REMARKS UPON SIMULATION OF FRACTURE IN FIBRE REINFORCED CONCRETE

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Abstract

To predict the crack growth resistance of fibre reinforced cement-based composites the simulation based on fracture mechanics is presented, treating mode I crack propagation and steel fibres. The resistance mechanism may be divided being: subcritical crack growth in the matrix and the start of the fibre-bridging phenomenon; post-critical crack propagation in the matrix such that the net stress intensity factor owing to the applied load and the fibre-bridging stresses continues constant, and an end phase when the resistance to crack separation is uniquely given by fibres. The response of concrete concerned in course of all stages was predicted from the knowledge of matrix fracture qualities and the pull-out load against slip dependence of single fibre. The model can be verified with the results of experiments performed on notched beams. It is necessary to fit loading in a closed-loop testing machine in order to keep a constant rate of crack mouth opening displacement.

Keywords: matrix, mechanical properties, modelling fracture, pull-out load, resistance mechanisms

1. Introduction

In general, reinforced concrete structures are designed to get ductile and stable characteristics in the non - linear region. Non-linearities that occur in the overall behaviour of the construction are mainly the result of cracking. Two complementary ways of tackling are possible to control this cracking:

- The form of arrangement of reinforcement bars within the reinforced concrete structures can be optimized so that the bars possess a macrocrack stitching operation. Subsequently, the distribution and orientation of reinforcement in the construction must depend on their boundary conditions.
- It can optimize also the different materials set up the composite structure of reinforced concrete, as well as their interfaces, to obtain a composite structure dissipating the greatest amount of energy possible before its unstable characteristics stage. Regarding the matrix of this composite structure, one of the solutions modified to reach the objectives system was to include fibres in order to control the cracks formed within this matrix. The latter approach can end in certain cases in the total or partial replacement of conventional concrete reinforcing bars by fibres

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which may be advantageous from the technological side and from the economic implication.

Fundamentals of fracture mechanics of fibre reinforced concrete were stated in [1]. In the field concerned recent research results are included in papers [3], [4] and [5].

2. Model for crack growth

The proposed model can be described in view of the load versus crack mouth opening displacement relationship of a notched beam demonstrated in Fig. 1. The unreinforced matrix is supposed to achieve the critical load-carrying capacity when the stress intensity factor K^S_{Ic} is attained.

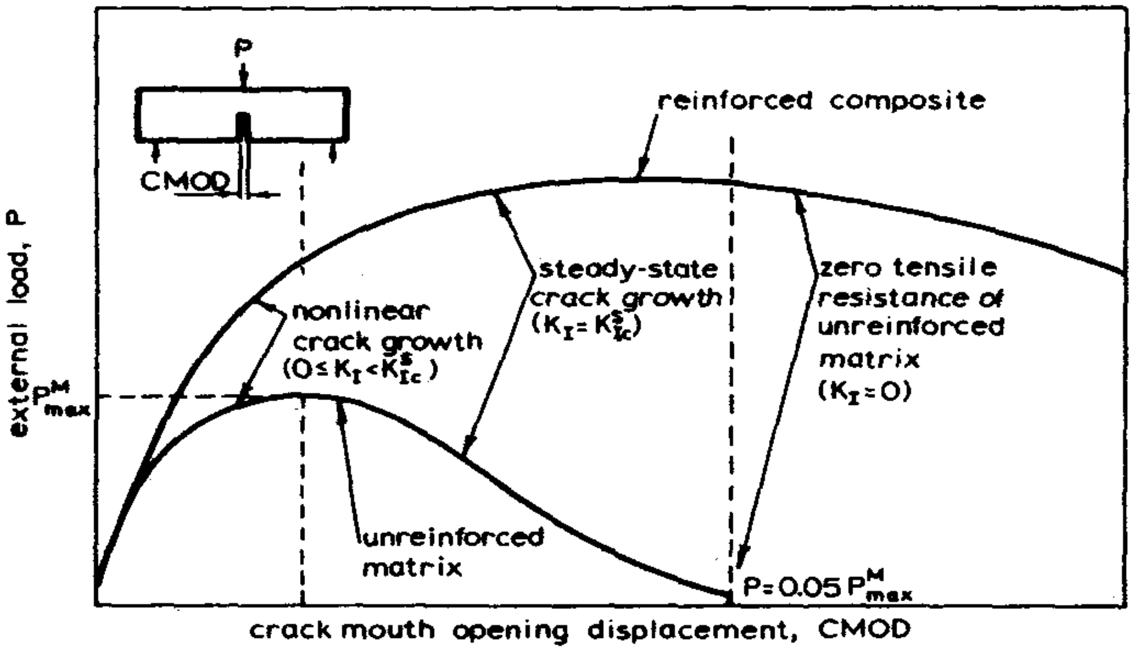

Fig. 1: Fracture resistance processes of fibre – reinforced concrete

The problem of cracking in fibre reinforced concrete is further solved from the following viewpoints:

- Intervention of fibres at different scales and phases of the concrete cracking course;
- Examples of experimental results dealing with the mechanical properties (tensile, compressive and flexural strength, behaviour under dynamic loading) of fibre reinforced concrete;
- State of our knowledge related to the simulation of fracture in fibre reinforced concrete.

In course of three phases of the crack process, the fibres interfere in various ways:

- During the first phase corresponding to uniform microcracking, the fibres have a stitching functioning on the microcracks, preventing them from growth this intervention of the fibres delays the microcracking location stage and therefore the object of macrocracks;

- When macrocracking appears, fibres will play the same role as reinforcement in concrete with regard to these macrocracks.

For fibre-reinforced composites, the crack propagation in the matrix is assumed to be governed by the same criteria as those for the unreinforced matrix. However, the fibre-bridging effect must be included in calculating the imposed stress intensity factor K_I. The total load P operating on the composite can be divided into three parts (Fig. 2):

$$P = P^M + P_k^f + P_s^f \qquad (1)$$

where P^M is the contribution owing to the matrix and is related to K_I; P^f_k is related to K^f_I just achieves K^s_{Ic}. Depending upon the volume of fibres, the maximum load for FRC may occur for a larger crack length than that corresponding to the peak load of the unreinforced matrix (Fig. 1). Beyond this load the cracks in FRC continue to extend while maintaining $K_I = K^s_{Ic}$, the corresponding value of P can be determined using the proposed model (Eq. 1).

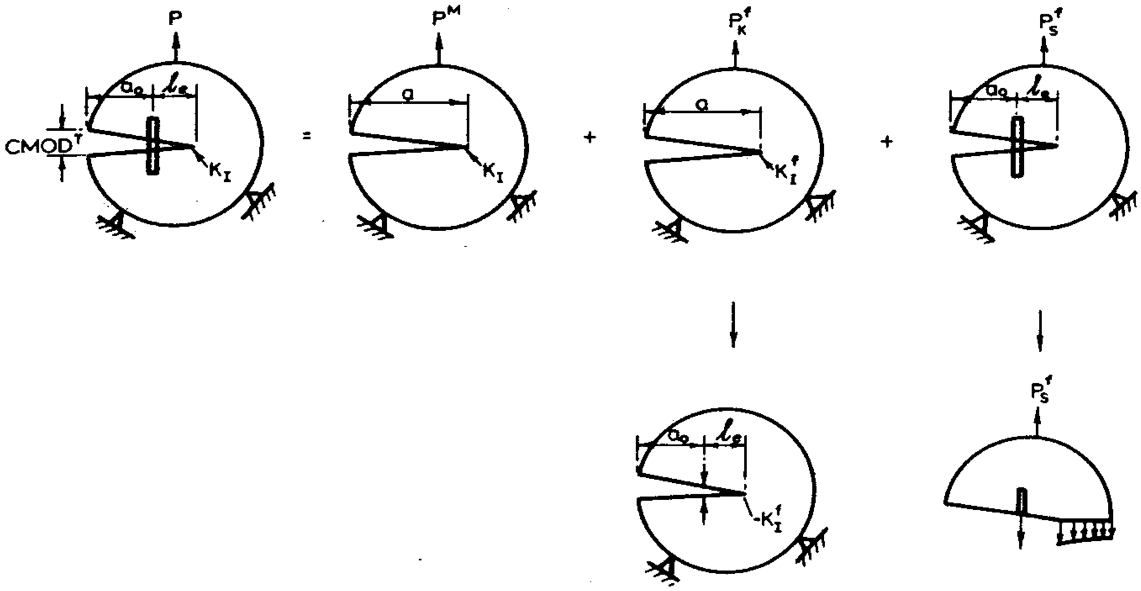

Fig. 2: Make-up of external load applied on fibre-reinforced construction

When the crack mouth opening displacement (CMOD in Fig. 1) becomes very large, the resistance offered by the matrix becomes negligible, and eventually the stress intensity factor K_I becomes zero. Further crack separation is now mainly resisted by fibres. At this stage the load P and the corresponding CMOD can be calculated from the global equilibrium consideration only. It holds:

$$P = P_s^f \qquad (2)$$

3. Intervention of fibres at the crack process

As a result, the fibres will interfere in two steps: at the material (or macrocrack) level and at the structural level (location phase). This will demand the optimization of the fibre dimensions and of the included percentage, too, according to the mechanical qualities to be improved. For rheological reasons (workability), two possibilities can be taken into account for the mix design of a fibre reinforced concrete: it is possible either to incorporate a high percentage of short fibres, or a low percentage of long fibres. In the first event, the strength of the material will increase, and in the second case, the ductility of the construction will be improved (to be effective regarding microcracking, the fibre must possesses a sufficiently long anchoring length).

The different strengths (compressive, tensile, bending) of these fibre concretes are generally higher than those of normal concrete. The energy absorbed by structures in fibre reinforced concrete within their non-linear characteristics region is also greater than in the case of traditional concrete structures, no matter if during static loading, fatigue loading, high strain rates or in course of shocks.

At present, some different and complementary approaches are used for the simulating fracture in concrete. Regarding fibre reinforced concrete, the main investigations solved particularly with two approaches. The first one is the conventional continuous method, in that the stress-strain law is introduced in an analysis, the second is the discrete procedure to the cracking effect that consists of investigating the growth of individual cracks.

Further, critical stress intensity factor and critical crack-tip opening displacement are specified in an experimental way. On top of that, for fibre reinforced composites, both load CMOD curves and load-deflection response are calculated.

4. Fracture simulation

Linear fracture mechanics renders to study crack propagation in mode *I*, *II* or *III* or the mixed mode, by finding out the toughnesses (eg. K_{Ic}, K_{IIc}), which are considered to be intrinsic qualities of the material. For fibre reinforced concrete, alike as for normal concrete energy dissipations, going with crack growth are greater in fibre concrete. Of course, this is owing to the dissipative events related to the presence of fibres, that is to say, the loss of bond between concrete and fibre, friction effects between fibre and concrete, and, plastification of fibres in the case of metallic fibres with a plastic plateau. It is deduced that these dissipative events result in a non-elastic region at the peak of the macrocrack, which is greater in fibre concrete than in normal concrete, and in a crack growth stage, under steady state circumstances, more difficult to achieve in the event of fibre concrete. Linear fracture mechanics is appropriate only if the crack propagates under steady state conditions that very obviously restrict its applicability to fibre concrete.

In contradiction with linear fracture mechanics which is a total way of tackling, non-linear fracture mechanics is a local approach demanding the application of either a non-linear local characteristics law of the material or a numerical method incorporating an iterative process for the solution of non-linear equations.

5. Two-parameter model

In the two-parameter model, according to [2] two intrinsic qualities determine the growth of a crack in concrete: K_{Ic} (toughness of concrete in mode I) and CTODc (critical value of crack tip opening displacement). The purpose of using these two parameters is to get a model independent of the scale effect and of the boundary conditions on the structure under investigation. In the event of fibre reinforced concrete, crack growth in the matrix is determined by the same criterion as for normal concrete, viz.:

$$K_I = K_{Ic} \rightarrow \text{propagation of crack} \tag{3}$$

The CTODc parameter renders the calculation of effective crack length (real crack + microcracked region) in the course of propagation. To calculate K_{Ic}, this crack length has to be known. The clampdown of the fibre in this model comes during the calculation of K_I. Actually, the total stress operating on fibre reinforced concrete is failed in the following form:

$$P = P^m + P_K^F + P_S^F \tag{4}$$

where P^m is the contribution of the matrix, relates to K_I, P_K^F is related to K_I and interferes on the singularity at the crack peak, and P_S^F is the stress produced by the fibres that have the stitching operation on the macrocrack; this stress satisfies the total equilibrium on the cracked construction. In the previous Fig. 2, this breakdown of the stress P is schematically demonstrated. Concurrently, it is important to know the crack closing stress P_S^F owing to the stitching action performed by the fibres. This stress is stipulated from pull-out tests on single fibres embedded in concrete.

Fibre stress-slip curves obtained experimentally may be approximated by the expression:

$$\frac{\sigma(w)}{\sigma_{max}} = \left(1 - \frac{w}{w_{max}}\right)^m \qquad \text{for} \qquad 0 \le w \le w_{max} \tag{5}$$

where: σ_{max} is the maximum stress reached divided by the overall cracking surface, w the fibre slip or crack opening, w_{max} the fibre slip when the stress becomes zero, $\sigma(w)$ is the stress belonging to each slip of the fibre divided by the crack surface, and m is a constant that depends on the fibre type.

Indeed, the maximum stress σ_{max} depends on the number of fibres passing through the cracked surface, and thus on the percentage of fibres included in concrete. On top of that, in a real fibre reinforced concrete, fibres are dispersed randomly and that is why are unaligned. This will have an influence on the values of σ_{max}. To take this side into consideration, the following relationship is supposed for straight fibres: $\sigma_{max} = 1.655\ v_{ef}$, where v_{ef} is an effective percentage of fibres acting on the crack surface. This percentage is set empirically.

In Fig. 3 test results from three-point bending are compared with predictions of the two-parameter simulation.

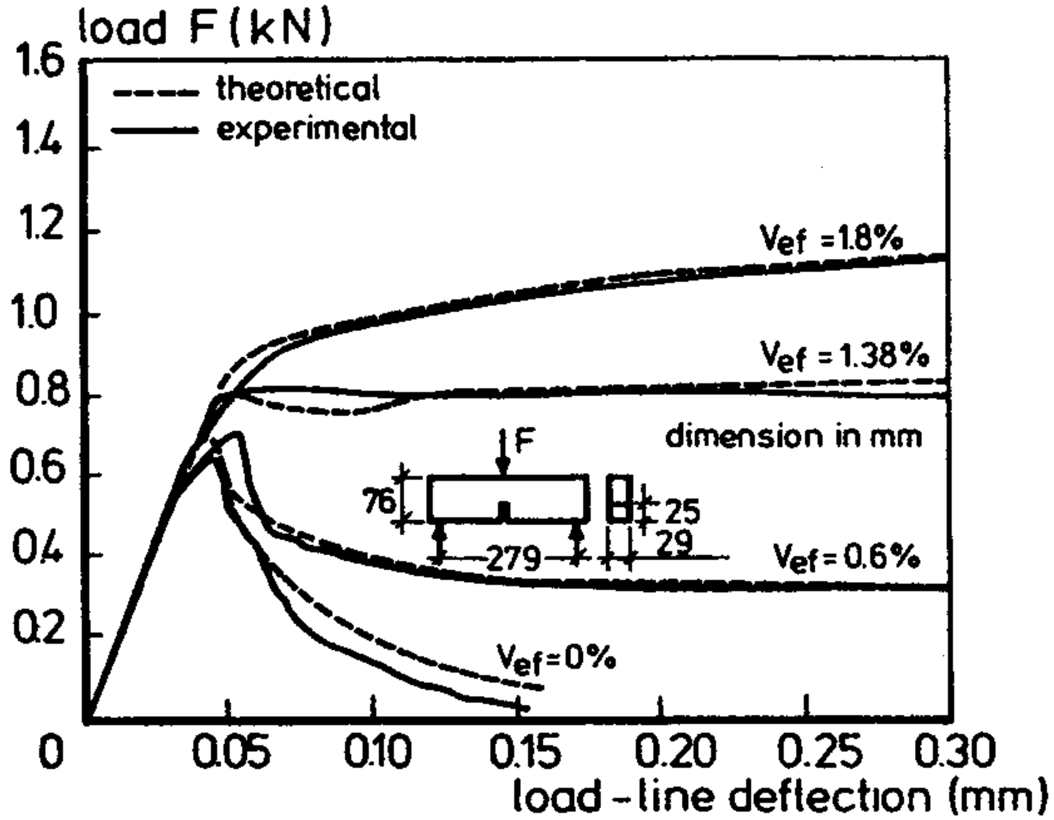

Fig. 3: Likeness of prediction and test results of load-deflection dependences

6. Conclusions

The model presented is based on the matrix fracture qualities, supposing that the crack growth in the matrix can be depicted by two parameters: the critical stress intensity factor and critical crack-tip opening displacement. Regarding the nonlinear slow crack growth, two fracture parameters are demanded. The stress intensity factor is calculated at the tip of the effective crack rather than the initial crack length. The effect of fibres is to reduce the stress intensity factor at the tip of the effective crack and to provide additional energy owing to debonding. These influences can be included in the proposed model if the pull-out low-slip relationship of a single fibre is known. The model predicts load versus deflection and load against crack mouth opening displacement dependence compared favourably with the experiments described.

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7. References

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