MODELLING OF CONCRETE DAMAGE

Radomír Pukl (1), Dobromil Pryl (1), Jan Červenka (1) and Drahomír Novák (2)

(1) Červenka Consulting, Prague, Czech Republic

(2) Brno University of Technology, Faculty of Civil Engineering, Brno, Czech Republic

Abstract

The paper deals with realistic modelling of concrete structures and material damage using nonlinear finite element method. Tensile and shear cracks or compressive crushing develop in concrete due to various reasons and can considerably influence resistance and durability of concrete structures. Numerical investigations have been carried out in order to analyze, predict and prevent concrete damage using nonlinear computer simulation based on advanced material models and finite element methods.

The numerical material models for concrete implemented in the nonlinear software ATENA are described. Various sources of damage such as volumetric loads due to concrete shrinkage or irregular temperature distribution, fatigue loading or material degradation can be assumed; relevant numerical procedures are developed and applied. In particular, tensile fatigue model is described more in detail.

Fatigue damage of concrete is an important problem in structures subjected to cyclic loading, like railway sleepers, anchoring regions of pre-tensioned bridges, or fundaments of wind power plants. Three-dimensional fracture-plastic model with fatigue extension has been used to simulate high-cycle fatigue of concrete specimens in three-point bending. Comparison of the analysis results to the experimental measurements is presented along with details of the simulation including the material model extension.

1. INTRODUCTION

The nonlinear finite element simulation is recently a well-established approach for analysis of reinforced concrete structures. Behaviour of the structure under service as well as ultimate conditions can be virtually simulated using computer methods quite realistically. Nonlinear fracture analysis accounting tensile capacity of material enables to exploit reserves, which are usually neglected or diminished in codes or in linear analysis. Numerical simulations have been recently included in the FIB New Model Code 2010 [1] where the appropriate safety formats are proposed for this purpose. This concept can be applied in design practise and can offer advanced and rational solutions to modern structural technologies [2], [3].

The nonlinear modelling of structural behaviour and damage under severe conditions is based on nonlinear fracture mechanics simulation of concrete which utilizes state of art techniques including: damage mechanics, fracture mechanics and plasticity material models, smeared crack approach - fictitious crack, crack band method, softening of concrete in both tension and compression, combination of nonlinear concrete response with discrete and smeared reinforcement in reinforced concrete or pre-stressed concrete structures.

2. NONLINEAR FINITE ELEMENT ANALYSIS

An algorithm for nonlinear analysis is based on three basic parts, see [2]: Finite element technique, constitutive model, and non-linear solution methods, which should compose a balanced approximation (Figure 1). Nevertheless, the constitutive models decide about the material behaviour and damage. Since concrete is a complex material with strongly nonlinear response, special constitutive models for the finite element analysis of concrete structures are employed.

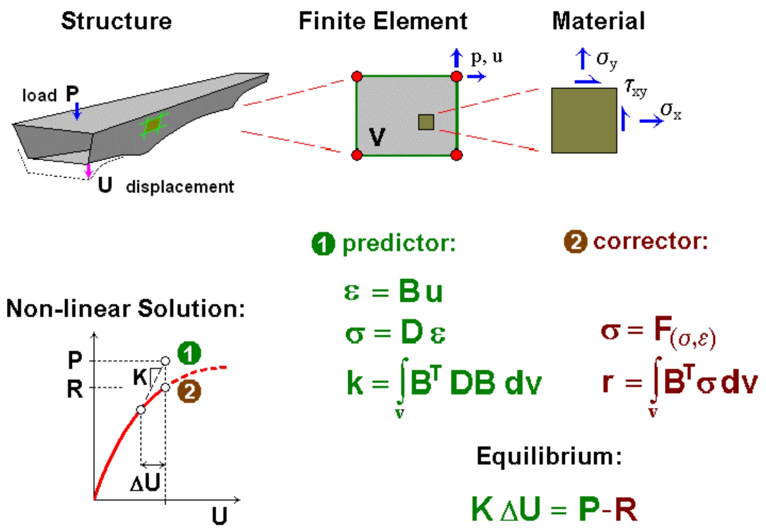


Figure 1: Scheme of the nonlinear finite element method

The finite element software ATENA is a proven tool for realistic computer simulation of damage and failure of concrete and reinforced concrete structures [4], [5], [6], [7]. In order to extend potential and features of the existing ATENA Engineering program, the recent development combines the calculating core with a new runtime environment (ATENA Studio) and a powerful third-party program GiD for pre- and post-processing. The resulting product ATENA Science covers broad range of structural and material behaviour in time and severe environmental conditions. It enables also to model geometrically complicated shapes and it is suitable for analysis of complex structural problems, such as:

- dynamic implicit analysis
- dynamic eigenvalue analysis
- static stress analysis
- fatigue analysis
- creep analysis
- transport of heat and fluids
- fire analysis.

3. NONLINEAR MATERIAL MODELS

For the computer simulation of reinforced concrete structures variety of nonlinear material models for concrete, quasi-brittle materials, soils and metals are available within the ATENA software:

- damage-based material model
- fracture-plastic cementitious material
- microplane material model
- Drucker-Prager plasticity model
- Von Mises plasticity model
- plasticity with hardening for reinforcement

etc.

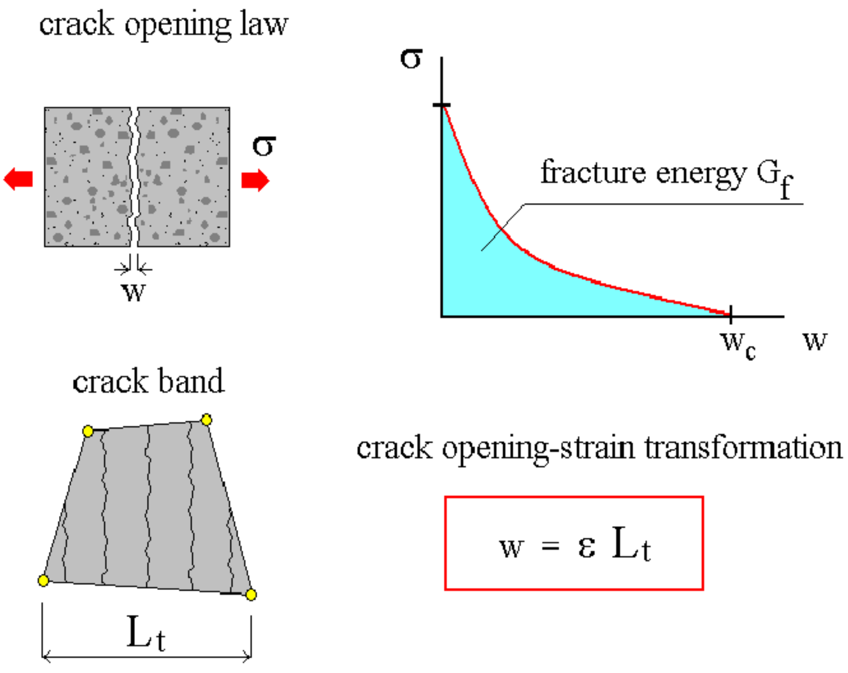


Figure 2: Smeared crack model for tensile behavior of concrete

Tensile behaviour of concrete is modelled by nonlinear fracture mechanics combined with the crack band method [8] and smeared crack concept (Figure 2). Main material parameters are tensile strength, fracture energy and shape of the stress-crack opening curve. For the normal concrete an exponential crack opening law derived by Hordijk [9] is applied.

A real discrete crack is simulated by band of localized strains (Figure 3). The crack strain is related to the element size. Consequently, the softening law in terms of strains for the smeared model is calculated for each element individually, while the crack-opening law is preserved. This model is objective due to the energy formulation and its dependency on the finite element mesh size is neglectable [10].

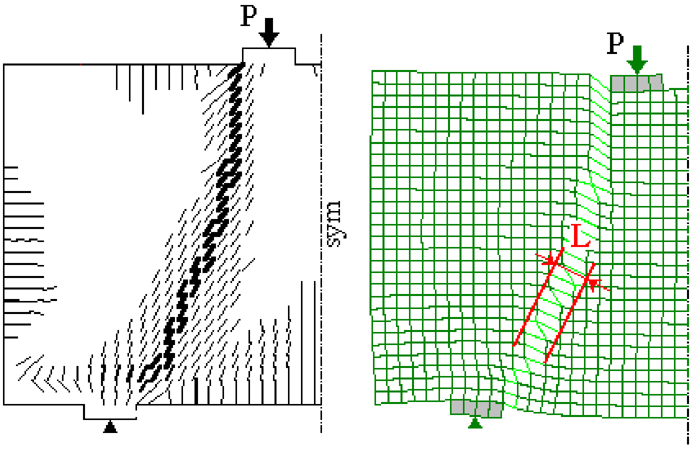


Figure 3: Cracks band with strain localization

The compressive behaviour of concrete is covered by special theory of plasticity proposed by Menétrey and Willam [11] (Figure 4) with a non-associated flow rule. This model describes well specific phenomena in concrete in compression, namely volume change after crushing or influence of the lateral stresses to the compressive strength, so called confinement effect.

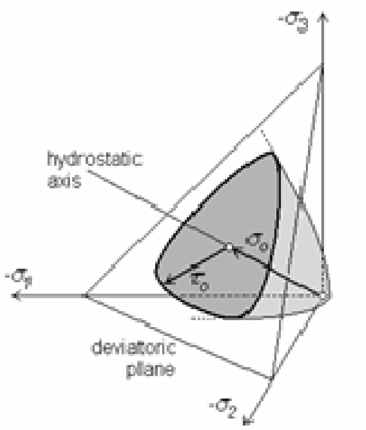


Figure 4: Plasticity function for concrete under compression in the fracture-plastic cementitious material model

An advanced three-dimensional material model combining fracture and plastic behaviour and damage of the cementitious (quasi-brittle) type of materials like concrete has been proposed by Červenka and Papanikolaou [12] and implemented into ATENA software.

4. MATERIAL MODEL FOR FATIGUE OF CONCRETE IN TENSION

Fatigue damage of concrete is an important phenomenon in structures subjected to cyclic loading. At the same time, there are not many high-cycle fatigue models available for use in conjunction with advanced concrete material models and nonlinear finite element analysis. The available models that are published in the literature, for instance [9], usually deal with the low-cycle fatigue when it is necessary to perform the numerical nonlinear analysis for all investigated cycles. This approach is definitely not applicable when it comes to high-cycle fatigue when it is usually necessary to consider millions of cycles. The available models, for instance [13], developed for high-cycle fatigue are based on linear elastic fracture mechanics considerations and they are not readily applicable to the finite element analysis using the smeared crack approach.

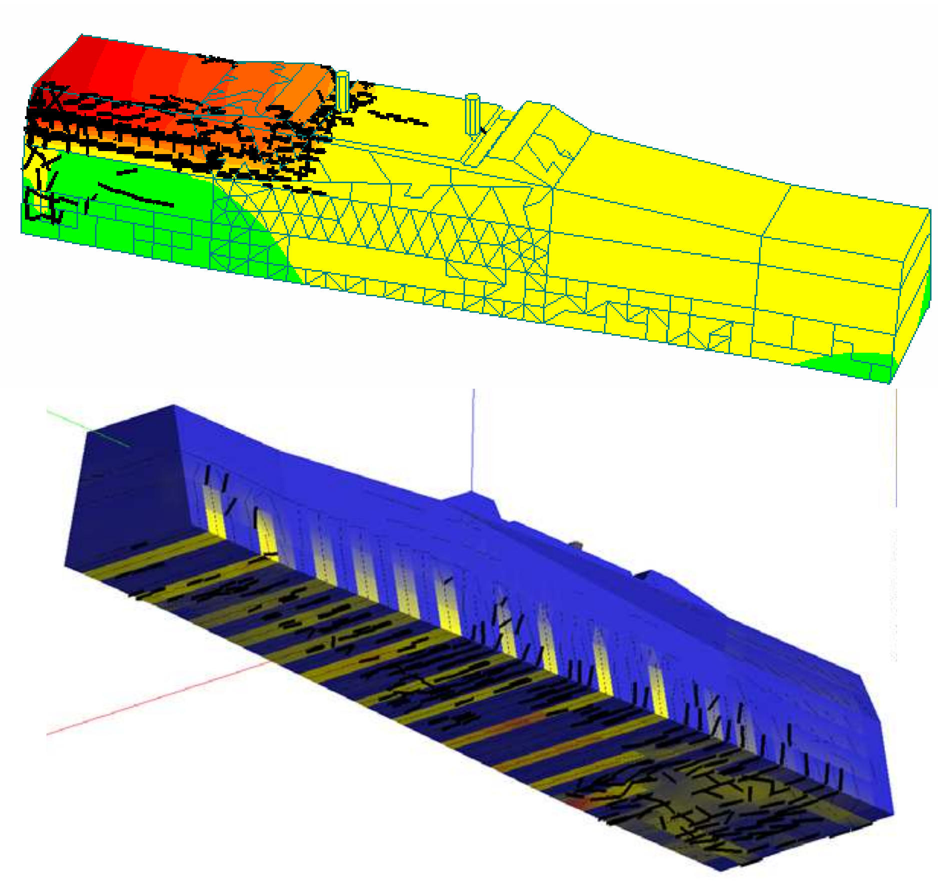


Figure 5: Results from numerical modelling of fatigue cracks on railway sleepers

Typical application of modelling fatigue damage can be cracking of railroad sleepers, as presented in Figure 5. Results from ATENA analysis of consequences of excessive fatigue load (traffic and temperature) are shown.

There are namely various cycling loads acting to the sleepers with various types, frequency and count:

- traffic loads
    - fast trains
    - slow and heavy trains
    - axle distances
- weather loads
    - daily temperature cycles
    - fast cooling (sun followed by rain)
    - frost cycles
    - debris falling into the developing cracks

Such actions on the structure should be appropriately taken into account in its numerical simulation. The presented model for fatigue crack initiation and development within the framework of the finite element smeared crack analysis has been initially developed for fatigue life predictions of pre-stressed railway concrete sleepers. It concentrates mainly on modelling fatigue behaviour of concrete under tensile load.

4.1 Fatigue Damage Calculation

Fatigue damage can be physically interpreted as a gradual growth of micro-cracks due to the repeated loading. In the fracture-plastic material model [12] the crack growth is controlled by the internal parameter ε^{f}_{max}, which represents the maximal fracturing strain reached during the cracking process at each crack. This parameter is used to determine the current tensile strength at each material point using the crack band size L_t and the tensile softening law $f_t(w)$ as depicted in Figure 6.

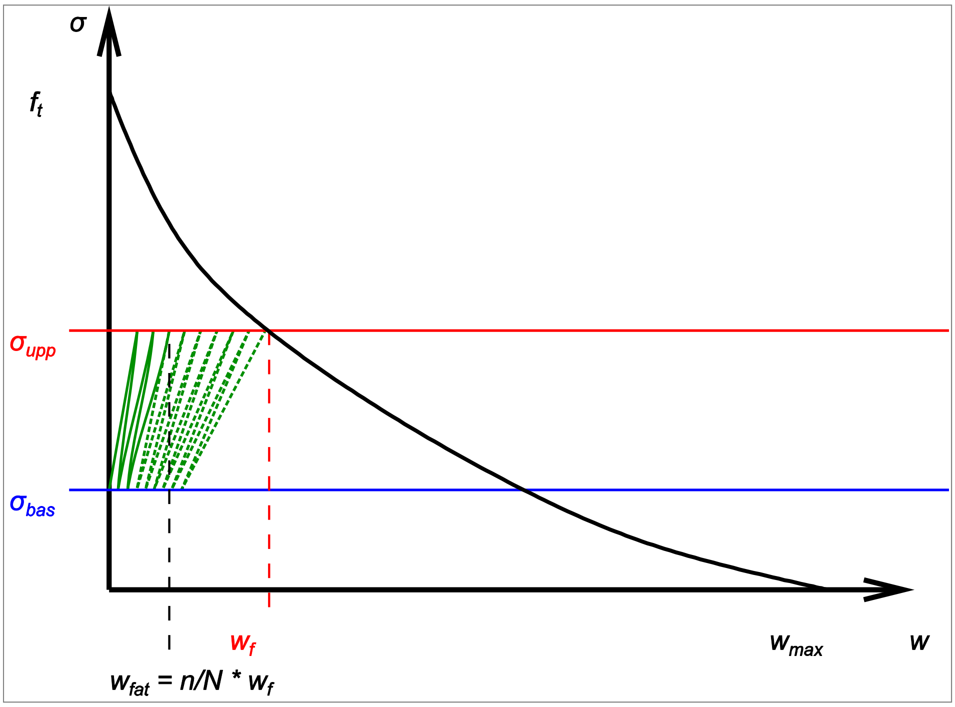


Figure 6: Softening law vs. crack opening displacement and fatigue damage

This means that the current tensile strength is determined using the tensile softening law as:

$$\sigma_t = f_t(w_{\max}),\ w_{\max} = \varepsilon^f_{\max} L_t, \tag{1}$$

where σ_t represents the current tensile strength, w_{max} is the maximal crack opening reached during the loading process and L_t is the crack band size, which is based on the finite element size.. In the proposed model, the fatigue damage is modelled by increasing the fracturing strain ε^f_{max} by two fatigue contributions. A contribution based on cyclic stress controlled by the additional material parameter β_{fat}, and the contribution from crack opening and closing in each cycle, controlled by the material parameter ξ_{fat}. The former is dominant before cracking occurs and controls crack initiation in originally undamaged material. The latter is dominant in already cracked material and controls growth of existing cracks. This means that the maximal fracturing strain is composed of the following contributions:

$$\varepsilon^f_{\max} = \varepsilon^s_{\max} + \varepsilon^\sigma_{fat} + \varepsilon^w_{fat} \tag{2}$$

where ε^s_{max} is the maximum fracturing strain from static loading, ε^σ_{fat} is the additional fracturing strain from fatigue due to cyclic stress and ε^w_{fat} is the additional fracturing strain from the cyclic crack opening.

It has to be emphasized that both the damage calculation and introduction proceed independently for each material point, i.e., unlike the traditional *S–N* usage when the criteria are evaluated globally, typically for the suspected weakest point.

4.2 Stress Based Contribution

The contribution from the cyclic tensile stresses is determined using a stress based model, that is employing the *S–N* (Wöhler) curve:

$$\frac{\sigma_{upp}}{f^t} = 1 - \beta_{fat}(1-R)\log N,\quad N = 10^{\left(\frac{1-\frac{\sigma_{upp}}{f^t}}{\beta_{fat}(1-R)}\right)}, \tag{3}$$

where σ_{upp} stands for the maximum tensile stress and f_t for the tensile strength, $R = \sigma_{bas}/\sigma_{upp}$ is the coefficient of cycle asymmetry. Then, the contribution to the maximum fracturing strain ε^f_{max} in each principal direction is adjusted by adding

$$\varepsilon^\sigma_{fat} = \frac{w^\sigma_{fat}}{L_t}, \tag{4}$$

where $w^\sigma_{fat} = n/N\, w_f$

and the failing crack opening displacement for the given stress $w_f = f_t^{-1}(\sigma_{upp})$ (see Figure 6).

4.3 Crack Opening Based Contribution

The damage due to cracks that open and close during the load cycles is determined as

$$\varepsilon^w_{fat} = \frac{w^w_{fat}}{L_t}, \tag{5}$$

where $w^w_{fat} = n\, \xi_{fat}\, \Delta w$, and Δw denotes the difference between the maximum and minimum crack opening during a cycle. The material parameter ξ_{fat} scales the damage contribution from cyclic crack opening and closing. The resulting ε^w_{fat} is added to the maximal fracturing strain ε^f_{max} before the fatigue damage is introduced into the material.

Details on the material model, including some notes about damage introduction and stress redistribution, can be found in [14].

5 HIGH-CYCLE THREE POINT BENDING EXPERIMENTS

5.1 Experiments

Two sets of specimens were tested in Brno made of C30/37 and C45/55 class concrete [15]. In both cases, the specimen dimensions were 400 mm (length) × 100 mm (height) × 100 mm (depth), supports distance 300 mm, notch depth 10 mm, Figure 7.

A few specimens from each set were loaded monotonically until failure to determine the basic material properties. All the remaining ones were subjected to cyclic force loads of various levels with cycle asymmetry R = 0.1. They were loaded until failure or 2 millions cycles (run-out), whichever occurs first.

More details on the experiments can be found in [16]. For all experimental data, the correction procedure for basic fatigue parameters with respect to specimen age has been applied [17]. This effectively standardizes all samples to 28 days of age.

Figure 7: Setup of experiments

5.2 Analysis

Measured Load-Displacement curves from static (unidirectional) experiments were used to adjust the appropriate parameters of the concrete material model. Numerical model of the tested specimen with the finite mesh is shown in Figure 8. The measured static response of three tested specimens along with the static analysis results are presented in Figure 9 as an example.

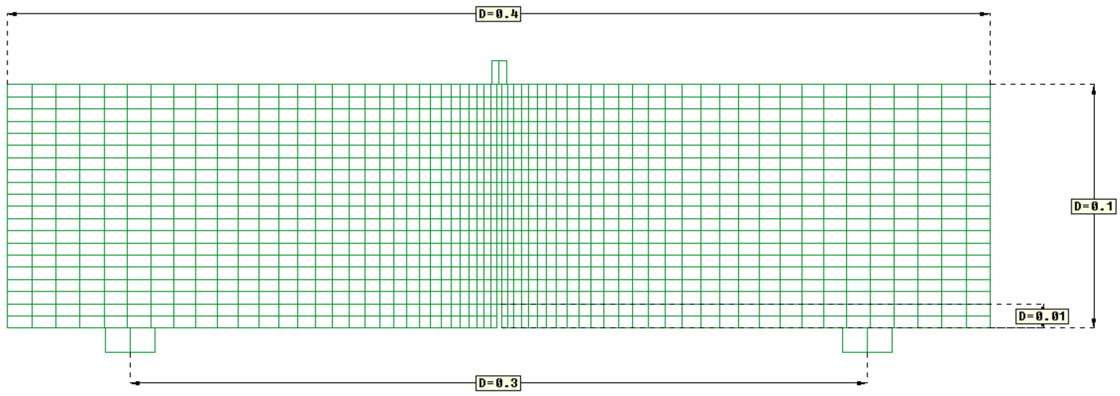


Figure 8: Numerical model of the tested and analyzed specimen.
Geometry, dimensions [m] and finite element mesh

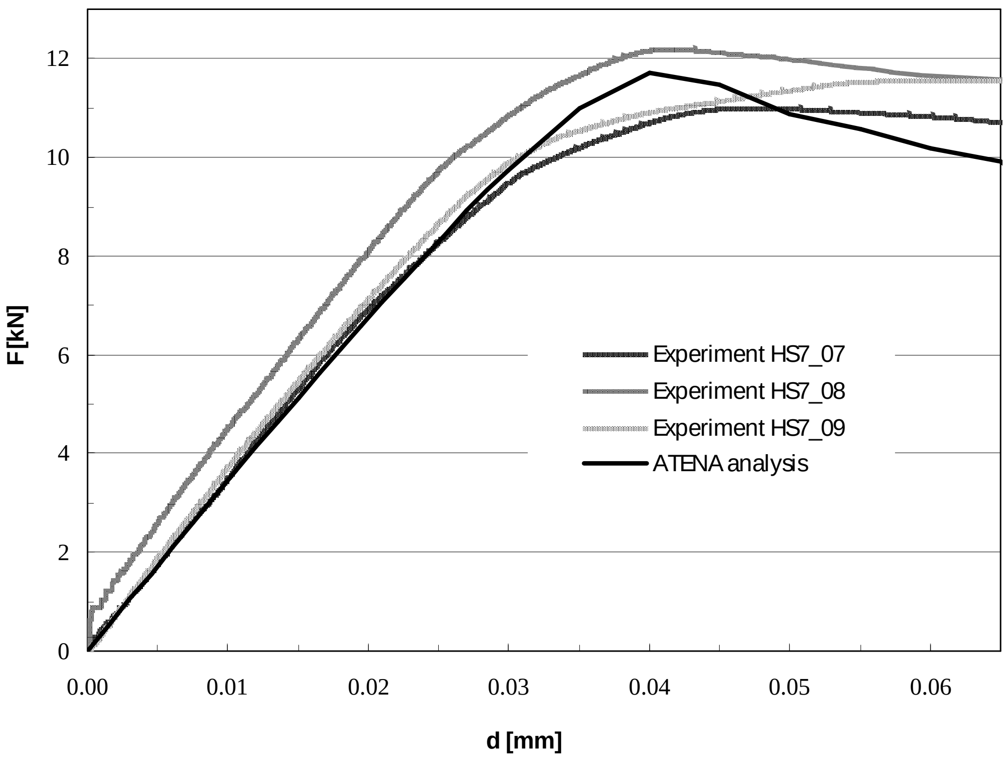


Figure 9: Static Load-Displacement graph of class C45/55

The cyclic load was applied the following way in the finite element model:

I. loading up to the base load level (2 analysis steps)
II. storing the base stress and crack fields

III. increasing the load to the upper level (18 analysis steps)

IV. calculating the fatigue damage due to 10 cycles based on the difference between the stored and current stress and crack fields

V. introducing the damage into the material (10 analysis steps). The damage results in a displacement increase.

VI. repeating steps 4 and 5 for increasing cycle counts until the model fails or 2 million total cycles are reached. The 2 millions cycles were divided into 37 sets of increasing size (10, 10, 20, 30, 50, ..., 250 000, 300 000, 400 000, 400 000). In total, there were 380 analysis steps.

VII. determining the number of cycles survived from the number of the last converged analysis step

5.3 Results

Numerical results - namely the crack pattern - represented very well the experimentally obtained response of the tested beams to the specified fatigue loading, see Figure 10.

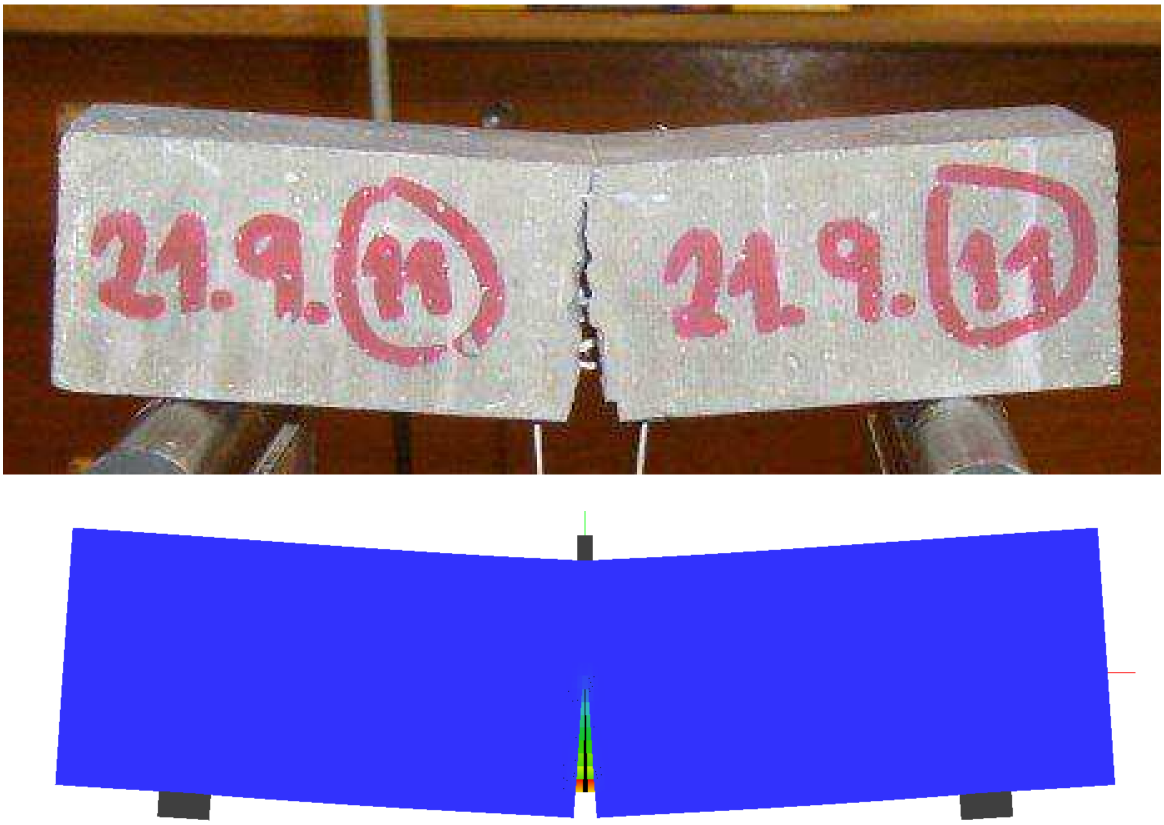


Figure 10: Comparison of experimentally obtained and calculated crack pattern

The analysis was conducted for several combinations of β_{fat} and ξ_{fat}. The best matching parameter sets were β_{fat} = 0.08 and ξ_{fat} = 0 for class 30/37 and β_{fat} = 0.11 and ξ_{fat} = 0 for class 45/55 concrete [18]. These results are presented in Figures 10 and 11 for class 30/37 and 45/55 concretes, respectively. The samples that did not fail in tests before reaching 2 000 000 cycles ("run-out") are marked by empty triangles. The comparison shows that the numerical model very well captures the mean values of the cycles to failure, observed in the experiment.

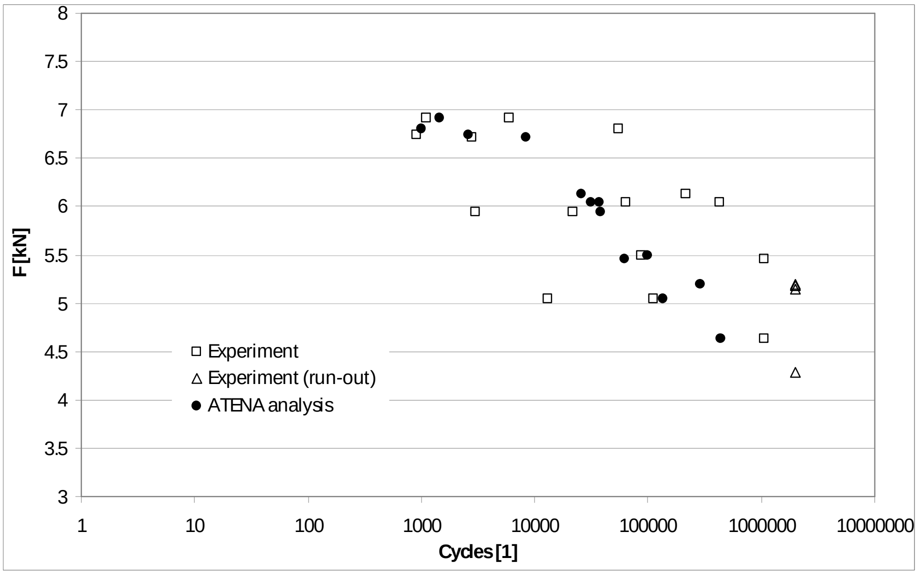


Figure 11: Comparison of measured and calculated results for C30/37 class concrete

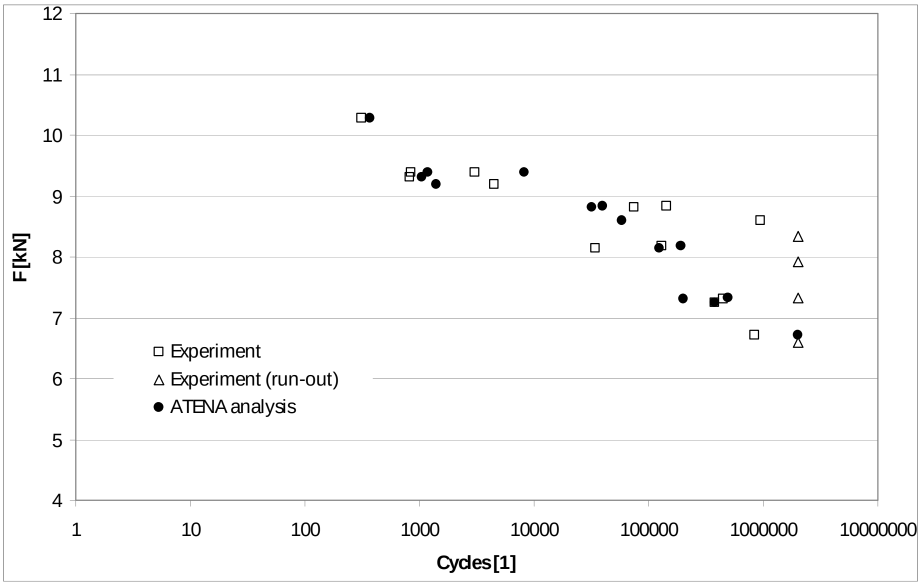
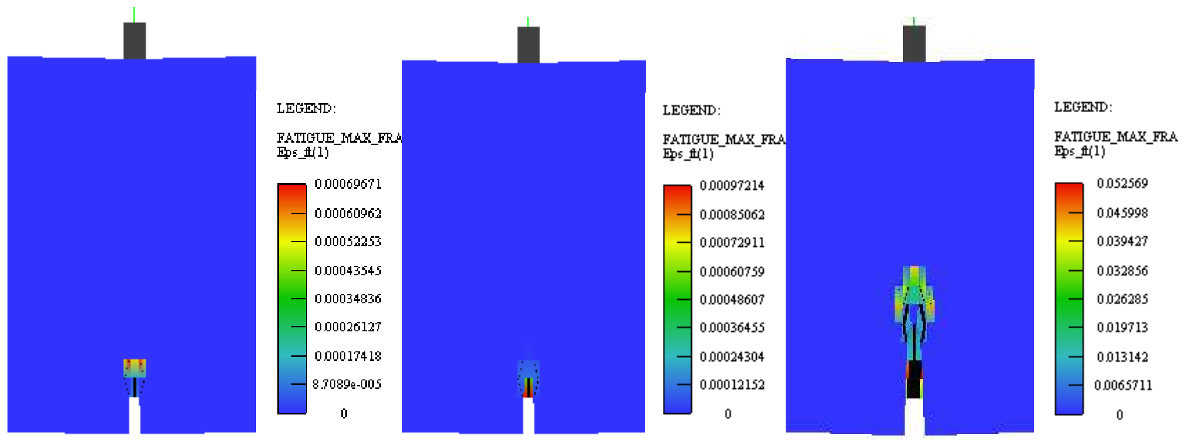


Figure 12: Comparison of measured and calculated results for C45/55 class concrete

Crack development in the middle of the numerical model of the tested specimen achieved during the fatigue loading for selected case (load level of 7 kN) is documented in Figure 13. The cracks are shown after (a) 100 (b) 1 000 (c) 10 000 cycles, and the damage increment on the scale is given for cycles (a) from 100 to 200 (b) from 1 000 to 2 000 (c) from 10 000 to 20 000. The deformation scale is 200.



(a) (b) (c)

Figure 13: Fatigue crack development for the load level of 7 kN

5.4 Notes on Stress and Crack Redistribution

In the numerical analysis, no unloading was modelled. As a consequence, redistribution was only considered for the upper (maximum) load level, while the base level stresses and cracks were assumed constant from the first cycle and used for all cycles. This gives additional damage for cracked areas even without using the crack opening-closing criteria ($\xi_{fat} = 0$), because the stress difference between the original 10% load and the stress after cracking is considered when calculating the fatigue damage (in step IV), and the stresses on cracks are typically significantly lower than at the 10% load.

This redistribution simplification in the analysis can explain the fact that some samples with higher applied load survive more cycles than other samples under lower load.

6 CONCLUSIONS

Tensile and shear cracks and compressive crushing, or combination of them, possibly even in the same region, and interacting with each other, can occur in concrete due to severe conditions, and can considerably influence reliability, resistance and durability of concrete structures.

Realistic numerical material models for concrete implemented in the nonlinear software ATENA are presented. In particular, new material model for fatigue damage of concrete under tension has been developed as an extension of an existing three-dimensional fracture-plastic material model and implemented into the finite element software code. Two fatigue contributions are considered: 1. crack initiation as a result of cyclic stress and 2. development of existing cracks based on crack opening and closing during the cycles. The damage is introduced into the material in form of maximum reached fracturing strain.

This model has been used to simulate high-cycle fatigue tests on notched three-point bending specimens. The numerical results exhibit an excellent agreement with the experimentally obtained response and measured data for both concrete classes tested.

ACKNOWLEDGEMENTS

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