Summary

Concrete is a quasi-brittle material. In deformation-controlled uniaxial tests of concrete prisms, one observes a gradual softening after reaching the maximum load, see Fig. 1.1 c. The reason of this is the heterogeneity of concrete. In contrast to linear elastic fracture mechanics (LEFM), the tensile fracture of concrete is not combined with a discrete crack but with a fracture process zone (FPZ), a densely microcracked volume. The aim of this thesis is the assessment of concrete's fracture behaviour and the size of the FPZ because of its major importance for material modeling. The width of the FPZ was quoted by [4, 52] to be 2–3 times the maximum aggregate size. However, the experimental evidence of this estimation is still lacking.

Several measurement techniques have been applied in the last decades to determine strain distributions within the FPZ. Most of them are integrating methods leading to smeared results. Due to this smoothing, discontinuities and high strain gradients cannot be visualized. A relationship between the volume of the FPZ and experimental parameters such as the degree of hydration, the maximum aggregate size, the concrete strength, the crack opening velocity etc. does not exist.

In this thesis, the post-peak behaviour of plain concrete is analyzed by means of the high sensitive Speckle Interferometry for the purpose of FPZ-Size evaluation. Displacement fields on the sample's surface are related to strain distributions allowing extraction of the FPZ-width in iso-strain fields.

In chapter 2, the fundamentals of fracture mechanics are presented. Fracture mechanics according to Griffith [31] is a method of characterizing failure and cracking of materials. At the beginning of the century, Griffith develops a formulation between the critical stress and the crack length in glass. The basic of that crack theory is the assumption of a smooth plane crack in a linear elastic material. Energetic considerations are made for the infinite size plate with a center crack subjected to tension as depicted in Fig. 2.1 c. This considerations lead to LEFM. Kaplan [60] attempts in his pioneer work to apply LEFM to concrete. He shows, that linear elastic assumptions are not sufficient to analyze concrete's fracture behaviour under tension appropriately. The three-dimensional extension of the plastic zone of concrete cannot be neglected. Energy dissipation due to plastic fracturing is localized. Non-linear reflections regarding concrete fracture behaviour are given in subsection 2.3. Microcrack development and crack growth are first subject of that subsection. The Fictitious-Crack-Model (FCM) after Hillerborg et al. [45], the Crack-Band-Model (CBM) after BAZANT & OH [4], the Two-Parameter-Model (TPM) after JENQ & SHAH [55] and the Size-Effect-Law (SEL) after BAZANT [5] are then described, see Fig. 2.8 to 2.11. For more informations
regarding non-linear behaviour of concrete, see e.g. [8, 75, 109, 118, 123].

In order to gain an insight into the FPZ-area, extensive investigations have been conducted. Section 2.5 reports about direct and indirect investigation methods. Some experimental results for the FPZ obtained using scanning electron microscope, acoustic emission, dye penetration, compliance technique and whole-field measurement techniques such as Moiré, holographic interferometry, speckle photography as well as electronic speckle interferometry are briefly outlined. The state of knowledge regarding the extension of the FPZ is briefly dealt with.

Chapter 3 deals with the experimental set-up used in this thesis. The tests were conducted on single-edge-notched concrete beams subjected to flexural load and on double-edge-notched prisms under uniaxial tensile stress in a 500 kN closed loop universal testing machine as depicted in Fig. 3.2. Thereby, stable crack growth is ensured by means of crack mouth opening displacement (CMOD) control using LVDTs placed across the notches, see Fig. 3.3. The dimensions of specimens depicted in Fig. 3.1 are shown in tab. 3.2 (tensile prisms) resp. tab. 3.3 (bending beams). The concrete mixes (tab. 3.1) had a strength of 35 MPa with a maximum aggregate size of 4, 8 and 16 mm and were examined after 2d, 7d and 28d. Besides these three mixtures, a high performance mix with silica fume and a fiber reinforced concrete were investigated. The degree of hydration of each mix was determined on the basis of the hydration heat release measured in an adiabatic calorimeter (Annex A.3).

Besides conventional measurement techniques using LVDTs, in-plane speckle interferometry was applied. Due to surface irregularities, the illumination of an optically rough surface with a coherent laser light leads to an interference pattern of the back-scattered light. The object surface seems to have a granular intensity (speckle effect). A metrology application of these speckles is realized by superposing the wave fields of two light beams with same incident angle on the object surface according to Fig. 3.6. The resulting pattern leads to a speckle field related to the displacement state of the specimen. Subtracting such a speckle field from a previous one according to a reference leads to a correlation fringe pattern (see Fig. 3.10 a) in which each fringe corresponds to an iso-displacement line. The noisy pattern which contains a displacement and even a deformation information has to be smoothed to improve fringe visibility as depicted in Fig. 3.10 b. The smoothing algorithms have to conserve phase jumps due to different fringe orders. The main direction in which the optical set-up is sensitive is chosen perpendicular to the notches.

Experimental results are shown in chapter 4. First, results regarding single-edge-notched tensile specimen are presented. Stress-strain-lines under tension are shown for the different mixes and the different specimen sizes studied. The influence of specimen's age, the
maximum aggregate size, the design strength and the specimen size on the ascending and on the post-peak branch of the stress-strain-line is investigated, see e.g. figs. 4.1, 4.3 and 4.7. The tensile strength $f_{ct}$, the Young's modulus of elasticity $E_{ct}$, the ultimate strain $\varepsilon_{cu}$, the fracture energy $G_F$ and the characteristic length are extracted from stress-strain-line. Their analysis regarding the influence of the experimental parameters is presented in subsection 4.2.2 to 4.2.6.

In addition, the FPZ is investigated in section 4.2.7. First, the exemplary development of the fracture process for specimen K0207D.3 is visualized in figs. 4.19 and 4.20. The load, the fracture energy and the measured width of the FPZ $l_{pr}$ are depicted vs. CMOD for each loading step. For a few of them, in-plane correlation patterns are also shown describing crack development. The fringe patterns are related to the post-peak response of the material. The reference for the assessment of $l_{pr}$ is the peak load. Then, the development of $l_{pr}$ vs. CMOD is shown in Fig. 4.21 at an age of 28 d. The FPZ-width increases with increasing CMOD. After reaching a peak $l_{pr,max}$, the curves are slightly decreasing with increasing cracking. The FPZ may be understood as the concrete volume, in which energy dissipation occurs. With increasing crack opening, the energy dissipation rate decreases, as depicted by the slope of $G_F$ vs. CMOD in Fig. 4.19. This seems to be the explanation for that behaviour. In the next steps, the influence of hydration, of the maximum aggregate size, of the design strength and of the specimen size is investigated and depicted in figs. 4.22, 4.23, 4.25 and 4.26. The maximum FPZ-width $l_{pr,max}$ is identified as a representative volume unit, in which concrete behaves non-linearly. Figs. 4.24 and 4.27 are showing the influence of the experimental parameters mentioned above on $l_{pr,max}$.

Section 4.3 deals with the experimental results of the three-point-bending specimen. According to the results achieved with the single-edge-notched tensile specimen, stress-displacement curves are analyzed with respect to the experimental parameters investigated (section 4.3.1). The influence of the experimental parameters on the flexural tensile strength $f_{ct,ft}$, on the ultimate flexural strain $\varepsilon_{cu,ft}$, on the fracture energy $G_F$ and on the fracture toughness $K_{lc}$ deduced from the stress-displacement-line is investigated, see section 4.3.2 to 4.3.5.

The extension of the FPZ is investigated in section 4.3.6. As in section 4.2.7, the fracture process of a specific notched beam is elucidated by the fringe patterns for several loading steps (Fig. 4.47). The development of $l_{pr}$ for several concretes is then depicted in Fig. 4.48. It shows an analog behaviour to the curves of the double-edge-notched specimen regarding $l_{pr}$ vs. CMOD. One observes, that the absolute value of the width of the FPZ and the slopes of the curves are different for both types of mode I experiments. In the case of flexion, the width $l_{pr}$ is about two to four times larger — depending on
the concrete — than that of uniaxial tension. The difference between the crack band in flexural tests and in uniaxial tests may be caused by deformation gradients. The deformation gradients along which energy dissipation in an uniaxial tensile test occurs seem to be much larger than in the case of flexural tests. Again, the influence of hydration, of the maximum aggregate size, of the design strength, of the crack opening velocity and of the specimen size on the FPZ-width is investigated and depicted in figs. 4.49, 4.51, 4.52, 4.53 and 4.54. The width $l_{pr,\text{max}}$ is also studied.

The results of chapter 4 are the base of the mechanical modeling in chapter 5. An extended model for the ascending branch is found in section 5.2.1. The post-peak behaviour was also modeled. The $\sigma_{ct}-\varepsilon_{ct}$-curve of concrete under tension can be expressed in the first part by a linear-elastic stress-strain-curve until microcracking occurs. The inelastic part has a parabolic slope. Microcracking begins in the ascending branch at a stress $\sigma_{\mu} = k_{\mu} \cdot f_{ct}$. The value for $k_{\mu}$ is in literature in the range of 0.3 and 0.9. In [66, 34], $k_{\mu}$ is assumed to 0.5. In this thesis, $k_{\mu}$ was found to be dependent on hydration. Eq. (5.2) is proposed for $k_{\mu} < \sigma_{ct} < f_{ct}$. This formulation of the stress-strain-curve fulfills the requirements from Eqn. (5.6) to (5.9). In [24], the post-peak response of concrete is described via a stress-crack width curve by arrangement of two friction blocks. The descending line is divided into a first steep branch describing the bond failure between grains and matrix and into a second flatter one interpreted as the friction between grains and matrix after cracking. This model presupposes spherical aggregate grains. A statistical investigation regarding the shape of the aggregate grains used showed an elongated resp. a flat shape. This shape distribution is taking into account by two flat friction blocks describing the friction between grains and matrix. A Gaussian and a Poisson-distribution are leading to the Eq. (5.21).

In the sections 5.3 to 5.9, hydration and size dependent models are proposed and verified for the uniaxial tensile strength, the Young's modulus of elasticity, the ultimate strain, the flexural tensile strength, the fracture toughness, the fracture energy and the characteristic length.

The stress transmission in the post-peak branch of the stress-strain curve occurs over the width of the FPZ, which has been determined in an experimental manner. The results have shown, that $l_{pr}$ is increasing with increasing CMOD. After reaching a maximum at (CMOD$_{pr,\text{max}}$: $l_{pr,\text{max}}$), $l_{pr}$ decreases to a value between 0.95 and 0.60 times $l_{pr,\text{max}}$. The slope of that decrease depends on the concrete strength and the specimen size. From structural point of view, $l_{pr}$ should vanish when CMOD=0 because the FPZ starts to develop at that point. The limit of $l_{pr}$ when CMOD tends to infinity should also vanish because of the completely cracked ligament height. The variable width of the FPZ is justified by a variable distribution of the fracture energy $G_F$ over the ligament height.
[11]. Therefore, the formulation after Eq. (5.41) is proposed.

**Numerical verifications** of the proposed models occur in chapter 6 by means of a multi-layer model as proposed in [48]. The calculation is performed in the axis of symmetry as depicted in Fig. 6.7. The beam is subdivided into $n$ layers of equal thickness $h$. The tensile strength and the Young's modulus of elasticity of each layer are distributed Normal-Gaussian. For each loading step, a "strain-controlled" strain distribution is chosen. For this given deformation, the neutral axis is determined by an *incremental procedure*. The resulting stress distribution is calculated for each layer taking the proposed model in Fig. 6.10 into account. Due to the fact that the FPZ-width decreases with increasing crack opening, a formulation for an *unloading* had to be found (see Eq. (6.11)). The corresponding normal force and moment are then determined. Equilibrium is found if the normal force is equal to zero. If it is not the case, the neutral axis has to be adjusted until equilibrium is found. With the corresponding moment, the *external load* is calculated. Fig. 6.4 depicts the flow-chart of the numerical procedure. Fig. 6.11 shows an exemplary stress distribution over the ligament height of beam P3928D_1. One may recognize the distribution of mechanical properties. A comparison between the load-CMOD-curve predicted by the multi-layer model and the experimental result is shown in Fig. 6.12. Numerical results regarding influence of specimen size are following, taking the size dependence of $L_{pr}$ into account. Stress distributions at fracture moment for different specimen heights are depicted in Fig. 6.13.