SIZE EFFECTS IN CRACKING OF CONCRETE: PHYSICAL EXPLAINATIONS AND DESIGN CONSEQUENCES

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1 Introduction

In the last years, size effects involved in cracking of concrete structures have been regarded at two levels:

- at the level of the material to determine intrinsic constitutive relations for the cracking of concrete,
- at the level of the structure to account for size effect in design methods and in finite element analysis.

Based on some experimental results obtained in uniaxial tension, this paper discusses the physical origins of size effects in concrete cracking, and the consequences on the design of concrete structures.

2 Experimental data on the mechanical size effects in concrete

It is beyond the scope of this paper to make an exhaustive review of the literature concerning the experimental data on the mechanical scale effect in concrete. Just some results are presented which allow to explain the physical origins of this scale effect. These data are taken from the series of uniaxial tension tests carried out by Rossi et al. (1994a). Two series of test were performed on:

- in the first study, three diameters of cylindrical specimens of slenderness ratio 2 were tested: 89, 113, 160 mm. One type of concrete was studied whith a maximum aggregate size of ∅ = 12 mm, and a compressive strength of f_c = 48 MPa. Approximatively 50 tensile tests per specimen diameter were obtained,
- in the second study, three diameters of cylindrical specimens of slenderness ratio 2 were tested: 30, 60, 150 mm. Three types of concrete were studied with a compressive strength respectively equal to 35, 56, 128 MPa. The diameter of the maximum aggregate size was the same for the three concretes: 20 mm.

The results relative to these two studies are given in tables 1 and 2.

Table 1. Results relative to the first study (details in Rossi et al. (1994a))

specimen diameter (mm)	89	113	160
number of values	46	54	49
mean tensile strength (MPa)	3	2.8	2.5
standart deviation (MPa)	0.3	0.3	0.2

Table 2. Results relative to the second study (details in Rossi et al. (1994a))

concrete 1, f_c = 35 MPa			
specimen diameter (mm)	30	60	150
number of values	15	15	16
mean tensile strength (MPa)	4.8	3.2	2.4
standart deviation (MPa)	1	0.6	0.2
concrete 2, f_c = 56 MPa			
specimen diameter (mm)	30	60	150
number of values	18	8	9
mean tensile strength (MPa)	5.1	4.3	3.3
standart deviation (MPa)	1	0.7	0.2
concrete 3, f_c = 128MPa			
specimen diameter (mm)	30	60	150
number of values	12	17	7
mean tensile strength (MPa)	6.4	6.0	6.0
standart deviation (MPa)	0.9	0.7	0.2

3 Physical explainations

Based on the theory of Weibull (1939), it is known that the scale effect in the cracking of materials is related to the number of initial defaults inducing unstable crack propagation in mode I (brittle materials), this number depending on the volume of loaded material.

Concerning concrete, these initial defaults are mainly located in the cement paste (initial cracks, bubbles...). This implies that size effects in concrete depend on the volume of loaded cement paste.

Based on the results given in tables 1 and 2, one may state that this volume of loaded cement paste depends on:

- the ratio 'volume of the loaded concrete/volume of the maximum aggregate size',
- the difference in the mechanical properties between the cement paste and the aggregates, for which the compressive strength is a good indicator (except for lightweigth concretes).

These two aspects related to the material define what we can call 'the mechanical degree of heterogeneity of concrete' which is at the origin of mechanical size effects in concrete when its cracking is mainly governed by mode I cracks propagation.

In the cases where the cracking of concrete is governed by others physical mechanisms than mode I cracks propagation, physical mechanisms which are at the origin of other energy dissipation, the size effects in the cracking of concrete decrease, and may even disapear in some cases (reinforced concrete structures with a high percentage of reinforcement).

The others physical mechanisms involved in the cracking of concrete structures can be, for example:

- the friction in the cracks lips,
- the aggregate interlock phenomenon,
- the friction at the rebars-concrete interfaces, and the yielding of these rebars in the case of reinforced concrete structures.

4 Consequences for the design of concrete structures

As great mentioned above, size effects in concrete structures play an important role in the cases where the cracking of these structures is governed by mode I crack propagation (this is the case, for example, of unreinforced concrete structures, or of reinforced structures with a low percentage of reinforcement).

In this case, due to safety reasons, size effects in design of concrete structures should be taken into account.

We distinguish, in this field, usual design methods used by engineers for 'standard' structures, and finite element analysis which can be used in the case of complex loading conditions in a geometrically complex part of the structure.

4.1 Usual design

For the engineer, the nominal tensile strength σ_N relative to a given structure is the necessary material parameter to design it. So, these last years, some theoretical studies have been performed to propose strength size effect laws.

At the present, two main different size effect laws can be found in the literature:

1. The 'universal size effect law for cracked and uncracked structures' proposed by Bazant (1995). This law is based on energy release arguments and dimensional analysis. This scaling law seems to be

independent of the type of concrete. That means that this law applied for high strength concrete leads to the same "scale sensitivity" as for an ordinary concrete. This is not consistent with the experimental results (see table 2).

2. The 'multifractal scaling law' proposed by Carpinteri et al. (1994). This law is based on a geometrical approach of cracking of concrete using a fractal model which considers that the microstructural disorder is predominant.

In the two laws are introduced a fracture parameter of concrete is introduced, which is defined for an infinite size of the structure (the tensile strength, or the fracture energy release). The determination of this parameter may cause some practical difficulties..

4.2 Finite element analysis

Two types of approach can take into account the scale effect related to the cracking of concrete structures:

- the deterministic models introducing in their formulation a characteristic length scale considered as a material property (non local concepts, Cosserat continua, higher-order deformation gradients approaches...),
- the probabilistic models using random distribution functions of the material properties (Young modulus, strengths, fracture energies...), or of the grain in the matrix to take into account explicitely the heterogeneity of concrete.

Concerning the first type of approach, it seems that the internal length scale introduced has no clear physical significance whith respect to the cracking phenomena in concrete. In return, probabilistic models are based on a physical ground consistent with the physical origins of the size effects in cracking of concrete (see Rossi (1994b) and Rossi and Ulm (1995)).

5 References

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