MODELLING THE FATIGUE CRACK GROWTH USING THE CRACK TIP PLASTIC DEFORMATION

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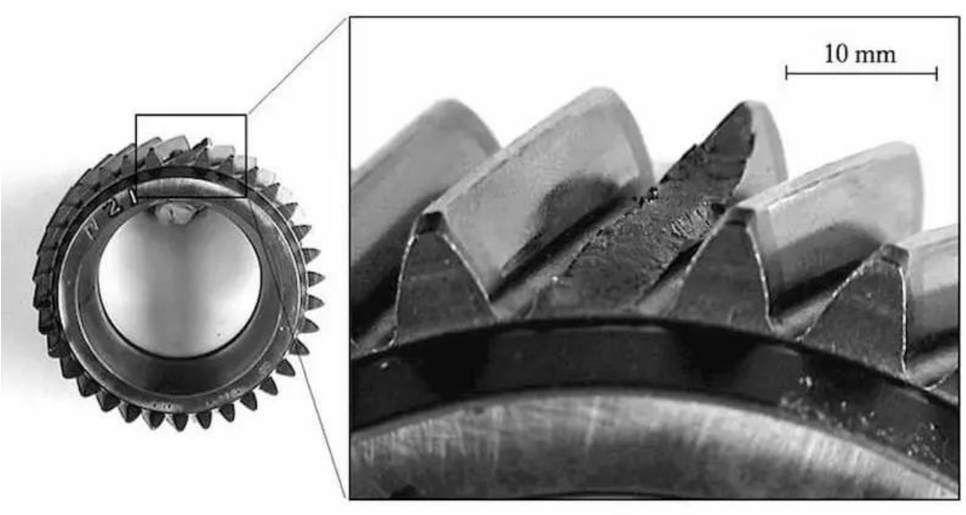
Introduction

Examples of fatigue failures

- There are thousands of components submitted to cyclic loads in different industries: **aerospace, locomotive, automotive, naval, etc.**
- **Catastrophic failures** of mechanical equipment can have huge human and economic consequences

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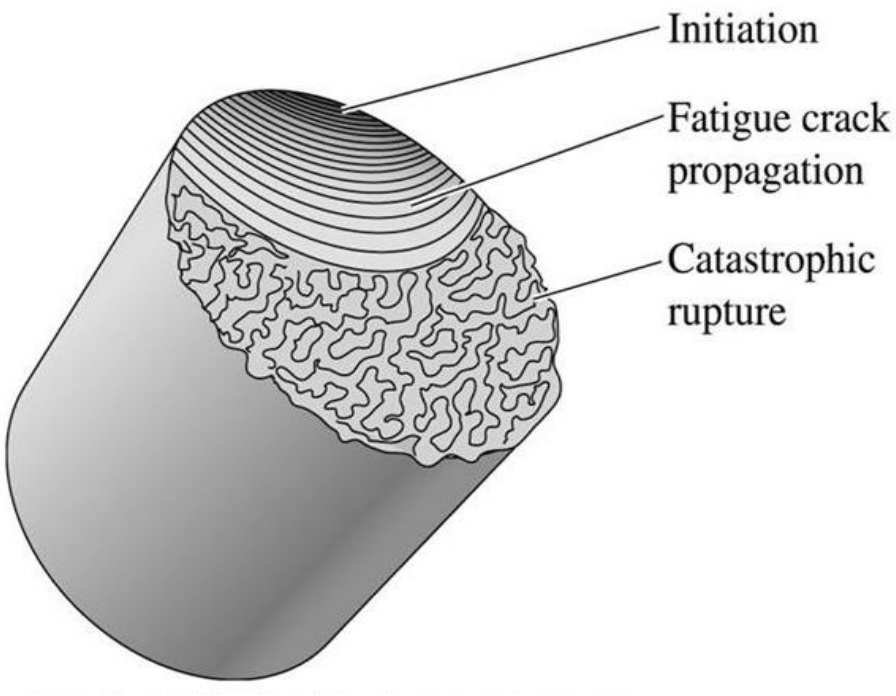
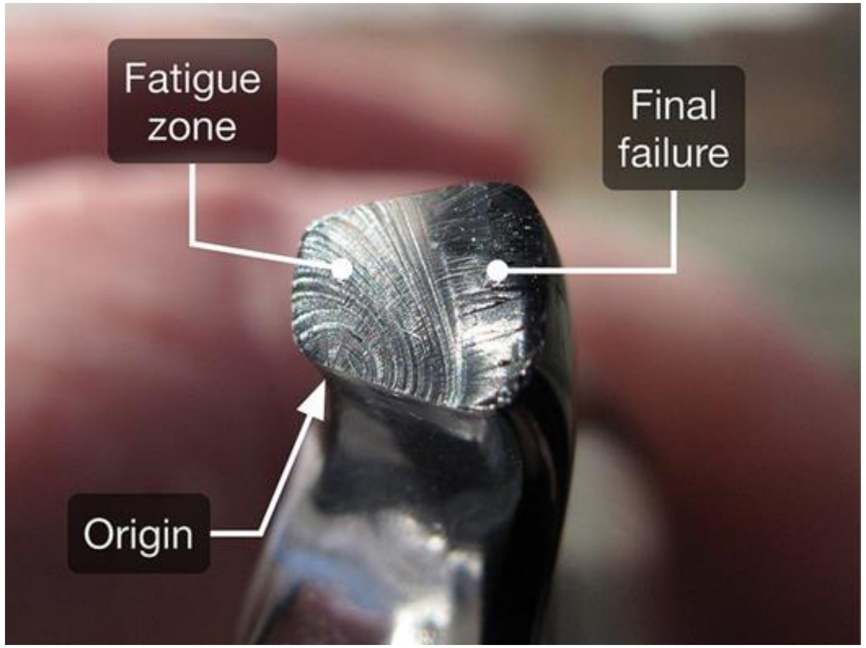
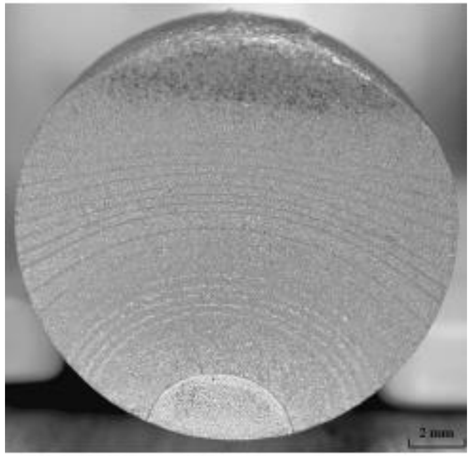
Introduction

Mechanisms of fatigue

- ☐ Fatigue can be defined into **3 phases**
  - **Initiation** (usually at surface)
  - **Propagation of fatigue crack** (beach marking)
  - **Final failure** (catastrophic)





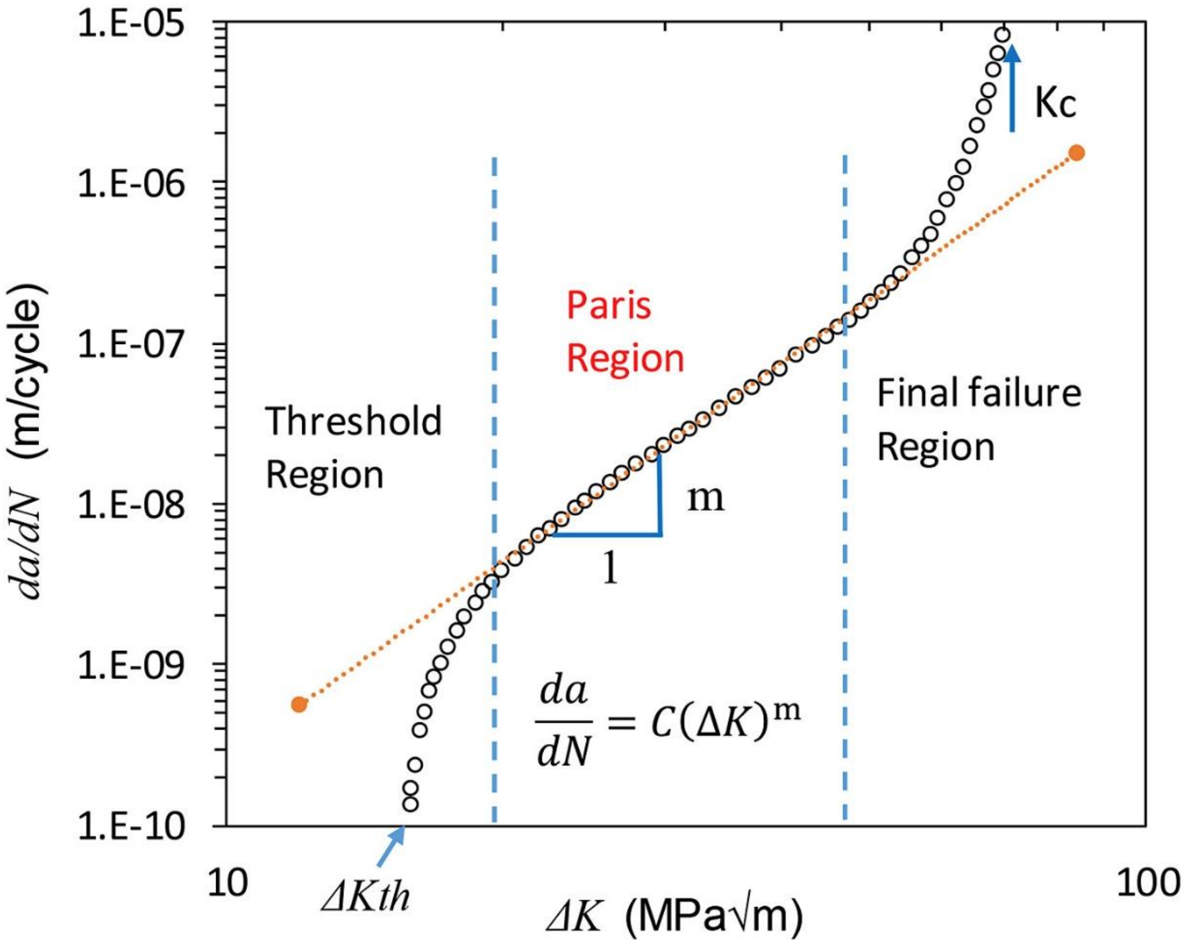


Introduction

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

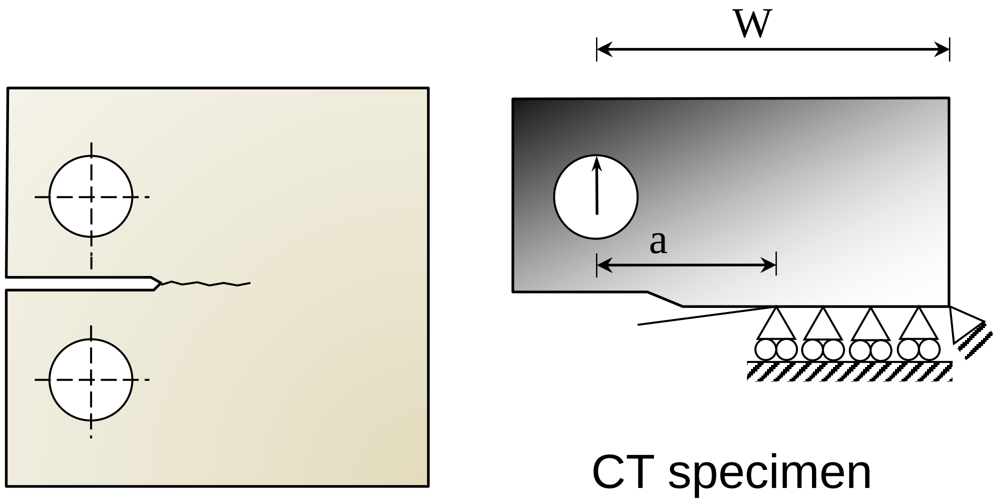
Procedure

- Normalized specimens: **CT specimen** and **MT specimen**
- Mechanical behavior described by a **rate-independent elasto-plastic** law
- Material parameters of the hardening law calibrated using data from **low-cycle fatigue tests**
- Both constant and variable amplitude **loading**
- Crack **propagation at minimum load** based on the plastic strain at the crack tip
- In-house finite element code **DD3IMP**

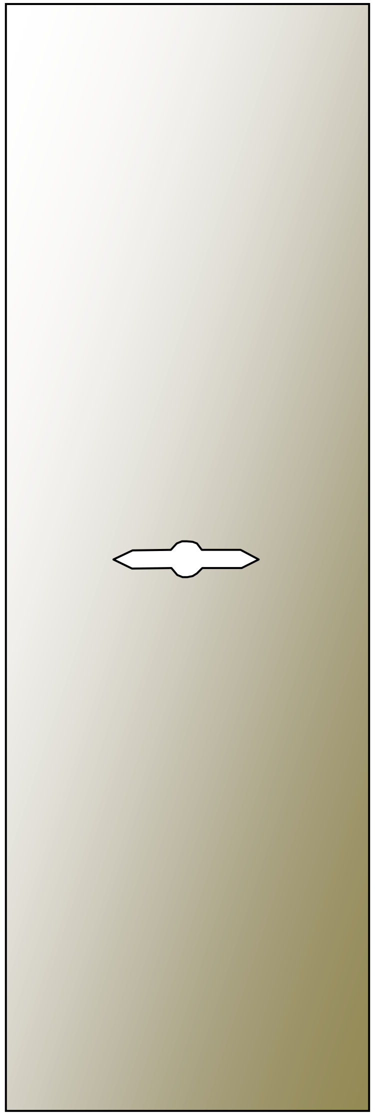
Numerical model

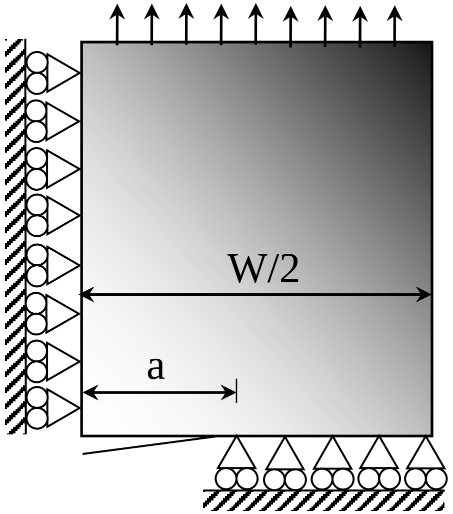
Specimen geometry and discretization

- ☐ 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



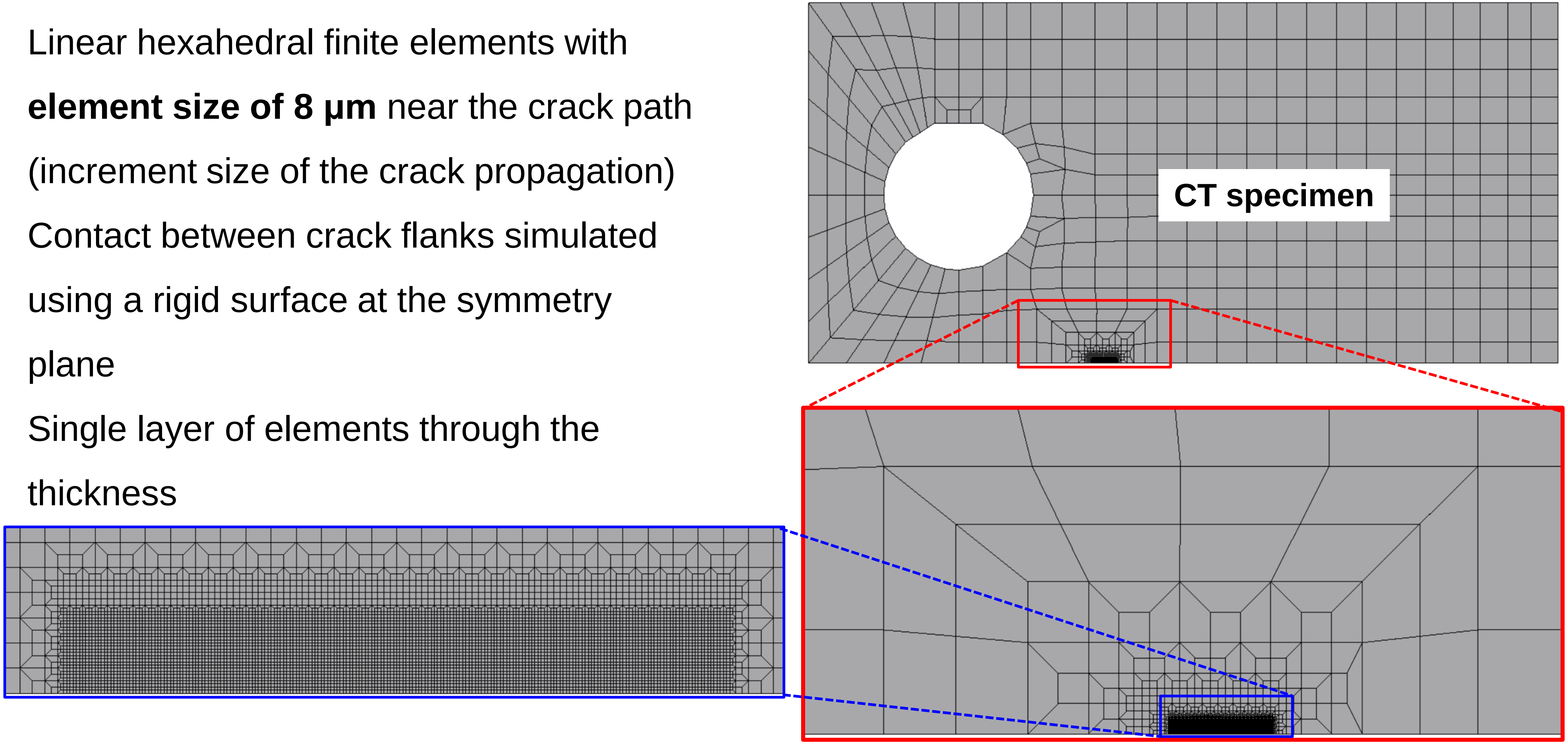


MT specimen

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

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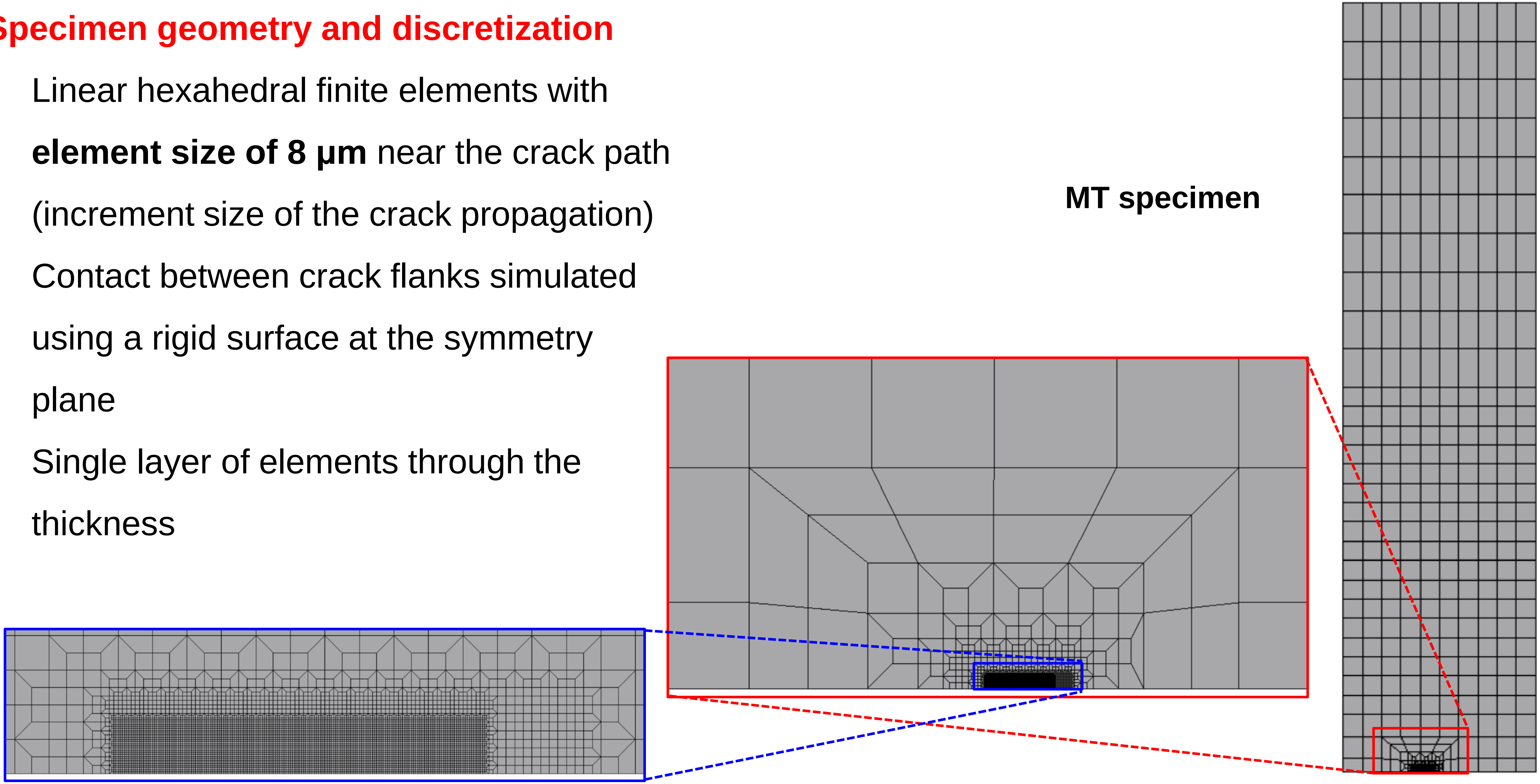
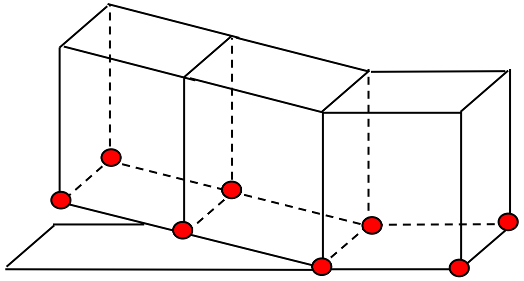


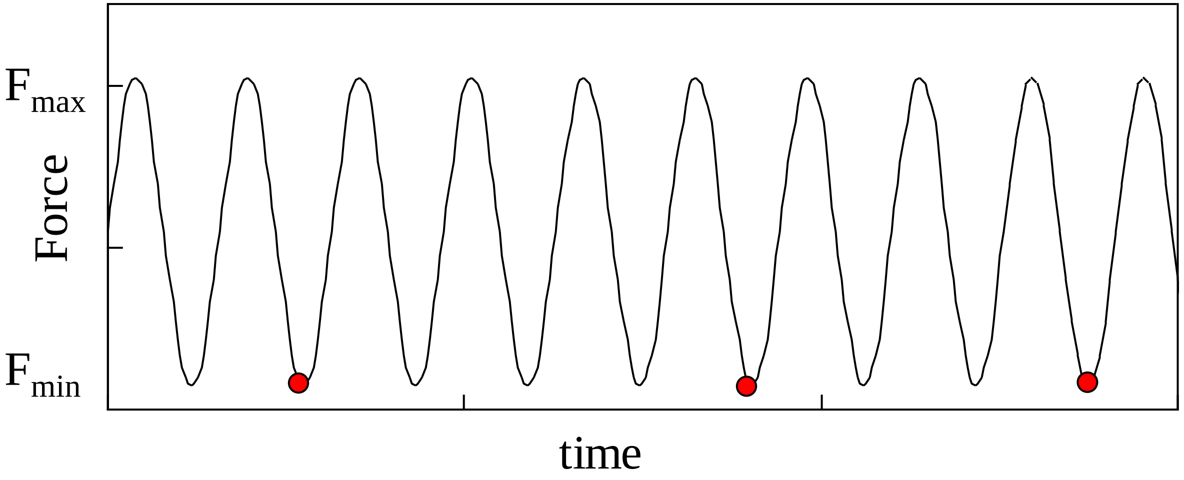
Numerical model

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
  - 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



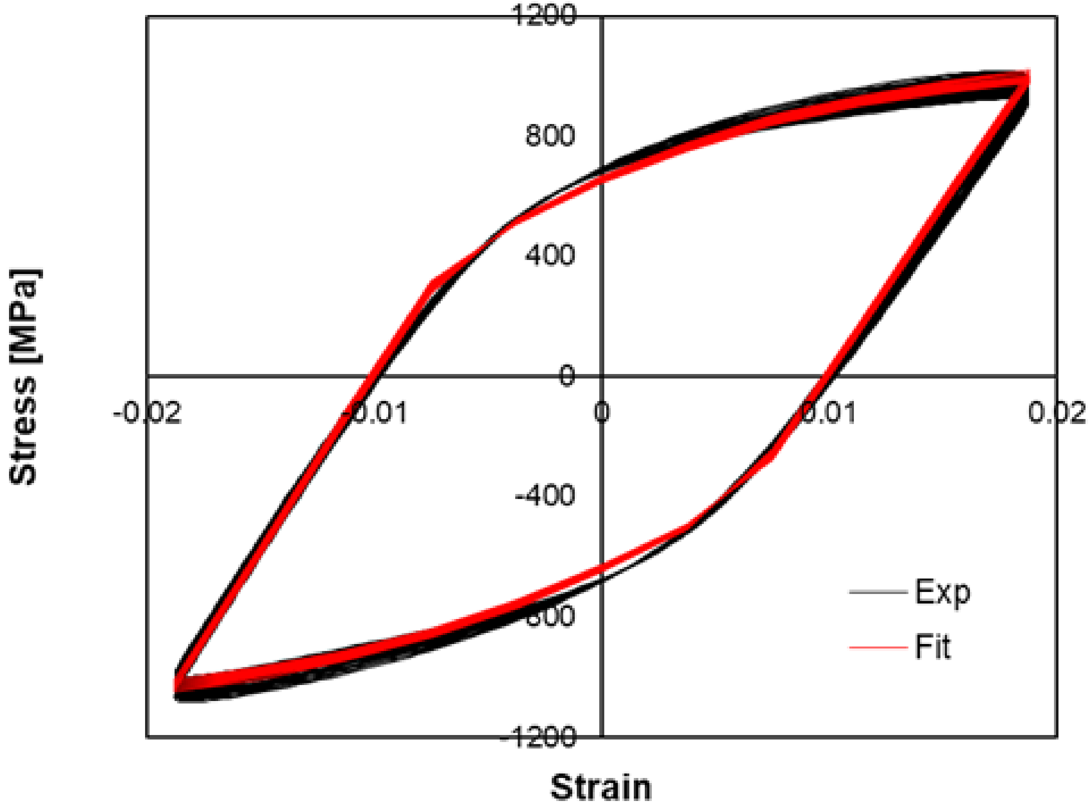
Numerical model

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**

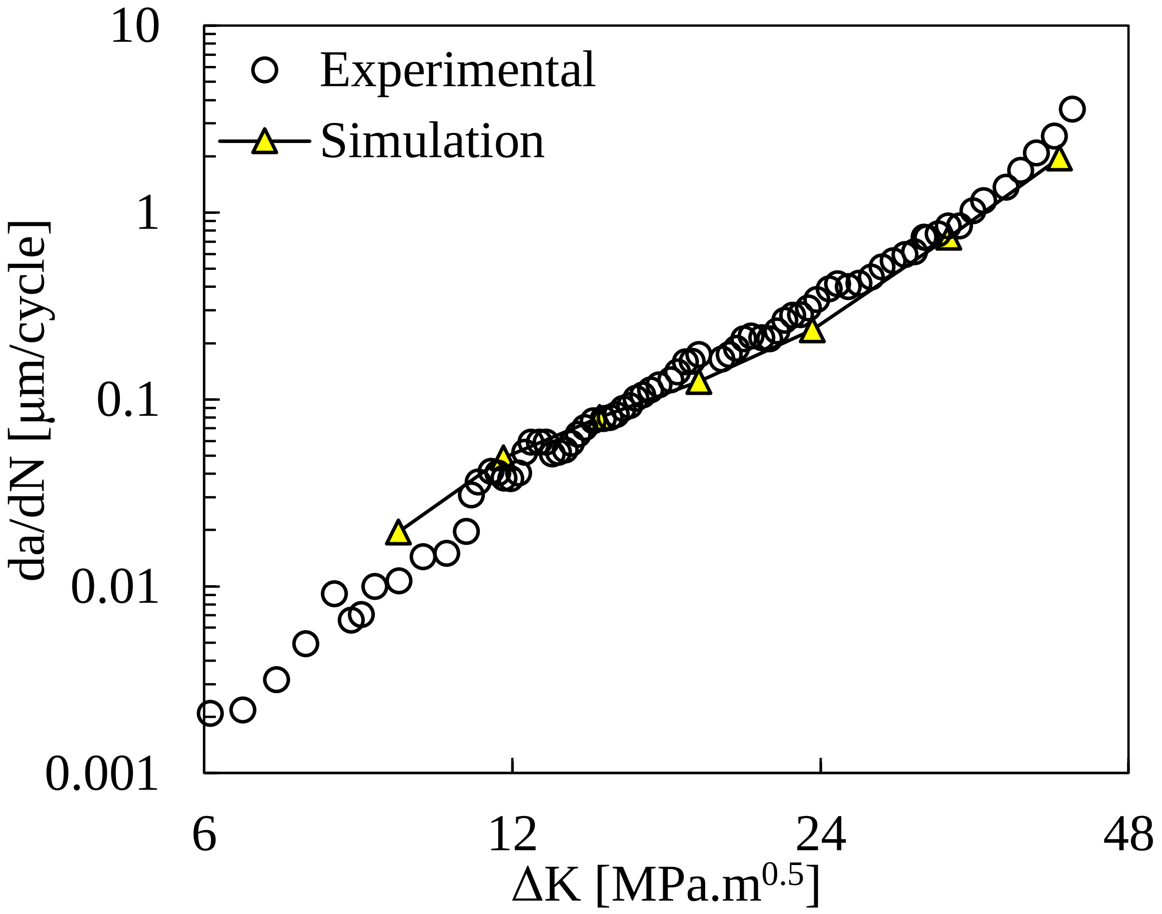


Comparison between experimental and numerical stress-strain loops for Ti-6Al-4V

Results

FCG rate under constate amplitude loading

- ❑ 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 very good agreement with the experimental measurements, allowing to validate the numerical model

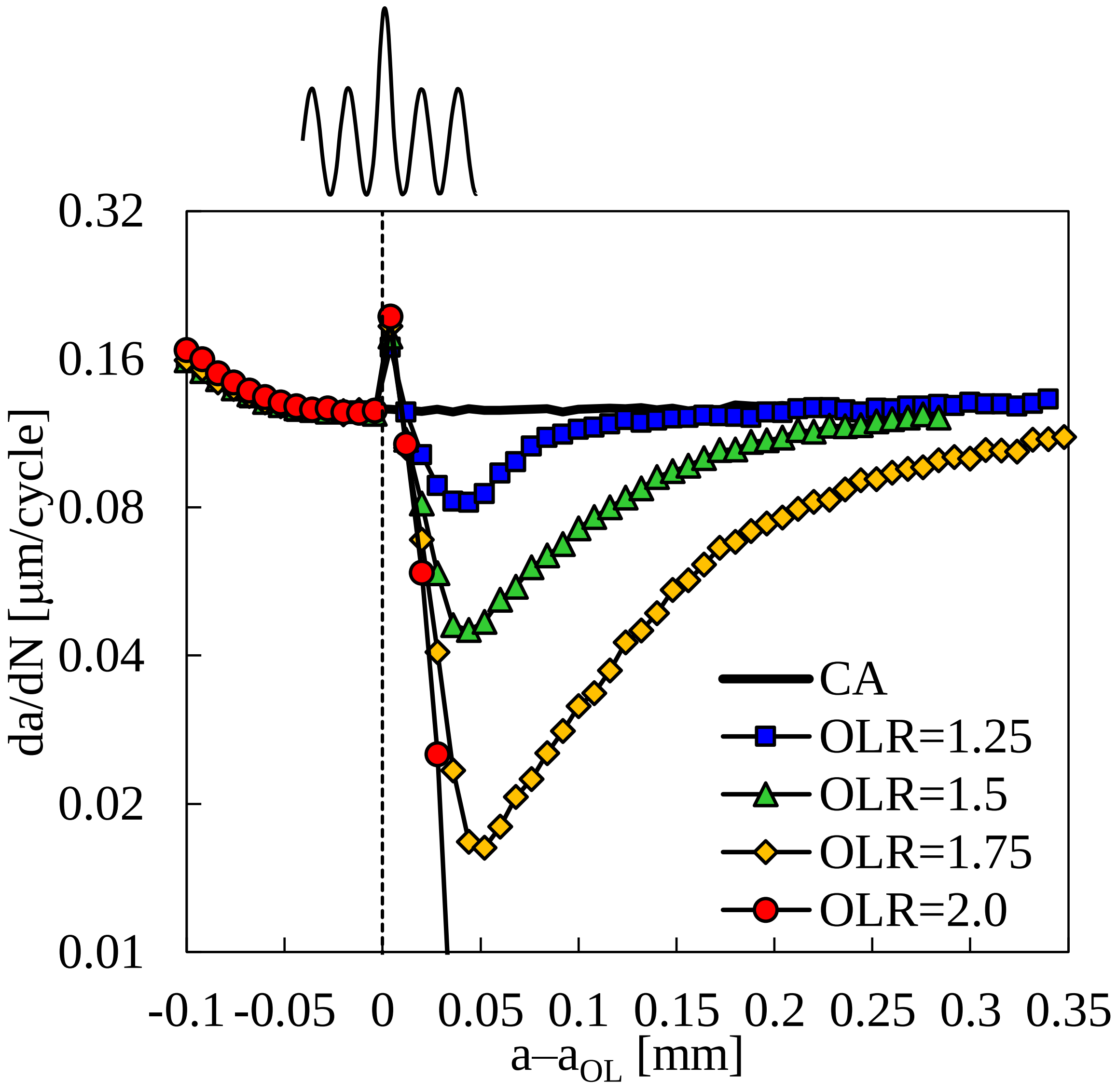
Results

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
  - ΔK_{BL}=18.3 MPa·m$^{0.5}$

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

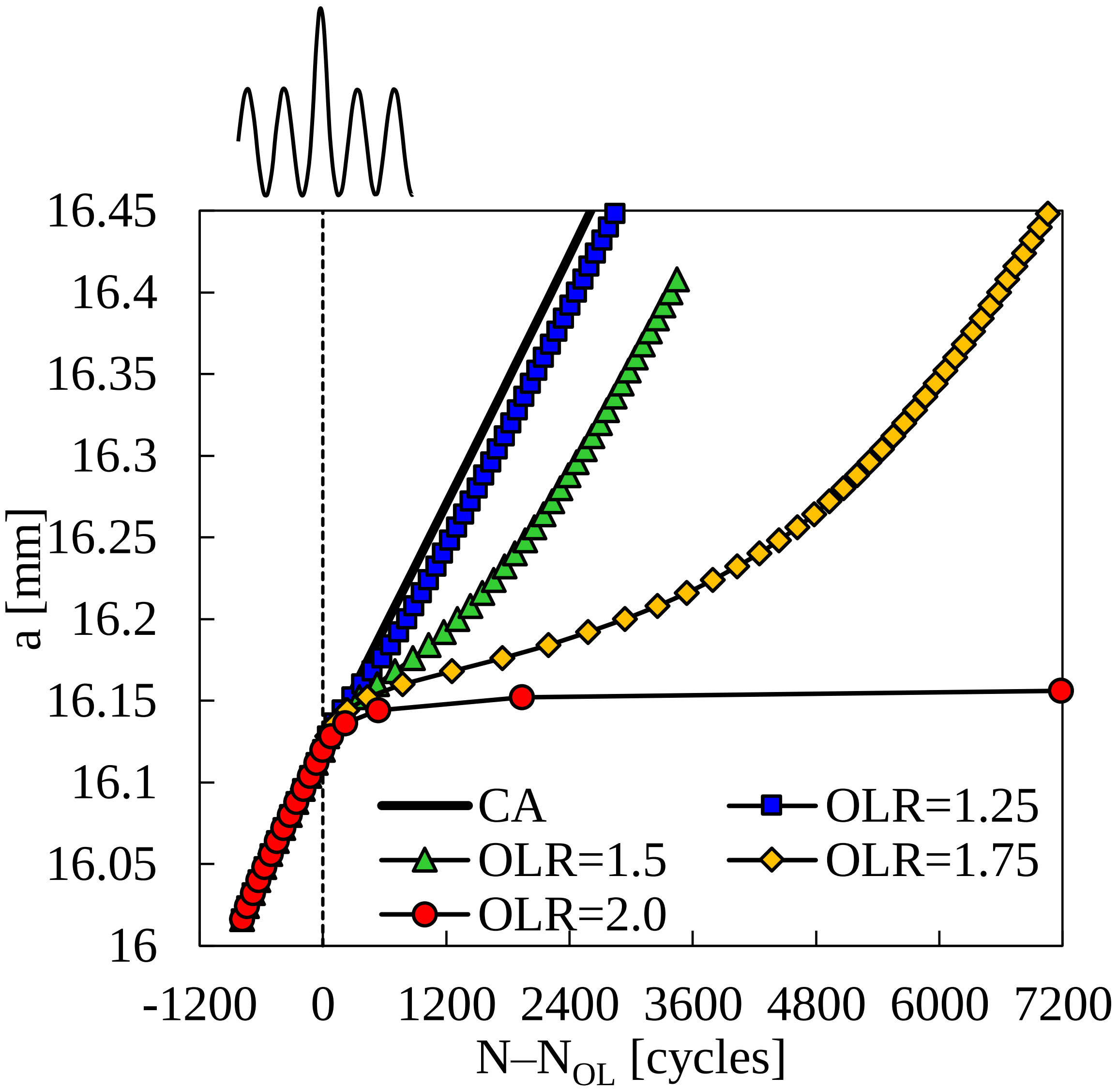


FCG rate under variable amplitude loading

❑ 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)

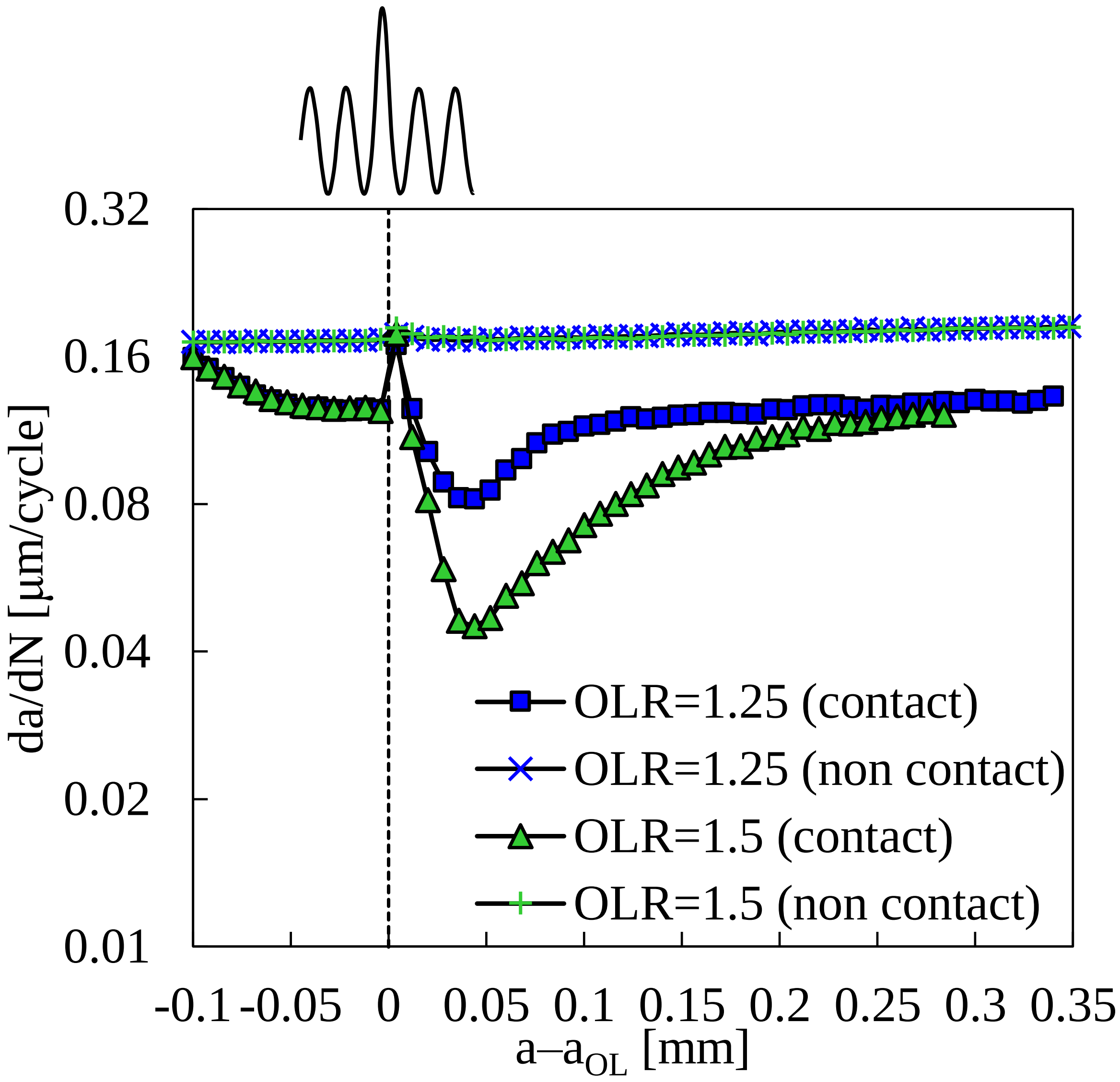


Results

FCG rate under variable amplitude loading

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

- 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

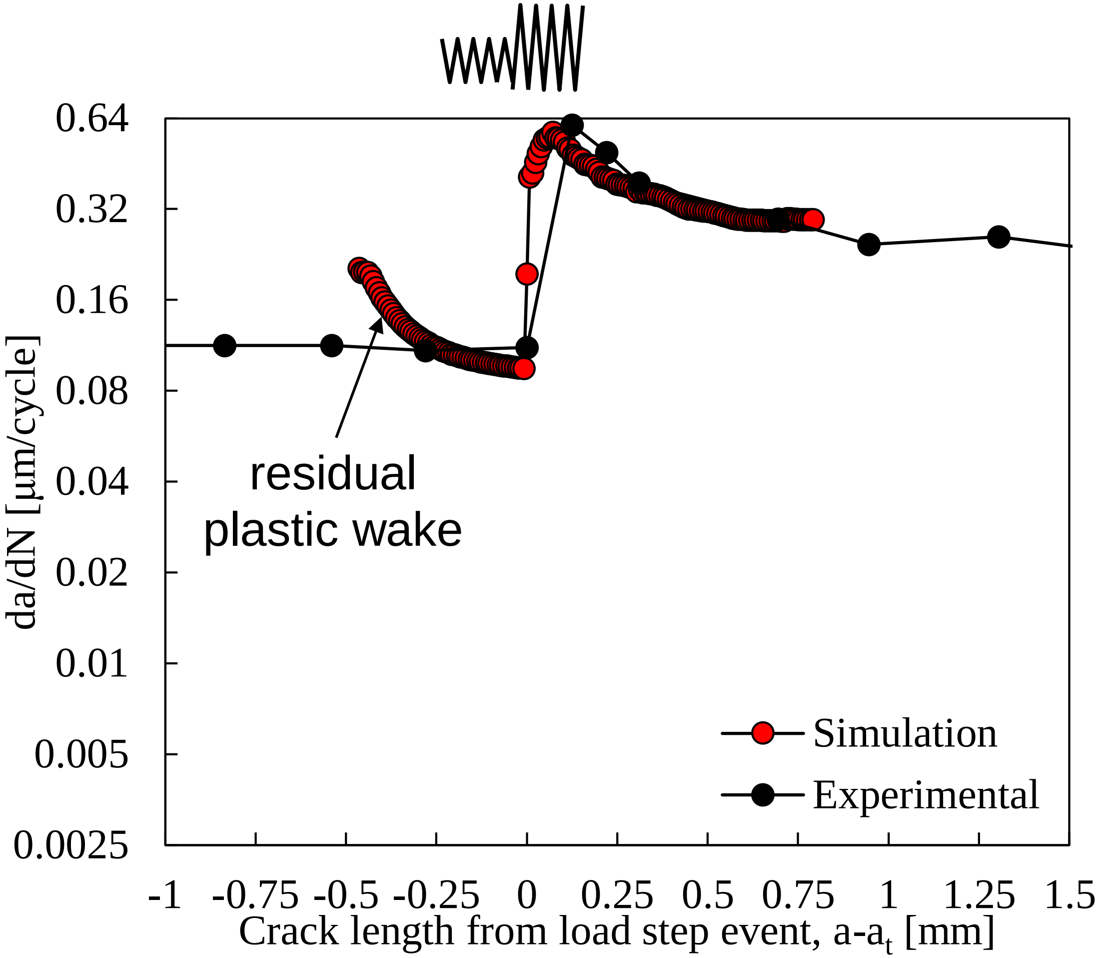


Results

FCG rate under variable amplitude loading

- ❑ Effect of **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)



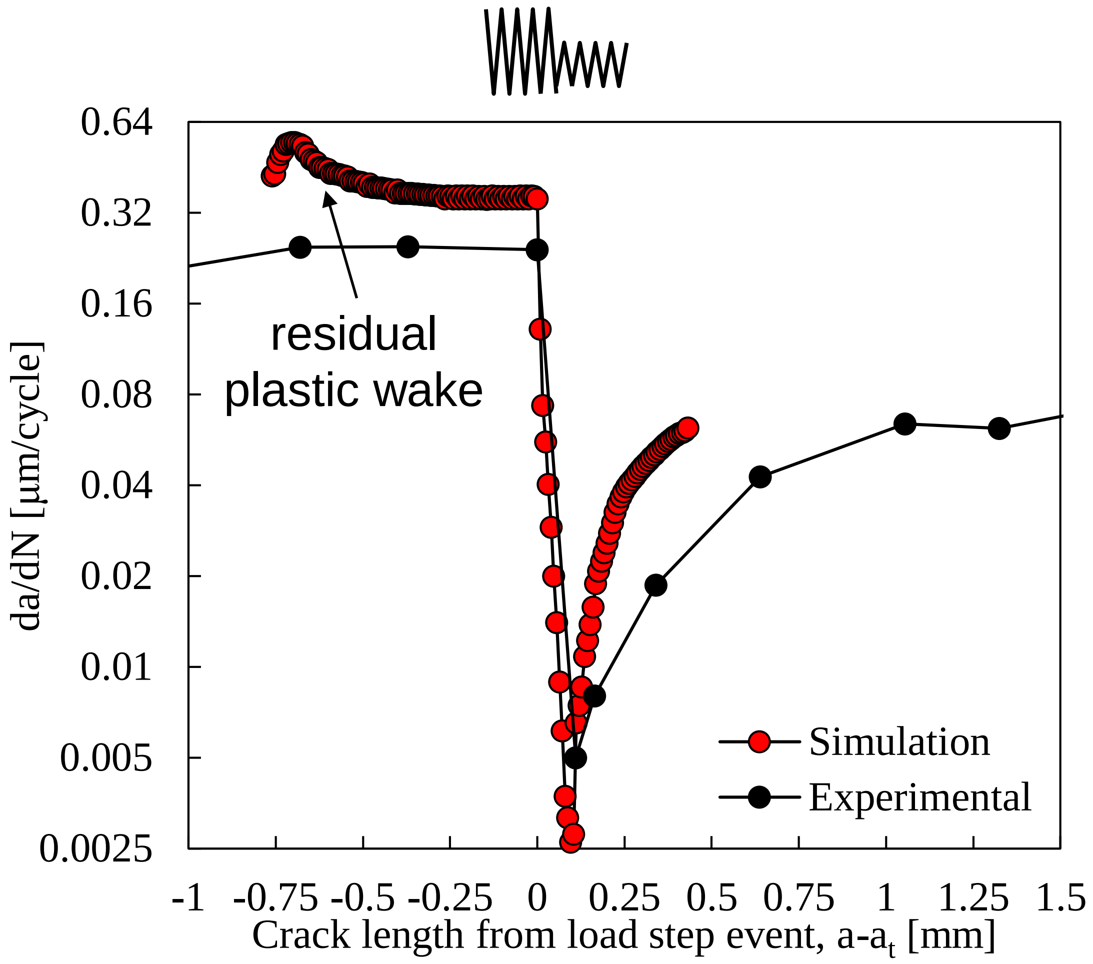
Results

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



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 when the plastic strain at the crack tip achieves a critical value

- Effect of stress intensity factor range (ΔK) on the predicted fatigue crack growth rate is accurately predicted for constant amplitude loading conditions, allowing to validate the model

- The typical variation of fatigue crack growth rate after an overload is accurately captured by the numerical model. Numerical results of load blocks are in good agreement with the experimental data

- 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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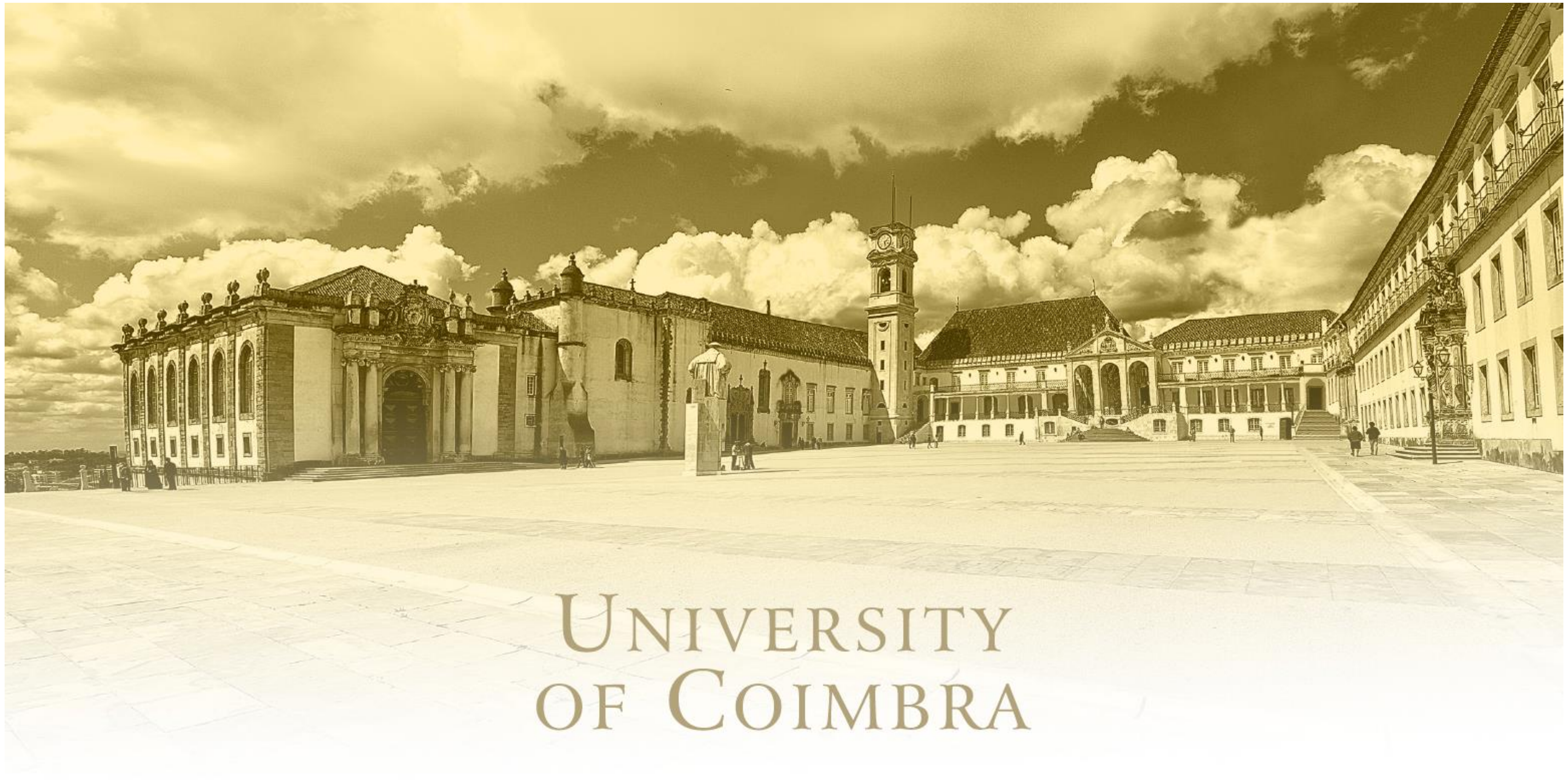

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