Improved methodology for determining tensile strength of fibre reinforced concrete

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Abstract. Two configurations are currently used to determine the tensile strength of fibre reinforced concrete: simply supported beams of square cross section loaded either by two forces at thirds of spans (four-point bending test) or by one force at the mid-span where the specified cross section is weakened on the tensile side by a notch (three-point bending test). Based on elementary formulas, the tensile strength of fibre reinforced concrete is then determined. Considering the unacceptability of these formulas to capture the 3D problem and, in particular, for the three-point bending test, also because of significant singularities at the notch and the degree of statistical uncertainty in determining the actual position of the weakest area of the test specimen, such a test does not respect the real stress distribution in the tensile area which is changing in the process of load increase. The proposed adjustment of the test specimen eliminates these fundamental drawbacks by removing the singular areas of the specimen and leaving only the cross-sectional areas where only uniaxial stress state may be assumed. The results obtained by this methodology are presented, statistically evaluated and compared with the currently used procedures.

1. Introduction

Tensile strength is the basic material characteristics of fibre reinforced concrete. Several tests are used to determine the tensile strength in practice. The tests are different in their layout, technical complexity and credibility of the results.

In practice, the most common test is the bending test. The three-point bending test performed on a beam with notch or the four-point bending of the beam without notch are commonly used. In particular, the fundamental deficiency of the three-point bending test with notch is the predetermined failure mode and location. The correct properties throughout the whole test beam are not detected at all. The state of stress above the notch is very complicated that cannot be described by the elementary technical formulas. A significant non-linear behavior occurs in the bending test prior to macrocracking. As a result of all influences, the value of the tensile strength determined by the bending test is always higher than the real axial tensile strength of the material.

The following relationships are recommended to calculate the axial tensile strength from the bending strength provided by the bending test:
three-point bending: \[ f_{fct,ax} = 0.6 \times f_{fct,fl} \]  

four-point bending: \[ f_{fct,ax} = f_{fct,fl} / 1.45 \]

where \( f_{fct,ax} \) is the axial tensile strength of fibre reinforced concrete and \( f_{fct,fl} \) is the value of the tensile bending strength from the bending test.

In particular, it should be noted that the source of the correction coefficients of 0.6 and 1.45 in these formulas cannot be confirmed. The principal drawback of formulas (1), (2) is that they use the same coefficients for all varieties of concretes. The formulas are exactly the same for different types and material characteristics of the concrete, type and content of fibres. This is, of course, an essential point to the unreliability of the formulas.

The only presently used test trying to provide the axial tensile strength value is the axial tension test: cylindrical test samples with a notch in the middle of the cylinder height - the crack location is thus unambiguously defined by the notch. Only one spot of the test specimen is examined, i.e. with all of the principal drawbacks mentioned above.

An alternative to the described arrangement is to use a test specimen with a variable cross section along the length ("a dogbone") [2]. Both test configurations make it possible to detect the strength of the material directly in the axial tension - but the first test provides tensile strength in a defined cross section only. However, the test arrangements are technically demanding since the axial tension test is very sensitive to the inevitable imperfections and the load control thus places high demands on the testing technique. For this reason, such a test technique is currently used only exceptionally, primarily as a calibration test for deriving strength conversion relationships.

The wedge test is currently a less widely used method for determining the axial tensile strength of fibre reinforced concrete composites. In this case, the test body forms a cube with a notch (on one or both sides) into which a steel wedge is pressed through the cylindrical bearings. However, even in this case it is not possible to obtain the value of the axial tensile strength of the material directly, because the 3D state of stress results in very complex distribution of stress in the critical region.

An alternative method for determination of the tensile strength of a concrete composite, used today rather marginally, is the Barcelona Test (Tensile splitting strength of fibre reinforced concrete).

2. New methodology

The proposed methodology meets the main demands for usability for standard tests:

- It is easy to perform and is very close to its arrangement and execution at standard beam bending tests.
- It does not require any additional equipment and tasks in the tests, except for the drilling of a hole in the specimen.
- Provides a distribution of tensile stresses that is very close to uniform at the examined region.

The principle of the new test is that the test beam of standard dimensions 150x150x700 mm is modified by drilling a circular hole in the middle of the span (Figure 1., Figure 7.). The test is arranged as a four-point bending, i.e. in the inner third of the span is bending only, without shear effects. This creates a system consisting of two narrow areas in the middle of the span - upper compression zone and lower tensile zone (Figure 3.).
Figure 1. Test Layout Scheme.

The main advantage of the proposed methodology is the fact that the circular opening with its smooth round contour ensures elimination of singularities. Such singularities would arise from sharp interventions in the test specimen, such as a notch in a three-point bending test. An even more important principle of the proposed methodology is that the trajectories of the stress circulate smoothly around the curved periphery of the hole. This results in stress increase at the aperture surface, which compensates for the tension reduction that would correspond to the elementary assumption of the plane stress distribution (Figure 2a). Thus, in the lower tensile zone, a practically uniform stress distribution is obtained over the full region depth. This results in real axial tension.

In Figure 2a, a false assumption of the stress distribution corresponding to the elementary Navier assumption is indicated. Figure 2b and Figure 3 then show the actual stress distribution affected by its concentration at the curved surface of the hole.

Figure 2. Stress Distribution in the Vicinity of the Hole.  
a)Wrong assumption  b)The real character of stress distribution

The proposed methodology will provide credible tensile strength values because the tensile zone is in a condition close to the uniform distribution of tensile stresses (Figure 3.). Based on a detailed analysis, it was found that the most uniform distribution of tensile stresses in the tensile narrow region corresponds to the distance of the centre of the hole (diameter 80 mm) from the lower surface of the beam:

$$v = \pi^2 h/20$$  \hspace{1cm} (3)

where h is the depth of the test beam cross-section

For the depth h = 150 mm, v = 7.5\pi^2 = 74 mm, the corresponding tensile stress distribution is shown in Figure 3. It appears that the deviations from the average stress (indicated by the dashed line in Figure 3.) are negligible.
Figure 3. Stress distribution in the tension zone.

However, the situation in the upper (compression) zone is different from the lower (tensile) region; the stress distribution is uneven here due to the proximity of the loading forces (Figure 4.).

Figure 4. Stress distribution in the compression zone.

This is to be taken into account when determining the magnitude of the internal force lever arm; the internal forces $N$ are the resultants of the stresses (Figure 5.). Considering also the insignificant unevenness of the stress distribution in the upper (compression) zone, this lever arm is $r = 111$ mm for the beam height $h = 150$ mm (Figure 5.).

Figure 5. Axial forces in the zones.

2.1. Test Evaluation – Final Relations:

Test beam geometry: depth and width of cross section 150 mm, span 600 mm
Hole diameter: 80 mm
The load action is realized by two forces $F$ [kN] (Figure 1.)
Bending moment in centre region of beam [kNm]
The thickness of the tensile zone resisting to axial tension $t = 34$ mm = 0.034 m
Tensile zone area of the lower region:
$$A = bt = 150 \times 34 = 5100 \text{ mm}^2 = 0.0051 \text{ m}^2$$
Lever arm of internal forces $r = 111$ mm = 0.111 m
Force in tension area:
$$N = M/r = (0.2F)/0.111 = 1.797F \text{ [kN]}$$
The tension stress in the tensile region:
$$\sigma = N/A = (1.797F)/0.0051 = 352.35F \text{ [kN/m}^2\text{...kPa]}$$
Obviously, this methodology is completely transparent. No fault can occur here, because the process is based solely on the equilibrium of the external load forces and the resisting internal forces. The results do not need to be refined by any corrective coefficients of doubtful origin, as in relations (1) and (2). This methodology uses only the assumption that tensile stress distribution in the lower region is close to the uniform (Figure 3).

2.2. Course of the test and its evaluation:
   a) Initially, the system operates according to Figure 2b: The lower region is in tension mode, the upper region is in compression.
   b) Lower region rupture means reaching the axial tensile strength, which is the aim of the test. The strength obtained corresponds to the cracking force and can be taken from the load F versus deflection diagram (Figure 8b).
   c) The highest load force value $F_{\text{crack}}$ is reached. (This is the force at which the crack develops.)
   d) Calculation of tensile strength of fibre reinforced concrete according to the mentioned relations (6).
   e) If the test process continues, the deformation continues to increase. The lower element is already broken and thus almost falls out of action. The system changes completely with a dramatic decrease in the load force: already only the stretched fibres are active in the lower area and the upper area has to take almost the entire flexure. Therefore, the upper region behaves like a low bent "beam", which has its lower surface in tensile regime (Figure 6, Figure 7), which means the formation of cracks at the lower edge of the upper, initially only compression part (Figure 7.).

![Figure 6. The final state.](image)

![Figure 7. Cracked Test Specimen with Hole.](image)
An experimental program was performed as a pilot project to demonstrate the advantages of the proposed methodology. Four-point bending tests were carried out on the classical arrangement of beam specimens (i.e., with no holes) and on the beam specimens prepared according to the proposed methodology with 80 mm diameter holes. The aim was to determine the axial tensile strength of fibre reinforced concrete experimentally.

In the beam tests, with 80 mm drilled holes (Figure 1), the total ultimate loading of 24.37 kN (two forces \( F = 12.18 \) kN) was reached (Figure 8b). The corresponding tensile strength in the lower element (according to formula (5)) is \( \sigma = 4.29 \) MPa.

According to the classic four-point bending test (without a hole), from the graph shown in Figure 8b, when formula (2) is used, the average tensile strength value of 5.16 MPa is obtained, which is 1.2 times higher than the tensile strength determined by the proposed methodology. The significant deviation from the calculated results according to the proposed methodology according to formula (5) is clearly evident.
Also, the thorough experimental study 2, performed using the “dog bone” method on samples with different fibre contents, showed that classical approach (Eq.(2)) provides higher, unrealistic, tensile strength values compared to reality. The “dog bone” method, which can be considered as a pure tensile test, thus shows the same tendency as the proposed methodology of specimens with holes.

Figure 8a Load-deflection diagrams of specimens with and without holes also demonstrate a suitability of the recipe of the fibre reinforced concrete used and the uniformity of the wire distribution in its structure.

In the frame of the experimental program, supplementary strength tests of the used fibre reinforced concrete were carried out; the following results were obtained:

- compressive strength - cube ... average of 6 measurements: 83.76 MPa
- tensile splitting strength ... average of 6 measurements: 7.94 MPa

3. Summary
The presented new test of concrete axial tensile strength (or of fibre reinforced concrete) proves to be much more suitable than standard tests used so far, as it is easy to perform them, it does not rely on any inexact assumptions and in particular it is able to fully respect the type and all material characteristics of the used concrete and the type and the fibre content, which is not attempted by standard tests of formulas (1) and (2).

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References
[1] Podstawka A, Kovář M, Foglar M, Křístek V 2015 Analytical and statistical Evaluation of FRC bending tests layouts. Advanced Materials Research. 2015, ISSN 1022-6680.
[2] Tipka M 2017 Tensile properties of structural fibre reinforced concrete. Ph.D. thesis. CTU in Prague, Faculty of Civil Engineering. Prague 2017