Behaviour of concrete under high tensile loading rates

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1 INTRODUCTION

Strain rate sensitivity of a material is important in impact research. Depending on the loading rate stiffness as well as strength may change. The application of these strain rate dependent material parameters is important e.g. in finite element simulations of impact endangered structures.

The purpose of the following short publication is to report on studies done to understand why material properties of concrete change in cases of high speed loading.

2 RELATED RESULTS GAINED BY OTHER AUTHORS

The increasing of strength, the variation of the ultimate strain and the changing stiffness behaviour due to high loading rates are described in a number of publications to which the reader is refered to: Zielinski (1982), Suaris/Shah (1983), Dargel (1984), Nilsson (1979), Ammann (1983), Bischoff/Perry (1985). The dependence of the tensile strength e.g. on the stress or strain rate is shown in fig. 1.

One possible explanation for an increasing strength is given by Körmeling/Zielinski/Reinhardt (1980) who discuss the fact that a different number of broken aggregates due to the applied strain rate has been watched at crack surfaces. They argue that the larger amount of broken high strength aggregates at fast rate loading results in a higher overall strength of concrete. Gödde (1986) has tried to simulate this behaviour numerically in order to find out why the amount of broken aggregates changes with strain rate. He concludes that the stress concentration in the stiffer material strongly increases by inertial effects and that this causes the aggregates failure.

Nevertheless this effect cannot cover the full range of dynamic strength increase.

In case of an aggregate strength which is 3 to 4 times higher than that of the mortar matrix and an assumed 30 % portion of aggregates in the crack surface one reaches at maximum a strength increase of about 160 to 190 % which cannot explain factors up to 6 watched in experiments.

Another fact which can hardly be understood until now is the discrepancy that in all existing formulations the dynamic strength increase

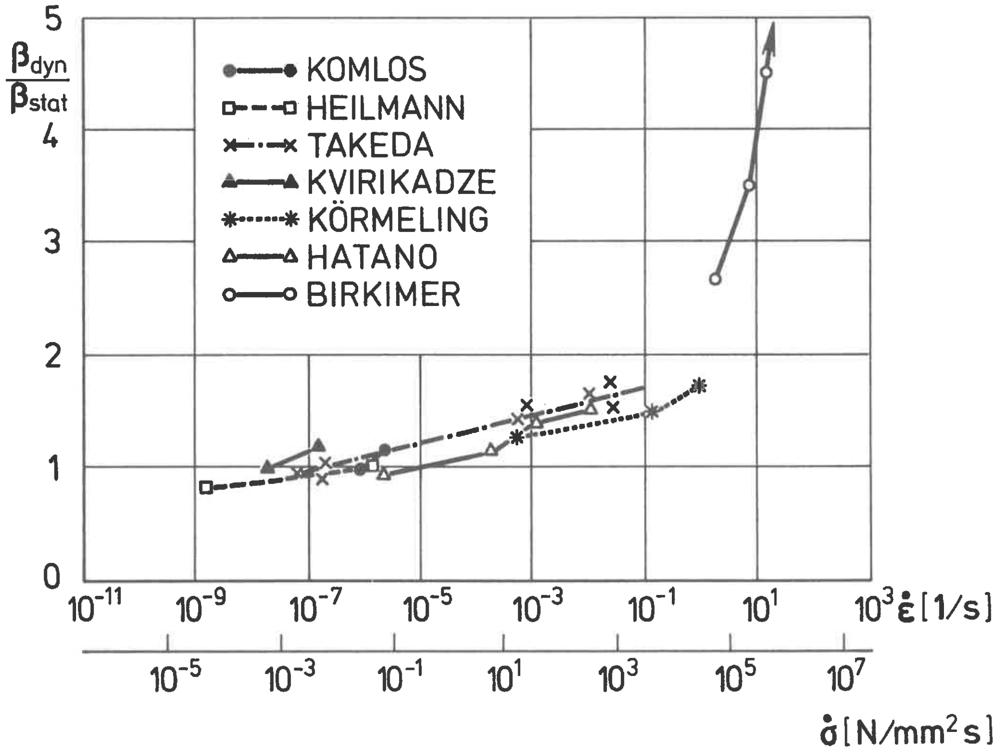

Figure 1. Tensile strength vs. stress or strain rate

approaches zero with strain rate approaching zero, while in experiments e.g. beams sustain increased dynamic peak loads with strain rate equal zero in their bottom fibres at maximum loads. This problem is discussed in detail by Eibl et al. (1986) resp. Curbach (1987).

3 INVESTIGATION DONE BY THE AUTHORS

To study the effects under discussion the authors carried out experiments as well as computer simulations, the last mentioned on the so-called meso-level using the definition given by Reinhardt (1985). This means that a continuum with small cracks existing already before external loads are applied is assumed. These cracks are mainly caused by stresses due to shrinkage of mortar around aggregates.

Due to applied external tensile loads the crack development and the stress distribution especially in front of the crack tip - see Hillerborg (1983) or Cornelissen et al. (1986) - have been studied and compared with overall stresses of the structure resp. test specimen on the macro-level. The numerical simulation of the crack growth in a plane strip with an notch (fig. 2, fig. 3) was calculated using the finite element technique with a constitutive law developed for this task. It takes into account internal friction within a rheological model trying to explain the descending part of the tensile stress-deformation curve.

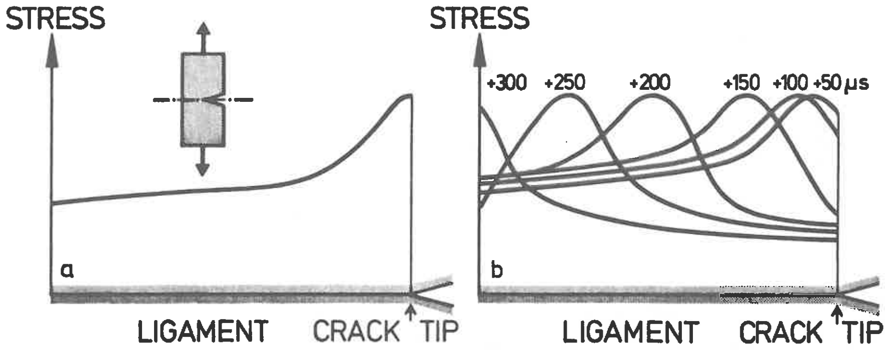

Figure 2. Stress distribution in front of a crack tip at the begin of crack growth after static loading (a); at different time steps during crack propagation (b)

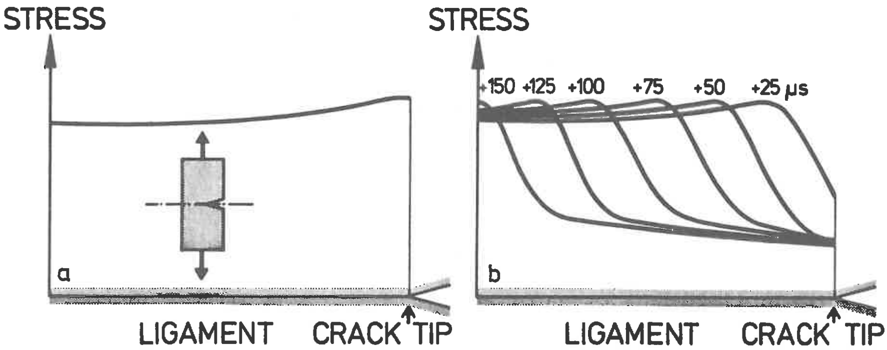

Figure 3. Stress distribution at the begin of crack growth after an applied high rate loading (a); at different time steps during crack propagation (b)

4 RESULTS

In fig. 2a first the wellknown stress distribution in front of a notch after quasi-static loading is shown contrasting the stress distribution with the same stress at the notch tip after high rate loading (fig. 3a). Fig. 2b resp. fig. 3b demonstrate the propagation of the stress peak resp. the crack tip within the following time. The remaining stresses after the peak are caused by the transferred tensile forces at the already opened crack as a consequence of the descending part of the stress-deformation diagram.

The explanation for the different stress patterns in case of a static or a dynamic loading before crack growth is (fig. 4) that in case of high rate loading the incoming stress reacts less to the changing boundary condition at the notch than in the case of static loading.

A comparison of fig. 2a and fig. 3a shows clearly that the overall stresses at the begin of crack growth after high rate loading may be much higher then in the case of static loading.

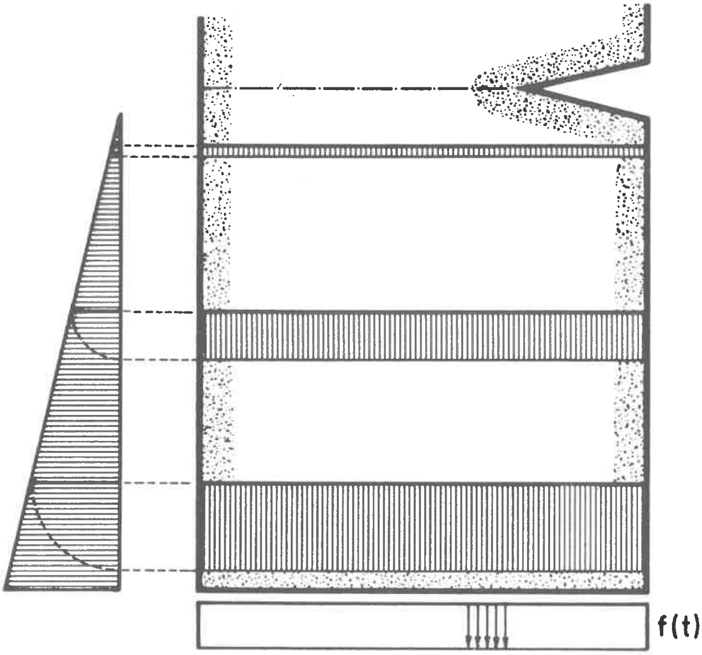

Figure 4. Propagation of high rate stress wave before arriving at the notch ligament

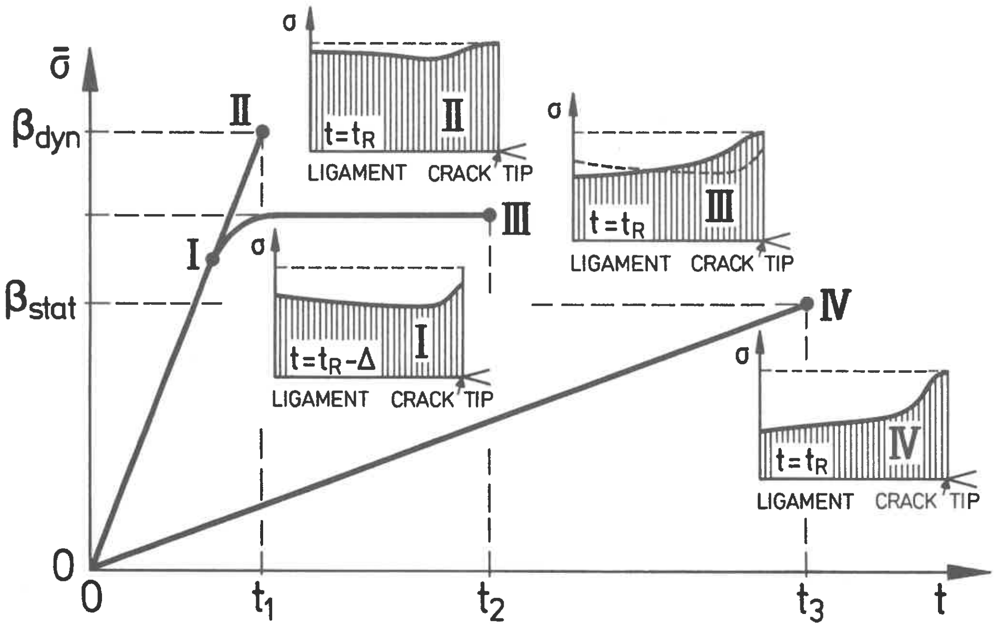

Figure 5. Different stress histories and the stress distribution belonging to them

The motion of the stress peak along the ligament corresponds to the advance of the crack tip. Tests done by Curbach (1987) have shown that the crack velocity of an unstable crack is nearly independent of the strain rate, and that the stress gradient in front of the crack tip is nearly constant in case of a stress rate "higher" then the crack velocity.

The authors were also interested in answering the question how dynamic strength changes in case of different load paths.

One interesting question is: At what time after fast loading from point 0 to I in fig. 5 does the increased dynamic strength decay to its static value if the load - after reaching I - is kept constant from I to III.

The different strength at dynamic (0 - II) resp. static loading (0 - IV) just before failure has been explained already by means of fig. 2 and 3. Further numerical simulations showed that loading according to the line 0-I-III leads to stress distributions in front of the crack tip as drawn beside path 0-I-III in fig. 5. The resulting overall stress is between high rate (II) and static strength (IV). During constant load (I - III) the stress distribution changes from the dashed line to the full line as shown at point III. That means that the maximum stress at the crack tip increases during a constant overall stress until failure starts. The ability of concrete to retain during the time of constant overall stress with stress rate equal zero the effect of the high loading rate applied previously could be termed as memory.

5 SUMMARY

Summarizing it can be said that the increasing of strength has beside the increasing number of broken aggregates two more different reasons: first the different stress distribution in front of a crack tip due to the heterogenity of concrete and inertial effects and secondly the limited crack velocity caused by the descending part of the stress-deformation curve. Time depending memory effects have to be taken into account if one has to predict the behaviour under complex stress- or strain histories.

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