Fracture and crack propagation energy in plain concrete

J. KASPERKIEWICZ
Institute of Fundamental Technological Research
of the Polish Academy of Sciences, Warsaw

Summary

Traditional fracture mechanics concepts are not suitable for concrete-like composites, in which plastic flow deformations are the exception rather than the rule on the level of micro-scale behaviour, and which have a highly heterogeneous structure. Properly arranged tests demonstrate that concrete can deform much more than is usually assumed, without sudden, brittle failure. Certain little known experimental observations are discussed. A concept of continuous inhomogeneity was previously proposed to explain the true behaviour of concrete. An experimental parameter which adequately describes the fracture properties of concrete is the average fracture surface energy γ_f. This parameter was investigated by testing concrete specimens, differing in their internal structure. The fracture process observations corroborate the concept of continuous inhomogeneity.

1 Introduction

There are controversies concerning the "brittleness" of concrete materials. It is fairly obvious what brittle fracture means in metals. However, in concrete materials the practical effect of the thickness of the specimen, i.e. the plain stress versus plain strain difference, seems to be non-exsistent or only of secondary importance.

"Plastic" deformations, such as those in metals, are unlikely in most cement-based composites. The expression "plastic deformations" will be reserved in what follows to the deformations associated with pure shear in metallic crystals. In such deformations the layers of the molecules slide one over another, passing through series of equilibrium states. An opposite situation occurs in the case of cleavage type molecular layer separation, which results usually in irreversible structural change, i.e. in the formation of a new surface.

Consider the crack propagation process in metallic materials. At the central plane of a thick metal specimen used for standard fracture tests there is an almost plane state of strain, and cleavage type separations are to be expected rather than plastic yielding [1]. The plastic zone is therefore limited in size (only at the specimen surfaces the plastic zone becomes larger). On the other hand, in a thin metal specimen the plastic deformations are much more obvious because the deformation state is close to the plane state of stress. The plastic zones could consequently be much larger [1]. The behaviour of the specimen will then be more "brittle" in the first situation than in the second. Similar differentiation seems non-existent in concrete.

The opinion as to the absence of plastic deformations ("plastic" - in the meaning as defined above) in concrete is supported by studies of the microstructure of the cement paste. If permanent (irreversible) deformations are to be observed inside the concrete, they must result from physical processes different from those which occur in metals. It could be, for example, multiple fracture or micro-fracture. The creep process in concrete will not be taken into consideration here, as it is most probably associated with some rebuilding of the microstructure at the molecular level, not to mention the dependence on time.

If the supposition about the absence of plastic deformation in concrete is correct, then certain important implications will follow. In particular, this supposition could explain the absence of specimen thickness effects in concrete fracture tests. There are experimental results which demonstrate the lack of the thickness effect, but these still need further verification. One should remember the possibility of the scale effects associated with the inhomogenous internal structure of concrete, which - compared with most metals - is a composite material of highly irregular internal structure. These scale effects could erroneously be confused with the effects of the specimen thickness.

It can be inferred that the general approach to the problem cannot be transferred directly to concrete from the fracture mechanics of metals.

It is now known that concrete reveals a strain softening behaviour during fracture tests. There is even a possibility of the presence of strain hardening effects, though these effects being even more difficult to observe, also require further testing. Traditionally, however, it has always been assumed that concrete is a "brittle" material. As there is no precise definition of brittleness, it is usually understood that concrete undergoes sudden failure under monotonic loading. The first papers on the subject - such as Kaplan's paper in 1961 - [2] - had been written on the assumption that such behaviour represents the only and true nature of the behaviour of concrete.

As a matter of fact all the experimental results in corroboration of this view were obtained in a particular manner: the critical situation was introduced by accepting poorly controlled (or completely uncontrolled) test conditions. The specimens were loaded in typical concrete laboratory testing machines designed for testing the standard compressive strength of concrete. They are usually of a "soft" type, as the rigidity of the machine is of secondary importance in compressive tests on concrete. During fracture tests such a machine stores up a substantial amount of elastic energy, which is available at the moment of fracture, when the energy is transformed into surface energy of the newly created fracture surface - which is the actual fracture energy - into uncontrolled kinetic energy of the fragments and into acoustic energy.

Due to comparing experimental data obtained from tests performed with different degrees of lack of control, there was a general confusion of opinions. Much of that confusion still remains.

The concept of so-called continuous inhomogeneity has been proposed to explain the actual behaviour of concrete [3, 4]. The term "continuous" is used to distinguish it from the well-known inhomogeneities of the "discrete" type, like aggregate grains, pores, etc. This concept, which is briefly explained in Chapter 3, was proposed taking into account a number of not widely known experimental observations. Such observations are described in the next chapter.

2 Some experimental observations

2.1 *Macro-structure in massive concrete specimens*

Measurement of strain tensor fields was performed in concrete prisms loaded in compression or in bending [5]. The measurements were performed with spatial rosettes (three-dimensional measuring devices, Fig. 1c, cf also [6]). Six independent strain readings were thus obtained at a measuring point within the specimen. Using these data three principal values of the strain tensor and their corresponding directions were calculated.

On comparing the principal values obtained in such tests it was possible to observe certain regularities, indicating the existence of a "structure". The results from the first loading at an age of about 2 months reveal similar features to those obtained on loading the same specimen at about 2 years, Fig. 1. The form of the distribution of the principal strain components was identical, Fig. 1a; and the principal directions, which were almost the same in both cases, shown in Fig. 1b.

Although it is impossible from such experiments to say anything more about the actual internal structure of the material, it seems that the invariability of some features of the strain tensor, observed in similar but certainly not identical loading conditions,

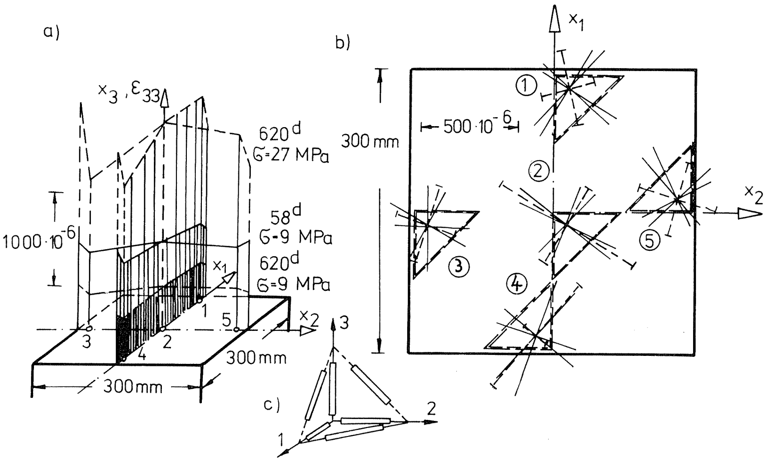

Fig. 1. The strain fields in an axially compressed concrete prism [5]. Strain tensors have been measured with electrical resistance strain gauges, using spatial rosettes – as shown in Fig. c, located at points 1 to 5. Fig. a compares axial strain distributions from the tests performed on concrete at 58 days and 620 days. In Fig. b – on a projection of a central cross-section of the prism – the correspondence between the principal directions estimated at the age of 58 days is represented (the sectors indicated result from the analysis of errors, cf. [6]), and the principal directions determined during the tests performed 1.5 years later (dashed lines).

proves the existence of a structure. The "macro" inhomogeneity is then a summed result of the small inhomogeneities of a discrete type. Naturally, such a macro-structure, or a structure characterized by a certain continuous inhomogeneity, must influence the development of all the fracture processes in the element under consideration.

2.2 *Fracture parameters variability in brittle matrices*

Fig. 2 shows examples of measurements of the critical stress intensity factor K_{Ic} in concrete (a) and fracture surface energy γ_f in granite (b), [7, 8]. In the first case it is possible to observe the variations of the fracture toughness during the crack propagation over distances of hundreds of millimeters. Fig. 2b shows the variability of the fracture surface energy, measured on small prisms cut from a larger volume of the material. It is shown here because the general fracture behaviour of rocks is in many aspects similar to that of concrete.

Both these rather unique diagrams seem to reflect a certain structure of the tested material.

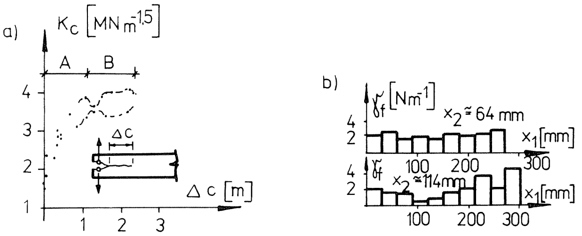

Fig. 2. Examples of the variability of the fracture mechanics parameters due to internal structure of the brittle materials [7, 8]. The concrete critical stress intensity factor oscillates between certain upper and lower limit values, after the initial effect has disappeared (a). Surface fracture energy measured on the specimens cut from the massive block of granite demonstrates two different types of variability (b).

2.3 *Increased deformability of concrete in the presence of crack arrestors*

For many years the limit deformability of cement based materials was a subject of debate. It was almost the general opinion that plain concrete cracks at a tensile strain above about 100 μ-strain (μm = microstrain = 1.10^{-6}). It was proved, however, in the last two decades that concrete can sometimes withstand much larger deformations without any dramatic loss of loadbearing capacity [9, 10, 11]. Relevant experimental results are unfortunately rather rare.

Quite unique test results relating to mainly a lightweight aggregate concrete were published in the 1950s by V. K. Balavadze [12–15], who performed direct tensile tests on heavily reinforced prismatic elements in which the cover to the bars was removed from the central part of the element. The remaining plain concrete cores were thus loaded parallel to the steel reinforcement. The resulting extremely rigid loading system resembles in a way the idea which was later used by Hughes and Chapman [9] and Evans and Marathe [10]. After attaching the strain gauges to the surface of the concrete core and to the steel bars, and taking into account the readings from the gauges of both types, it was possible to determine the stress-strain relation for the material of the core, Fig. 3.

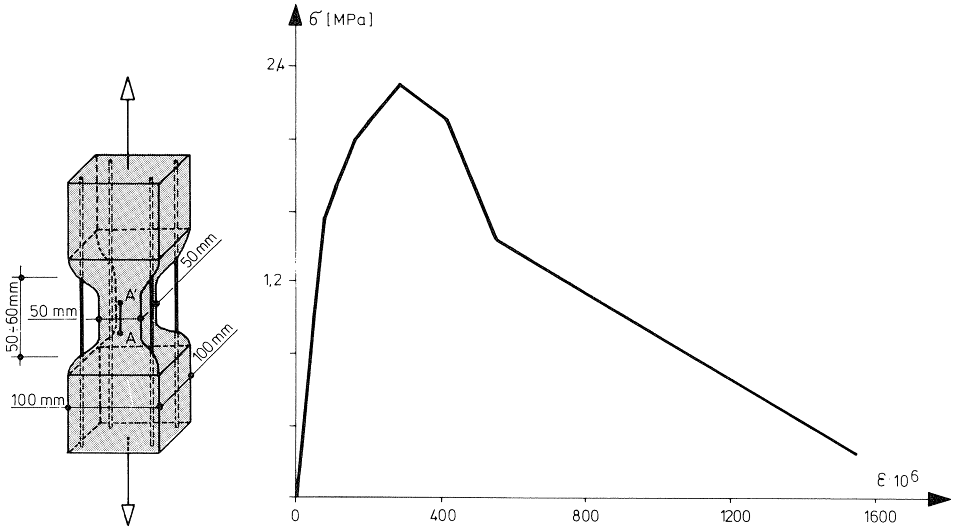

Fig. 3. The idea of Balavadze's tests [12, 15]. The strain (ε) was measured on the uncovered portion of the central core along the basis AA. The area under the curve is approximately 1840 MPa, which, for the given dimensions of the specimen, corresponds to a fracture surface energy of about 51 N/m.

The axial load in the prisms was increased so long as the deformation in the concrete was about 15–20 times the ultimate strain in the non-reinforced material. After unloading of the specimens, close surface inspection did not reveal any cracks of the core. It was also observed that if the imposed deformations were limited to only 600 microstrains, the value of the tensile strength of the core was the same as in the virgin material. All these observations confirmed an earlier opinion of Balavadze, that concrete - if enabled - deforms in a "purely plastic" way [12–14].

An example of the stress-strain diagram from [15] is given in Fig. 3.

3 The concept of continuous inhomogeneity

The concept of so-called "continuous inhomogeneity" [3, 4] was advanced as an explanation of the experimental observations mentioned above. It is believed that the actual tensile behaviour of concrete, can be explained by variability of fracture surface energy γ_f, Fig. 4, which results from local variations of the surface energy γ. In contrast with γ_f, the parameter is a thermodynamic constant, different for different components of the composite material. The average value of the fracture surface energy γ_f can easily be measured as the specific energy of fracture in a process of localized crack propagation. It

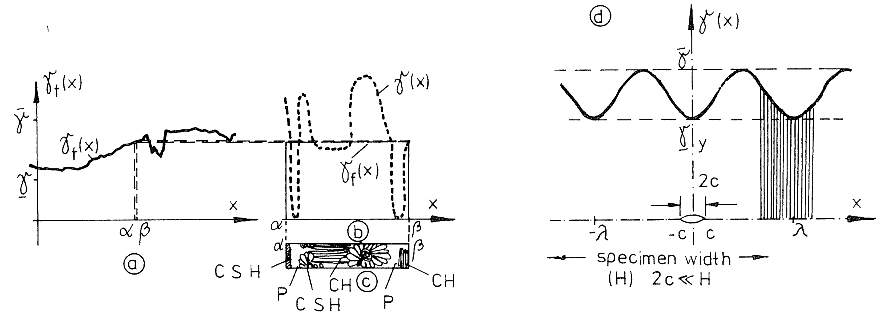

Fig. 4. The concept of continuous inhomogeneity [3, 4]. Along a potential crack propagation direction (x) the actual microstructure of the cement paste (Fig. c) is characterized (Fig. b) by a certain discrete distribution of surface energy $\gamma(x)$. Averaged values of γ give the local value of fracture surface energy $\gamma_f(x)$ represented here as a continuous inhomogeneity in Fig. a. Fig. d shows 3-parametric distribution of the inhomogeneity, used in the examples given in [3, 4].

can then be determined for example from properly controlled tests on notched beams loaded in bending.

Contrary to traditional assumptions, the material parameter γ_f is, not a constant, but a function depending on the position within the specimen. A certain form of variability of γ_f is believed to characterize every composite material. Such characteristics must result from the actual internal structure of the material. It is not yet possible to propose any particular type for such variability which would be connected in a rational way to various structural observations.

To discuss the proposed concept a certain regular form of γ_f has been assumed instead of the actual (unknown) distribution. A simplified, sinusoidal variability, characterized by three parameters: $\bar{\gamma}$, $\underline{\gamma}$ and λ, made possible the prediction of the behaviour of model materials of plain and fibre reinforced concrete. For these models, without assuming plastic deformations of the matrix, a strain softening behaviour of a cracking element was obtained, Fig. 5. This corresponds to the actual behaviour of concrete observed by many investigators [9, 10, 11, 15].

As for the other observations mentioned previously, the variability of the material properties directly explains the observations mentioned in Section 2.2 above. It also offers a natural explanation for the "frozen" macro-structure observed in concrete elements, as mentioned in Section 2.1.

4 Fracture surface energy tests on concrete

On the basis of all these considerations the fracture surface energy is assumed to be a proper parameter describing crack propagation behaviour. It is believed that its value does not depend on the method of measurement. Pure bending should then be as useful as direct tension, the only condition being a stable loading configuration (rigid testing machine).

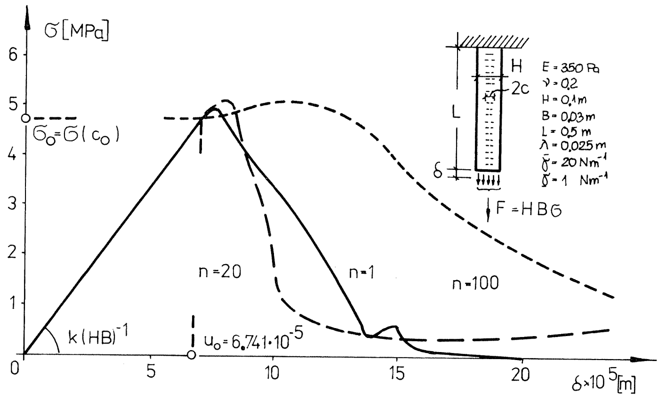

Fig. 5. Force-elongation diagrams obtained in the examples given in [3], on the assumption of continuous inhomogeneity defined as $\gamma_f(x) = (\bar{\gamma} + \underline{\gamma})2 - (\bar{\gamma} - \underline{\gamma}) \cos (2\pi x/\lambda)$, Fig. 4d. The diagrams relate to three different cases of the total number of cracks: n = 1, 20 and 100. The diagrams have only a qualitative significance: the area under the curve, even in case of n = 1, corresponds to a fracture surface energy of about 200 N/m, while the experiment – if it was performed using similar dimensions and material constants – would result in uncontrolled crack propagation.

Three series of notched beams, made of different types of concrete, were loaded in pure bending, with full monitoring of the specimens' behaviour. Among other quantities the deflections under the force, the crack opening, the crack tip position, etc. were measured, Fig. 6. The loading system was designed by Schenck and was equipped with a very rapid servo-hydraulic circuit allowing accurate testing at constant crack opening rate. The details of the tests are described in [16].

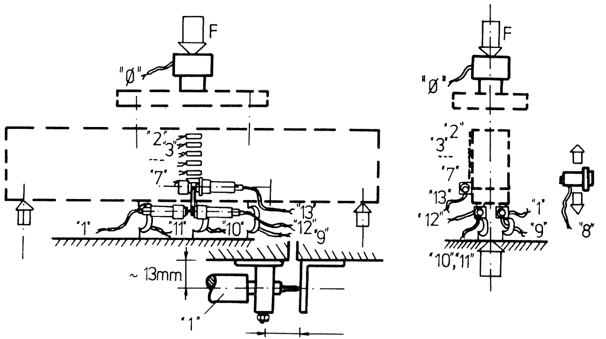

Fig. 6. System of gauges used for monitoring the fracture behaviour of concrete. Electrical resistance surface gauges (2–7), spring (deflection) or electrical resistance gauges (0, 9–11), and inductive displacement gauges (1, 8, 12, 13) were used for automatic measurement of the crack propagation process. Inductive gauge No. 8 was attached to a microscope used for locating the actual position of the crack tip.

Fig. 7 shows typical force-deflection diagrams. The area under the curve made possible the estimation of the mean value of γ_f, which was about 73 N/m. Comparison with – for example – the results of [15] indicate the same order of magnitude of the fracture energy. Investigation of the structure of the material have not yet been completed, but the differences due to structural differences between the materials tested have been observed.

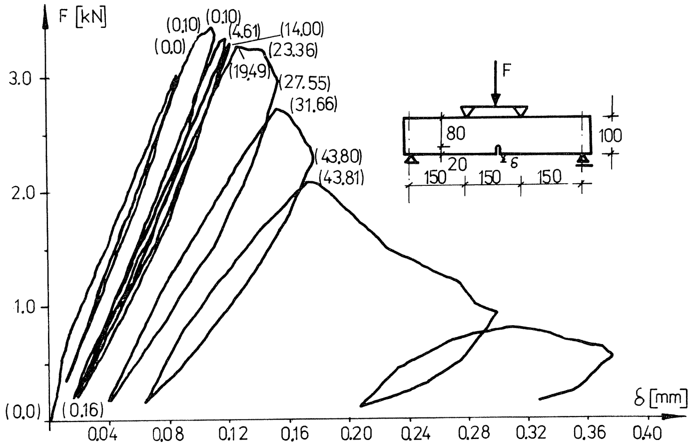

Fig. 7. Force-deflection diagram for the notched specimens tested in bending (thickness of the specimens was ca 48 mm, the other dimensions were as indicated). The numbers in parentheses indicate, in mm, the position of the crack tip; the crack starts from the notch and proceeds upwards, through the 80 mm depth of concrete.

The initial analysis of the crack propagation process presents the following picture. In agreement with the continuous inhomogeneity model the crack which starts from the notch develops in "jumps". The crack visible on the side surface of the specimen alternately advances and stops, irrespective of the development of the irreversible deformations of the beam. Fig. 7 indicates the observed crack positions at various stages of the process. It seems to correspond to the situation in the model presented in Chapter 3, when the initial (primary) crack of a certain starting position – in relation to the distribution of the continuous inhomogeneity – starts and then stops, to give priority of development to other cracks (inside the material, thus invisible to the observer) which are at that moment in "more critical" condition. The visible crack "restarts" when it again becomes the critical crack.

5 Conclusions

The concept of continuous inhomogeneity applied to the fracture surface energy provides an explanation for certain peculiarities of the behaviour of concrete and concrete-like composites.

The mean fracture surface energy γ_f, obtained in properly designed tests, is a parameter which describes the behaviour of concrete quite well. "Properly designed" means that the tests should be done using only a testing machine possessing adequate rigidity.

Investigations on crack propagation in concrete materials differing in internal structure are needed. Combined with the monitoring of their actual structure (e.g. by stereological methods), such investigations should make it possible to estimate the actual form of the continuous inhomogeneity function $\gamma_f(x)$.

Due to the highly heterogeneous structure of concrete, crack propagation in this material proceeds in a non-steady manner. Locally the crack develops in jumps, corresponding to the continuous inhomogeneity model.

6 Acknowledgements

This paper was prepared during the author's stay at the Delft University of Technology (DUT), in 1985, which was made possible by a fellowship granted by the Fellowship Committee of that University, for which he here writes wishes to express his thanks. The tests mentioned in Chapter 4 and in References [16]. were performed in the Stevin I Laboratory.

7 References

1. Kasperkiewicz, J., An introduction to the problems of fracture of concrete and concrete-like composites (in Polish). In: "Wybrane zagadnienia z mechaniki kompozytow", Wydawnictwa Politechniki Bialostockiej, Bialystok 1982, pp. 37–112.
2. Kaplan, M. F., Crack propagation and the fracture of concrete, ACI J., Proc., v. 58, 1961, pp. 591–610.
3. Kasperkiewicz, J., Modelling of inhomogeneity in certain cement-based composites. The Int. J. of Cement Comp. a. Lghtw. Concr., v. 5, No.1, 1983, pp. 41–48.
4. Kasperkiewicz, J., On a certain model of brittle matrix composite. Seminar "Present state of investigations and applications of fibre reinforced cement-based materials". IFTR a. Inst. of Bldg Mat-s, Cracow Technical University, Cracow, 28–30, IX. 1983, pp. 58–67.
5. Baus, R., Brandt, A., Brenneisen, A., Analyse de déformation des éléments en béton sous charges statiques. Mémoires C.E.R.E.S. (Université de Lièges), No. 42, mars 1973, 88 pp.
6. Brandt, A. M., Kasperkiewicz, J., On the errors in experimental measurements of strains in concrete and prestressed concrete elements. Mat et Constr., v. 4 (1971), No. 21, pp. 147–153.
7. Chhuy, S. M., Etude de la propagation d'une fissure dans un béton non armé. Bull. de Liaison des Lab. des Ponts at Chaussées, No. 98 (nov.-dec.), 1978, pp. 73–84.
8. Mc Garry, F. J., Fracture mechanisms in natural rock. In "Structure, Solid mechanics and Engineering Design", Proc. of C.E. Mat-s Conf., Southampton 1969, Ed. M. Te'eni, Wiley Interscience, London 1971, pp. 205–230.
9. Hughes, B. P., Chapman G. P., The complete stress-strain curves for concrete in direct tension. RILEM Bulletin, No. 30, 1966, pp. 95–97.
10. Evans, R. H., Marathe, M. S., Microcracking and stress-strain curves for concrete in tension. Mat. et Constr., v. 1, 1968, No. 1, pp. 61–64.
11. Reinhardt, H. W., Cornelissen, H. A. W., Post-peak cyclic behaviour of concrete in uniaxial tensile and alternating tensile and compressive loading. Cement a. Concrete Research, v. 14, 1984, No. 2, pp. 263–270.
12. Balavadze, V. K., Some problems of cracking in lightweight aggregate concrete (in Russian). Soobshchenya Akad. Nauk GSSR, v. 17, No. 4, 1956, pp. 329–336.

13. Balavadze V. K., On some peculiarities of lightweight aggregate concrete (in Russian). Soobshchenya Akad. Nauk GSSR, v. 18, No. 5, 1957, pp. 577–584.
14. Balavadze V. K., Determination of limit deformability and tensile strength of reinforced concrete by the method of Féret (in Russian). Soobshchenya Akad. Nauk GSSR, v. 19, No. 3, 1957, pp. 313–320.
15. Balavadze V. K., The influence of the reinforcement on the properties of concrete in tension (in Russian). Beton i Zhelezobeton, No. 10, 1959, pp. 462–465.
16. Kasperkiewicz, J., Dalhuisen D., Crack propagation process in ordinary concrete beams subjected to bending (June–May 1984). Stevin Report, Technical University of Delft, Delft 1985, ca. 60 pp.