DEPENDENCE OF CRACK OPENING ON DEFLECTION DURING BENDING TEST OF FIBRE REINFORCED CONCRETE

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Abstract

Valid standards and the other current codes allow two methods for description of fibre reinforced material model: stress-strain law (σ-ε) or stress-crack opening relationship (σ-w). Both models can be derived from material testing (usually bending tests) and they can be used in static calculations and numerical simulations. Both deformation parameters (strain ε, crack opening w) describe the response of the same material on the specific load, so they should somehow be interlinked. The fibres in a concrete structure usually bring more cracks, crack opening decreases with increasing fibre dosage. This is positive for serviceability and durability of the structure. This paper deals with the correlation between crack opening and deflection of specimens in the three-point and four-point bending tests, depending on the fibre dosage in concrete matrix. In experiments there were used materials characterised by tension softening behaviour or hardening behaviour after macrocrack formed. Comparison of test results and relations between both deformations parameters for fibre reinforced concrete with various fibre dosages was the aim of experimental analyses. The study shows different behaviour of fibre reinforced concrete, depending on the arrangement of tests and material mixture.

Keywords: fibre reinforced concrete, bending tests, deflection, crack opening

1. Introduction

Fibre reinforced concrete is a structural material whose ductility is higher than for plain concrete. The differences in behaviour are considerable especially in tensile stress. Tensile strength of fibre reinforced concrete is the basic parameter for description of tension behaviour. Knowledge of peak- and post-peak tensile strengths at the particular values of strain allows defining the stress-strain diagram of material. The deformations properties of material can be universally described using the strain ε or using the crack width w. The material model is so described by σ-ε curve or σ-w curve. Stress and strain are not however the measurable parameters and must be derived from different (loading force F, deflection δ, crack mouth opening displacement *CMOD*, longitudinal deformation Δ or other). The specific case depends on the type and arrangement of using test.

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Tensile properties of fibre reinforced concrete are usually determined by performing a three-point bending test on a notched beam according to [6] (Fig. 1a) or by performing a four-point bending test on an un-notched beam according to [7] (Fig. 1b)

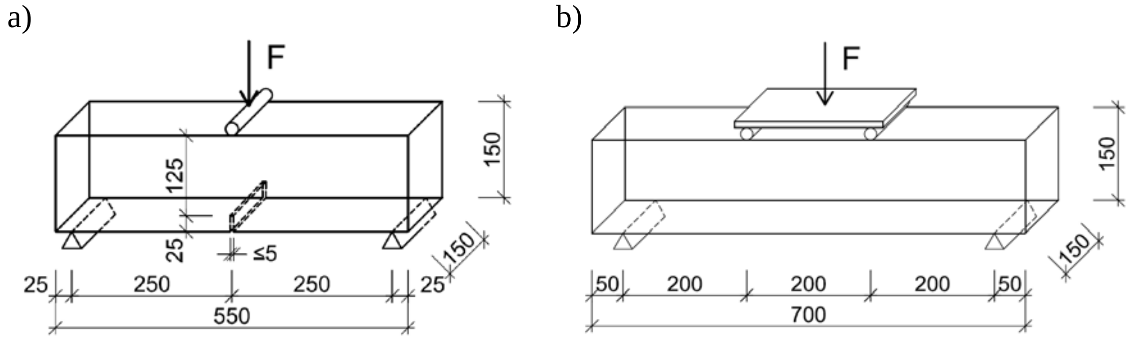

Fig. 1: Arrangement of bending tests: a) 3-point bending test, b) 4-point bending test

Both options have their advantages and disadvantages and currently it is not a uniform view in the world. Three-point bending test with notched beam exactly defines the cracking point and it allows installing the notch mouth opening displacement measuring gage. The dependence F-δ or *F-CMOD* can be the direct test output. On the other hand, the area, where crack is formed, may not be the weakest point of the material and the complicated state of stress near the notch distorts the results of the material tests. The crack formed in the material weakest point (the middle third of the specimen span) in the four-point bending test. But this point isn't known in advance, so crack mouth opening displacement can't be directly measured.

2. Behaviour of FRC in tension

The tension test results also depend on the type of tested material. Two types of structural fibre reinforced concrete behaviour can be distinguished:

- tension softening behaviour
- tension hardening behaviour

In the case of tensile softening behaviour the maximum load capacity of the specimen occurs when macrocrack is forming. When the value of tensile stress exceeds the material strength, the macrocrack is formed. The rigidity decreases in this cross section and all subsequent deformation localizes in this crack (Fig. 2a). There are no more cracks and the loading force decreases with increasing deformation (Fig. 3a). This case is typical for FRC with lower dose of fibres. Material and ended shape of fibres and the quality of the cement matrix are also important factors.

In the case of tensile hardening behaviour there is immediate activation of fibres after cracking. The fibres are able to transfer the stress, which was previously transferred with concrete. The rigidity of critical cross section is higher that rigidity of unbroken cross sections and so additional crack appear (Fig. 2b). The loading force continues to increase with increasing deformation of specimen until material reaches a certain value of strain (Fig. 3b). At this moment one crack becomes the dominant, it absorb all deformation, while other cracks are closing and the loading force drops.

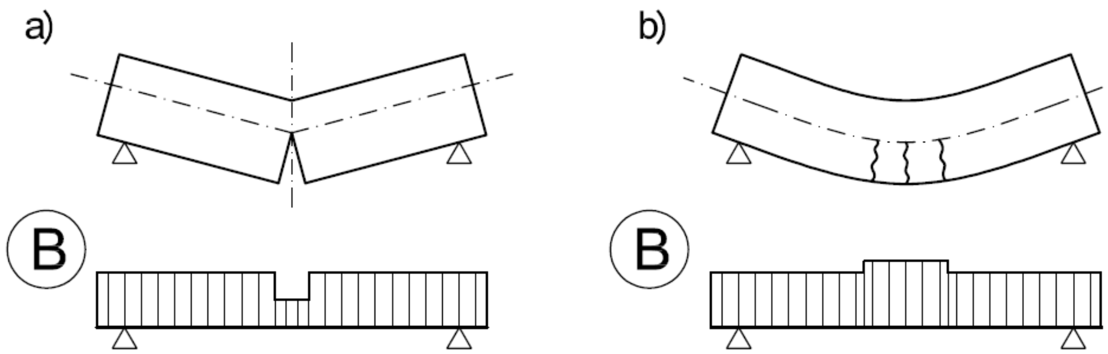

Fig. 2: Flexural rigidity of FRC after cracking: a) softening behaviour, b) hardening behaviour

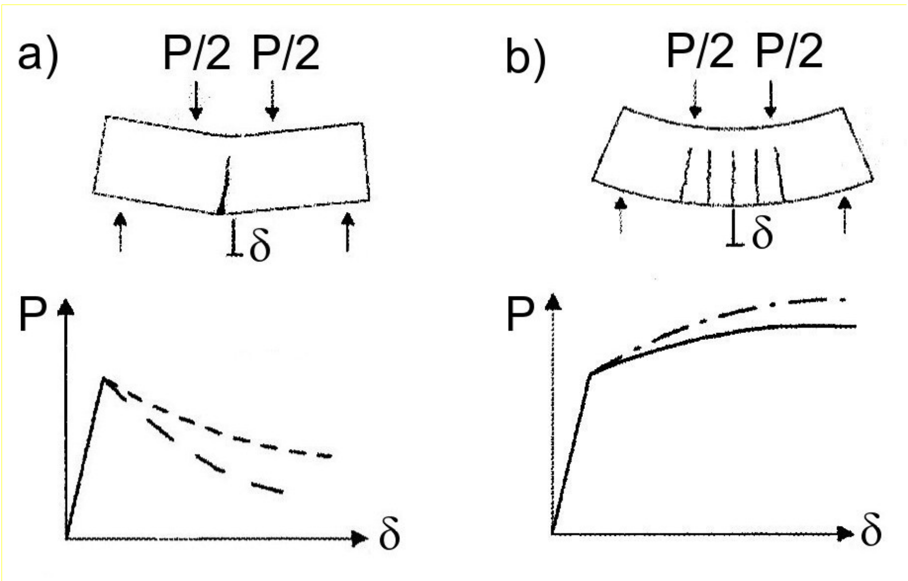

Fig. 3: F-δ diagram of FRC: a) softening behaviour, b) hardening behaviour

3. Dependence CMOD versus mid-span deflection

Deflection and crack width are two variables which describe the deformation behaviour of the test specimen in bending tests. Because both variables describe the behaviour of the same material, they must necessarily be somehow dependent. In [1] and [2] it is possible to find the basic relationship between the crack mouth opening displacement *CMOD* and the mid-span deflection δ of beam in three-point bending test according to Fig. 1a:

$$CMOD = 1{,}18 \cdot \delta - \beta \qquad \text{with } \beta = 0{,}0416\, mm \tag{1}$$

It is universal relationship between *CMOD* and δ, which is independent of the fibre content and of the composite strength. This equation is based on an averaging of the different relationships which were obtained using a lot of experimental and analytical results.

A similar, but inverse relationship is shown in [6]:

$$\delta = 0{,}85 \cdot CMOD + 0{,}04 \tag{2}$$

The influence of a particular type and dosage of fibres on the crack width is analytically very difficult to determine. For simplicity, let's consider only one mid-span crack. Before the crack is formed, material behaves elastically (Fig. 4a). In the post-peak part of stress-strain diagram, the flexural rigidity of critical cross section is significantly lower than in other part of beam. So each increase of deflection is reflected by rotating only the critical section and by the increase in crack opening (Fig. 4b). It is typical for material with post-peak softening behaviour.

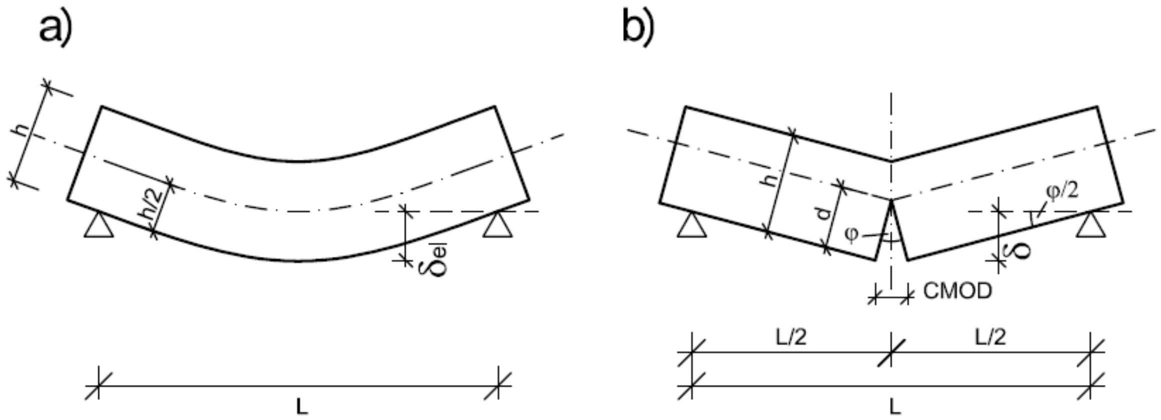

Fig. 4: Deformation of FRC beam in bending: a) before the crack, b) after the crack

Geometrically we can build the following equation:

$$CMOD = \frac{4 \cdot d \cdot \delta}{L} \tag{3}$$

where L is span of beam and d is crack length.

Crack length is variable parameter and is related to the value of deflection and tensile strength of the material. When the crack width grows, its length grows too, the height of the compression zone reduces and the neutral axis moves to the pressed edge. The crack length can be determined from equal normal forces in the critical cross-section (Fig. 5)

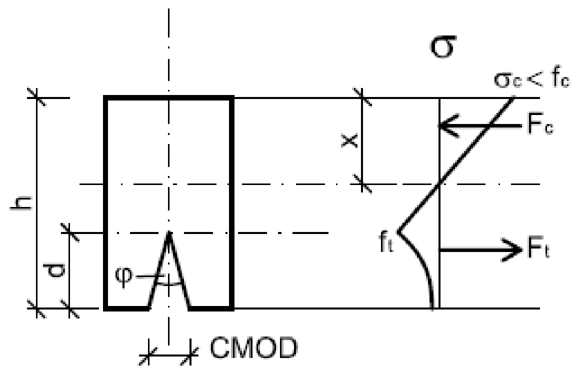

Fig. 5: Stress analysis of the critical section

But it is only simplified theoretical model, dependence for particular composite must be derived experimentally.

4. Experiments

The aim of experiments was to verify the dose-effect fibre on crack opening in bending stress of fibre reinforced concrete. Three types of cementitious composites were tested. The basic and reference material was the plain concrete with average cube compressive strength 66.3 MPa. The other composites had the same concrete matrix and steel fibres TriTreg 50/1,05mm in volume dose 0.5% and 1.0% were used as an admixture. The average cube compressive strengths of these composites were 79.9 MPa and 76.0 MPa.

4.1 Tests arrangement

Six sets of 3 concrete and fibre reinforced concrete specimens were prepared. Three sets of specimens (with volume fibres dose 0, 0.5 and 1.0 %) were prisms with dimensions 150×150×600 mm and 25 mm deep mid-span notches. The specimens were simple supported (a span of 500 mm) and were tested in three-point bending test (Fig. 1a). The dependence loading force F versus mid-span deflection of specimen δ was recorded. The notch mouth opening displacement measuring gage was installed in notch on the bottom surface of specimen. The results were the *F-CMOD* curves.

The other three set of specimens were prisms with dimensions 150×150×700 mm, without notches. They were also simple supported (a span of 600 mm) and were tested in four-point bending test (Fig. 1b). In these cases only F-δ curves were recorded, because there wasn't known the positions of failure and so it wasn't possible to place CMOD gage. After cracking the crack mouth opening displacement *CMOD* was measured on the bottom surface of the specimens with external scale.

4.2 Results of experiments

The recorded curves of experiments (F-δ curves, F-CMOD curves) are shown on Fig. 6 and 7. Because brittle failure is typical for the plain concrete specimens without fibres, it wasn't possible to measure crack mouth opening displacement in this case (Fig. 7b).

All specimens with 0.5 % volume dose of fibres showed the tension softening behaviour after cracking. There is only one crack, in which is localized all subsequent deformation of material after failure. The loading force drops with increasing deflection of specimen, but its value at a deflection of 3.5 mm is higher than third of peak value. Ductility of this material is sufficient and it is possible to consider this material as a structural fibre reinforced concrete.

All specimens with 1.0 % volume dose of fibres showed the tension hardening behaviour. After crack appeared, the loading force continues to grow and maximal loading capacity of specimen is achieved at deflection from 0.5 mm to 1.0 mm. Although it is generally possible that more macrocracks will formed for tension hardening material in four-point bending test, in all experiments only one macrocrack formed (the formation and development of microcracks in another place can't be proved or ruled out). Small loading force decrease after cracking is evident in Fig. 5b. It is caused by the delayed activation of fibres in the composite.

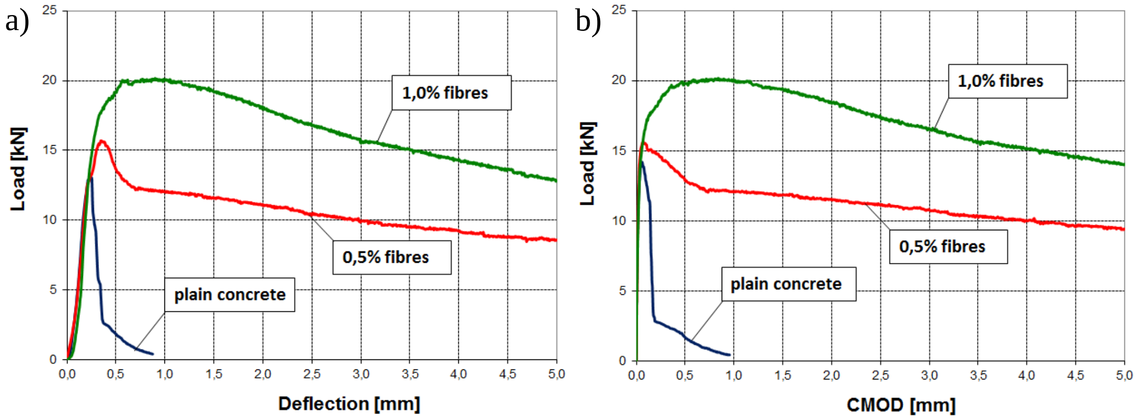

Fig. 6: Average results of 3-point bending test: a) F-δ curves, b) F-CMOD curves

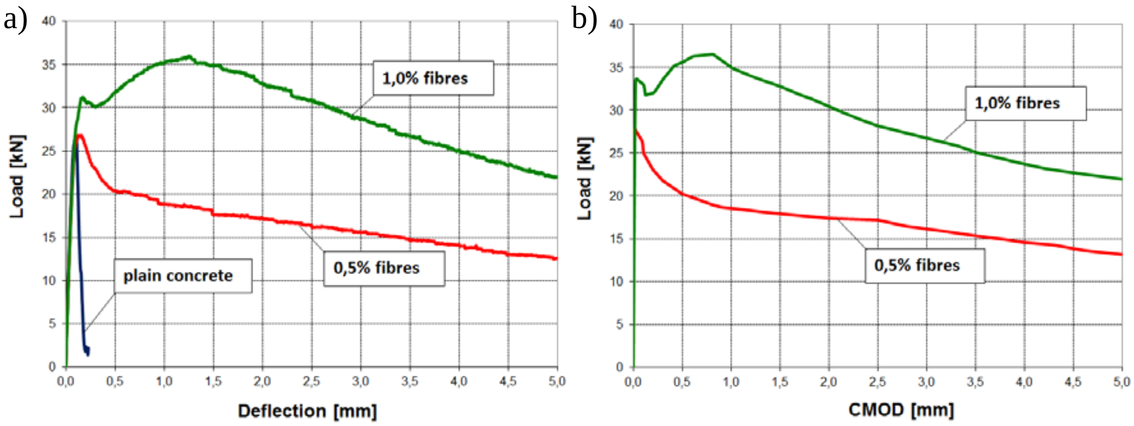

Fig. 7: Average results of 4-point bending test: a) F-δ curves, b) F-CMOD curves

4.3 Dependence CMOD versus mid-span deflection

From the experimental results (Fig. 8) the dependences *CMOD* versus mid-span deflection δ were derived for the particular materials and particular test arrangements. A linear approximation was chosen in the linear form:.

$$\delta = a \cdot CMOD + \delta_0 \tag{4}$$

where a is the ratio between deflection δ and measured value of *CMOD* and δ_0 is value of deflection at which a crack appeared.

The relations in inverse form:

$$CMOD = k \cdot \delta + \beta \tag{5}$$

are shown in Tab. 1.

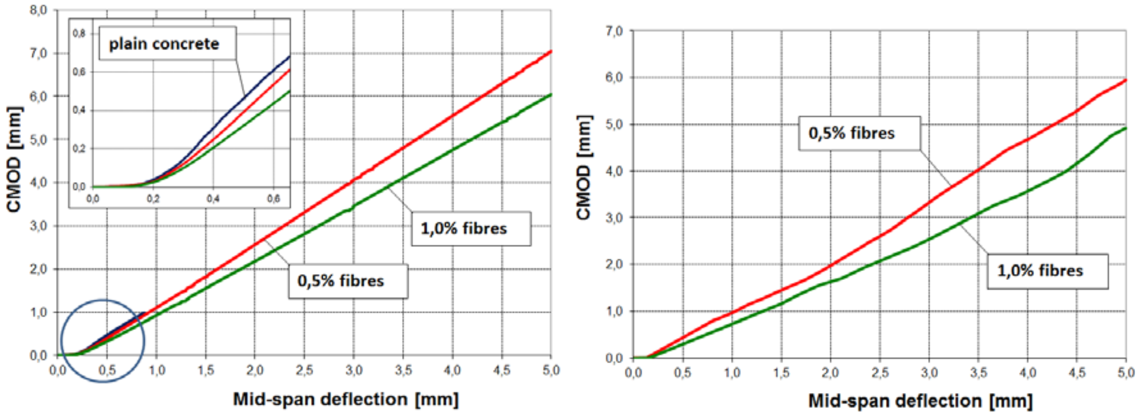

Fig. 8: CMOD versus mid-span deflection: a) 3-point bending test, b) 4-point bending test

Both types of tests have shown that the higher dose of fibres has resulted in lower crack mouth opening displacement at the same deflection (Fig. 8). The dose of fibres has also influenced the time at which the first crack appeared. It is generally possible to say that fibres limit the development of microcracks and delays the macrocrack formation.

Tab.1: Average relationships between *CMOD* and δ

three-point bending test	
plain concrete	$CMOD = 1{,}474 \cdot \delta - 0{,}299$
0.5% FRC	$CMOD = 1{,}496 \cdot \delta - 0{,}427$
1.0% FRC	$CMOD = 1{,}278 \cdot \delta - 0{,}363$
four-point bending test	
plain concrete	-
0.5% FRC	$CMOD = 1{,}215 \cdot \delta - 0{,}178$
1.0% FRC	$CMOD = 0{,}977 \cdot \delta - 0{,}223$

5. Conclusions

Experimental results confirmed the assumption that the fibres present in the composite material structure have a positive contribution to cracks opening when the deformation is induced.

The ratio between crack mouth opening displacement and the specimen deflection in bending test is approximately linear, but the particular parameters depend on test arrangement and mainly on the composition of the composite.

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