SIMULATION OF FATIGUE CRACK GROWTH USING THE CUMULATIVE PLASTIC STRAIN AT THE CRACK TIP

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Sixth IJFatigue & FFEMS Joint Worshop
Characterisation of Crack/Notch Tip Fields

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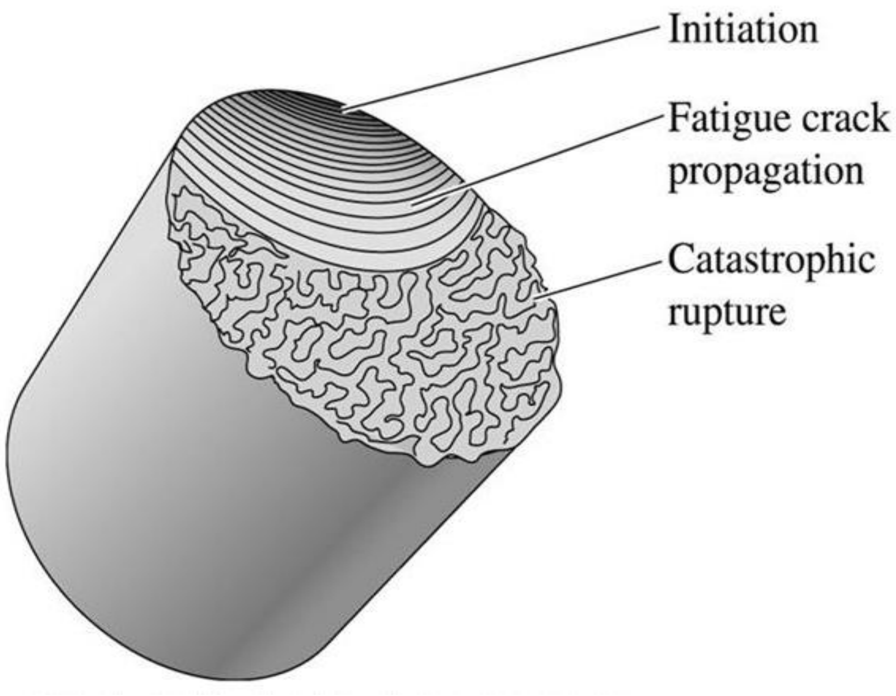
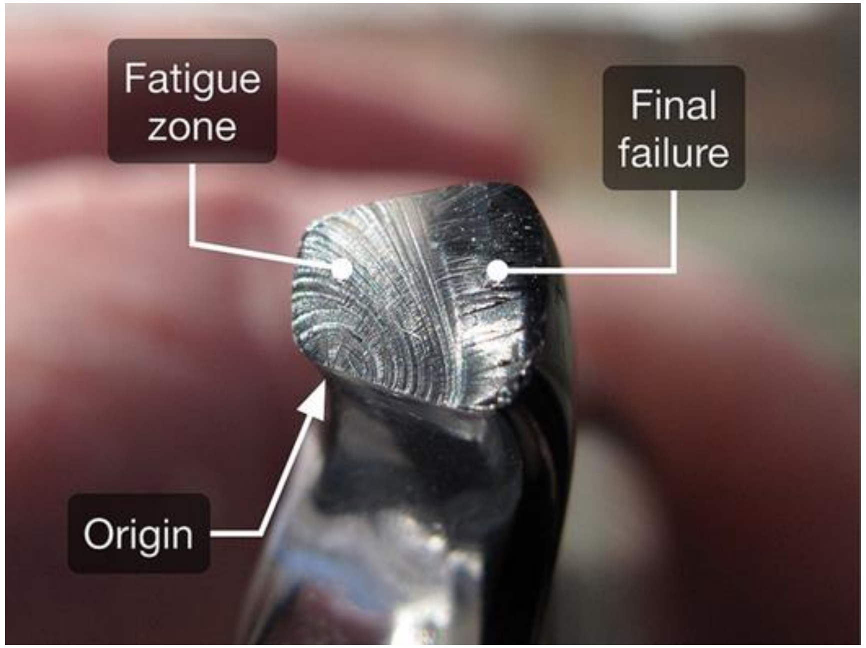
Introduction

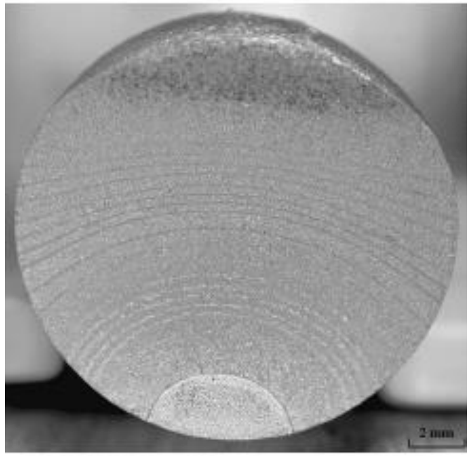
Mechanisms of fatigue

❑ Fatigue can be defined into **3 phases**

- **Initiation** (usually at surface)
- **Propagation of fatigue crack** (beach marking)
- **Final failure** (catastrophic)





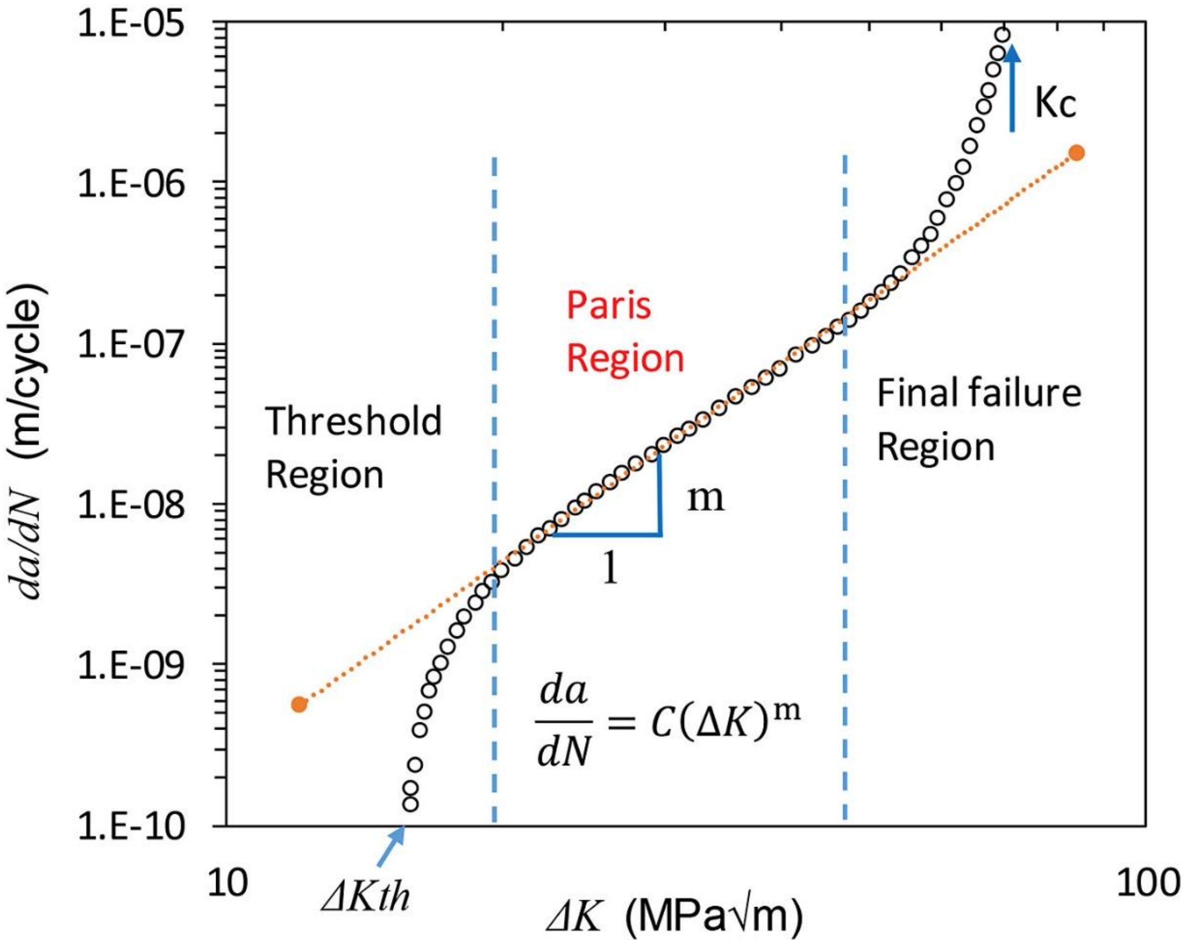


Introduction

Fatigue crack growth

- ☐ **Damage tolerance** approach requires the prediction of the **fatigue crack growth**
  - Most of the crack growth models are based on the stress intensity factor range (*ΔK*)
  - Typically based on experimental data obtained from constant amplitude fatigue tests

- Some crack growth models have been developed to include the **stress ratio**, **overloads** and **load history effects**



Objectives

Main objective

- Numerical **prediction of the fatigue crack growth rate** using the finite element method
- Considering the **plastic strain at the crack tip** as the crack driving force

Procedure

- Mechanical behavior described by an **elasto-plastic** constitutive law
- Material parameters of the hardening law calibrated using data from **low-cycle fatigue tests**
- Normalized specimens: **CT specimen** and **MT specimen**
- Both constant and variable amplitude **loading**
- In-house finite element code **DD3IMP**

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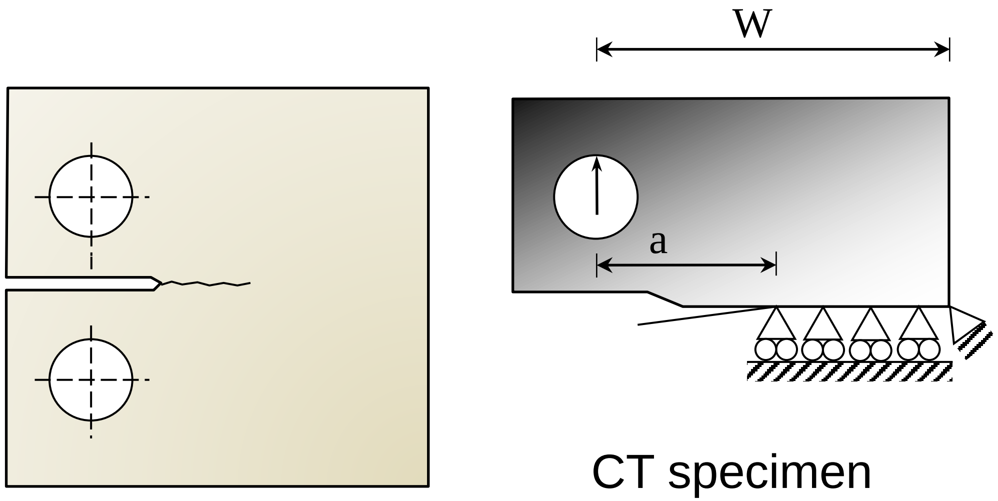
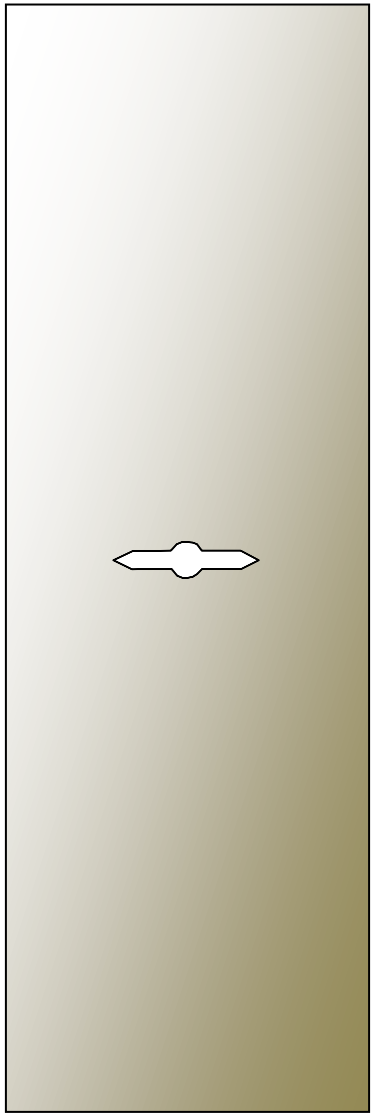
Numerical model

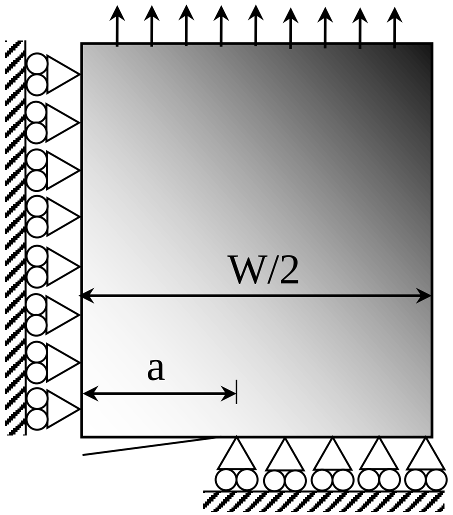
Specimen geometry and discretization

- ☐ Compact Tension (**CT**) specimen
- ☐ Middle-cracked Tension (**MT**) specimen
    - Geometric, material and loading symmetry
    - Modeling ½ of CT specimen geometry
    - Modelling ¼ of MT specimen geometry



CT specimen



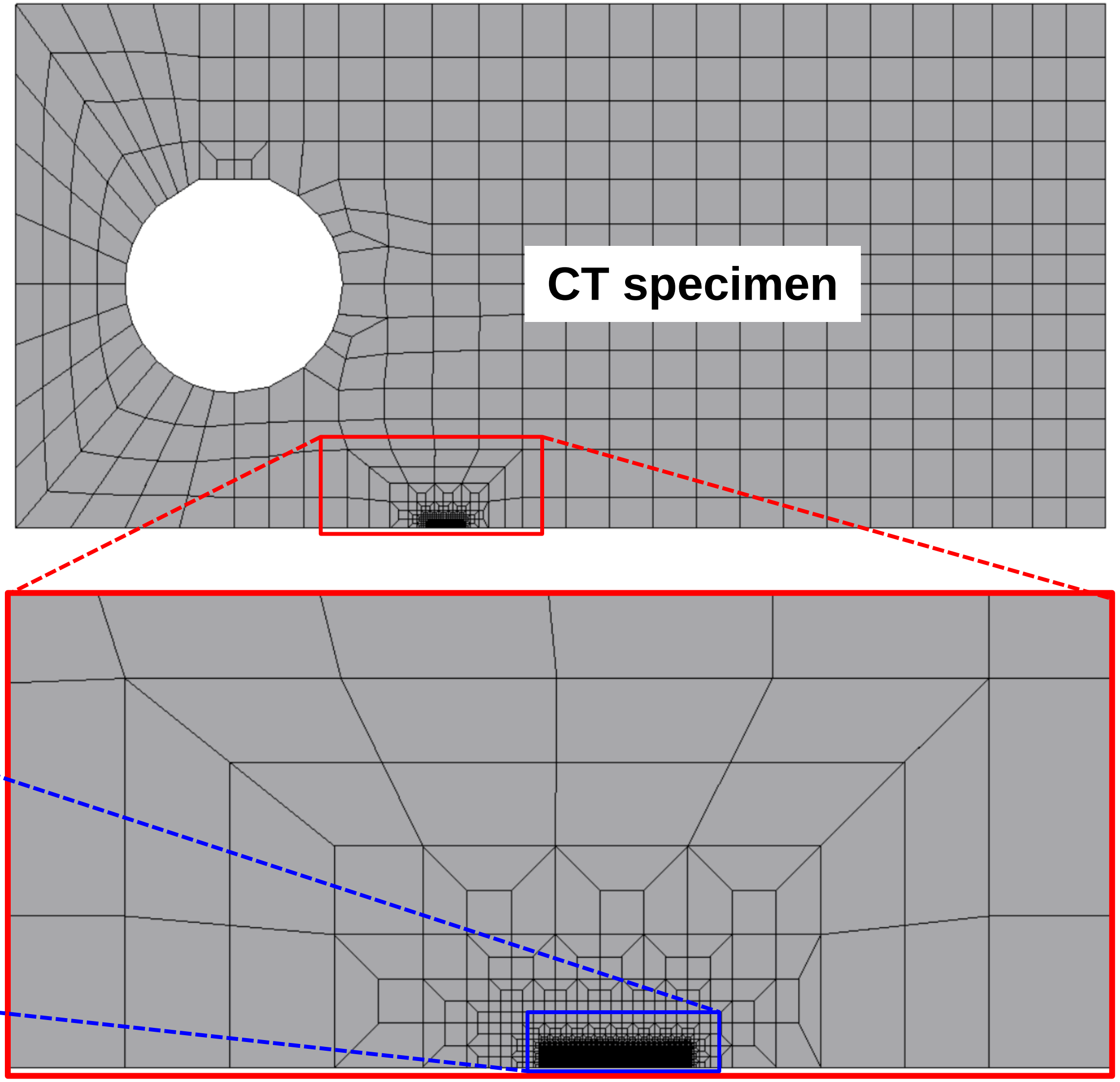


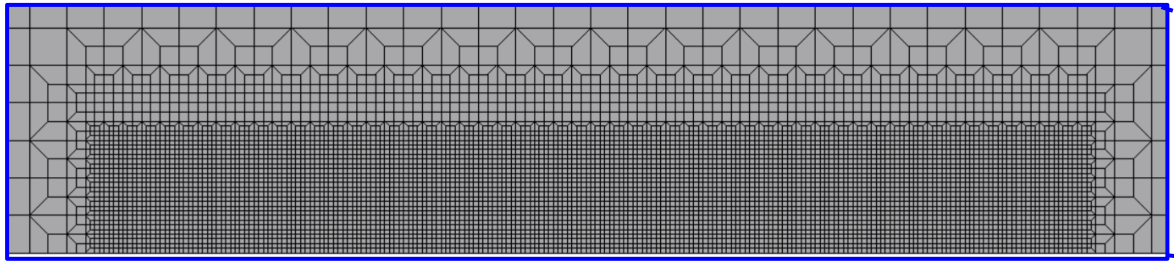
MT specimen

Numerical model

Specimen geometry and discretization

- Linear hexahedral finite elements with **element size of 8 µm** near the crack path (increment size of the crack propagation)
- Contact between crack flanks simulated using a rigid surface at the symmetry plane
- Single layer of elements through the thickness





Numerical model

Specimen geometry and discretization

- Linear hexahedral finite elements with **element size of 8 μm** near the crack path (increment size of the crack propagation)
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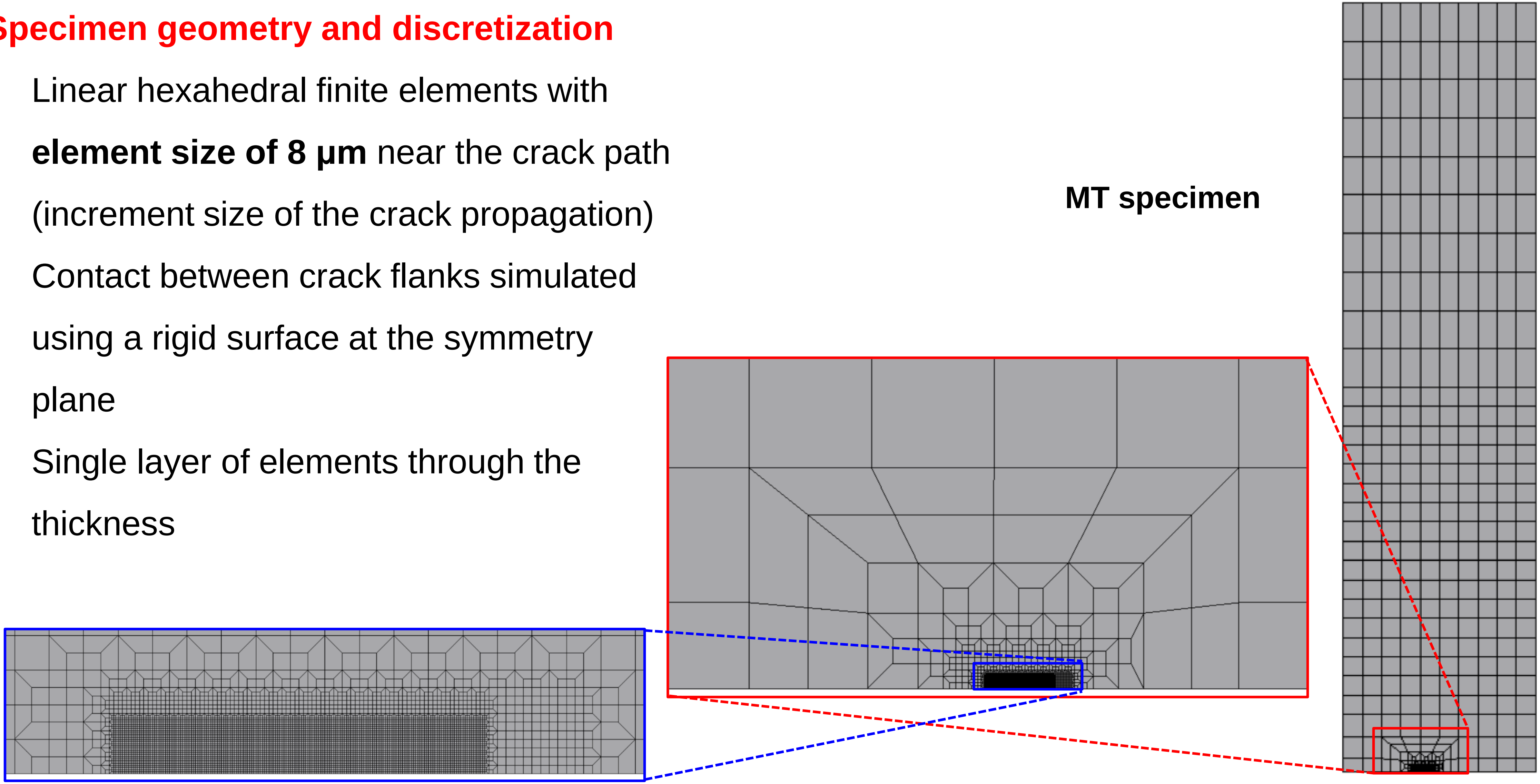
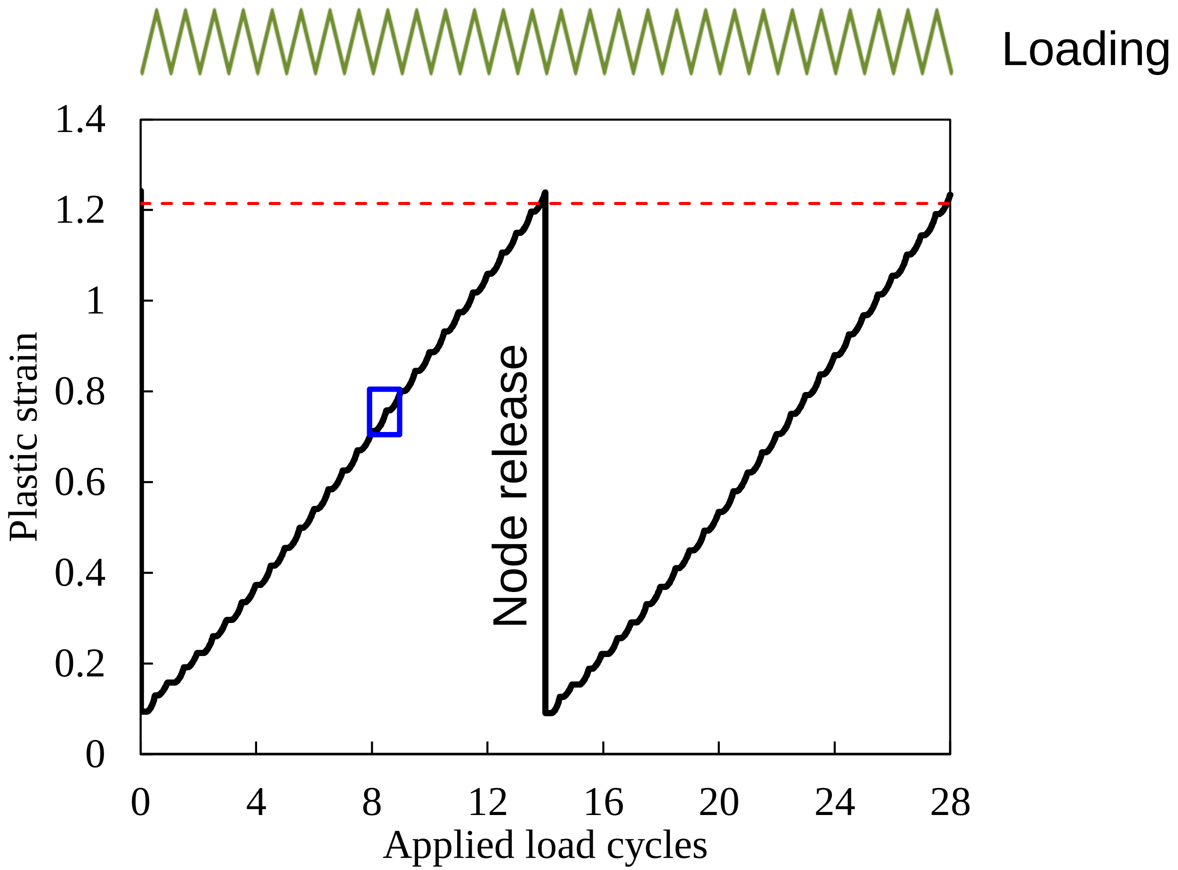


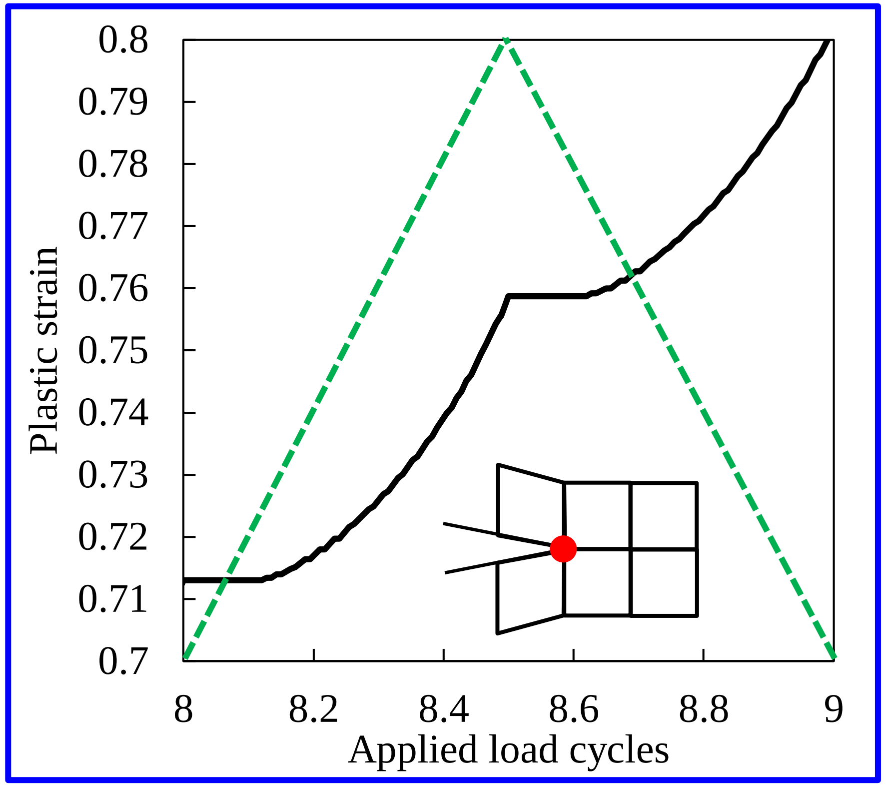
Numerical model

Crack propagation algorithm

- ❑ Crack propagation based on the **plastic strain evaluated at the crack tip**
  - Total plastic deformation at the crack tip increases during the cyclic loading



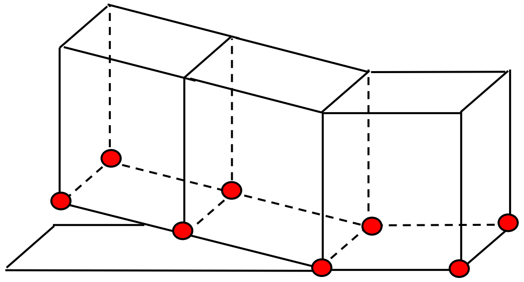
Single loading cycle



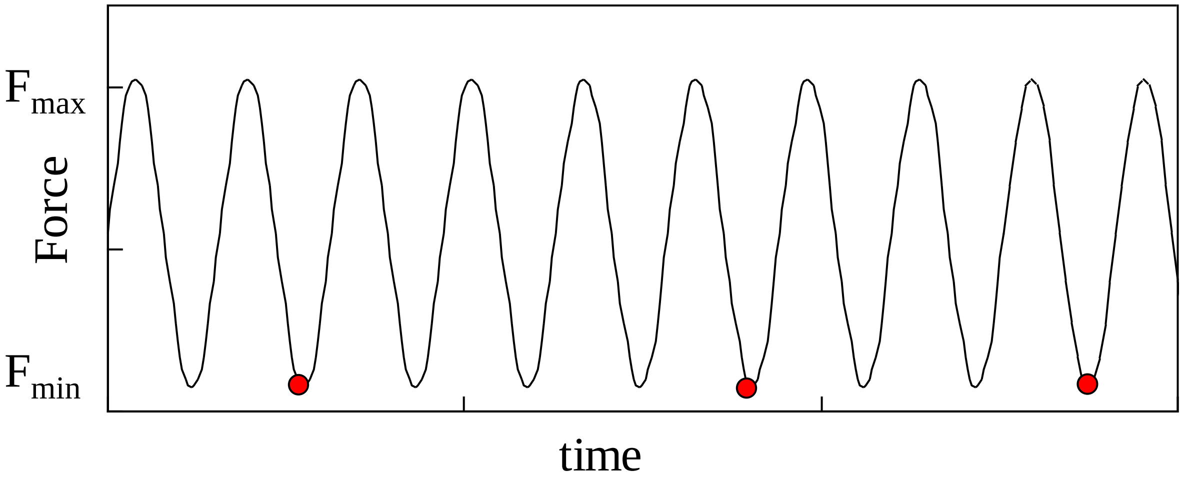
Numerical model

Crack propagation algorithm

- ☐ Node release (at minimum load) when the plastic deformation reaches a critical value
- ☐ The **predicted fatigue crack growth rate** is the ratio between the crack increment (8 μm) and the number of load cycles required to achieve the critical value of plastic strain at the crack tip



Both nodes released simultaneously

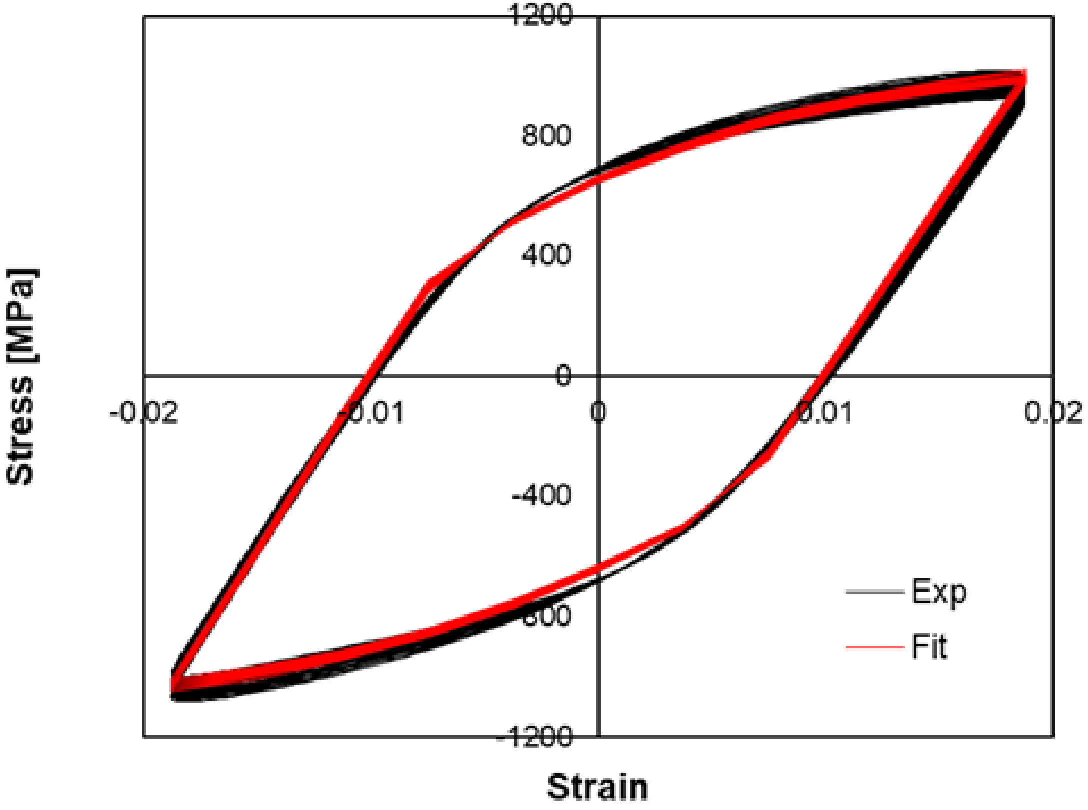


Numerical model

Constitutive model

- ❑ **Elasto-plastic behavior**
  - Elastic behavior is defined by the **Hooke's law**
  - Isotropic work hardening described either by **Swift or Voce laws**
  - Kinematic hardening described by the **Armstrong-Frederick model**

- ▪ Material parameters calibrated using the experimental stress–strain curve from the **low cycle fatigue tests**



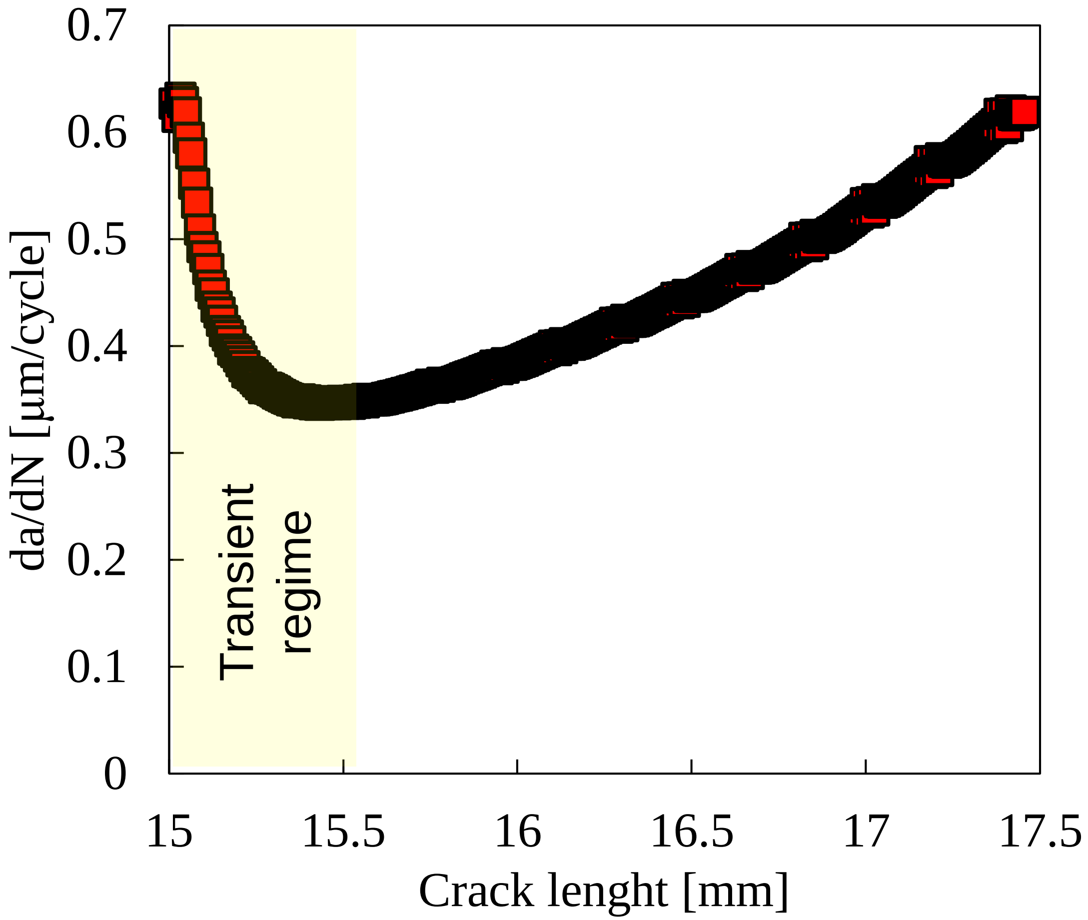
Comparison between experimental and numerical stress-strain loops for Ti-6Al-4V

Results

FCG rate under constate amplitude loading

- ❑ **Transient behavior** at the beginning of the predicted fatigue crack growth rate
  - Material: AA2024
  - CT specimen (W=36 mm)
  - Stress ratio: R=0.1
  - Plane stress conditions in the simulation

- Decrease of the crack growth rate (increase of the crack closure) during the transient behavior due to the <u>residual plastic wake</u> generation

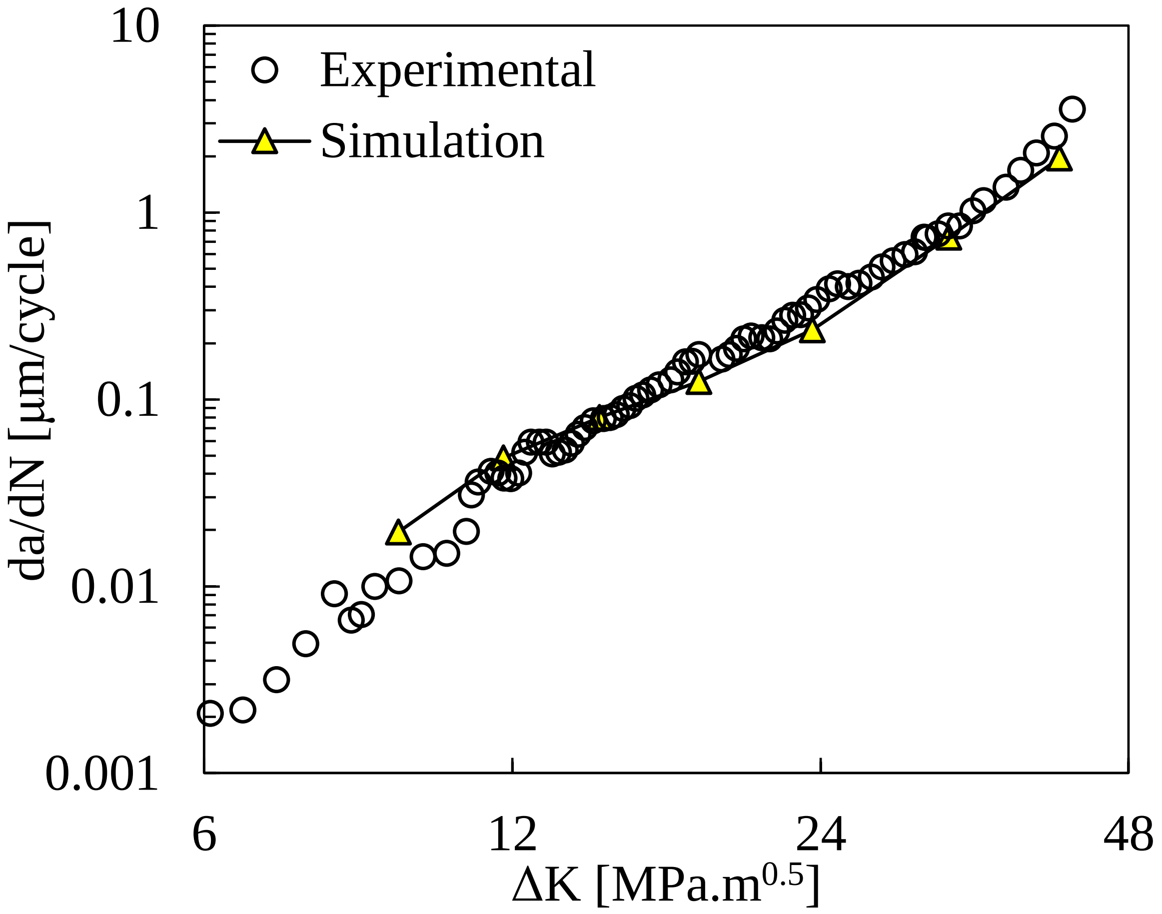


Results

FCG rate under constate amplitude loading

- ❑ Effect of **stress intensity factor range** (ΔK) on the **predicted fatigue crack growth rate**
  - Material: Ti-6Al-4V
  - CT specimen (W=36 mm)
  - Stress ratio: R=0.05
  - Plane stress conditions in the simulation

- Development of residual plastic wake before evaluate the FCG rate
- Numerical predictions are in <u>very good agreement</u> with the experimental measurements, allowing to validate the numerical model



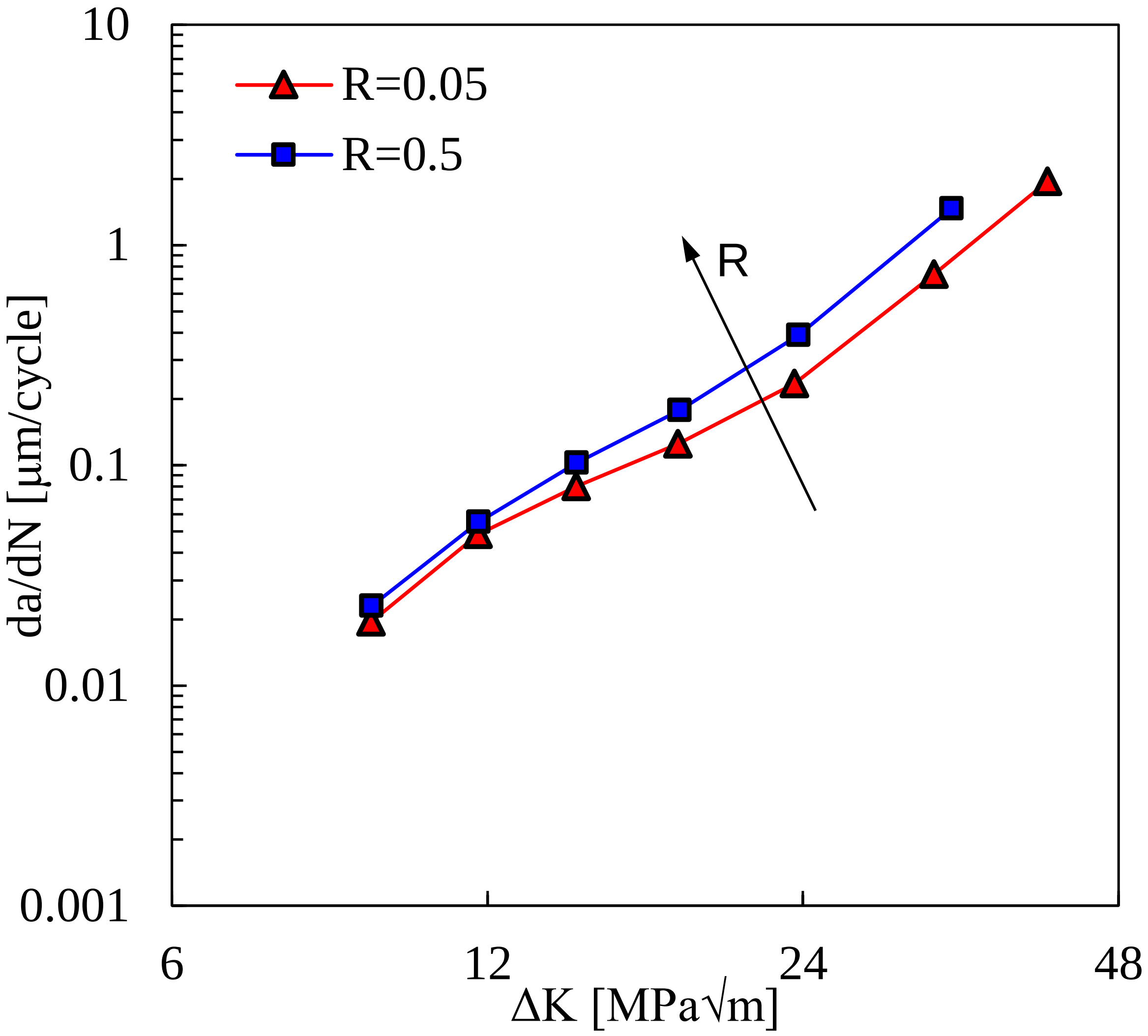
Results

FCG rate under constate amplitude loading

❑ Effect of **stress ratio (R)** on the **predicted fatigue crack growth rate**

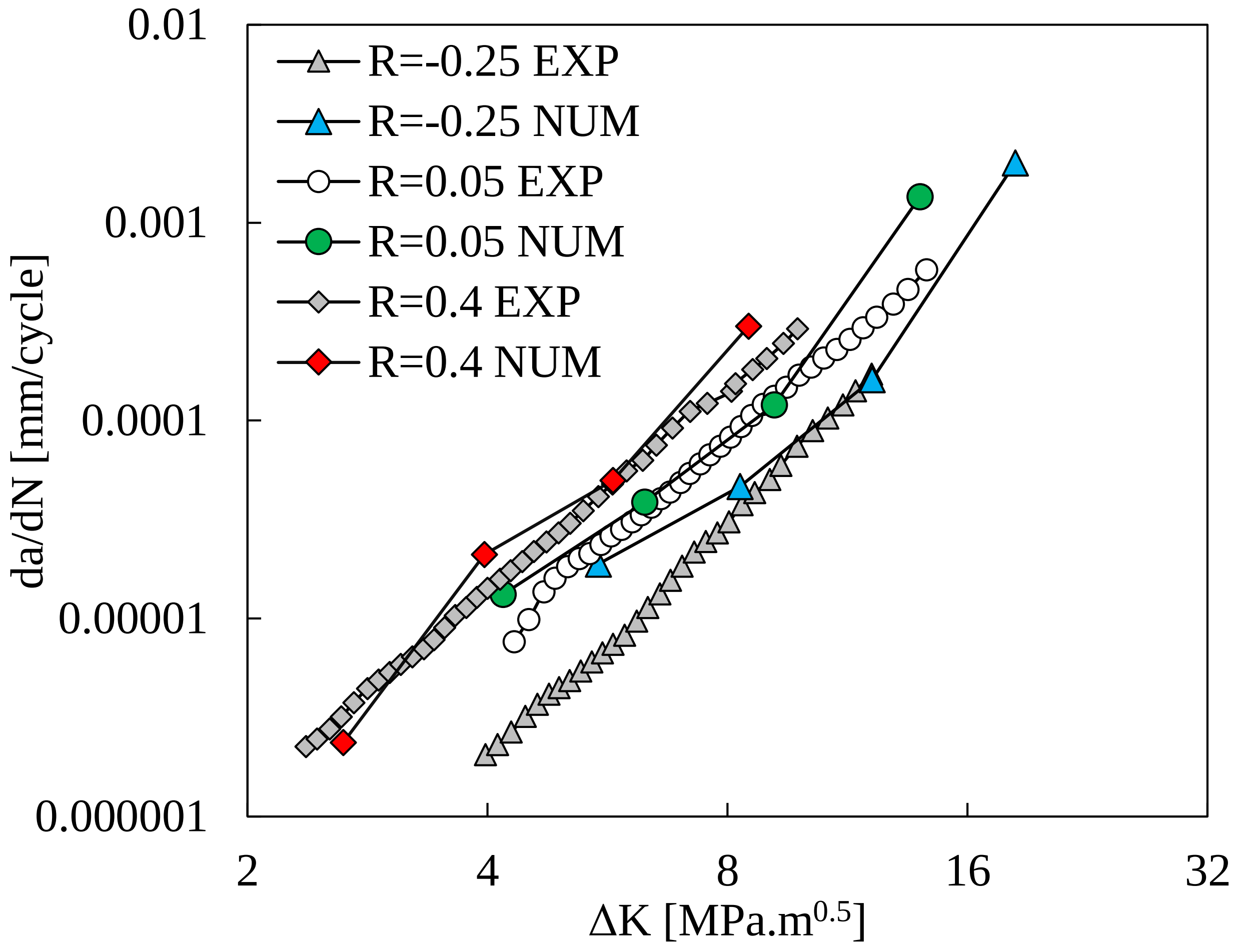
- Material: Ti-6Al-4V
- CT specimen (W=36 mm)
- Plane stress conditions in the simulation

- Increase of the crack growth rate for increasing values of stress ratio



FCG rate under constate amplitude loading

- ☐ Effect of **stress ratio (R)** on the **predicted fatigue crack growth rate**
  - Material: AA6082-T6
  - MT specimen (W=100 mm)
  - Plane stress conditions in the simulation



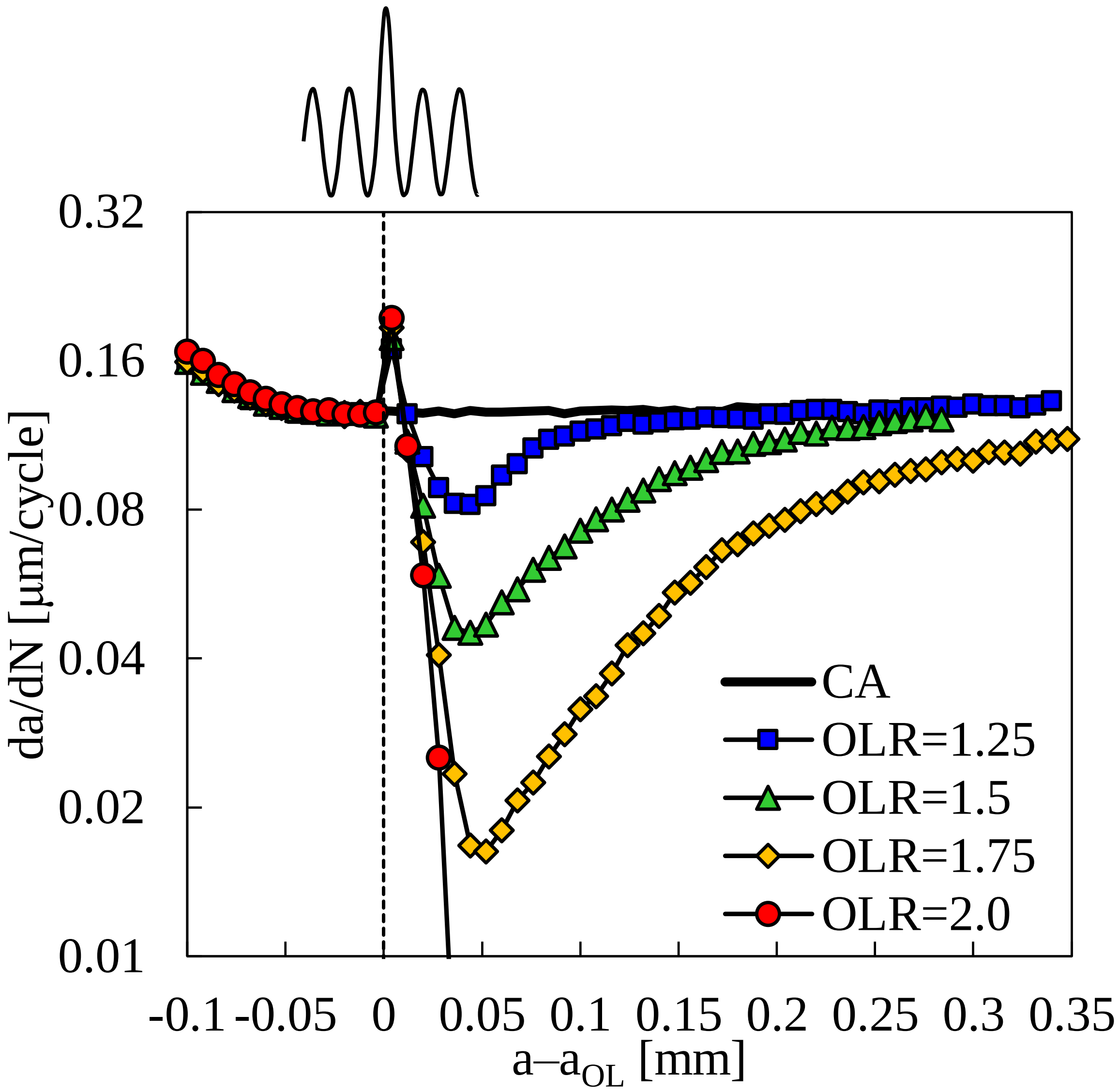
- Increase of the crack growth rate for increasing values of stress ratio
- Numerical predictions are in good agreement with the experimental measurements

Results

FCG rate under variable amplitude loading

- Effect of a **single overload** on the **predicted fatigue crack growth**
    - Material: Ti-6Al-4V
    - CT specimen (W=36 mm)
    - Stress ratio: R=0.05
    - Plane stress conditions in the simulation
    - $\Delta K_{BL}=18.3\ \text{MPa}\cdot\text{m}^{0.5}$

- Sudden <u>increase of the FCG rate followed by a decrease to a minimum value</u> (reached at some point ahead of the overload application) and finally a gradual approximation to the constant amplitude crack growth rate



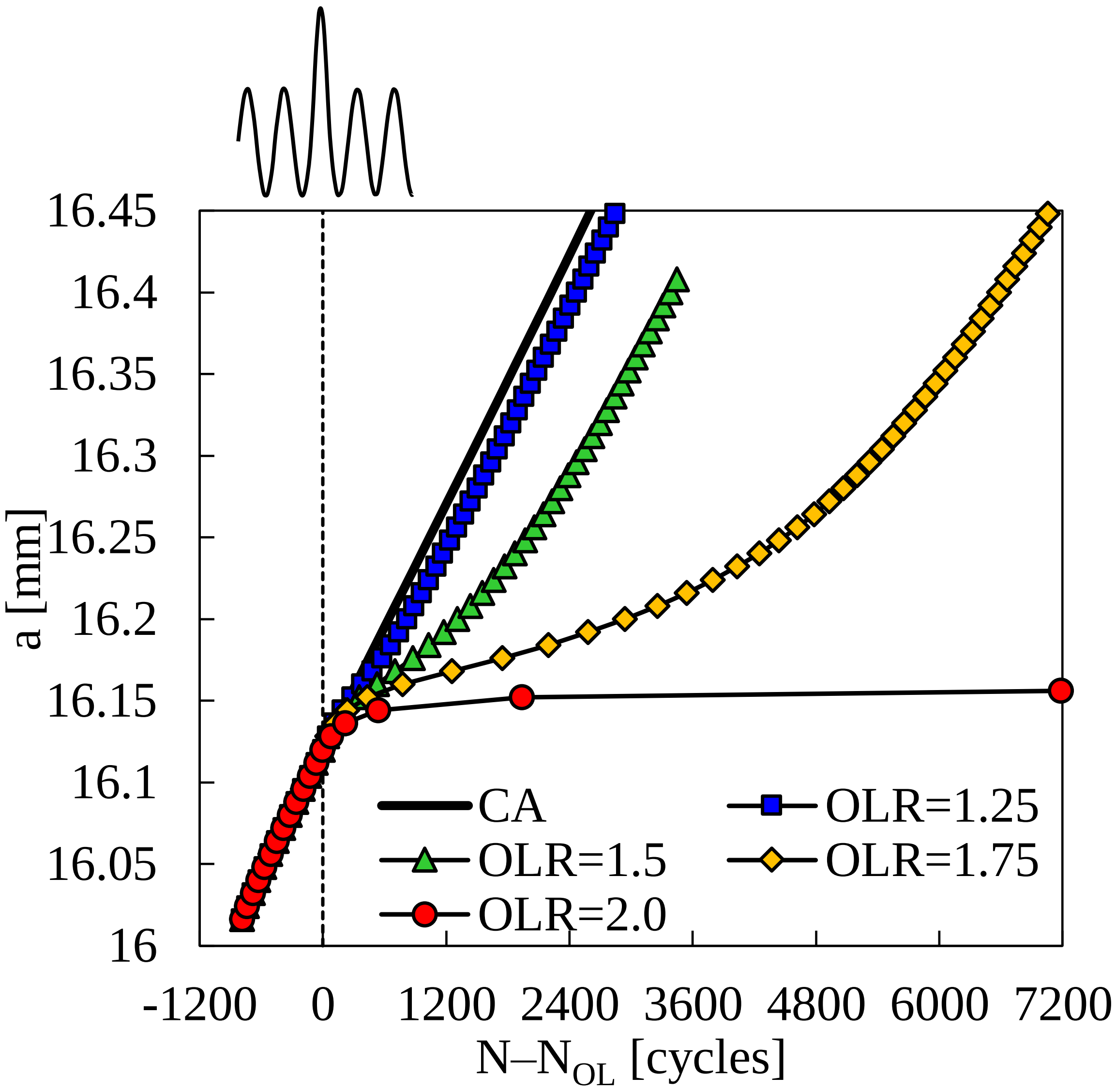
Results

FCG rate under variable amplitude loading

☐ Effect of a **single overload** on the **predicted fatigue crack growth**

- Increasing overload ratio leads to an increase of the number of delay cycles.
  - ✓ 250 cycles for OLR=1.25
  - ✓ 5100 cycles for OLR=1.75

- Crack arrest for OLR=2.0 since there is no increment of plastic deformation at the crack tip (high level of crack closure under this condition)

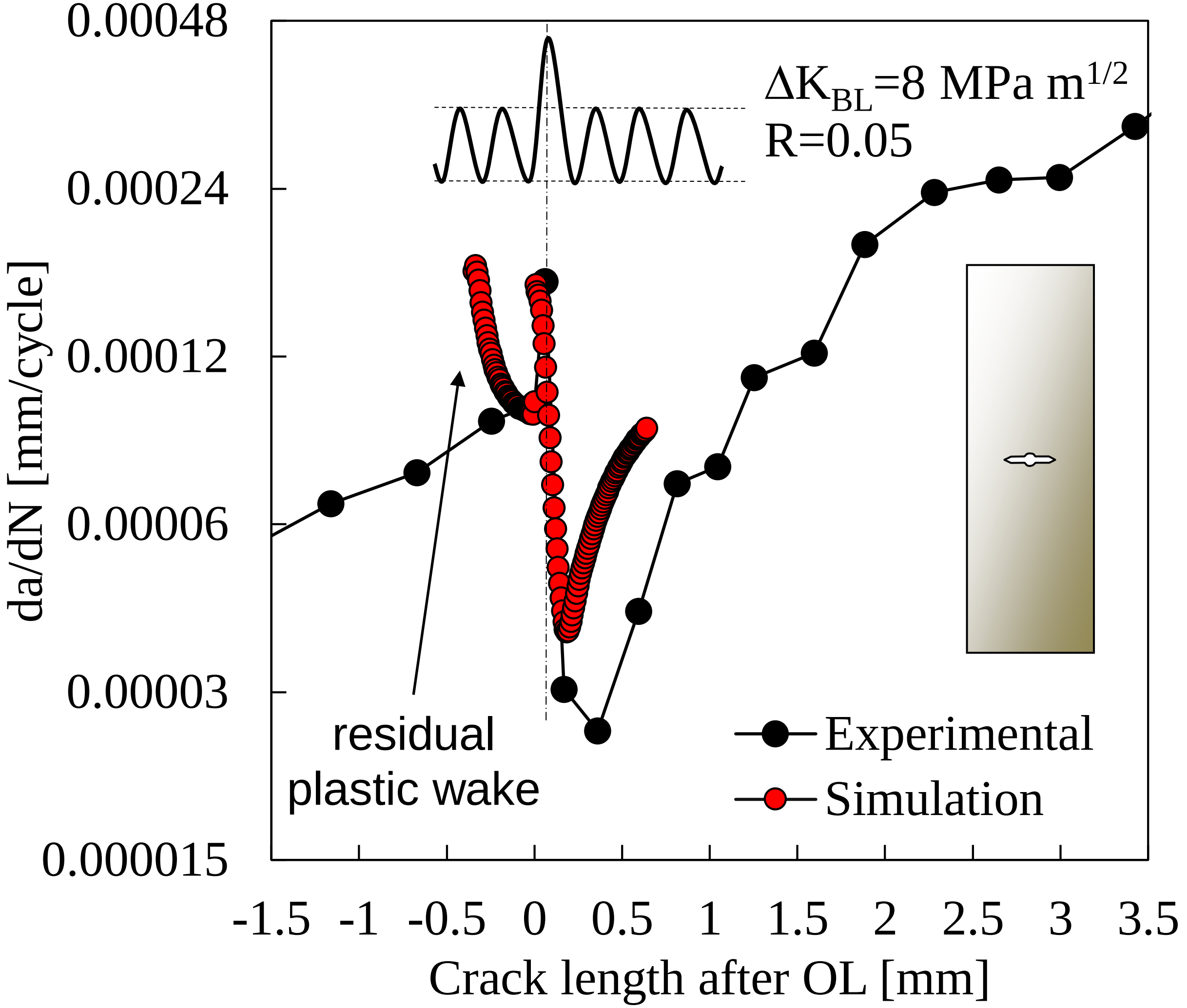


Results

FCG rate under variable amplitude loading

- ❑ Effect of a **single overload** on the **predicted fatigue crack growth**
  - Material: 6082-T6 aluminum alloy
  - MT specimen (W=50 mm)
  - OLR=1.5
  - Plane stress conditions in the simulation
  - ΔK_{BL}=8 MPa·m$^{0.5}$

- Increase of the FCG rate followed by a decrease to a minimum value and finally a gradual approximation to the constant amplitude crack growth rate

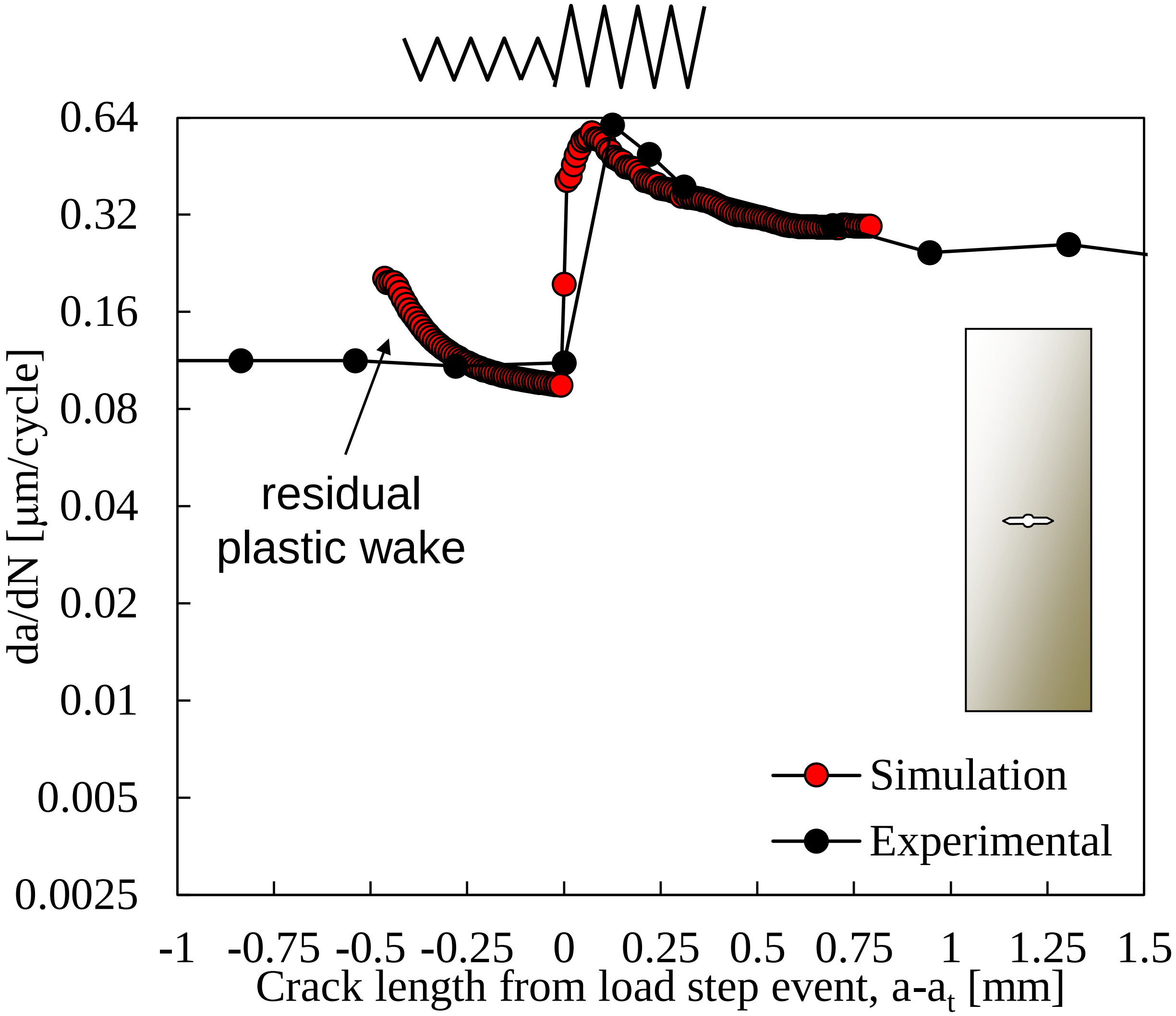


Results

FCG rate under variable amplitude loading

- Effect of **load blocks** on the **predicted fatigue crack growth rate**
  - Material: 6082-T6 aluminum alloy
  - MT specimen (W=50 mm)
  - Stress ratio: R=0.05
  - Plane stress conditions in the simulation
  - Low-high load pattern (ΔK_1=9 MPa·m$^{0.5}$ and ΔK_{BL}=12 MPa·m$^{0.5}$)

- Acceleration after block transition, leading to the maximum crack growth rate (about twice the value after transient regime)

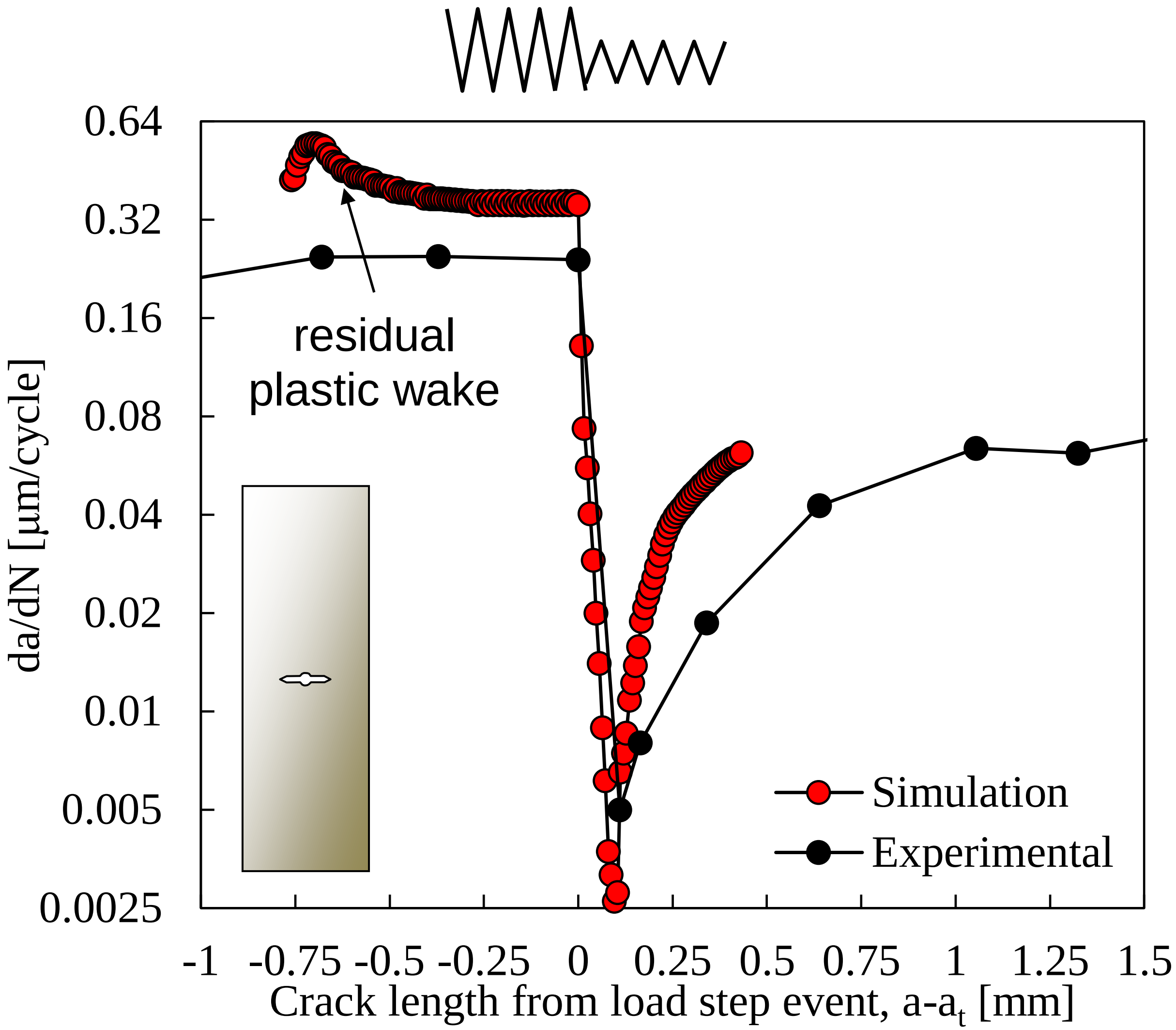


Results

FCG rate under variable amplitude loading

- ❑ Effect of **load blocks** on the **predicted fatigue crack growth rate**
  - Material: 6082-T6 aluminum alloy
  - MT specimen (W=50 mm)
  - Stress ratio: R=0.05
  - Plane stress conditions in the simulation
  - High-low load pattern (ΔK_1=12 MPa·m$^{0.5}$ and ΔK_{BL}=9 MPa·m$^{0.5}$)

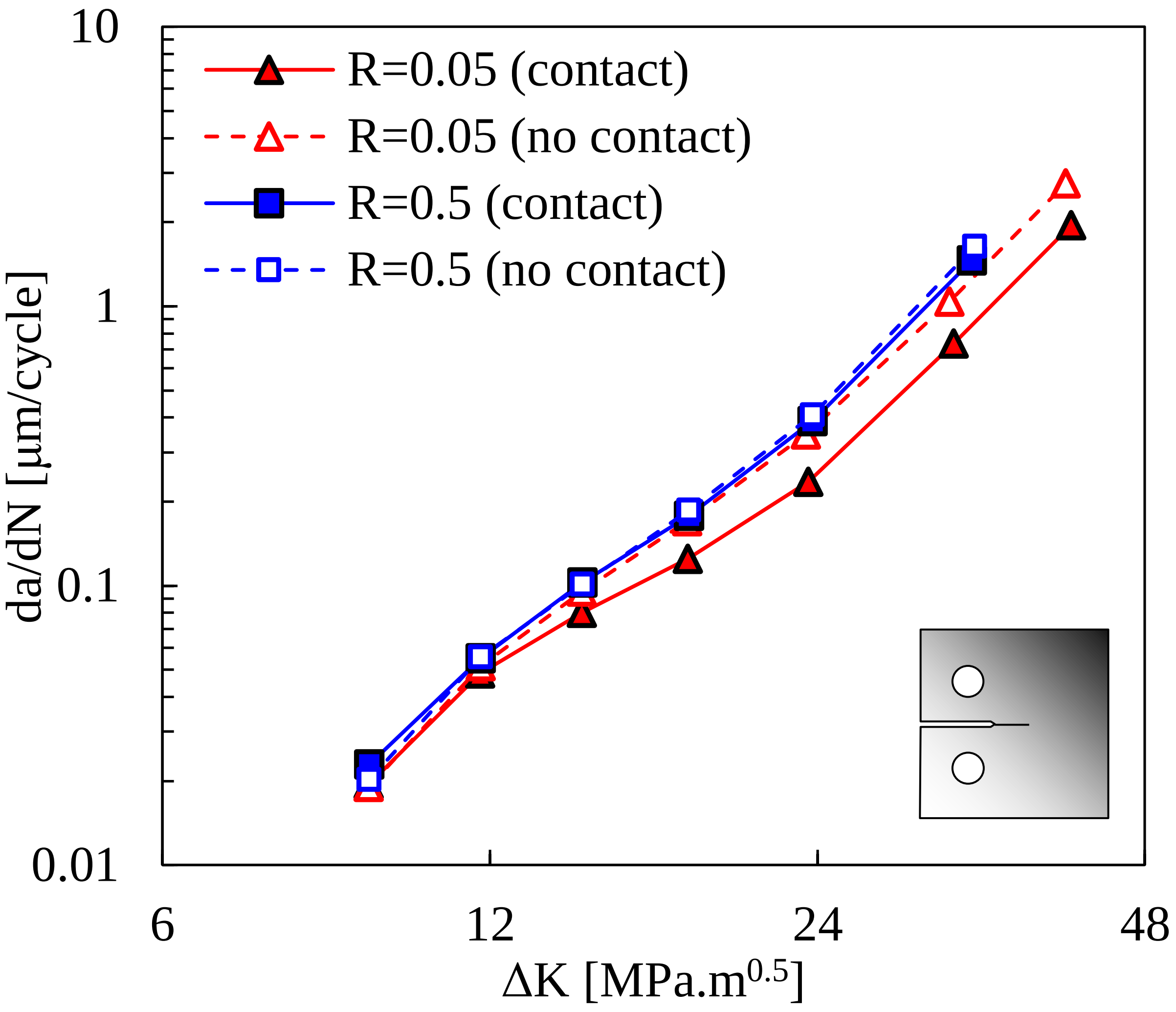
- Crack growth retardation after the transition, followed by a progressive increase of the FCG rate towards the constant amplitude value



FCG rate under constate amplitude loading

❑ Effect of **crack closure** on the predicted fatigue crack growth

- Fatigue crack growth obtained with and without contact of crack flanks
- Negligible effect of the stress ratio on the fatigue crack growth when the contact of crack flanks is removed
- The inclusion of contact between crack flanks is fundamental in the numerical simulation



Results

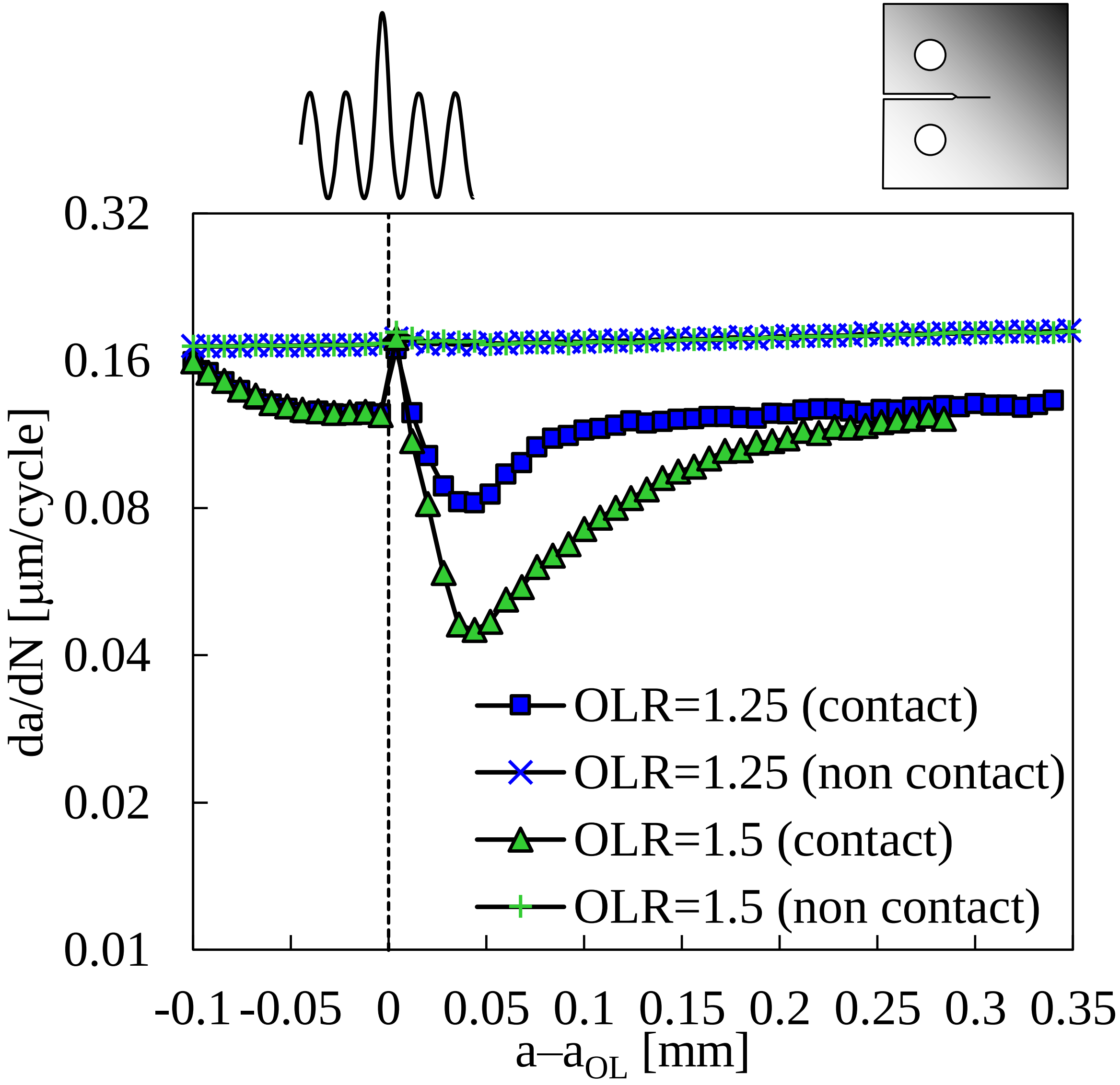
FCG rate under variable amplitude loading

- Effect of **crack closure** on the predicted fatigue crack growth in a **single overload**

  - Fatigue crack growth obtained with and without contact of crack flanks

  - No effect of the overload on the fatigue crack growth when the contact of crack flanks is removed

  - The inclusion of contact between crack flanks is fundamental in the numerical simulation

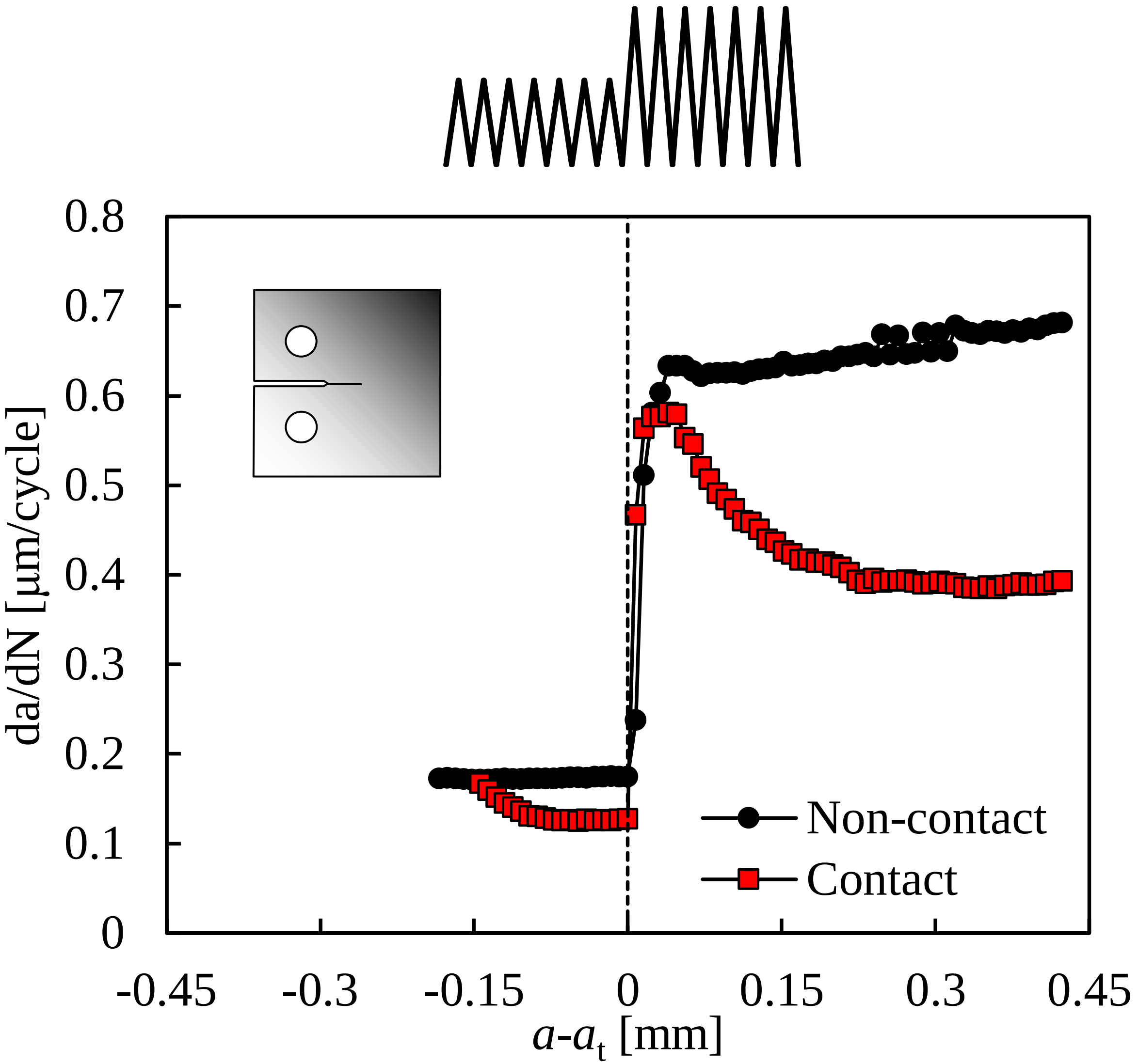


Results

FCG rate under variable amplitude loading

☐ Effect of **crack closure** on the predicted fatigue crack growth in a **low-high load block**

- Fatigue crack growth obtained <u>with and without contact of crack flanks</u>
- <u>No transient effect</u> on the fatigue crack growth when the contact of crack flanks is removed. The fatigue crack growth rate switches quickly to the value of the new loading amplitude
- The inclusion of <u>contact between crack flanks is fundamental</u> in the numerical simulation



Results

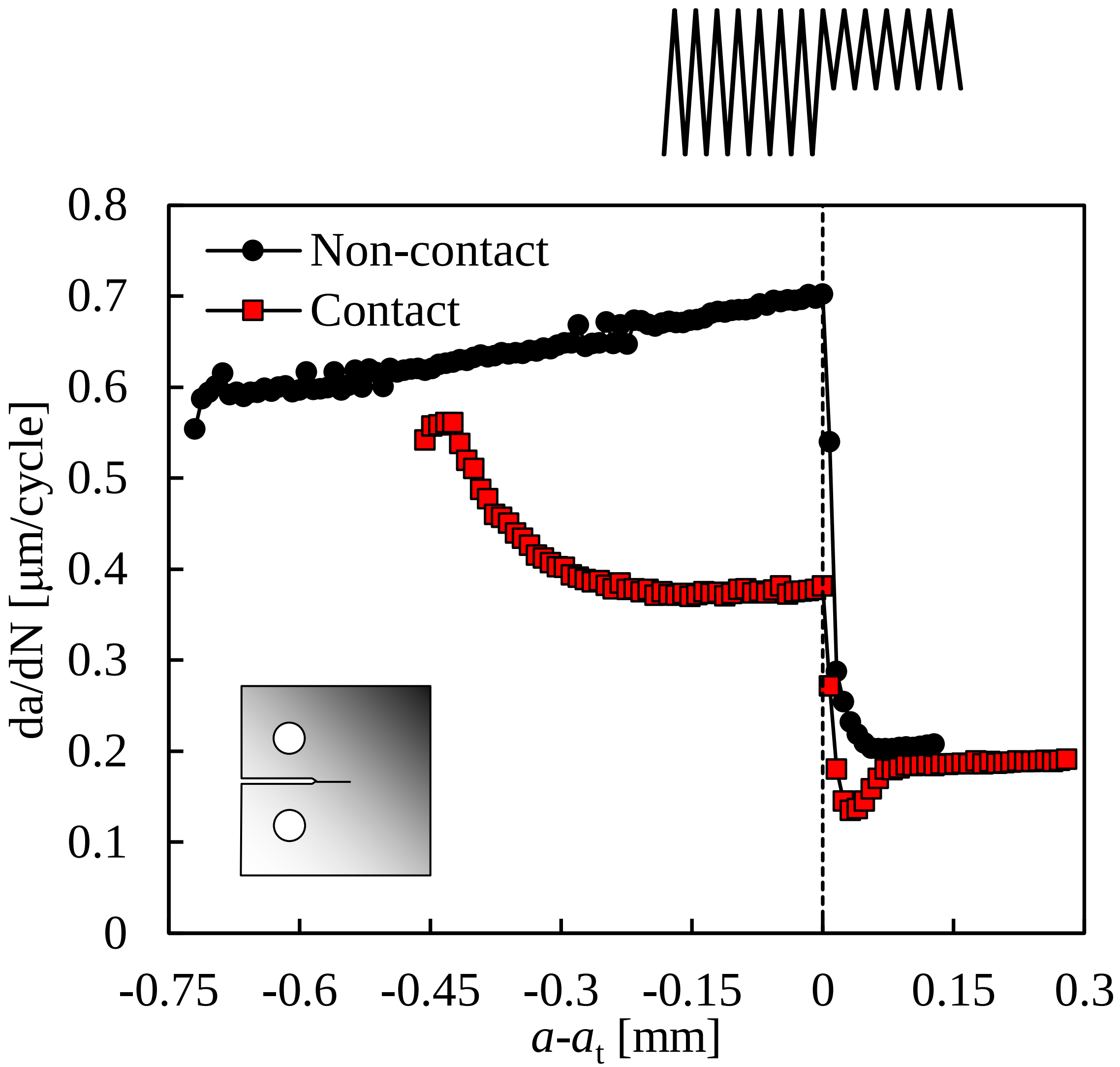
FCG rate under variable amplitude loading

- Effect of **crack closure** on the predicted fatigue crack growth in a **high-low load block**

  - Fatigue crack growth obtained with and without contact of crack flanks

  - No transient effect on the fatigue crack growth when the contact of crack flanks is removed. The fatigue crack growth rate switches quickly to the value of the new loading amplitude

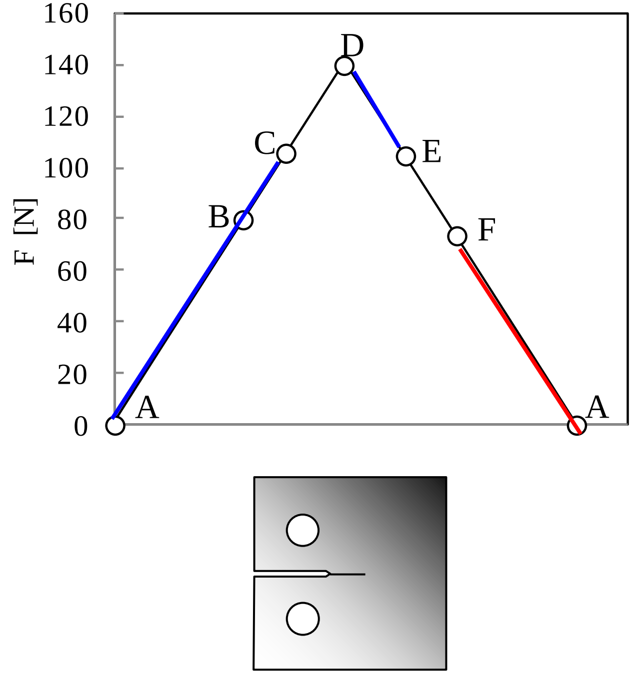
  - The inclusion of contact between crack flanks is fundamental in the numerical simulation

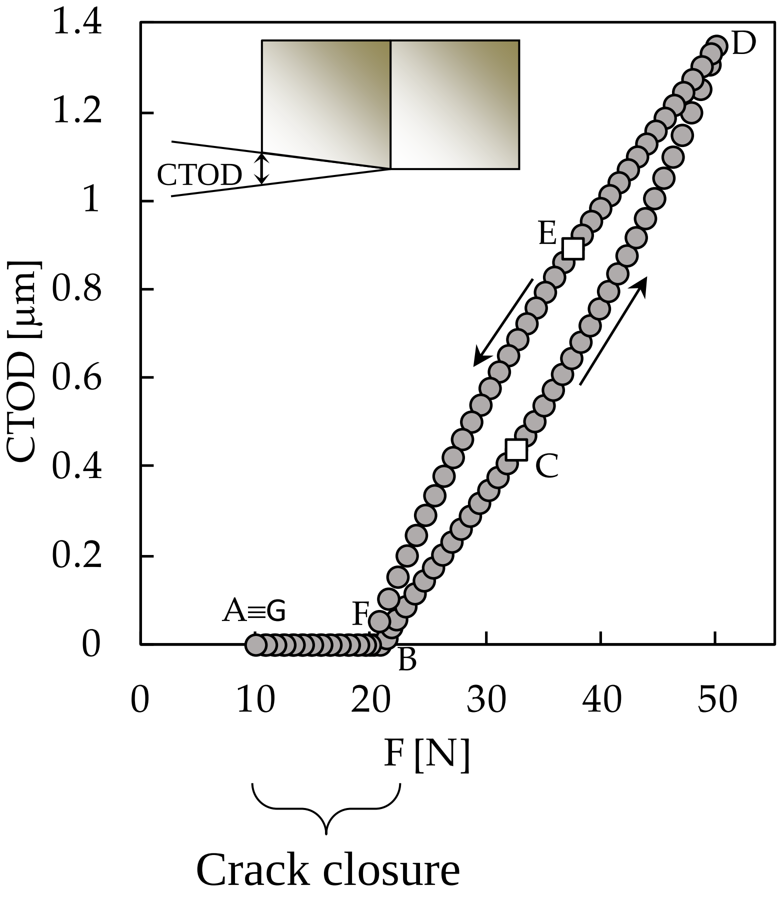


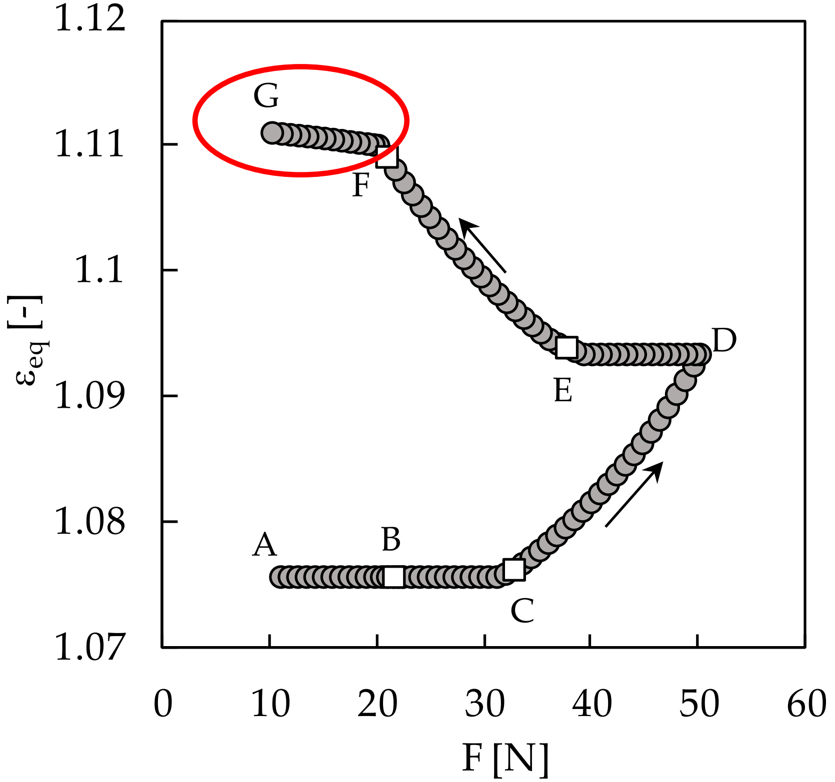
Results

Plastic strain evolution under constant amplitude loading

- ❑ Plastic deformation increases in the segment FG, during which the crack is closed
  - ▪ The crack closure concept must be redefined since occurs plastic deformation for loads below $F_{closure}$







Conclusions

- Finite element model to simulate fatigue crack growth, assuming that crack tip plastic deformation is the main crack driving force (crack propagation occurs by nodal release)

- Numerical results are in good agreement with the experimental data:
  - ✓ Effect of stress intensity factor range (ΔK)
  - ✓ Effect of stress ratio (R)
  - ✓ Effect of a single overload
  - ✓ Effect of load blocks

- The inclusion of contact between crack flanks is fundamental to obtain accurate predictions in the numerical simulation (high importance of crack closure)

Acknowledgements

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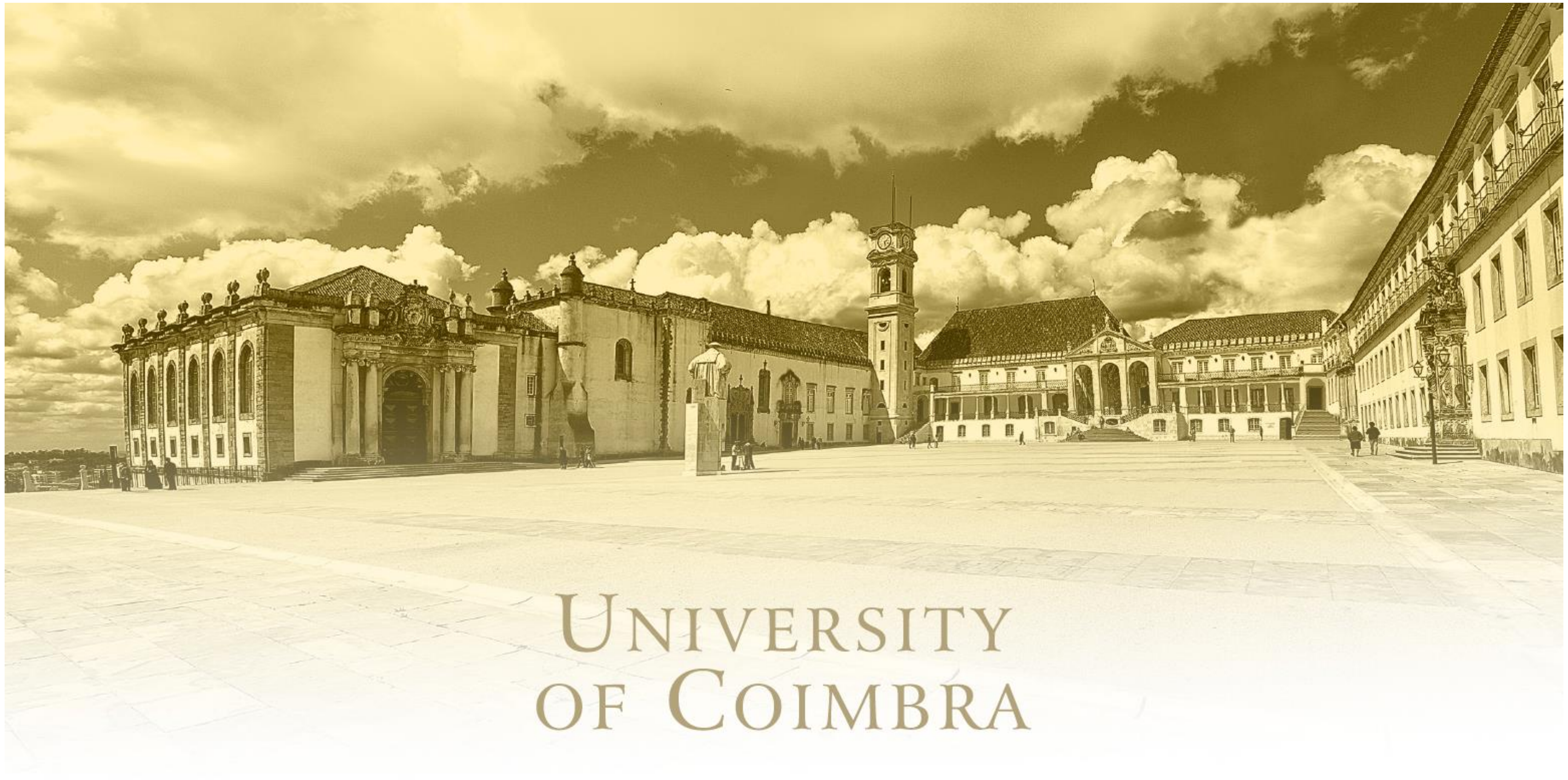

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