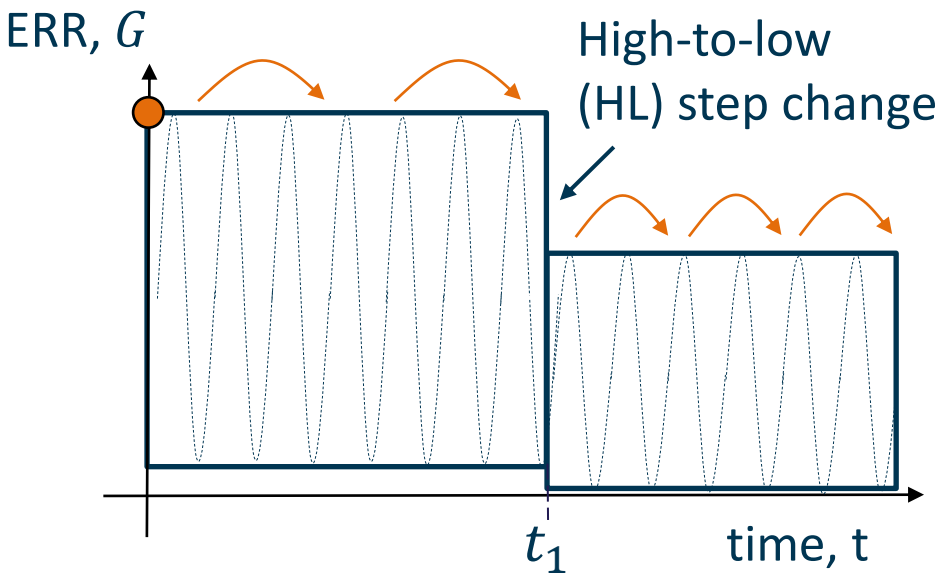
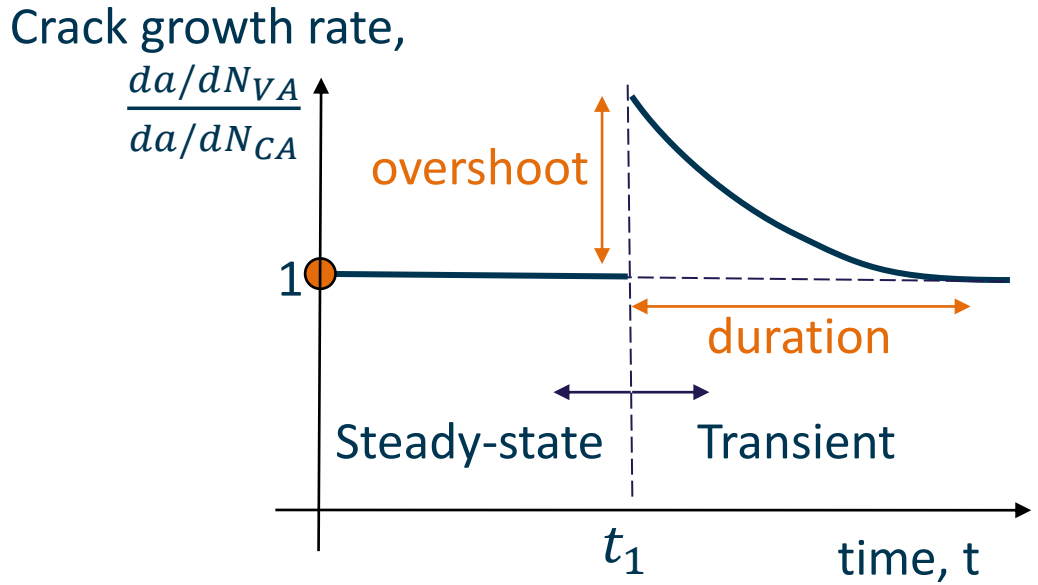
Cyclic transient crack growth

- The same setup is convenient to analyze **transient crack growth** (see example)
- Transient phenomena have been identified (Jensen et al., 2021) and proved significant
- **Current focus**: Find CGR functions to describe the transient phenomena





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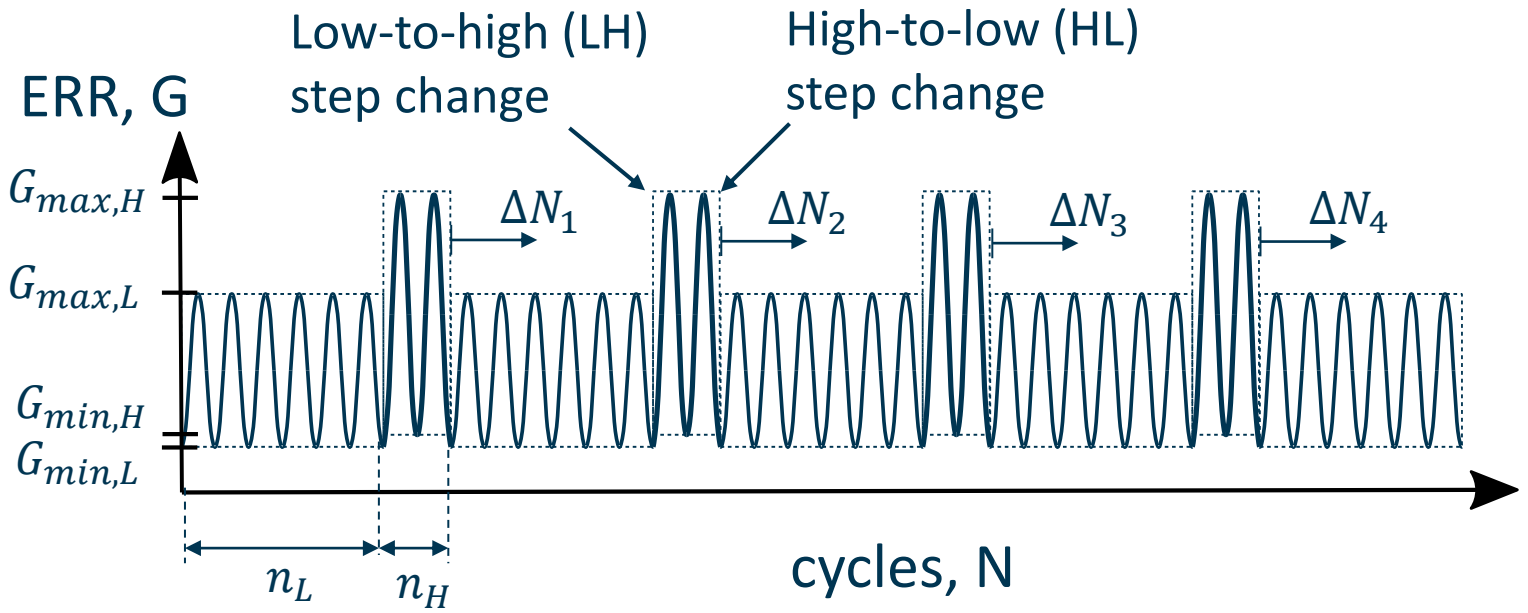
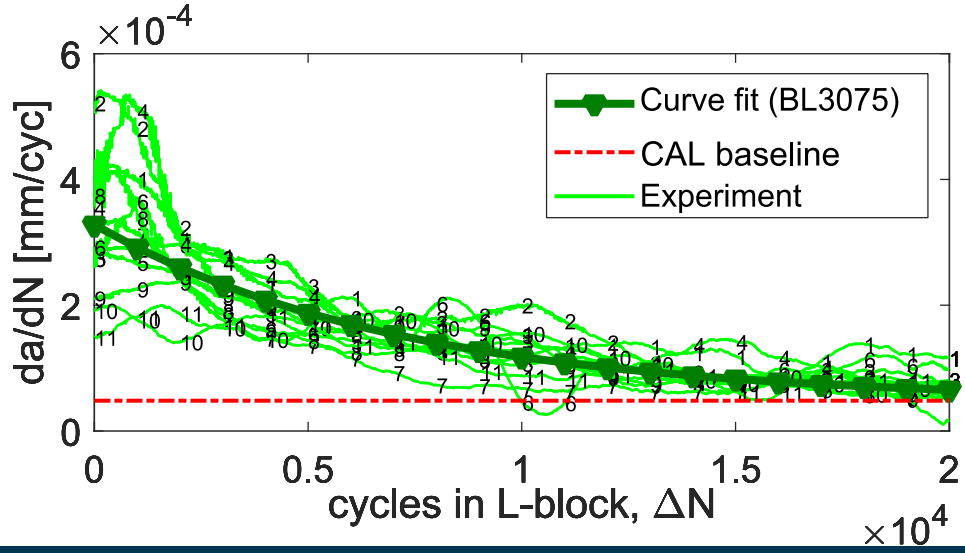
Characterize cyclic transient crack growth

- Apply **two-level block loading** to DCB specimens in ERR-control
- To characterize the **transient CGR following HL step changes**:
  - Measure CGR following every HL step change and generate (ΔN_i, *da/dN*)-curves
  - Superimpose results
  - Generate curve fit
- Transient CGR is well-described by an **exponential decay** function





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Transient CGR functions

- Investigate **how the transient responses vary with** fatigue load parameters, for example ΔG_{max}

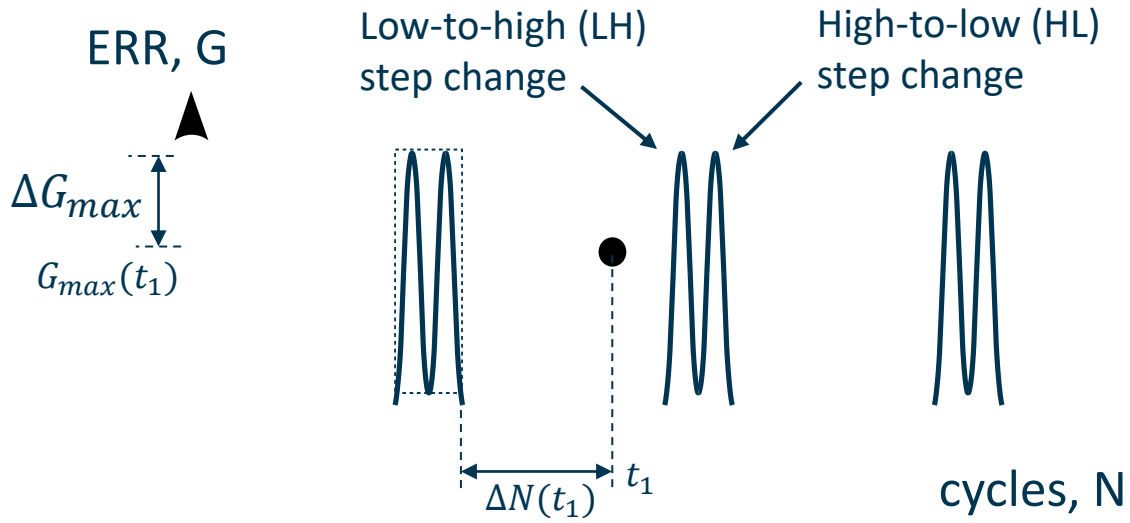
- The transient term in the CGR model will be described by **an exponential decay function, F_{tr}**:

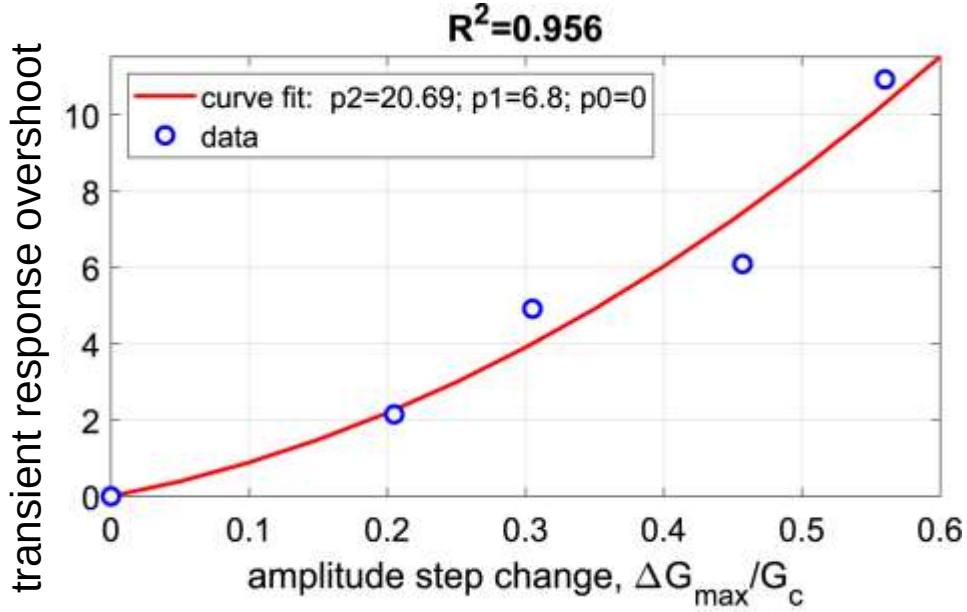
$$\frac{da}{dN_{tr}} = F_{tr}(\underbrace{G_{max}}_{\text{Instantaneous}}, \underbrace{\Delta N, \Delta G_{max}}_{\text{Load history}})$$

In:

$$\frac{da}{dN} = \frac{da}{dN_{SS}} + \frac{da}{dN_{tr}}$$

- Note: The model only includes transient responses following **HL step changes**. Transient effects due to **LH step changes** are neglected.





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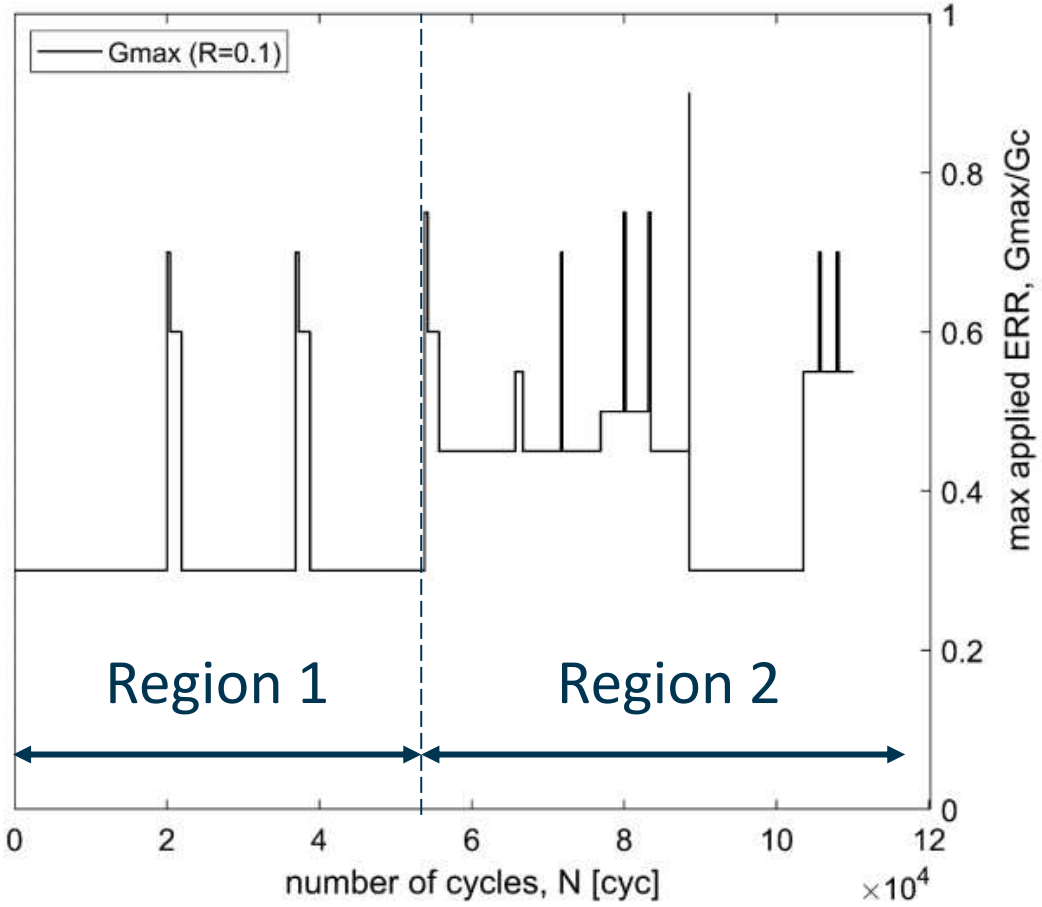
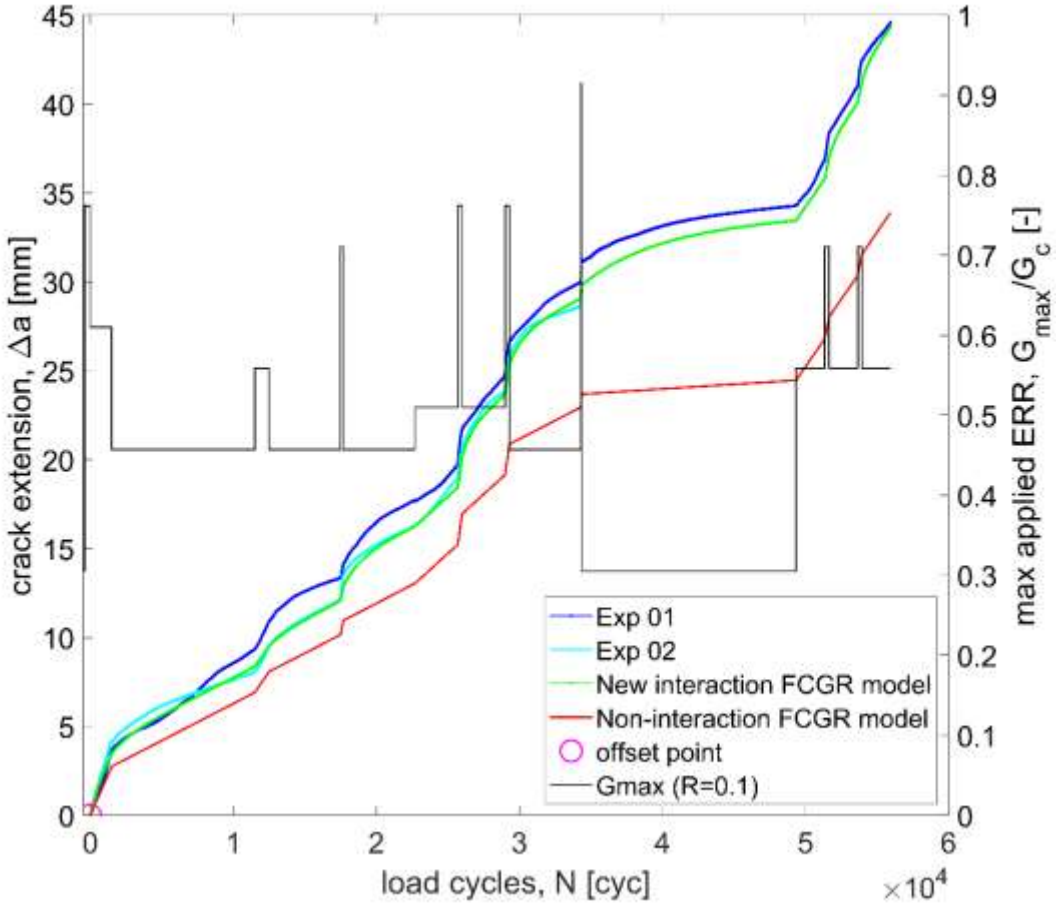
Multi-level block loading benchmark: Region 2

- How will the model perform in the multi-level block loading test? It depends…
- Good results for **Region 2**: Total crack extension and transient phenomenological behaviors





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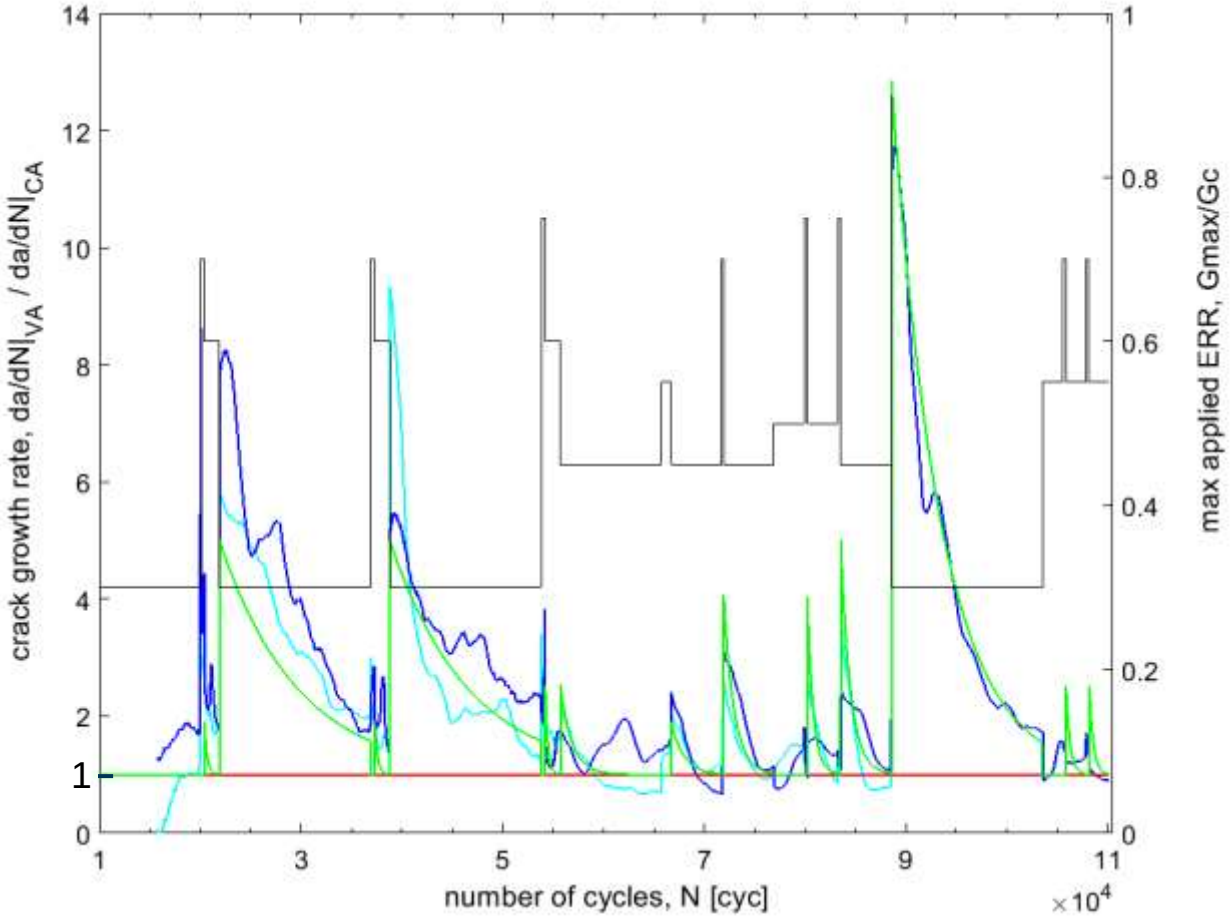
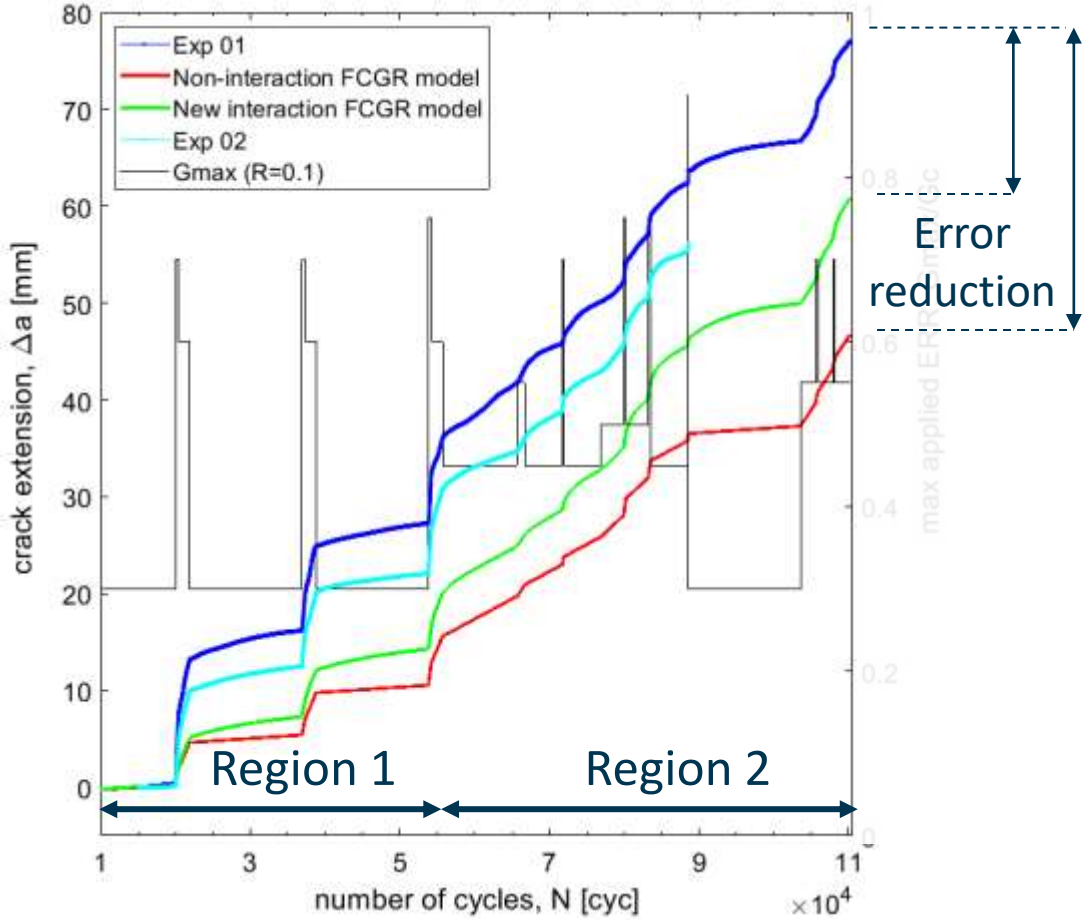
Multi-level block loading benchmark: Full

- An error remains – partly due to the neglected transient effects following **LH step changes**
- The experimental CGR is clearly different from the non-interaction model
- The new CGR model **captures exponential decay-type responses** at HL step changes





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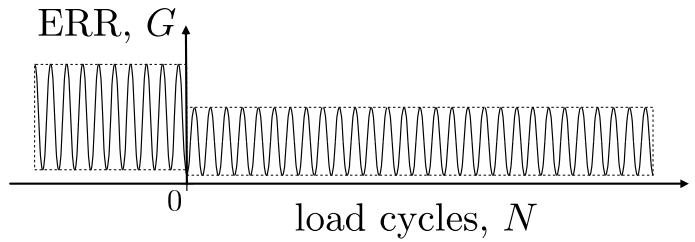
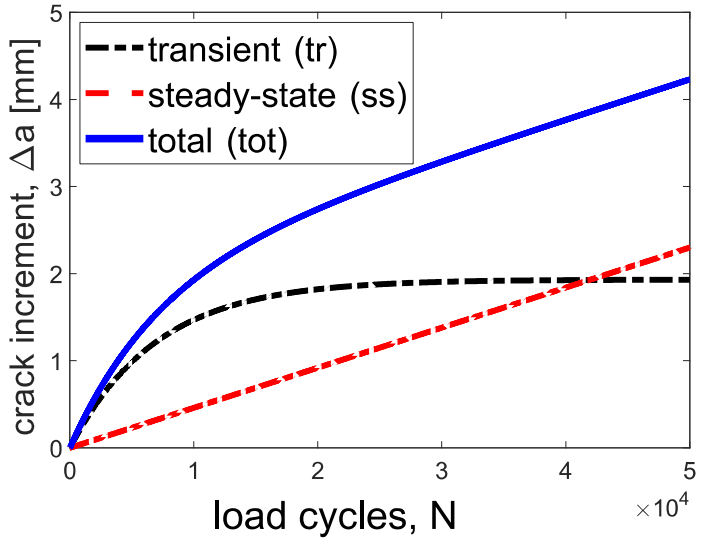
Conclusions

- The CGR following amplitude step changes can be decomposed into a **steady-state** and **transient** response
- A method to characterize steady-state and transient CGR functions is proposed using **ERR-controlled DCB tests**
- A new **CGR model with load history** effects is formulated
- The model can predict delamination in a significant portion of a **new multi-level block loading benchmark** test





$$\frac{da}{dN} = \frac{da}{dN_{ss}} + \frac{da}{dN_{tr}}$$

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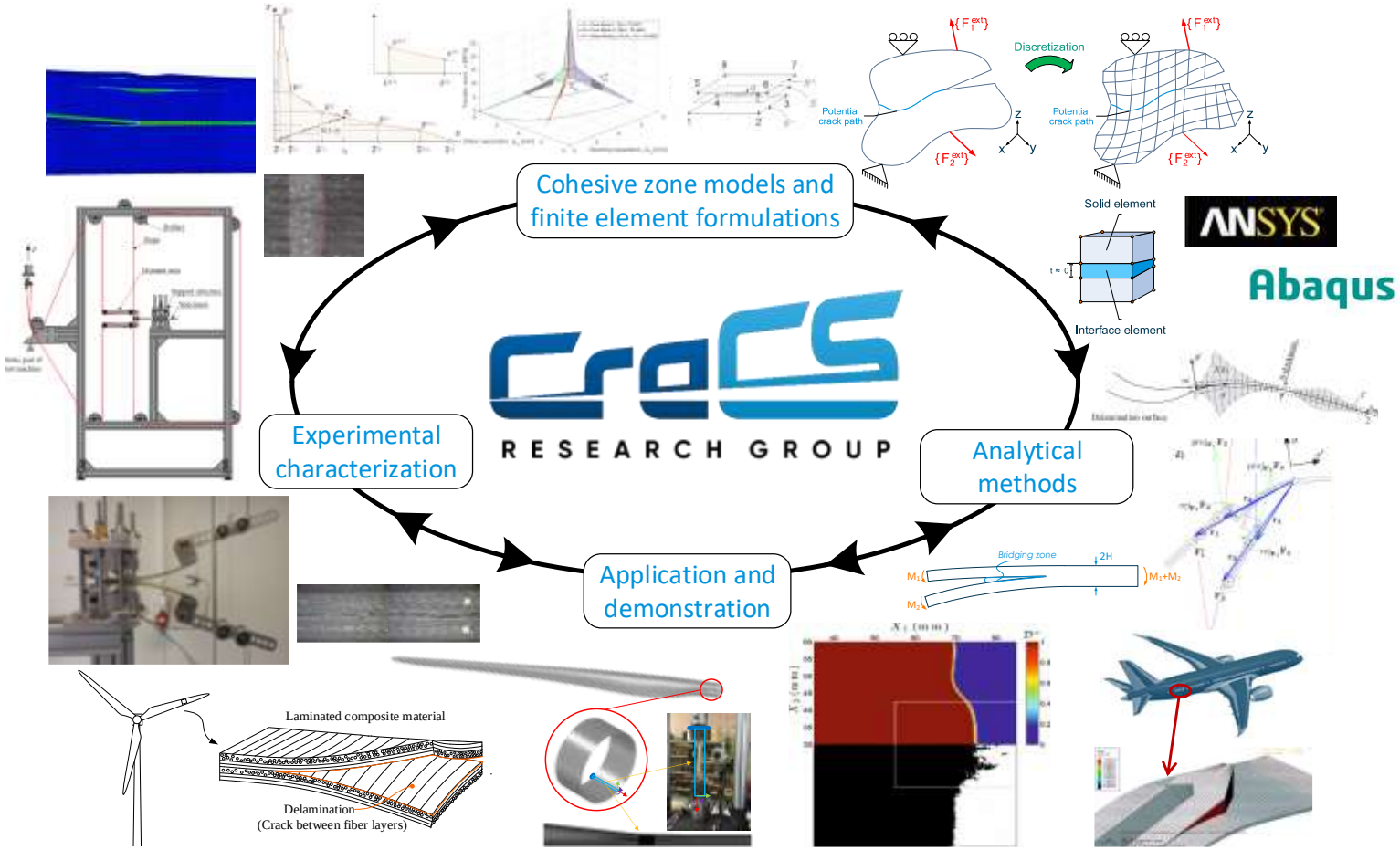
THANK YOU FOR YOUR ATTENTION



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Project partners:

LM WIND POWER
a GE Renewable Energy business

The von Karman Institute for Fluid Dynamics

Fraunhofer

PONTIS

SAMTECH

WAVESTONE

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AMADE

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SIEMENS

Envision

SIEMENS Gamesa
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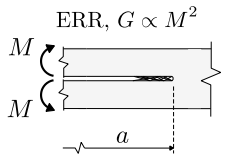

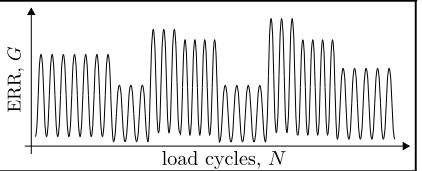

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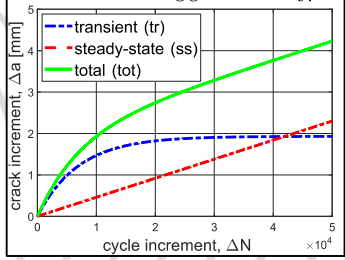

Experimental testing

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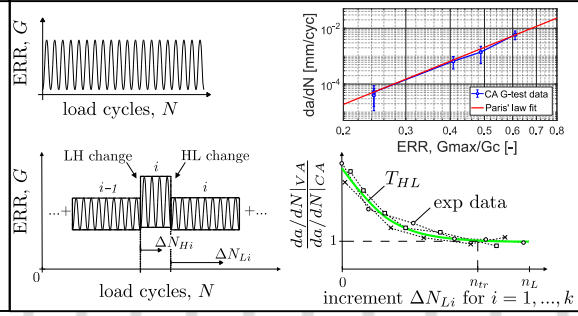
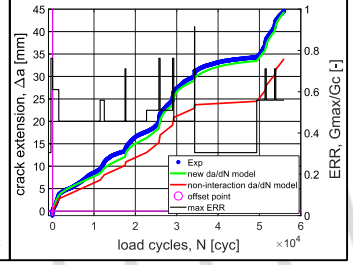


Demonstrate



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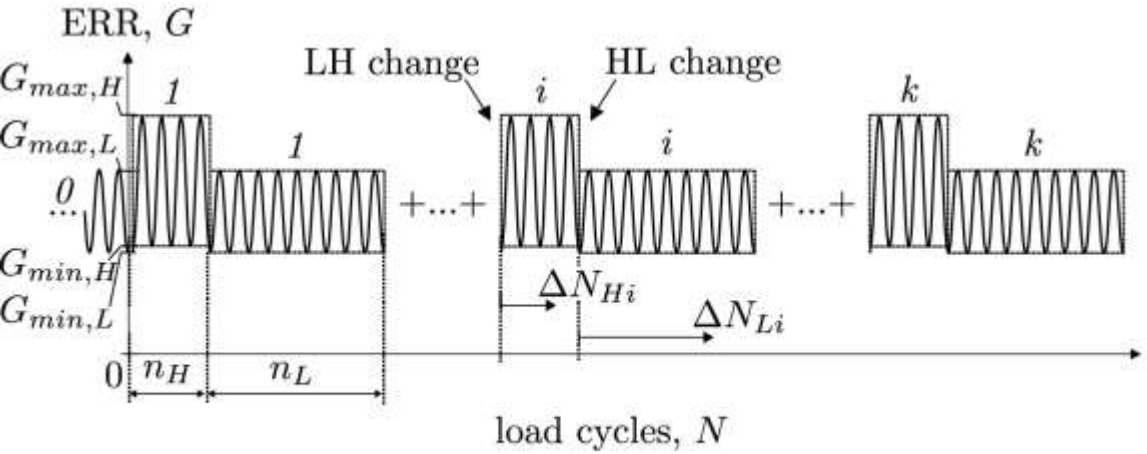
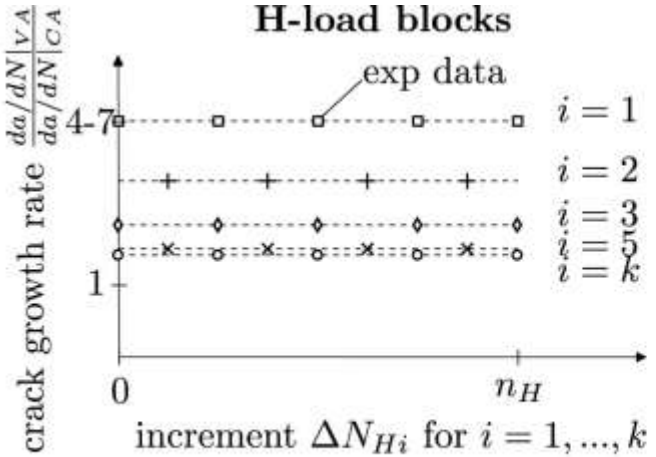
BONUS SLIDES

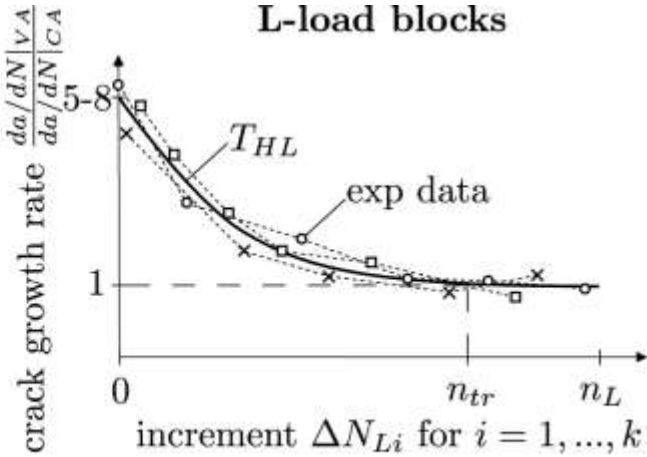
Bonus slides 01



(a)



(b)



(c)

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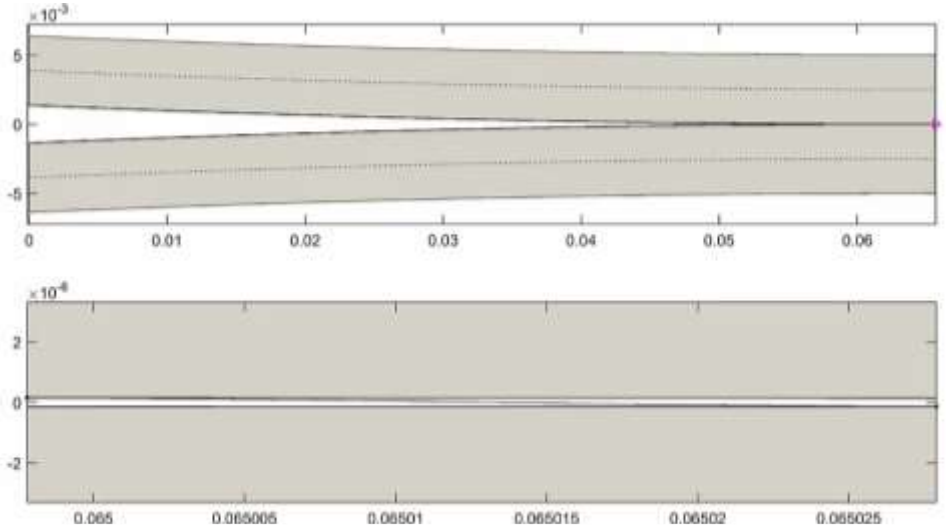
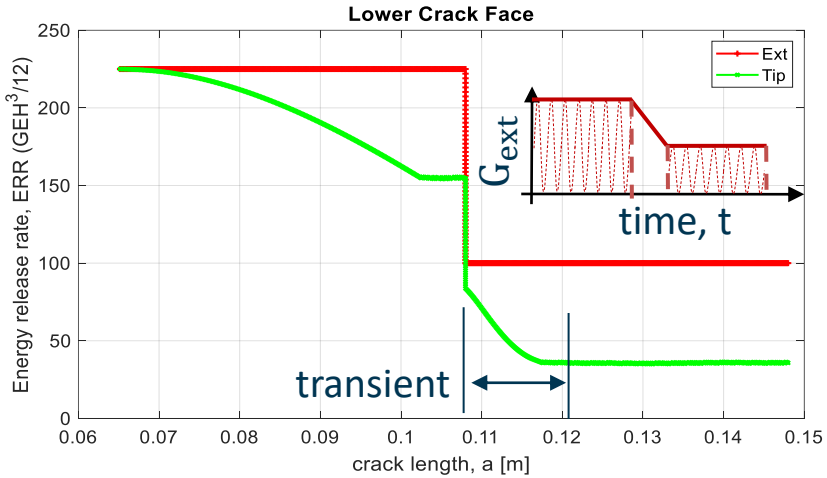
Bonus slide 02

- A phenomenological model: **Transient** responses are **not derived from the actual physical** processes on meso-/micro-scale
- The model ignores the underlying mechanisms and **concentrate on the gross macroscopic crack** tip propagation using empirical relations, $f_{tr}(ERR)$
- **Physical-based models** of governing mechanisms in the FPZ and their interaction are necessary
- How are the crack tip shielding effect of bridging fibers other **underlying mechanisms affected by VA loading**?

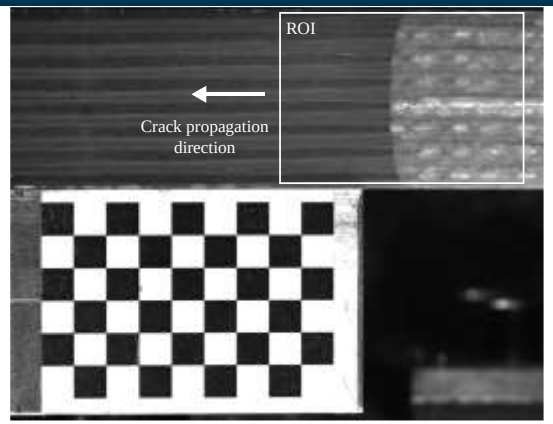


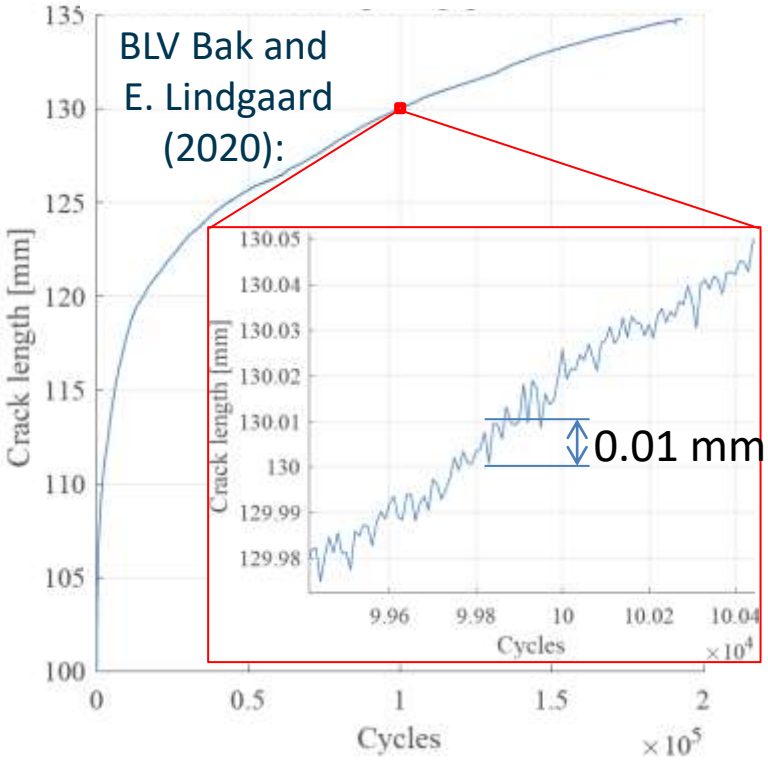


Jensen SM, Bak BLV, Lindgaard E & Renart J (2021) *Micromechanisms of load history effects in fatigue-driven delamination growth*, **8th ECCOMAS thematic conference on the mechanical response of composites** 2021, Gothenburg, Sweden.

Bonus slide 03

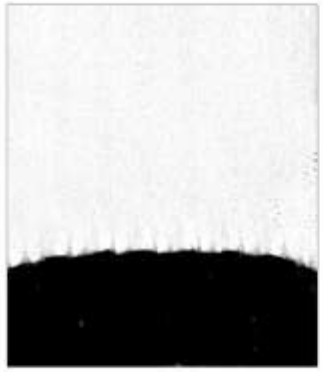
- Crack length measurements: A camera records the top surface of the DCB specimen (FOV).
- A fully automated and continuous process.
- Low noise and high resolution in crack front identification.
- Important when detecting small crack increments due to load interactions.





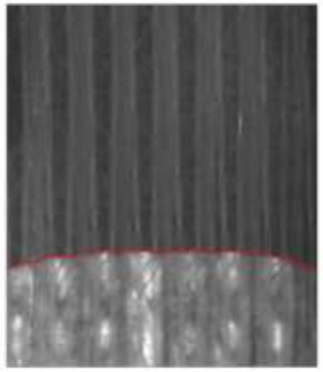
Digital-image based technique and image processing operations:

Image division



Contrast scaling

Binary output



Crack front (red)

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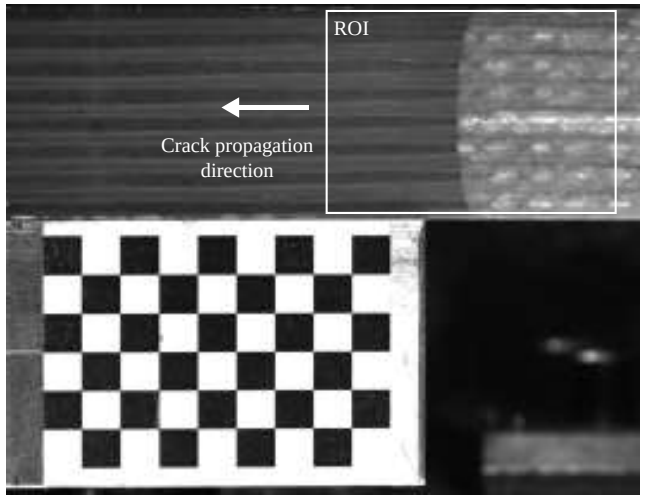
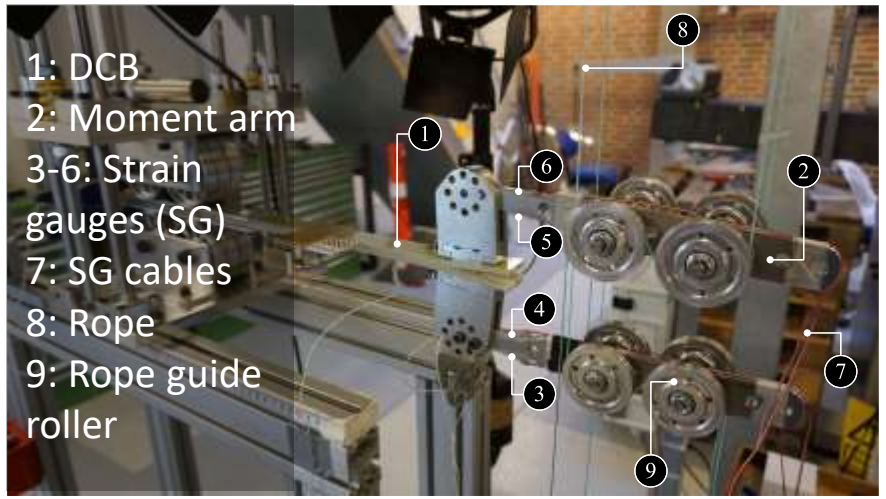
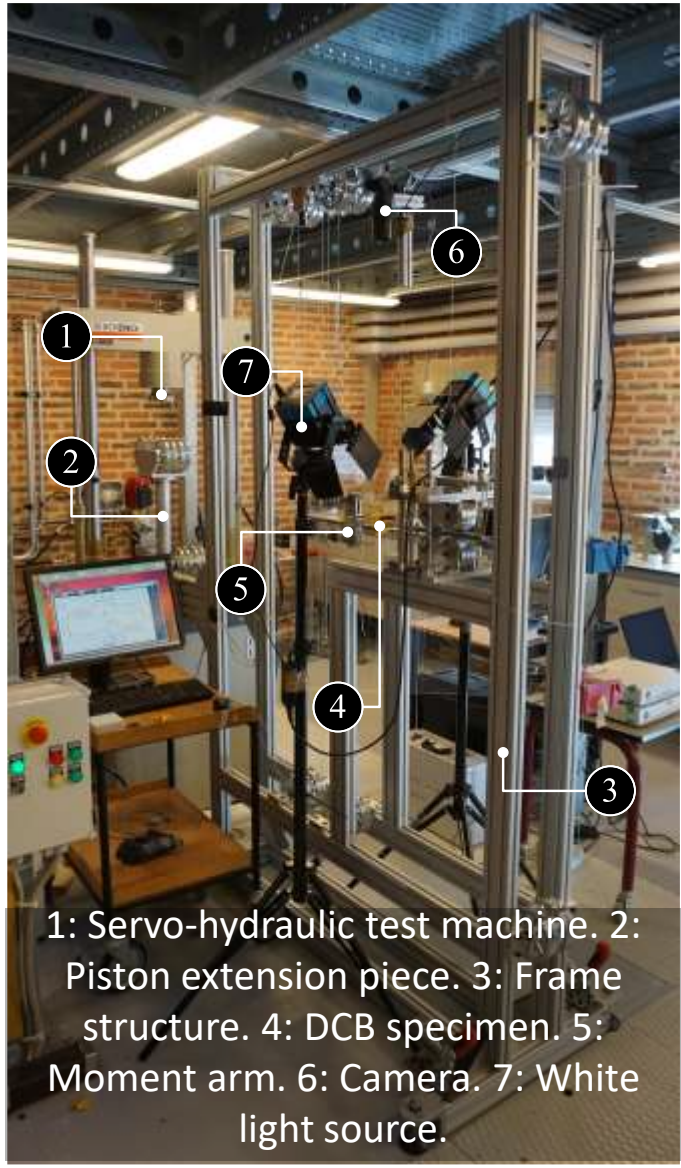
Bonus slide 04

- A highly capable test setup for detecting small Δa due to the isolated effect of load interactions is a prerequisite.

- Highlight two features which are especially important here:
  - G-controlled cyclic testing using the pure moment loaded DCB test configuration.
  - Automated digital image-based technique for tracking of the delamination front.







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