Cyclic cohesive model for fatigue crack growth in concrete

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- 2nd International Symposium on Multiscale Experimental Mechanics: Multiscale Fatigue

DTU

Concrete subjected fatigue loading

- Concrete highways and bridges
  - app. 5,000,000-50,000,000 passes over critical point during design period
- Port- and industrial pavements
  - app. 250,000-5,000,000 passes over critical point during design period
- Airport pavements
  - app. 10,000-250,000 passes over critical point during design period

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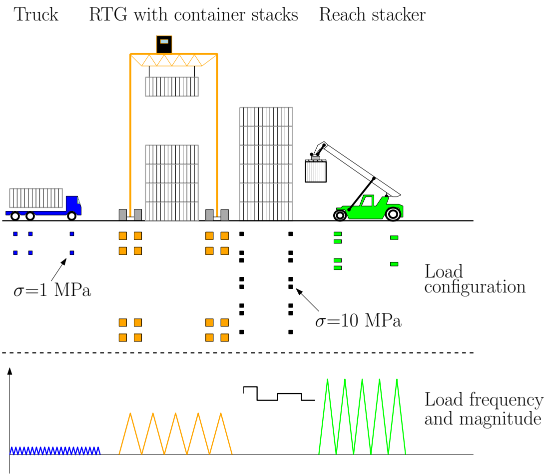
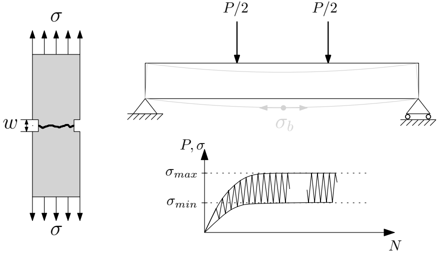
Concrete subjected arbitrary loading

..moreover, some concrete structures are subjected to a wide spectrum of loads and load configurations..



Design methodology

The cyclic behaviour of concrete have mainly been described by Mechanistic-Empirical methods



- Mechanical part: Measured or calculated response (stress or strain level, stress intensity etc.)
- Empirical part: Transfer function (S-N curve) converting the response into number of allowable load cycles
- The M-E models does not distinguish between elastic and inelastic work
- Model parameters A, B and C are regression constants without physical meaning

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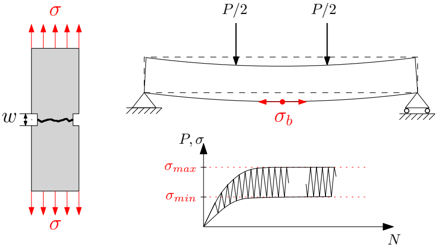

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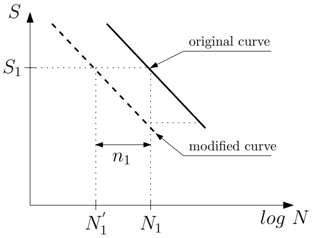

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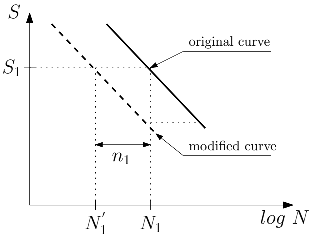

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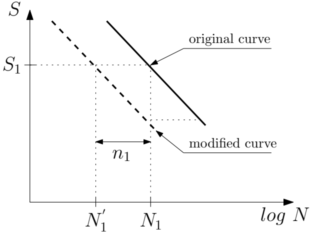

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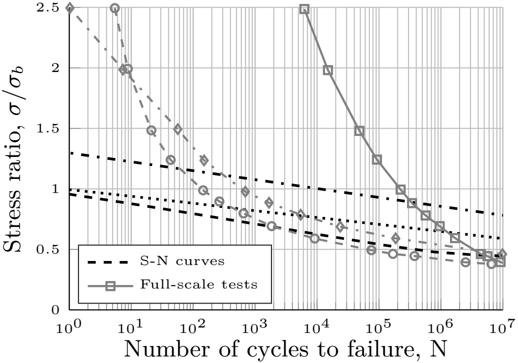
M-E models vs. full-scale experiments

S-N curves and full-scale tests with concrete slabs on ground



- The M-E models have difficulties in accurately predicting realistic behaviour
- Fatigue and monotonic behaviour are badly linked

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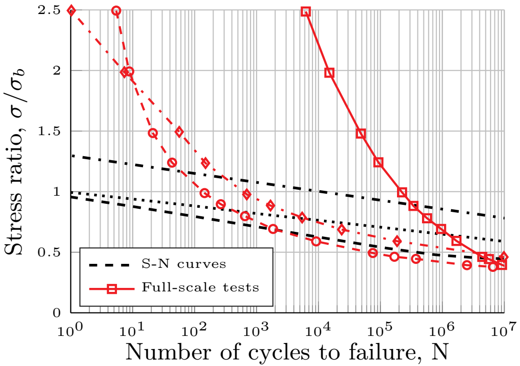

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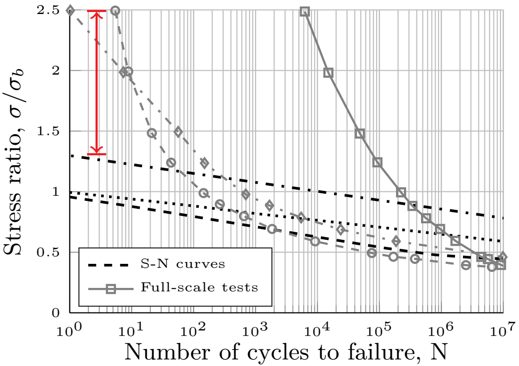

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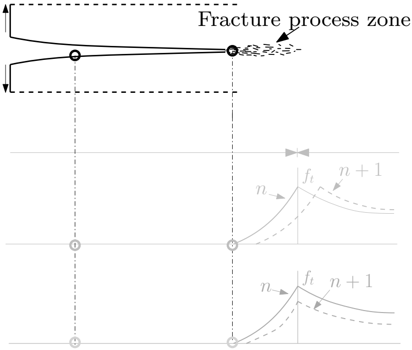
Model framework



In order to create a modelling framework that accounts for the material behaviour during arbitrary loading one need to link:

- The development of the fracture process zone (FPZ);
- the damage of the existing fracture process zone (FPZ), i.e. reduction of the bridging stresses;
- and the monotonic material characteristics

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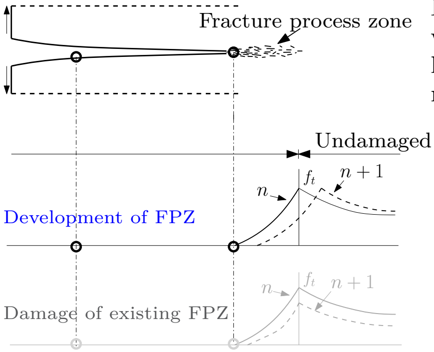

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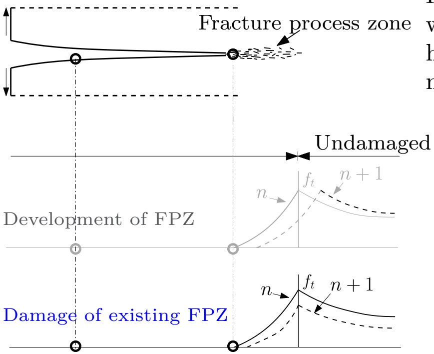

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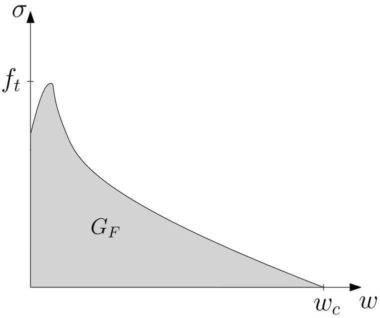

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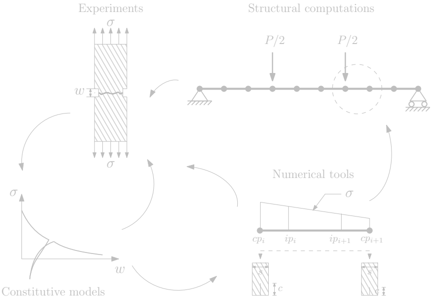
Multi-scale model

For this purpose the paper presents a multi-scale model. The model consists of three levels:

- (i) Fiber level: Develop a cyclic cohesive model considering a fiber of concrete material in uni-axial tension
- (ii) Hinge level: Incorporate the fiber response in a hinge model for description of bending fracture
- (iii) Beam level: For structural analysis, the hinge model is then applied as a constitutive model in a non-linear beam element



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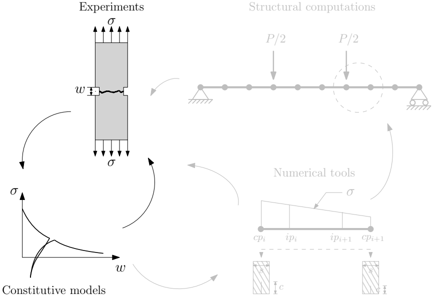

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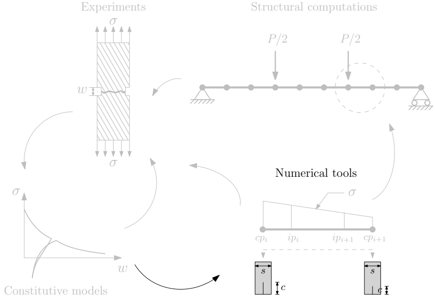

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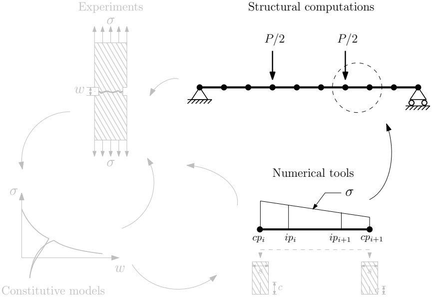
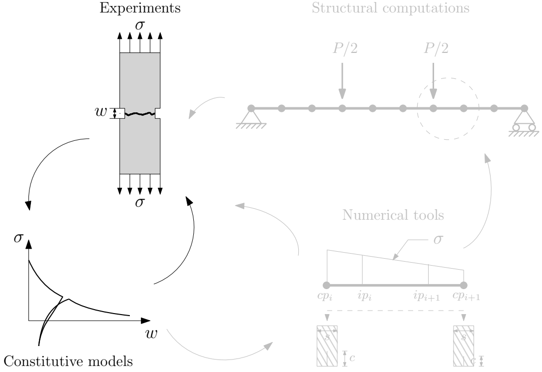
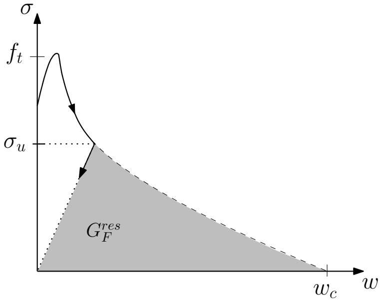


(i) Fiber level: Energy based cyclic cohesive model



Energy based fatigue model

- **Reduction of bridging stresses is controlled by deterioration of the fracture energy**
- Damage initiation is given by simple relations from geometrical interpretation
- Unloading- and reloading follow straight lines
- Modifications of the model possible, e.g. adjusting the unloading response
- The deterioration of the fracture energy is controlled by the work during fatigue loading, defined as the area below the curve
- A simple linear relationship is selected, where k_{fat} is used to scale the energy dissipated during fatigue loading as a fraction of accumulated work



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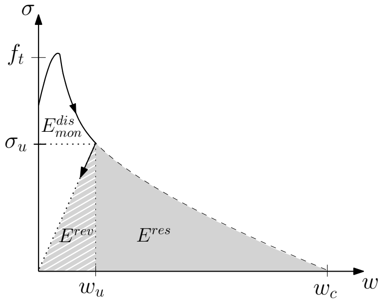

$$G^{res}_{F,i} = G_F - E^{dis}_{mon} = E^{rev} + E^{res}$$

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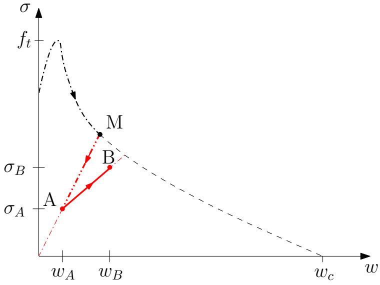

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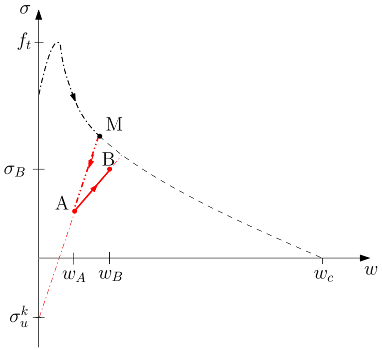

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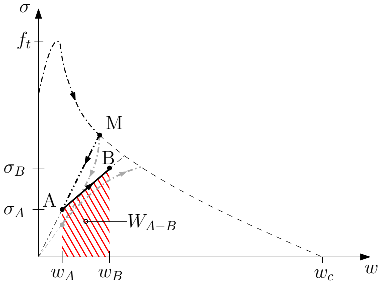

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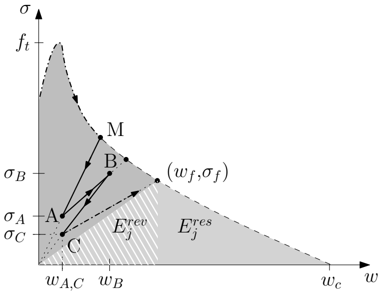

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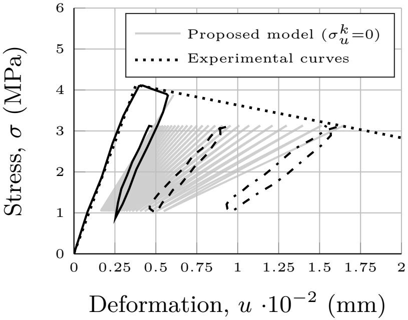
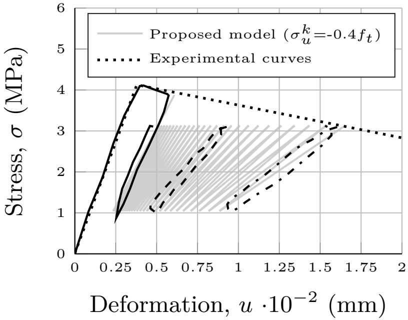
Numerical study of cracked concrete in uni-axial tension (Plizzari et al., 1997)





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- Realistic response with unloading towards σ_k^u (suitable for inverse analysis)
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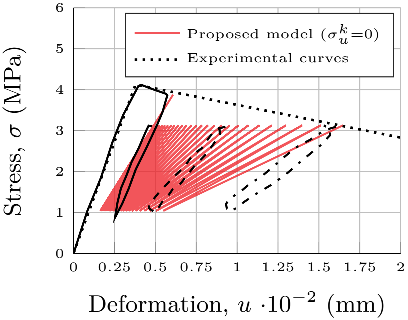

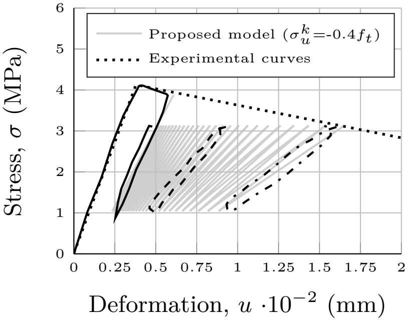

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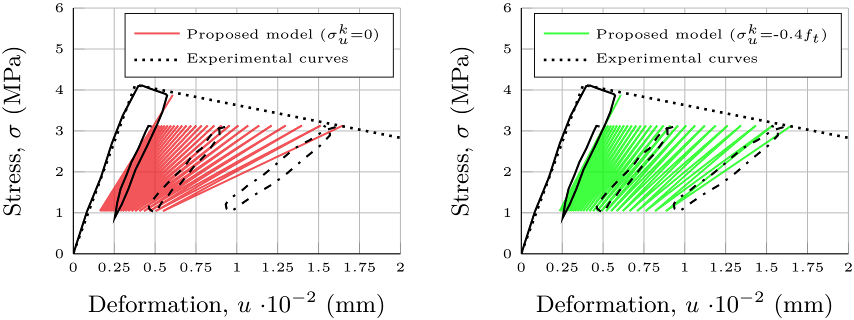

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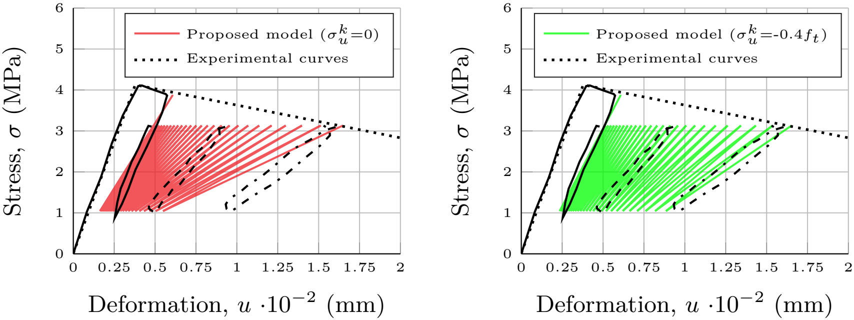

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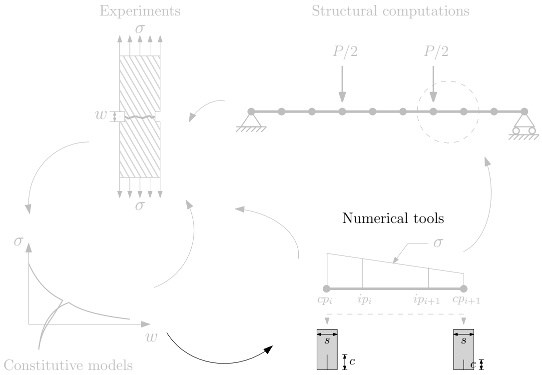
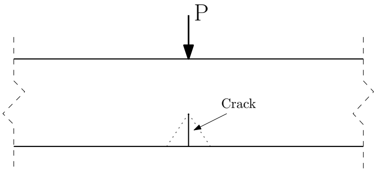
(ii) Hinge level: Hinge model for description of bending fracture



The hinge model - basic assumptions

- **A crack influence the stress and strain field of a structure locally**
- The discontinuity is expected to vanish outside a certain width, defined as the hinge width s
- Thus, the propagation of a crack can be modelled as a hinge, whereas the rest of the beam can be treated as elastic bulk material



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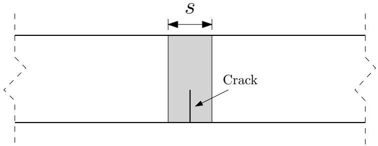

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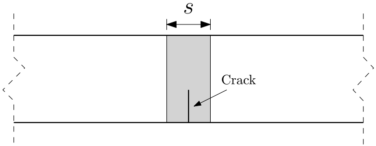
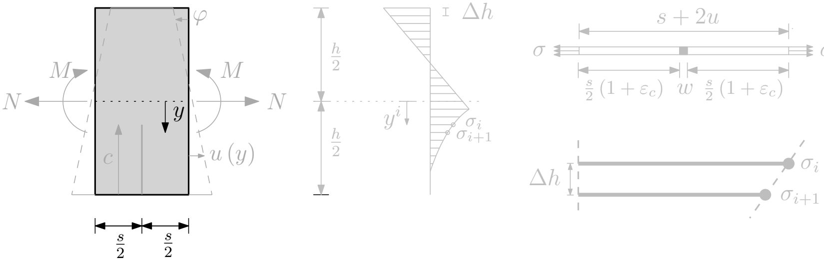


The hinge model - basic mechanics



- From the elongation of a fiber located at, y_i, and the softening response, $\sigma_i = b_i - a_i s$,
- the relevant stresses can be found for each fiber in the cracked phases
- The sectional forces can be found from integration over the hinge height, i.e. the sum of contributions from each strip

$$N(\bar{\varepsilon}_0, \bar{\kappa}) = t \int_{-h/2}^{h/2} \sigma_c \, \mathrm{d}y = \sum_{i=1}^{n} N_i \quad , \quad M(\bar{\varepsilon}_0, \bar{\kappa}) = t \int_{-h/2}^{h/2} \sigma_c y \, \mathrm{d}y = \sum_{i=1}^{n} M_i$$

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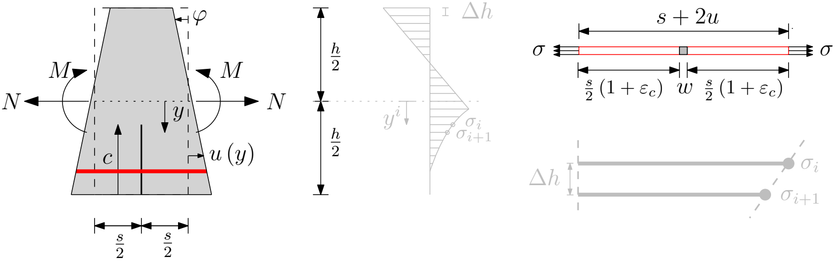

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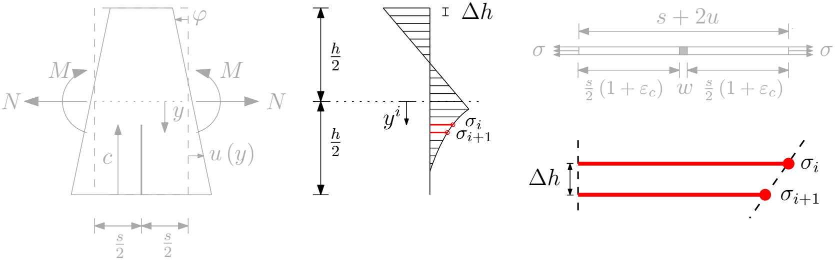

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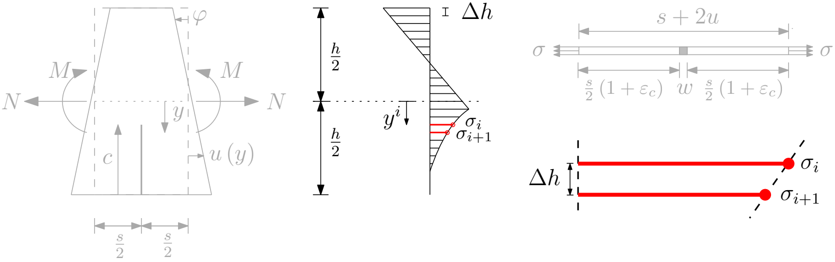

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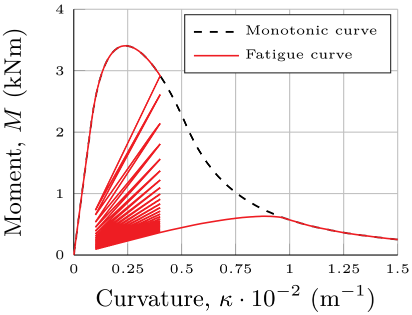
$$N(\bar{\varepsilon}_0, \bar{\kappa}) = t \int_{-h/2}^{h/2} \sigma_c \, \mathbf{d}y = \sum_{i=1}^{n} N_i \quad , \quad M(\bar{\varepsilon}_0, \bar{\kappa}) = t \int_{-h/2}^{h/2} \sigma_c y \, \mathbf{d}y = \sum_{i=1}^{n} M_i$$

Cyclic response of fiber-hinge

- **Considering a hinge subjected to constant curvature loading**
- Visualising the response of a fiber on the upper part of the hinge (green) and the bottom fiber (red)
- The bottom fiber enters fatigue after the first load step, as the lower part of the hinge deteriorate, new fibers in the upper part are activated
- The upper fiber is first in compression, then in linear elastic tension, before entering a short stage of low-cyclic damage and finally fatigue loading - the model accounts for all the cracked phases in a unified manner



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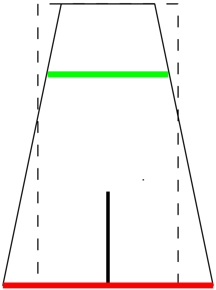

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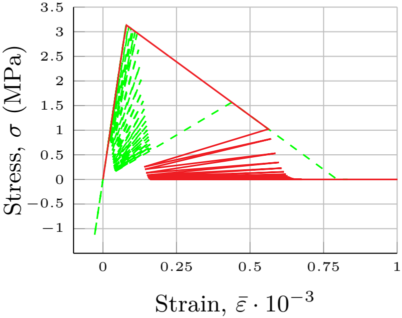

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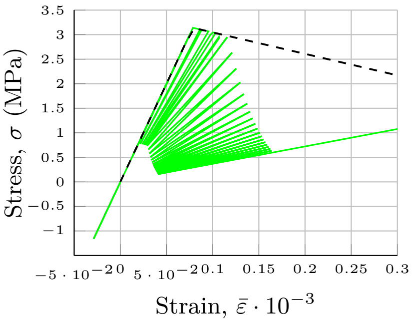
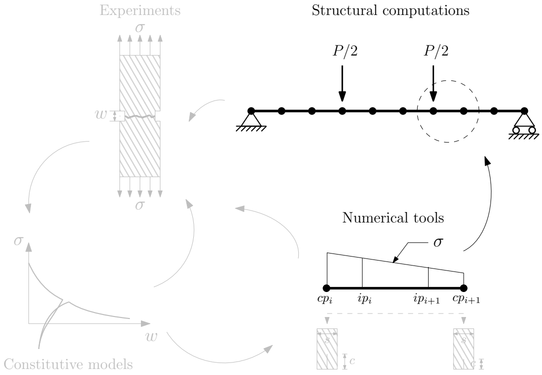
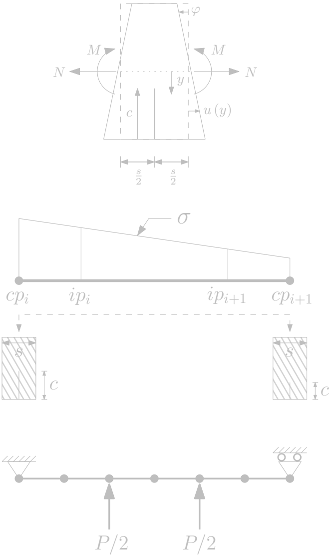


(iii) Beam level: Hinge as constitutive model in a non-linear beam element



Beam model

- **The proposed hinge is implemented in a user built finite element code applying a three node beam element**
- The underlying description of the hinge is based on the formation of discrete cracks
- However, when implemented into a beam element, the constitutive behaviour of the hinge is smeared (smooth)
- Making the model applicable for structural analysis, e.g. area outside the loaded points (where the moment distribution is no longer constant)



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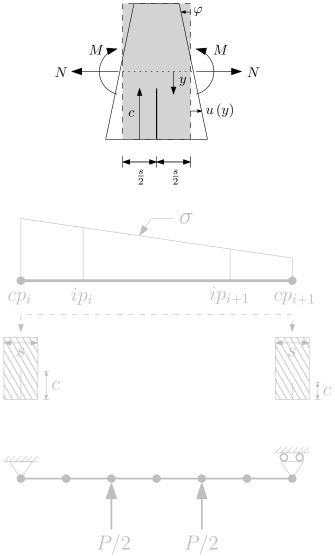

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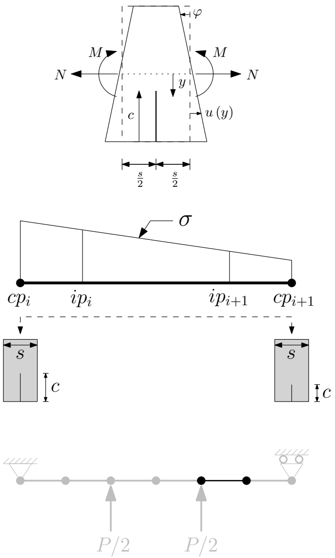

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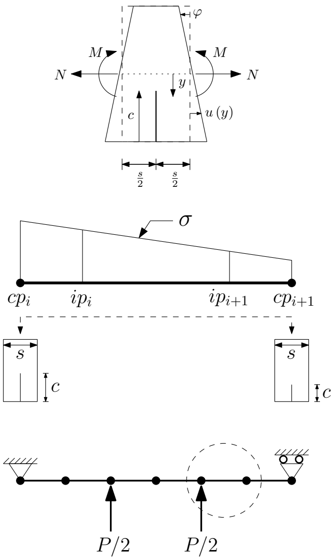
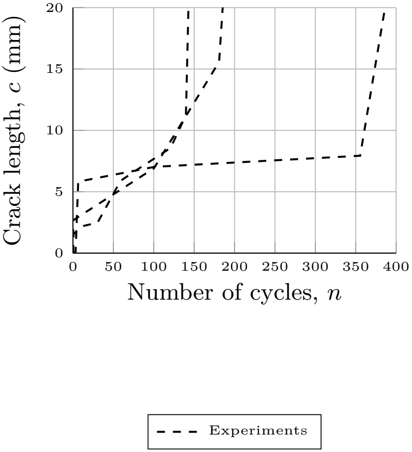


Numerical simulation of three point bending beams in fatigue (Toumi and Bascoul, 2002)



- Damage parameter k_{fat} calibrated to match the first experiment and then kept constant
- The model is able to capture the crack growth development and number of cycles to failure
- The initial crack length increase with increasing fatigue load
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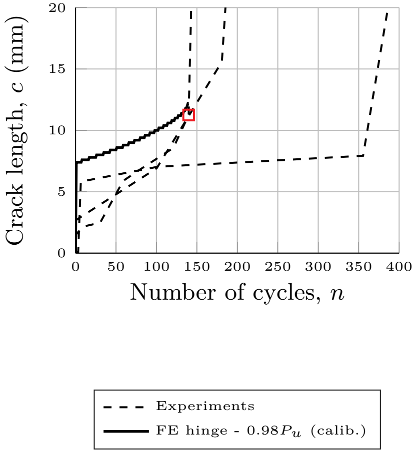

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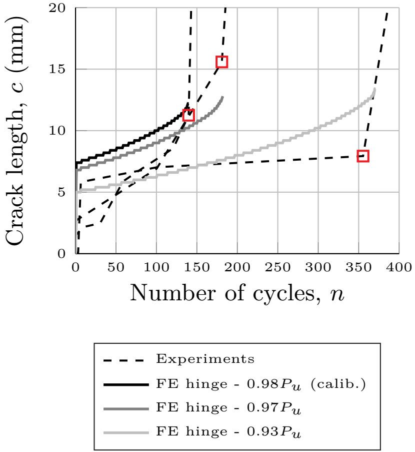

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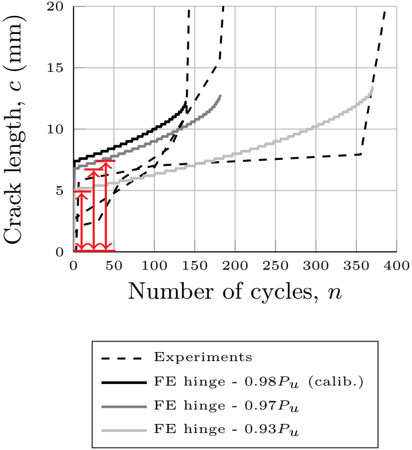

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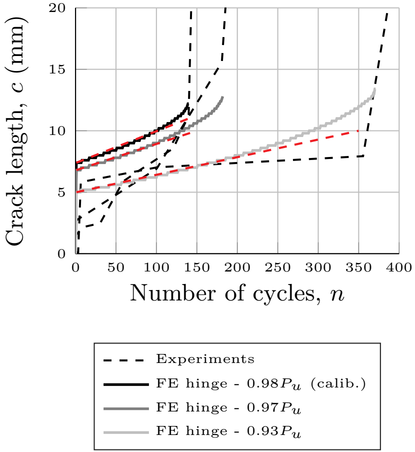

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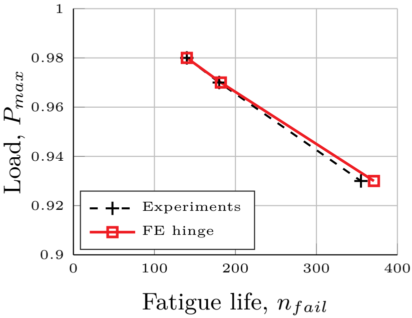

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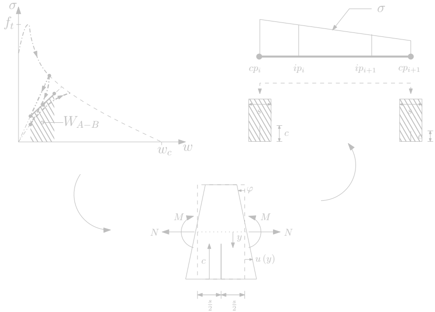

- (i) A general cyclic cohesive model was developed based on energy considerations
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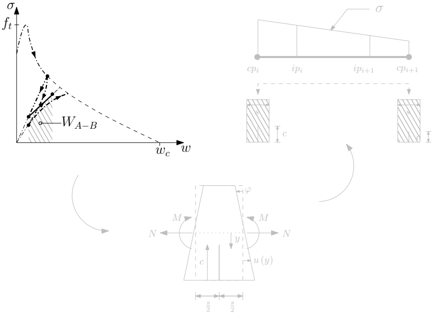

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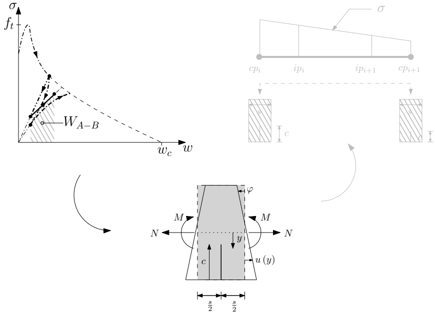

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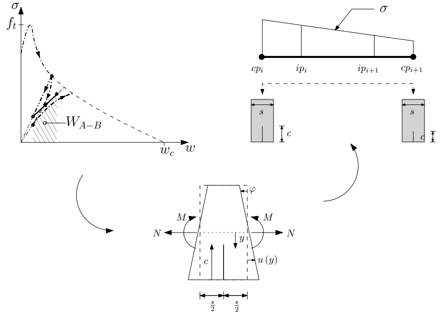

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