MECHANICAL TESTING OF METALLIC FIBRE CONCRETE

J. Jerga[1] and M. Križma[2]

Abstract

The mechanical properties of metallic fibre concrete are very sensitive to the mixture composition and the mode of execution (e.g. orientation of fibres). Based on the stress-strain diagram from the strain-rate controlled testing procedure an overview of methods for toughness evaluation according to different standards and recommendations is presented in the contribution. The suitability of torsion tests, so as the revival of methods based on the splitting tensile strength is discussed. Some remarks on presented methods are added.

Keywords: Fibre reinforced concrete; residual flexural tensile strength; energy absorption capacity; toughness.

1 Introduction

Fibre reinforced concrete (FRC) found the use in various structures, where the application of classic reinforcement would be impossible or impracticable and contemporary the load caring capacity at large deformations is required. It is obvious that the material is often acting in the post-cracking region. Hence except of strength, elasticity, fatigue and rheological properties, the ability of FRC to absorb energy is crucial and should be demonstrated before its use in the structure. Various tests were introduced during the years – based on the evaluation of the stress-strain diagram with both ascending and descending branches from tests at the strain rate controlled (stiff) testing procedure. An overview and comparison of the test methods is presented in the following.

2 Beam and slab tests

The ability of FRC to deform plastically and to absorb energy before fracture is termed as *toughness*. *Ductility* expresses the magnitude of deformation before fracture, but it is not itself a guarantee of a high toughness. The strength during the strain increase is the second parameter involved. Hence the area under the stress-strain curve (e.g. from a tensile test) is a proper way for the characterization. Three variables have a significant influence on the toughness: *strain rate*, *temperature* and *notch effect*. Usually toughness decreases (due to ductility decrease) if the rate of loading increases or the temperature decreases. The

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[1] Ing. Ján Jerga, PhD., Institute of Construction and Architecture of the Slovak Academy of Sciences, Dúbravská cesta 9, 845 03 Bratislava, Slovakia, phone: +421 2 59 30 9224, mail: jan.jerga@savba.sk

[2] Ing. Martin Križma, PhD., Institute of Construction and Architecture of the Slovak Academy of Sciences, Dúbravská cesta 9, 845 03 Bratislava, Slovakia, phone: +421 2 59 30 9228, mail: usarkrim@savba.sk

multiaxial stress state is caused by the notch, influencing the toughness as observed at uniaxial stress distribution.

The shape of tested elements is determined by their origin. Generally we can distinguish the samples from *cast* FRC, *sprayed* FRC and samples *taken from the structure*. They are usually the centre-point or third-point loaded prisms (three-point or four-point flexural tests), with or without the notch in the centre of the span (Fig. 1), so as the plates. Two types of beams are introduced by the European standards. The centre-point loaded prisms 150 x 150 mm with the span equal to 500 mm [7] cast into the moulds (concrete with aggregate size no longer than 32 mm and metallic fibres no longer than 60 mm) have mid-span notch (50 x 25 mm) sawn through the width of the specimen.

On the other hand the specimens according to [5] are sawn from a sprayed panel and tested with the bottom uncut moulded face in tension – to avoid cutting end anchorages of the steel fibres. The prism with the cross-section 125 x 75 mm without the notch is third-point loaded (span 450 mm). The same dimensions and arrangement is proposed by EFNARC [3]. The Japan Society of Civil Engineers [28] and ASTM [1] present the tests on unnotched third-point loaded prisms with the span equal to 450 mm (= 3d) in their recommendations.

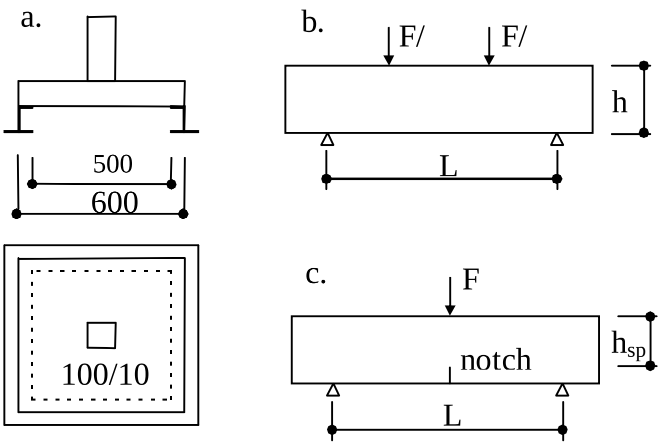

Fig. 1 Scheme of flexural test.
(a – plate, b – unnotched beam, c – notched beam)

For the energy absorption capacity determination of sprayed concrete the using of slabs is widespread. In EN [6] the plate with dimensions and arrangement according to Fig. 1a is prescribed. The load is applied to the sprayed face, the smooth moulded side of the test slab being on the bottom during the test. At slab tests according to the EFNARC specification [3] the load is applied opposite to the spraying direction. The advantage at [6] may be the better bedding conditions (due to evenness) in the contact with the supporting frame. Another slab test is defined in [2]. The centrally loaded round panel specimen with nominal dimensions 75 mm in thickness and 800 mm in diameter is supported on three pivoted points, arranged symmetrically around its circumference (defining the circle with the diameter equal to 750

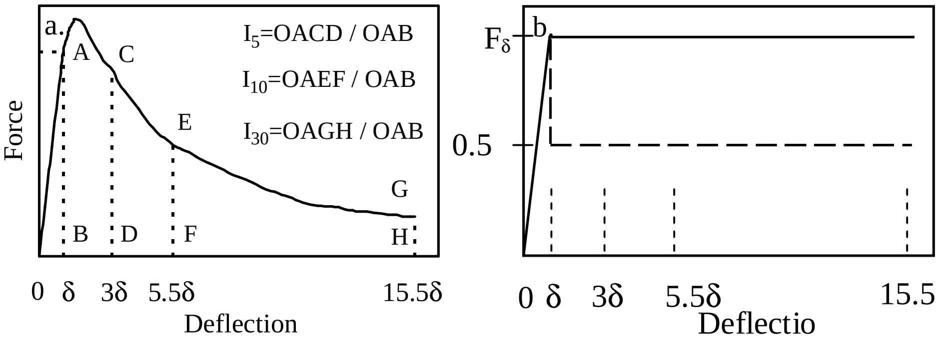

Fig. 2
Toughness indices.

mm).

The testing procedures do not differ significantly among the individual specifications, but a greater variety of practices could be found at the interpretation of results. Some methods used for the mechanical properties characterization of metallic fibre concrete are presented in the following.

In the ASTM method [1] (withdrawn in 2006) the toughness indices I_5, I_{10}, I_{20} and I_{30} are defined as the ratio of the absorbed energy (area below the load-deflection curve) up to the given deflection ($3d$, $5.5d$, $10.5d$ and $15.5d$) to the absorbed energy up to the deflection at the first crack d (Fig. 2a). The index represents its value for the material fully elastic up to the first crack and fully plastic after the first crack (solid line in Fig. 2b). The ***residual strength indices R*** [15] express the ratio of the average strength in given interval (descending branch) to the first crack strength. Introducing the absorbed energy we receive for the interval $\langle 3d, 5.5d\rangle$ $R_{5,10} = 20(I_{10} - I_5)$ in percentage and similarly $R_{10,20} = 10(I_{20} - I_{10})$. For the load-deflection diagrams in Fig. 2b indicated with the solid line and dashed line, both the $R_{5,10}$ and $R_{10,20}$ will be 100 and 50 respectively.

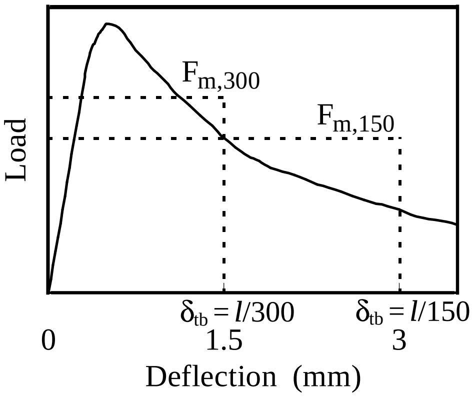

Fig. 3 Equivalent flexural strength

The equivalent flexural strength method is recommended by the Japan Society of Civil Engineers [28] for the toughness characterization. Forces $F_{m,300}$ and $F_{m,150}$ are calculated from the load-deflection diagram (Fig. 3) up to the deflection 1/300 l and 1/150 l, where l is the span of the beam equal to 450 mm. The condition is kept that the absorbed energy up to given deflection is equal to the energy corresponding to the action of the constant equivalent force. It is obvious, that the pre-peak, so as the post-peak energy absorption behaviour is involved in this characterization.

The EFNARC specification [3] defines the residual strength classes. The descending branch of the load-deflection diagram should comply with requirements on residual stress at prescribed beam deflection. Five residual strength classes are defined by means of stress boundaries up to the deflection limits of the corresponding deformation class (low – 1 mm, normal – 2 mm and high - 4 mm).

The modified equivalent strength method according to RILEM [29] is one of the procedures introduces recently. Two parameters f_{eq2} and f_{eq3} characterizing the equivalent flexural strength are defined. Similar as at JSCE method [28] the equivalent force is calculated from the load-deflection diagram (Fig. 4). However the absorbed energy corresponding to the ascending branch and the triangle with the base equal to 0.3 mm is not taken into the consideration [25]. The equivalent strengths are given by the expressions

$$f_{eq2} = \frac{3}{2}\left(\frac{D^f_{BZ,2,I}}{0.65} + \frac{D^f_{BZ,2,II}}{0.50}\right)\frac{L}{bh^2_{sp}}, \tag{1}$$

$$f_{eq3} = \frac{3}{2}\left(\frac{D^f_{BZ,3,I}}{2.65} + \frac{D^f_{BZ,3,II}}{2.50}\right)\frac{L}{bh^2_{sp}}, \tag{2}$$

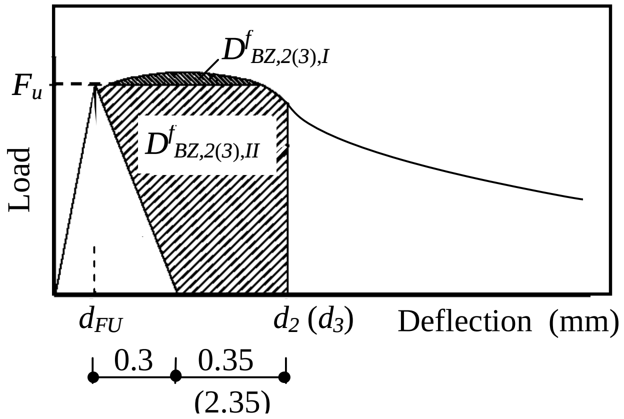

Fig. 4 Equivalent flexural strength (RILEM [29])

where L, b and h_{sp} is the span, width and ligament depth of the beam.

The residual flexural tensile strength values derived from the load-crack mouth opening displacement (CMOD) curve or load-deflection curve are used for the tensile behaviour of metallic fibre concrete evaluation according to [7]. The corresponding CMOD_j (j = 1,2,3,4) is 0.5 mm, 1.5 mm, 2.5 mm and 3.5 mm.

The residual strengths of sprayed concrete according to [5] are calculated from the minimum loads on the load/deflection curve between 0.5 mm and 1 mm, 2 mm and 4 mm (for the low – D_1, normal – D_2 and high – D_3 deformation classes according to [4]). The residual strength class D2S2 means – the strength exceeds 2 MPa at deflections 0.5÷2 mm.

In the plate tests (Fig. 1) the energy absorbed up to a specified central deflection expresses the ability of fibre concrete to carry the load after cracking and is related to the toughness of the material. As stated in ASTM comments to [2] the energy absorbed up to 5 mm central deflection is suitable if it is required to hold the cracks tightly closed – e.g. water-tight tunnels. For the material exposed to extensive deformations (e.g. shotcrete linings in mine tunnels) the limit 40 mm is more applicable. The energy absorption capacity in Joules derived from the load-deflection curve up to a deflection of 25 mm is prescribed by [6] and [3]. Toughness classifications *a*, *b* and *c* with energy absorption boundaries
500 J, 700 J and 1000 J are defined in [3].

3 Other tests and comments

The sampling of specimens from the structure is often carried out by drilling of cores, less convenient for flexural testing. Two modes of loading seem to be suitable – splitting tensile test and torsion. The cylinders with the sawn notch in the plane crossing the longitudinal axis [27] are often used for splitting tensile tests. The *double punch* (*Barcelona*) *test* [26] (compressing a vertically placed cylinder with two steel circular punches centred at the top and bottom surfaces – height and diameter of the cylinder usually identical, diameter of the punch – one fourth of the cylinder diameter) offers lower coefficients of variation of toughness comparing with beam tests. Very illustrative is the overview of test specimens in different recommendations according to *failure surface* and *specific failure surface* (related to the volume) [26]. Even though the Barcelona test could not rival with slab tests in the failure surface (though higher than at slab tests), the specific failure surface is unambiguously the most favourable. At the torsional loading the preparing of cylinders do not require the use of special devices and the results provide with information about greater area of the material [9].

Some comments should be added briefly. There are some uncertainties at the determination of the deflection *d*, registered at the first cracking, necessary for the toughness indices according to ASTM [1]. The microcracks alone cause the decrease of stiffness, before the creation of visible macrocrack. The neglecting of the support settlement effect of bended beams could be another source of uncertainties. Objections exist sometimes, that the ascending branch of the load-deflection diagram is involved in the evaluation at the JSCE method [28] (taken into account in RILEM Recommendations [29]). It is prescribed that the plates should be finished immediately after the spraying on the nominal depth with the tolerance of (-0/+ 10 mm) [3] and (-0/+ 5 mm) [6]. However the hardening accelerator is added usually to the concrete mixture, so that the levelling of the specimen on a given dimension is practically impossible. Greater depth variations should be expected therefore. Due to the lack of any possibility for fixing on the surface of the element, the manipulation with the wet plate of 90 kg mass presents an enhanced risk of an accident. The influence of fibre type on the deformation properties of lightweight concrete [24], so as the excessive strain treatment of structural aerated concrete members [12] with respect to the probability based solution of resistance [11] are important areas of future investigation, similar as the application of performance classes at the evaluation [8]. New challenge for the test methods innovation is the use of fibre concrete in structures for radioactive waste management [13] with the emphasis on nondestructive methods involving the artificial neural networks [10]. The interpretation of toughness results should comprehend the analysis of influence of aggressive media on the brittleness and the progress of the reinforcement corrosion [14, 19, 20, 21]. Interesting could be a comparison of testing methods applied to fibre concrete with recycled aggregate [30] from the point of view of variation coefficient of results, so as the optimization of sampling and testing procedures at strengthening and repair of existing structures by prestress [16, 17, 18]. An impulse for seeking new testing methods could be the application of fibre concrete for structures subjected to seismic actions [23] by the application of risk based safety analysis [22].

4 Conclusions

Systematic testing of metallic fibre concrete is essential for quality management in the stage of preparation, realization and maintenance of building structures.

Except of approved testing methods embodied in standards and recommendations another procedures are known and well suited to application at special occasions.

Methods based on torsion and splitting tensile strength are proper when samples are taken from the structure by drilling.

The position and the orientation of the specimen in the structure should be taken into account at the interpretation of results especially at sprayed fibre concrete.

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