

THE SIZE EFFECT IN CONCRETE STRUCTURES

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Abstract

In the present paper the results of a size effect study on plain concrete unnotched and notched beams loaded in three-point bending are shown and compared with experimental results and the size effect law. The numerical results, obtained using the nonlocal microplane finite element code, confirm a strong size effect for smaller beam sizes. However, for larger unnotched beams the nominal strength tends to a constant value related to the uniaxial tensile strength. These results are in good agreement with what has been observed in experiments. However, for larger beam sizes they disagree with the recently proposed size effect law. The reason why the nominal strength of large unnotched beams should approach a limit value different from zero is investigated and the range of applicability of the size effect law is discussed. It has been concluded that the applicability of the size effect law is dependent on the problem type i.e. if the crack propagation before peak load is very stable the size effect law may be used in a rather broad size range. However, if this is not the case, the validity of the size effect law is limited to a smaller size range. Therefore, before extrapolating the size effect from tests with a small size range to a very large size range experimental data from a large size range should be available. Keywords: Three-point bending, Concrete, Fracture, Size effect, Size effect law, Nonlocal analysis.

1 Introduction

The size effect in quasibrittle materials such as concrete is a well known phenomenon and there are a number of experimental and theoretical studies (Rüsch et al., 1962; Leonhardt and Walter, 1962; Kani, 1967; Bhal, 1968; Taylor, 1972; Walsh, 1976; Walraven, 1990; Chana, 1981; Reinhardt, 1981 a,b; Iguro et al., 1985; Hillerborg, 1989; Eligehausen et al. 1992) which confirm the existence of it.

There are two aspects of the size effect: (1) Statistical and (2) Deterministic, based on fracture mechanics. In the past, the size effect has been mainly treated from the statistical point of view (Weibull, 1939; Mihashi and Zaitsev, 1981; Mihashi, 1983). However, presently there is much evidence that the main reason for the size

effect lies in the release of strain energy due to fracture growth. (Bažant and Cedolin, 1991).

According to Bažant (1984) the size effect can be approximately described by the size effect law:

$$\sigma_N = B f_t (1 + \beta)^{-1/2}; \quad \beta = d/d_0 \quad (1)$$

in which d is a measure of the structure size (for example beam depth), f_t = tensile strength of concrete, B and d_0 are two constants, to be determined either experimentally or by a more sophisticated analysis. According to Eq. (1) the nominal strength σ_N of large structures tends to zero and the failure load increase with \sqrt{d} .

Under the assumption that the material properties are constant (the same concrete), the derivation of the size effect law is based on four basic hypotheses: (1) The propagation of a fracture or crack band requires approximately a constant energy supply per unit length and width (concrete fracture energy G_F , independent of the specimen size) (2) the energy released from the structure due to fracture growth is a function of both (a) the fracture length and (b) the area of the cracking zone (fracture process zone) at the fracture front. If the potential energy release is a function of only the fracture length, the size effect is that of linear elastic fracture mechanics, and if it is a function of only the cracking area, there is no size effect. (3) At peak load, the fracture shapes and lengths in geometrically similar structures of different sizes are also geometrically similar, and (4) the structure does not fail at crack initiation i.e. fracture propagation must be possible.

It has been shown that the size effect law is valid for a large number of practical applications (Bažant, Ozbolt and Eligehausen, 1993). However, there are some examples which show that the size effect law is not valid for larger specimens. For instance, in a number of experiments with unnotched beams (Malkov and Karavaev, 1968; Heilmann, 1969) and notched beams with a constant notch depth (Alexander, 1987), it has been observed that the normalized bending strength approaches a limit value different from zero. This behaviour can also be confirmed by linear elastic fracture mechanics (LEFM) under the assumption that the initial notch length remains constant or zero for all member depths (Elices and Planas, 1992; Tang, Shah and Ouyang, 1992).

To investigate the size effect in more detail, in the present study the behaviour of notched and unnotched plain concrete beams loaded in three-point bending are studied using the nonlocal microplane finite element code. One of the main aims of the present study is to check if the assumption of the crack length proportionality at peak load is fulfilled.

2 Size Effect in three-point bending of plain concrete beams — review of the evidence

In literature a number of test results for notched and unnotched three-point bending specimens have been reported. In Fig. 1 test results for three similarly scaled notched beam specimens, performed at Northwestern University (Bažant and Pfeif-

fer, 1987), are shown. In the same figure these results are compared with numerical results (Eligehausen and Özbolt, 1992) and the size effect law. The depth of the beam specimens has been varied in a rather small size range i.e. from $d=76$ mm to 305 mm with a constant thickness $b=38$ mm. The nominal strength at failure is calculated using the elastic beam theory formula $\sigma_N = 15P_U/4bd$ with P_U being the ultimate load. From Fig. 1, a significant size effect is observed i.e. the nominal strength σ_N decreases with increasing size. The size effect law shows a good agreement with the experimental results.

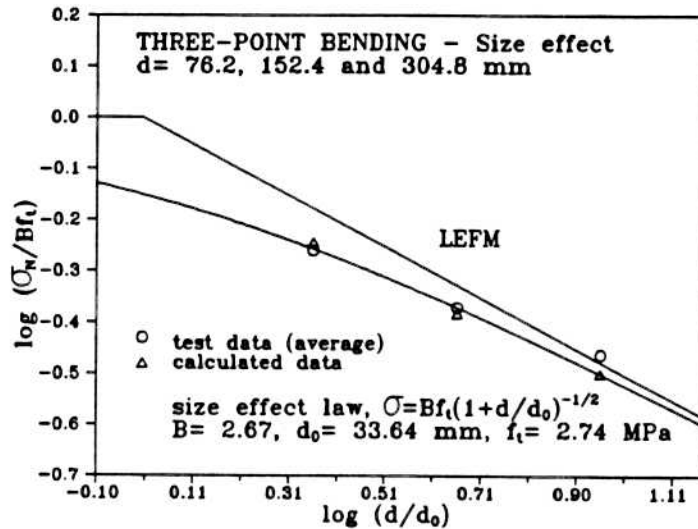


Fig. 1 Size effect in three-point bending notched specimens

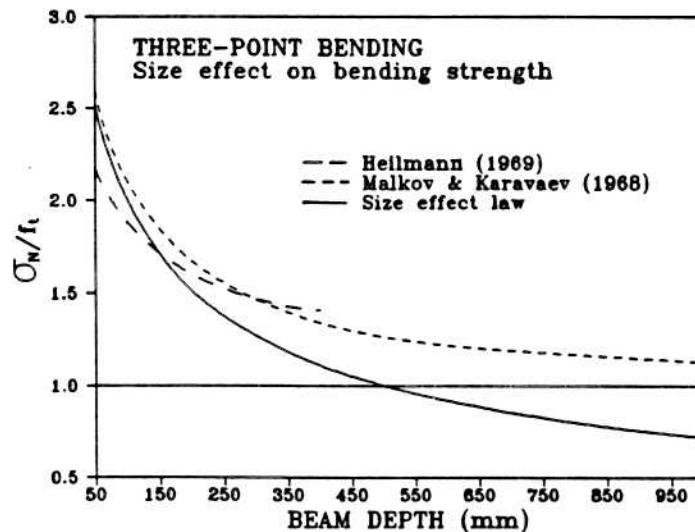


Fig. 2 Size effect in three-point bending unnotched specimens - larger size range

The test results reported by Malkov and Karavaev (1968) and Heilmann (1969) for unnotched plain concrete three-point bending specimens are plotted in Fig. 2. The beam depth range was up to 1000 mm. As can be seen from Fig. 2, test results

up to a beam depth of approximately $d=500$ mm exhibit a significant size effect in good agreement with the size effect law. However, for larger specimens, the nominal strength tends to the uniaxial tensile strength of concrete.

In Fig. 3 the nominal strength of notched beams, with constant notch size, tested by Alexander (1987) are plotted as a function of the member depth. As in the case of unnotched specimens, the nominal strength of large beams tends to a constant value different from zero.

Since the experimental results plotted in Figs. 2 and 3 clearly indicate a disagreement with the size effect law for larger beams it is obvious that the size effect law assumptions are not fulfilled.

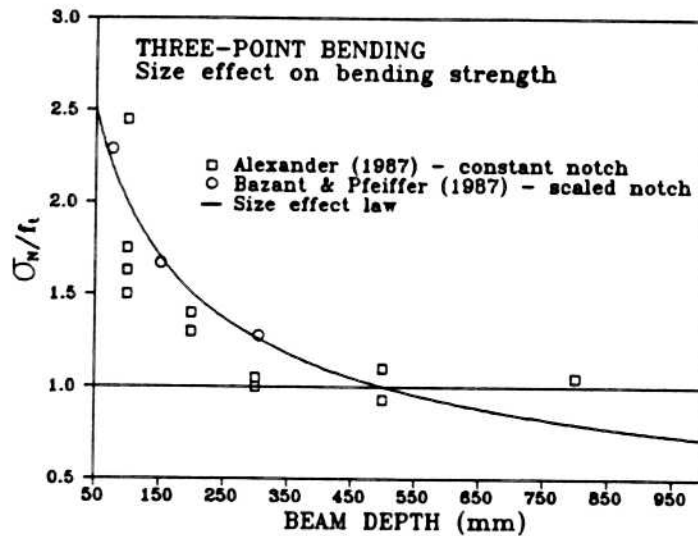


Fig. 3 Size effect in three-point bending notched specimens (constant notch size) – larger size range

3 Numerical study

3.1 Beam geometries and material properties

Beam specimens of four different sizes with a constant span-depth ratio $L/d=5$ are analyzed. The depths of the beams are $d=100, 200, 800, 1600$ and 3200 mm with a constant width of $b=38$ mm (see Fig. 4). Unnotched specimens (Fig. 4a) and notched specimens with a notch depth of $a=d/6$ and a width of $w=30$ mm are analyzed. The material properties are taken as follows: tensile strength $f_t=4.5$ MPa, uniaxial compressive strength $f_c=40$ MPa, Initial Young modulus $E=32000$ MPa, Poisson's ratio $\nu=0.18$, fracture energy $G_F=0.12$ N/mm and maximum aggregate size $d_a=16$ mm. The uniaxial tensile strength and fracture energy have been calibrated on a notched tensile specimen with a length-depth ratio $L/d=175/75$ mm using the nonlocal finite element code (microcrack interaction approach). The characteristic length was kept constant in all case studies as $l=d_a=16$ mm.

The nonlinear nonlocal fracture analysis is performed by use of the microplane model and the nonlocal microcrack interaction approach (Ožbolt and Bažant, 1992;

Ožbolt, 1992; Ožbolt and Petrangeli, 1993). The load is introduced by controlling the vertical displacement at mid span of the beam (see Fig. 4). Only one half of the beam is modelled and the size of the elements in the fracture process zone are approximately the same for all beam sizes.

For unnotched beams two sets of runs are carried out. In the first, in order to limit the size of the fracture process zone at mid span, a nonlinear zone of width $t = 200$ mm for all beam sizes is introduced. Outside this zone the material behavior is assumed to be linear elastic (see Fig. 5a). In the second case the nonlinear zone is proportionally scaled with the size of the beams and is taken as $t = L/5$ (see Fig. 5b) in order to allow for the spreading of damage along the beam length. For notched beams, only finite element meshes with a large nonlinear zone width are used ($t = L/5$).

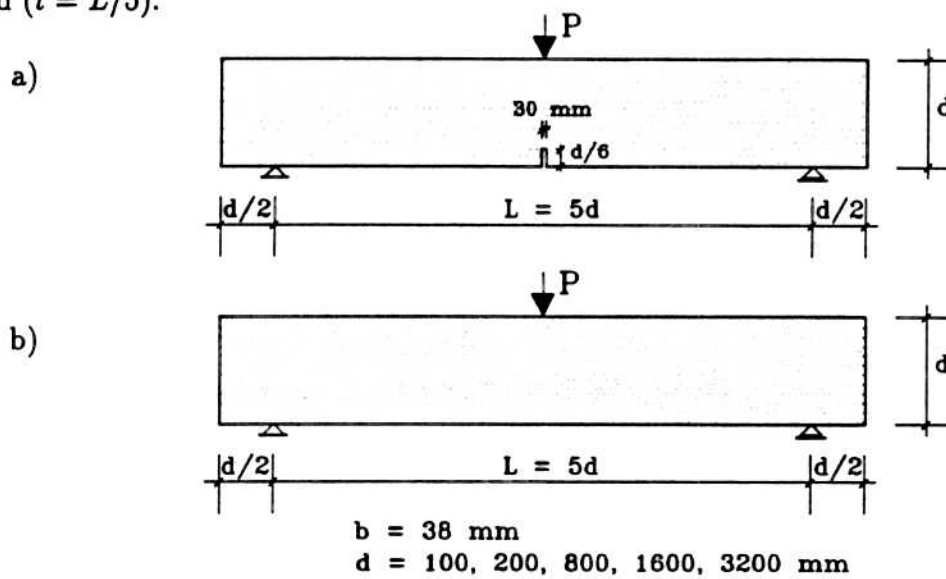


Fig. 4 Geometry of the beams used in the numerical analysis
a) notched b) unnotched

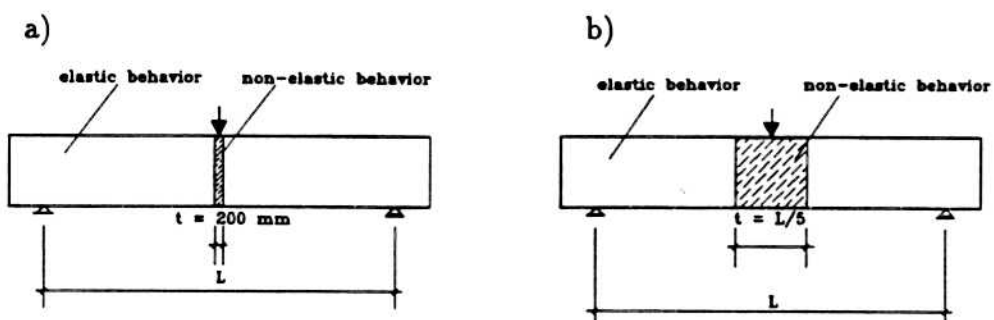


Fig. 5 (a) Small nonlinear zone (b) Large nonlinear zone

3.2 Results of the analysis – unnotched beams

In Fig. 6 the nominal strengths, for both unnotched beam sets are plotted. The nominal strength has been defined as the maximum stress of an equivalent elastic beam subjected to the ultimate load P_U found with the nonlinear analysis. Experi-

