STRUCTURAL SFRC FOR PRECAST SEGMENTS OF THE TUNNEL LINING

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Summary

The paper is focused on the strength parameters of the designed structural steel fibre reinforced concrete (SFRC), which are important for the capacity of the tunnel lining segments and their damage during manipulation. Generally the segments are more loaded during tunnel lining installation (long term load is lower). The realised investigation was focused on SFRC with various dosages of steel fibres, two types of fibres were tested. One of the reasons of the testing was also fixed low thickness of the segments (only 250 mm). Structural SFRC with fibre dosages 50 kg/m^3 and 70 kg/m^3 were tested (i.e. dosages recommended by authors of this texts considering low thickness of the segments and their high temporary load). The paper also includes results of testing of two different key segments (ordinary RC key segment and SFRC key segment with fibre dosages 50 kg/m3).

Keywords: Steel fibre reinforced concrete, SFRC, Segmental tunnel lining, Laboratory testing, crack propagation, Strength, Mix design.

1. Introduction

The utilisation of steel fibre reinforced concrete (SFRC) instead of traditional reinforced concrete (RC) for appropriate concrete structures can bring many advantages. All advantages are given by properties of SFRC, partly by strength properties, mainly by strain characteristics.

An appropriate concrete structure for utilisation of SFRC can be tunnel lining generated from precast concrete segments. The loading of precast concrete segments, namely during installation of segments, leads often to mechanical damage of joints. The utilisation of SFRC for tunnel segments can reduce damage of joints, which is one of many advantages of the SFRC utilisation for tunnel segments.

The main purpose of this paper is not to list all advantages of SFRC for tunnel segments. The main goal is to show approach of authors to change of utilised material (i.e. from the design of concrete composition to results of experimental testing of key segment generated from SFRC without traditional rebars).

Two dosages of steel fibres (50 kg/m^3 and 70 kg/m^3) together with two types of steel fibres (Dramix and Tri Treg) were verified by laboratory testing to achieve material stability during transport, tunnel lining installation, and during its lifetime, mainly with regards to given thickness of segments 250 mm (construction of Prague metro line A extension).

The compression of a key segment generated from SFCR with fibre dosage 50 kg/m^3 is described in this paper (this test of segment was realised the first), all other test of SFRC segment will be described in other papers later. Results of compression test of the SFRC key segment will be compared to results of the same test of RC segment, which was realised as well. The paper also includes photos of the segment damage after its testing.

2. Results of material testing

The concrete mix with steel fibres Dramix with fibre dosage m_f = 50 kg/m^3 was proposed and verified for tested key segment. The first of all compression strength was verified on cubes with size 150 mm according to the Czech standard CSN EN 12390-3 (see tab. 1). The average cube strength $f_{fc,\ mc,\ cub}$ = 67.3 MPa is resulting from tab. 1.

The following parameters can be derived from tab.1:

- standard deviation of 6 samples: $s_6 \approx 2{,}58$ MPa
- standard variance: $\Delta f_{kc,\ cub,\ 3} = 1.48 \cdot 2.85 = 4.25$ MPa
- cube strength: $f_{fc,\ kc,\ cub} = 67.3 - 4.25 = 63.05$ MPa

Tab. 1 Compression strength tested on SFRC cubes

No.	Sample dimensions			Weight	Unit weight	Uniaxial force	fc,i
	b	h	l				
	[mm]	[mm]	[mm]	[g]	[kg/m^3]	[kN]	[MPa]
4	149.0	147.6	150.4	7968	2409	1520	69.1
5	148.5	150.8	150.5	8209	2436	1437	64.2
6	151.0	150.5	151.2	8285	2411	1634	71.9
10	150.5	155.9	150.6	8214	2325	1565	66.7
11	147.7	154.0	150.3	8156	2386	1474	64.8
12	150.2	155.3	150.7	8359	2378	1561	66.9
Average value:					**2391**	**1532**	**67.3**

The compressive strength class of the SFRC samples was derived from the table 2.7.1b from TP-FC 1-1 (i.e. the closest lower value of characteristic cube strength:

$$f_{fc,\ kc,\ cub} = 60 \text{ MPa} < 63.05 \text{ MPa}$$

The SFRC material can be marked as: **FC $f_{fc,\ kc,\ cyl} / f_{fc,\ kc\ ,cub}$ = FC 55/60**
Ratio 0.9 of cylindrical and cube strength was considered.

Four point bending tests of SFRC beams were executed to get tension strength of the material. The tests were realised in Klokner testing laboratory of the Czech Technical University (CTU) in Prague and results of stress-strain diagrams ($F_R - \delta_t$) were determined for agreed deflections δ_{ti} of standard beam for all six specimens.

Graphical output of stress-strain diagrams (F_R – δ_t) is presented on fig. 1. Idealised diagram is also presented in fig.1 (red colour) to simplify derivation of SFRC strength for two limit deflections:

a) limit for macrocracks $\delta_{t,\ cr}$,
b) agreed limit deflection $\delta_{t,\ 3.5}$ = 3.5 mm

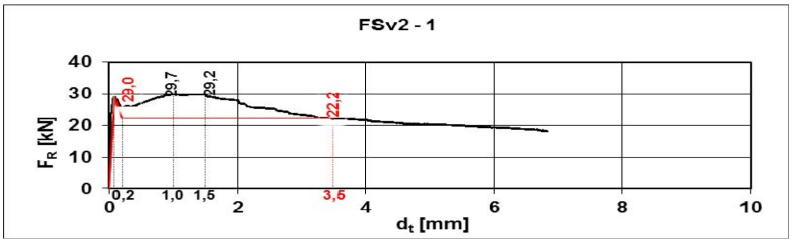

Fig. 1 Stress-strain diagram

Strength evaluation of all tested beams is presented in fig. 2:

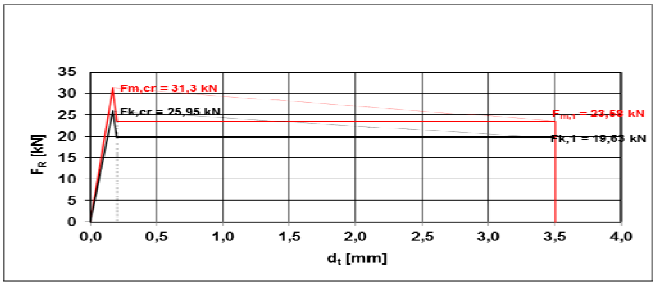

Fig. 2 Simlified idealised stress-strain diagrams: average, characteristic

1) Average strength of beams on macrocrack limit:
   $F_{Rm,\ cr}$ = 31.3 kN, with standard deviation s_6 = 3.64 kN
   Standard variance of all six beams:
   $\Delta F_{Rk,\ 6} = 1.48 \cdot 3.64 \approx 5.4$ kN, therefore characteristic strength is:
   $F_{Rk,\ cr}$ = 31.3 – 5.4 = 25.9kN

2) Average strength of beam for limit deflection δ_t = 3.5 mm:
   $F_{Rm,\ 1}$ = 23.6 kN with standard deviation s_6 = 2.7 kN
   Standard variance of all six beams:
   $\Delta F_{Rk,\ 6} = 1.48 \cdot 2.7 = 4.0$ kN, therefore characteristic strength is:
   $F_{Rk,\ eq,\ 1}$ = 23.6 – 4.0 = 19.6 kN

<u>Average and characteristic tensile strength of SFRC:</u>
The following general formula is valid for standard four point bending test of beams:

$$M_E = \frac{1}{2} F_R \frac{l}{3} = F_R \frac{l}{6}$$

1) The bending moment on macrocrack limit $F_{Rm,cr}$ = 31,3 kN is the following:

$$M_{m,cr} = 31.3 \cdot \frac{0,6}{6} = 3.13 kNm..$$

The average tensile strength in bending based on quasilinearly elastic behaviour of beams is afterwards $f_{fc,\ tm,\ fe,\ cr} = 6 \cdot M_{m,cr}/bh^2 = 6 \cdot 3.13/0.15^3 \approx 5.56$ MPa.

Similarly the following formula is valid for characteristic tensile strength in bending:

$$F_{Rk,cr} = 25.9 \text{ kN is } M_{k,cr} = 2.59 \text{ kNm}$$

Characteristic tensile strength in bending: $F_{fc,tk,fe,cr} = 6 \text{ x } 2.59/0{,}15^3 = 4.61$ MPa.
Derived characteristic central tensile strength on macrocrack limit:

$$f_{fc,tk,cr} = f_{fc,\,tk,\,fe,\,cr} / 1.45 = 4.61/1.45 = 3.18 \text{ MPa}$$

Central tensile strength class of SFRC is according to Tab 2.7.2 TP FC 1-1 (fig. 3):

$$f_{fc,tk} = 3.1 \text{ MPa}$$

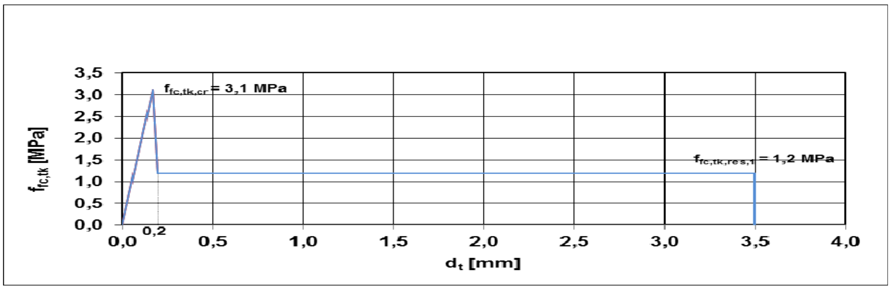

Fig. 3 Example of stress-strain diagram ($f_{fc,tk} - \delta_{t,i}$)
i.e. (char. Central tensile strength – deflection) using simplified diagram

2) The following values are valid after reaching of limit deflection $\delta_{t,1} = 3.5$ mm:
$F_{m,1} = 23.6$ kN; $M_{m,1} = 0.1 \text{ x } 23.6 = 2.36$ kNm ; $f_{fc,\,tm,\,eq,\,1} \approx 2.2 \text{ x } 2.36/0.15^3 \approx 1.54$ MPa
The derived equivalent characteristic strength of SFRC in central tension in $\delta_{t1} = 3.5$ mm (according to the TP FC 1-1, draft – February 2012)

$$f_{fc,tk,eq,1} = 2.2\, M_{m,1}/bh^2 = 2.2 \cdot 1.963/0.15^3 = 1.28 \text{ MPa},$$

$$\text{where } M_{m,1} = 0.1 \cdot 19.63 = 1.963 \text{ kNm}$$

Strength class FC in central tension in $\delta_{t1} = 3.5$ mm (according to the 2.7.3 TP FC 1-1)

$$f_{fc,\,tk,\,res,\,1} = 1.2 \text{ MPa}$$

Strength class FC in compression determined on cubes is: FC 55/60
Therefore full labelling of tested SFRC generated in Senec with 50 kg/m^3 of Dramix fibres is: **FC 55/60 – 3.1/1.2**.

3. Loading test of key segment

Testing of both RC key segment and SFRC key segment was realised in Klokner laboratory of the Czech Technical University in Prague. Key segments were loaded by axial force to simulate pressure from rams located on the back part of the tunnelling shield (TBM technology) during its penetration into the ground (i.e. tunnel lining is loaded in longitudinal direction).

Values of acting force and corresponding values of deformations were continually recorded. Deformations were monitored by both potenciometers and tensometers located on the segment surface (see fig. 4).

Key segments were placed on the testing machine. 9 mm thick plastic plate was placed on the upper part of the segments and steel plate 20 mm thick was placed over it. Both plates corresponded with dimensions and material of tunnelling shield rams.

The acting force was increased with 300 kN steps, the segment was unloaded to 90 kN between all loading steps.

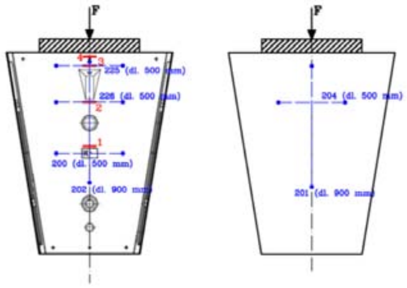

Fig. 4 The test arrangement including locations of potenciometers and tensometers

Tab. 2 Comparison of resulting measured forces of compression test realised on two key segments with a different reinforcement

Concrete	RC	**SFRC**
The first crack - force F_{cr} [kN]	3300	**4200**
Maximum reached force F_u [kN]	5868	**cca 7200**

A) SFRC key segment

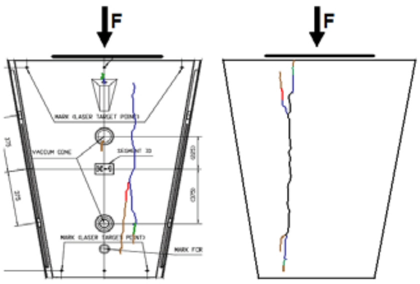

Fig. 5 Record of macrocrack location under maximum load – SFRC key segment – $F_{fc,u}$ = 7200kN

B) RC key segment

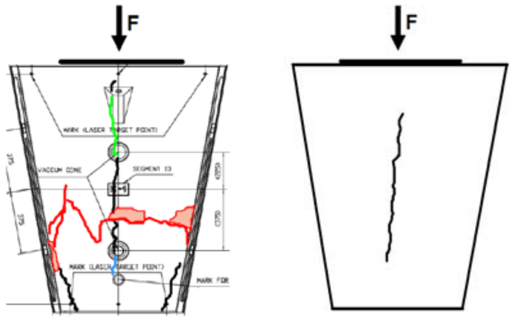

Fig. 6 Record of macrocrack location under maximum load – RC key segment – $F_{c,u}$ = 5868kN

Fig. 7 Comparison of damaged key segments after reaching their capacity:
a) RC key segment, b) SFRC key segment

4. Discussion of results

The following findings can be presented from results of realised SFRC testing:

a. Results of SFRC material testing due to unit weight of cast SFRC specimens show acceptable homogeneity of the material. Similarly variance of compression strength and bending tensile strength is within acceptable limits.
b. The SFRC material can be labelled to strength class according to FC TP – 1 part 1.
c. The realised testing of key segment proved better behaviour of SFRC segment in comparison to RC segment – later generation and propagation of cracks, manner of failure and higher load leading to the failure.

5. Conclusion

The tested SFRC key segment showed in both load cases (macrocrack generation and compression capacity) higher values, which were about 25% than in case of RC segment.

The load value of the first macrocrack generation is namely important, because it correspond with SLS (serviceability limit state).

Testing results showed about 3 times higher capacity in comparison to required maximum axial force of tunnelling shield on Prague metro line A extension F_E = 2430 kN.

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