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Test Specimen for Testing of Cementitious Composite Fracture Mechanics Properties

Jan Zatloukal[1] & Marcel Jogl[2]

Abstract: Fracture mechanics properties as fracture energy and fracture toughness of cementitious composites are usually tested by bending test of beam specimen with some form of fabricated notch. Due to the characteristic length (in terms of fracture mechanics) of concrete and similar composites being in the range of 100 mm, specimens with dimensions 150x150x700 mm, weighting around 40 kg are mostly used for these tests, making large scale experiments costly in material and labor required for manufacturing, handling and consumable equipment, especially diamond coated saw blades required for notch cutting operations. New specimen design with special initial crack geometry providing test results of similar quality but not requiring the costly cutting operation phase of manufacturing and with mere one quarter of mass of the original one is proposed and compared in this paper.

Keywords: Fracture Mechanics; Test Specimen

1. Introduction

Fracture mechanics properties of cementitious composites like concrete or fiber reinforced concrete are subject of investigation of various research institutions for years. Experiments are being held on beam shaped specimens with some sort of notch modeling the initial crack, mostly this notch is sawn into the specimen. The process of sawing deals some amount of damage to the surrounding material, resulting in material behavior different from theoretical premises given by the fracture mechanics theory and also requires specialized heavy machinery and trained personnel.

With the macroscopic granular structure of concrete, another problem arises: to comply with the characteristic material length of concrete being in the proximity of 100 mm, test specimens fulfilling this size criterion are quite large, heavy and difficult to manipulate in laboratory conditions, as the typical minimal sectional dimension is required in the range of 150 mm. Beams with dimensions 150×150×700 mm, weighting about 40 kg are used for fracture characteristic tests.

New type of beam test specimen was developed, trying to submit to these conditions: perform in accordance with fracture mechanics theory, be small and light

[1] *Ing. Jan Zatloukal; Experimental Centre, Faculty of Civil Engineering, Czech Technical University in Prague; Thákurova 6, 166 29, Prague, Czech Republic; jan.zatloukal@fsv.cvut.cz*

[1] *Marcel Jogl; Experimental Centre, Faculty of Civil Engineering, Czech Technical University in Prague; Thákurova 6, 166 29, Prague, Czech Republic;marcel.jogl@fsv.cvut.cz*

enough for manipulation, to be easy to prepare and to be affordable in terms of machinery and personnel required for production.

The principle of the test specimen preparation is to completely skip the costly and time consuming sawing phase of the manufacturing process and to introduce the initial hairline crack into the specimen while being cast.

2. Specimen design

The specimens introduced have dimensions of 100×100×400 mm with a notch in one side of the prism. The hairline crack was to be formed by plastic foil 0.05 mm thick which was lightly stressed to hold in position during concrete compacting in the casting phase of manufacturing. Special molds with opening in the bottom for the foil to slit through and with some foil fixation in the upper section were required.

In the first phase of testing, the crack depth of 20 mm was chosen (i.e. $\alpha = a/h = 0.2$), but in the second phase the initial crack depth was set to 30 mm (i.e. $\alpha = 0.3$). The material grade used in the two phases was also different, the first phase used 28 days old concrete grade C30/37, in the second and third phase C60/75 was used, aged 7 and 28 days for phase 2 and 3 respectively.

2.1. Experimental setup

The testing procedure involved subjecting the specimens to three-point bending with base supports span of 300 mm with displacement-controlled load cycle and measuring loading force, vertical displacement at midpoint and crack opening, using inductive displacement transducers. For crack opening measurement the specimens were fitted with glued sensor holders and sensor core restraints.

After destructive tensile tests all resulting halves of cracked specimens were subjected to compressive strength measurement (non-destructive and destructive), so that was made sure the material properties of all specimens used during tests were in accordance.

2.2. Specimen manufacturing

There were three groups of specimens used in the testing procedure of each phase, consisting of four specimens each in phase 1 and three specimens each in phases 2 and 3. First group was used as reference for testing tensile strength of the basic material and no notch was formed in these specimens.

Second group had a 20 or 30 mm deep and 5 mm wide notch sawn with diamond circular blade to a side of the specimen. The orientation of the specimen during testing was rotated 90°, so that the notch was facing downwards and the rough surface of cast concrete was on the side, not interfering with testing equipment. Tensile strength of notched specimen was measured together with crack opening during loading.

Third group had 20 or 30 mm deep notch formed during casting by presenting a thin plastic foil into the casting mold in vertical direction. The foil was not removed from the specimen until the destructive testing was finished. The orientation, instrumentation and testing procedures on the specimens from third group in all phases were identical to those from second group.

3. Results

In each phase of testing (distinguished by material of the specimen and initial crack depth) three groups of specimens were tested, each focusing on specific property. First group of specimens was used as reference for measuring tensile strength of the material. The ultimate tensile stress f_t was calculated from the force measured at three point bending test using the formula

$$f_t = \frac{3FL}{2bh^2}[\text{Pa}] \tag{1}$$

where

b is width of the beam

h is height of the beam

F is force load applied in three-point bending

L is span of three-point bent beam

All specimens were afterwards tested for compressive strength to verify the compliance of the quality of the material of all groups of specimens.

The Eq. (1) was also used for calculation of the theoretical tensile strength of the specimens from group 2 (sawn notch) assuming the sawn notch behaves like a section reduction rather than sharp crack.

With second and third specimen group, fracture toughness was calculated for each test. Theoretical model of three-point bent prism and infinite bent prism were taken into account with the resulting formula for fracture toughness in 1st mode of cracking (K_{IC}):

$$K_{IC} = \frac{6M}{th^{3/2}}k(\alpha) = \frac{3FL}{2th^{3/2}}k(\alpha)\left[\text{Nm}^{-3/2}\right] \tag{2}$$

where

M is bending moment in infinite beam

t is width of the beam

h is height of the beam

F is force load applied in three-point bending

L is span of three-point bent beam

$k(\alpha)$ is factor of notch ratio

The $k(\alpha)$ factor was calculated as a extrapolation of $k(\alpha)$ factors for infinite beam and for finite beam subjected to three point bending and $L = 4h$. The actual experimental setup had $L = 3h$. The $k(\alpha)$ factor was approximated with value 0.745 for crack depth 20 mm ($\alpha = 0.2$, phase 1) and 0.960 for crack depth 30 mm ($\alpha = 0.3$ mm, phases 2 and 3).

3.1. Results for phase 1 (C30/30, 28 days, notch 20 mm)

Material in phase 1 of the testing was concrete C30/37, tested at 28 days of age. The notch depth of the specimens was 20 mm.

3.1.1. First group (no notch)

Material properties obtained from the first group of specimens:

Compressive strength: f_c = 55,88 MPa

Tensile strength: f_t = 6,19 MPa

3.1.2. Second group (sawn notch)

The results for second group of specimens, prepared in standard way by sawing the notch:

Compressive strength: f_c = 55,25 MPa

Theoretical tensile strength: $f_{t(T)}$ = 6,13 MPa

Fracture toughness: K_{IC} = 924,7 $kNm^{-3/2}$

The material of second group had almost the same compressive strength as of the first group and the calculated fracture toughness may be considered as reference value for further testing.

3.1.3. Results for third group (foil notch)

The third group of specimens, with notch formed by thin foil prior to casting the concrete displayed the resulting material properties:

Compressive strength: f_c = 53,00 MPa

Fracture toughness: K_{IC} = 750,4 $kNm^{-3/2}$

For C30/37 and 20 mm initial crack depth, the value of fracture toughness acquired by testing the third group of specimens is about 19% lower than the reference value given by the second group. The compressive strength of the third group is within 5% interval of the compressive strength of first and second group, thus can be considered the material for all groups of specimens has more or less alike properties.

3.2. Results for phase 2 (C60/75, 7 days, notch 30 mm)

Material in phase 2 of the testing was concrete C60/75, tested at 7 days of age. The notch depth of the specimens was 30 mm.

3.2.1. First group (no notch)

Material properties obtained from the first group of specimens:

Compressive strength: f_c = 67,25 MPa

Tensile strength: f_t = 6,66 MPa

3.2.2. Second group (sawn notch)

The results for second group of specimens, prepared in standard way by sawing the notch:

Compressive strength: f_c = 72,16 MPa

Theoretical tensile strength: $f_{t(T)}$ = 6,92 MPa

Fracture toughness: K_{IC} = 1034,5 $kNm^{-3/2}$

3.2.3. Results for third group (foil notch)

The third group of specimens, with notch formed by thin foil prior to casting the concrete displayed the resulting material properties:

Compressive strength: f_c = 71,92 MPa

Fracture toughness: K_{IC} = 890,1 $kNm^{-3/2}$

For C60/75 and 30 mm initial crack depth, the value of fracture toughness acquired by testing the third group of specimens is about 14% lower than the reference value given by the second group. The compressive strength of the third group is within 5% interval of the compressive strength of second group, while the first one is misplaced by 7%. Still, it can be considered the material for all groups of specimens has more or less alike properties.

3.3. Results for phase 3 (C60/75, 28 days, notch 30 mm)

Material in phase 3 of the testing was concrete C60/75, tested at 28 days of age. The notch depth of the specimens was 30 mm.

3.3.1. First group (no notch)

Material properties obtained from the first group of specimens:

Compressive strength: f_c = 78,83 MPa

Tensile strength: f_t = 12,07 MPa

3.3.2. Second group (sawn notch)

The results for second group of specimens, prepared in standard way by sawing the notch:

Compressive strength: f_c = 76,95 MPa

Theoretical tensile strength: $f_{t(T)}$ = 9,00 MPa

Fracture toughness: K_{IC} = 1301,4 $kNm^{-3/2}$

3.3.3. Results for third group (foil notch)

The third group of specimens, with notch formed by thin foil prior to casting the concrete displayed the resulting material properties:

Compressive strength: f_c = 71,65 MPa

Fracture toughness: K_{IC} = 1180,9 kNm$^{-3/2}$

For C60/75 and 30 mm initial crack depth, the value of fracture toughness acquired by testing the third group of specimens is about 9% lower than the reference value given by the second group. The theoretical tensile strength of the sawn notched specimens from phase 3 is also about one quarter lower than the tensile strength of specimen without notch. The specimens form phase 3 displayed brittle behavior during testing with abrupt failure.

4. Conclusions

For material displaying some ductile post-cracking behavior (i.e. C30/37 and 7 days old C60/75) the difference between sawn and sharp foil notch is very significant. It can be stated, that sawn notch in specimen of these dimensions does not introduce crack tip behavior into the specimen, rather forming a reduced height cross section. Theoretical tensile strength is almost the same for specimens without notch and with sawn one, not depending whether 20 or 30 mm deep. The relative difference between calculated value of fracture toughness for sawn and sharp foil notch is about 19% and 14% lower for initial cracks 20 and 30 mm deep respectively.

The tensile behavior of very brittle material as the high-performance C60/75 concrete was influenced by the sawn notch significantly, yet the sharp notch formed by foil reduced the calculated values of fracture toughness by about 10% compared to the sawn notch.

Tests on quasi-brittle material, as non-fibre-reinforced concrete have been performed with above results, test on ductile materials are about to be performed in near future.

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