On the Toughness Characterization of Fibre- Reinforced Concrete Using Notched Beam Tests

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Abstract The significant benefit of using fibre-reinforced concrete (FRC) is its improved energy absorption capacity, termed as toughness, and the consequent enhanced post-cracking load carrying capacity, which have resulted in applications such as tunnel linings, pavements, industrial floors, etc. There is limited knowledge regarding notched beam testing in India for flexural toughness characterization of FRC though it is prevalent in Europe. In the current work, the flexural behaviour of concrete with different dosages of hooked-ended steel fibres are characterized by centre-point loaded (CPL) notched beam testing, according to the EN 14651:2005 and RILEM TC 162-TDF recommendations. The flexural toughness parameters assessed are based on the load-crack mouth opening displacement (CMOD) curves and load–deflection (δ) curves obtained experimentally. A detailed analysis also revealed that for steel FRC, a good correlation exists between equivalent and residual flexural tensile strength parameters.

Keywords Fibre-reinforced concrete · Flexural toughness · Notched beam test · Crack mouth opening displacement

1 Introduction

The enhanced performance of fibre-reinforced concrete is due to its increased energy absorption capacity during fracture, which is termed as 'toughness'. The main objective of toughness characterization is to measure the effectiveness of the fibres and the resistance offered against crack propagation. The test configuration commonly used for toughness characterization is the bending of prismatic

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specimens. From the fracture mechanics perspective, the notched beam test is mostly recommended for toughness characterization due to its rational analysis [1, 2].

Over the past few decades, extensive research has been carried out on the material properties of FRC. Consequently, based on the state-of-the-art knowledge, FRC is introduced in the fib Model Code 2010 to provide design guidelines for the design of FRC structural elements, at both serviceability and ultimate limit states. In this code, material classification of FRC is based on the flexural toughness parameters with respect to post-cracking tensile strength, determined from bending tests on notched prisms according to EN 14651 [3, 4].

Considering the fact that notched beam test gives a more reliable test data and post-cracking response of FRC, relevant for structural applications, it is proposed as the basis of the present work. The notched beam test with Centre Point Loading (CPL) is performed as per EN 14651:2005 (E) and RILEM TC 162-TDF: Test and design methods of steel fibre-reinforced concrete, Bending Test: Final Recommendations [5, 6].

2 Flexural Toughness Testing Based on the Notched Beam Test

The tests are performed in a closed-loop servo-controlled Controls testing system as shown in Fig. 1. The test control and data acquisition is done through a Controls software interface Advantest. The test is performed initially under load control by increasing the load at a constant rate of 100 N/s up to about 40% of the estimated peak load, and then by changing to crack mouth opening displacement (CMOD) control. However, both deflection and crack mouth opening are measured as shown in Fig. 2. The specimen dimensions are $150 \times 150 \times 700$ mm, and the span is 500 mm. A notch is cut through the width of specimen at mid-span on a face that is

Fig. 1 Experimental setup

Fig. 2 Position of the clip gauge and 2 LVDTs for measuring CMOD and deflections, respectively

perpendicular to the casting direction. Since the crack opening is measured at a distance of y (=3 mm) from the bottom face of the specimen, the value of CMOD has to be corrected as

$$\text{CMOD} = \text{CMOD}_y \frac{h}{h+y} \tag{1}$$

where h is the depth of the specimen (i.e. 150 mm) and CMOD_y is the measured value. For measuring the deflection, two LVDTs are mounted on rigid frames fixed to the either side of the specimen and the tips rest on 1 mm-thick steel plates placed across the notch.

2.1 Notching Procedure

A notch is cut through the width of specimen at mid-span on a face that is perpendicular to the casting face using a water-cooled diamond-edged disc saw. Specimens are rotated 90° over their longitudinal axis and then sawn as shown in Fig. 3. The notch depth adopted for 150 mm deep beam was 25 mm.

1. Top surface during casting
2. Notch
3. Cross-section of test specimen.

h_{sp} is the distance between the tip of the notch and the top of the specimen, in millimetres.

The test specimens are cured for a minimum of 3 days after sawing. Toughness testing is performed at 28 days. The width of the notch is about 3 mm.

Fig. 3 Position of the notch with respect to the test specimen as cast
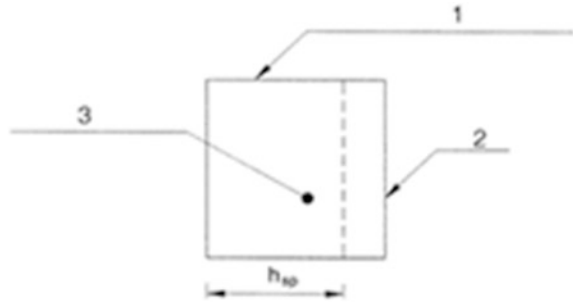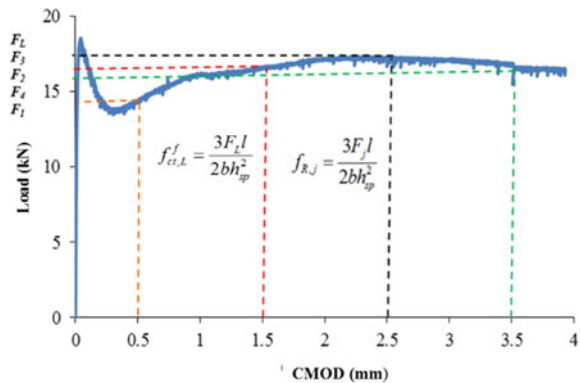

2.2   Flexural Toughness Parameters

Flexural toughness parameters in are derived from the load–CMOD curves and load–deflection curves. The Limit of Proportionality f^f_{ct} (LOP) and Residual Flexural Tensile Strength (f_R) are the parameters recommended by EN 14651:2005 (E) [3], which are obtained from load–CMOD curve as in Fig. 4. The LOP represents the flexural strength of the composite obtained using the first peak load of the FRC specimen. Residual flexural strength is an estimate of flexural strength retained by FRC after cracking at particular crack widths of 0.5, 1.5, 2.5 and 3.5 mm.

Additionally, the equivalent flexural strength (f_{eq}) has been calculated from the load–δ curve, as recommended by RILEM TC 162-TDF, using the average load over certain deflection ranges as in Fig. 5.

The energy absorption $D_{BZ,2}$(or $D_{BZ,3}$) is equal to the area under the load–deflection curve up to a deflection δ_2 (or δ_3), and is taken to be the sum of the contribution of the plain concrete and that of the fibres ($D^f_{BZ,2}$or $D^f_{BZ,3}$) as in Fig. 5. The two contributions are separated by a straight line connecting the point on the curve corresponding to F_L and the point on the abscissa equal to "δ_L +0.3", where δ_L is the deflection at F_L.

Fig. 4 Estimation of LOP and residual flexural strength from typical load–CMOD curve

F (kN)

area $D'_{BZ.2}$

$$\delta_2 = \delta_L + 0.65$$

δ_2

deflection δ (mm)

F (kN)

area $D'_{BZ.3}$

$$\delta_3 = \delta_L + 2.65$$
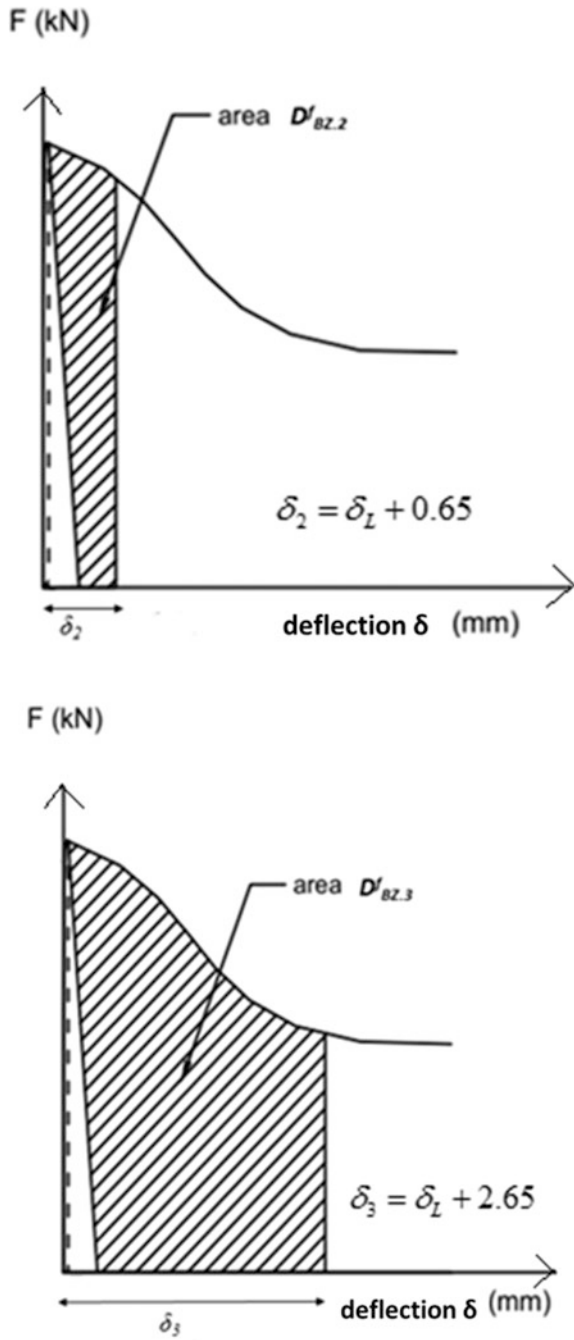
δ_3

deflection δ (mm)

Fig. 5 Estimation of the equivalent flexural strength parameters from the load–deflection curve

The equivalent flexural tensile strengths $f_{eq.\,2}$ and $f_{eq.\,3}$ can consequently be determined [6] as

$$f_{eq,2} = \frac{3}{2}\frac{D^f_{BZ,2}}{0.5}\frac{L}{bh^2_{sp}}$$

(2)

$$f_{eq,3} = \frac{3}{2}\frac{D^f_{BZ,3}}{2.5}\frac{L}{bh^2_{sp}}$$

(3)

3 Experimental Programme

The flexural behaviour of concrete, having 40 MPa design compressive strength (denoted as M40), reinforced with hooked-ended steel fibres was characterized. The fibre details are given in Table 1, as specified by the manufacturer. The nominal mix proportion for the concretes is given in Table 2.

The concrete was mixed for about 3 min after fibre addition. Specimens such as cubes of $150 \times 150 \times 150$ mm and prisms of $150 \times 150 \times 700$ mm, were cast for plain concrete and different dosages of steel fibre-reinforced concretes (SFRC).

Nine prisms were cast, along with nine cubes for each dosage of the mix, and a high-frequency vibrating table was used for compaction of the concrete in moulds. Reference concrete without any fibres was also cast. The specimens were left in the moulds for 24 h after casting, then demoulded and cured for the next 27 days in the mist room. Three days prior to the testing, a notch of 25 mm length was cut across

Table 1 Details of fibre

Type	Specific gravity[a] (g/cc)	Aspect ratio	Tensile strength[a] (MPa)	Fibre dosages (kg/m³)
Hooked-ended steel fibres	7.8	80	1225	10, 15, 20, 30, 45

[a]Specified by the manufacturer

Table 2 Nominal mix proportions in kg/m³

Material	Quantity
Cement	380
Fine aggregates	760
5–10 mm coarse aggregates	390
10–20 mm coarse aggregates	700
Water	171

the longitudinal section and the specimen was kept again in the mist room for curing. Flexural tests were performed at the age of 28 days.

4 Results and Discussion

4.1 Fresh Properties

There was a loss in workability due to the addition of fibres with lower slump being obtained. Consequently, a poly-carboxylate (PCE)-based superplasticizer (with a density of 1080 kg/m^3 and solid content of 33%), was used to obtain a reasonable workability to be handled during fabrication. The superplasticizer dosage, by weight of cementitious materials, was increased from 0.19% in plain concrete to 0.4% for 45 kg/m^3 of steel fibres and the slump could be maintained at 100 ± 20 mm. In general, all mixes showed similar trends of workability reduction with an increase in fibre dosage.

4.2 Compressive Strength

Compressive strength tests were conducted on cubes at the ages of 3, 7 and 28 days using a 3 MN capacity Controls compression testing machine; a minimum of three specimens were tested at each age. Note that in the mix designation, M40 denotes the concrete grade, SF denotes the use of steel fibres and the number at the end denotes the fibre dosage in kg/m^3. The compressive strength values along with the standard deviation are given in Table 3, for specimens of different fibre volume fractions.

From Table 3, it can be observed that, the incorporation of steel fibres resulted in an improvement in the compressive strength compared to plain concrete, from 3 to 12% for the fibre dosages of 10–45 kg/m^3. This can be attributed to the bridging of cracks by the fibres, which produces some internal confinement, increasing the

Table 3 Compressive strength of SFRC

Concrete	Compressive strength (MPa) (mean $\pm$ standard deviation)		
	At 3 days	At 7 days	At 28 days
M40SF0	22.3 ± 1.2	33.7 ± 0.5	47.1 ± 0.3
M40SF10	22.5 ± 0.8	34.4 ± 0.9	48.4 ± 0.8
M40SF15	23.5 ± 0.7	35.6 ± 1.5	49.2 ± 0.6
M40SF20	26.7 ± 0.8	36.7 ± 1.6	50.4 ± 1.3
M40SF30	27.9 ± 1.3	37.3 ± 0.7	51.5 ± 1.7
M40SF45	28.6 ± 0.4	38.0 ± 0.9	52.8 ± 0.7

compressive strength. The variability of compressive strengths is within the usual range and is not influenced by the type or amount of fibres.

4.3 Flexural Behaviour of SFRC and Toughness Parameters

Typical load–CMOD curves for the SFRCs are shown in Fig. 6. For all the mixes it was observed that, the post-peak load-carrying capacity and the area under the load–CMOD curve increase with the fibre dosage, as expected. There is a gradual change from softening- to hardening-type response with an increase in fibre dosage ($10–45$ kg/m^3), especially at larger deflections (after a CMOD of 0.2 mm). In fact, for the M40SF45 mix, the post-crack load-carrying capacity was even higher than the peak load after a CMOD of 1 mm. For lower dosages of steel fibres (10 and 15 kg/m^3), the softening branch is followed by a region of constant residual load. The typical load–deflection curves of the different mixes, presented in Fig. 7, show similar trends as in the load–CMOD curves. The flexural toughness parameters obtained for all the mixes are given in Table 4, as mean and standard deviation
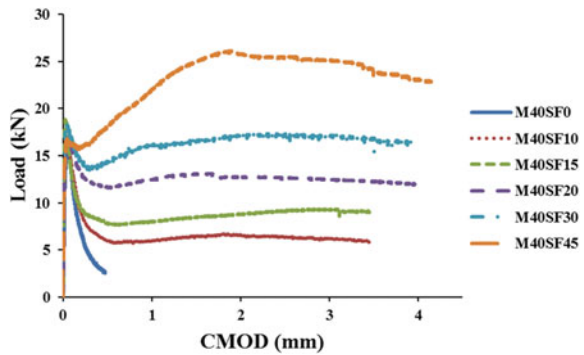

Fig. 6 Typical load–CMOD curves
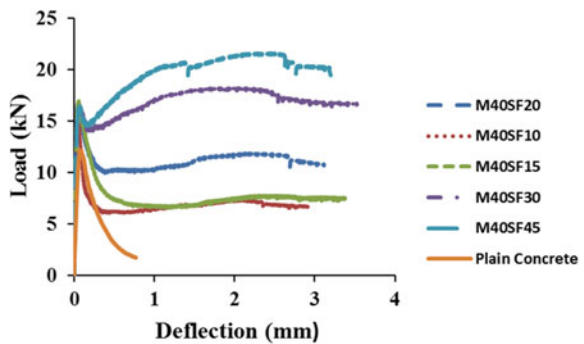

Fig. 7 Typical load–deflection curves

Table 4 Flexural toughness parameters of SFRC

Concrete	LOP, f_{ct} (MPa)	$f_{R,1}$ @CMOD = 0.5 mm (MPa)	$f_{R,2}$ @CMOD = 1.5 mm (MPa)	$f_{R,3}$ @CMOD = 2.5 mm (MPa)	$f_{R,4}$ @CMOD = 3.5 mm (MPa)	$f_{eq,2}$ (MPa)	$f_{eq,3}$ (MPa)
M40SF0	5.22 ± 0.42	–	–	–	–	–	–
M40SF10	5.33 ± 0.39	2.19 ± 0.18	2.11 ± 0.20	2.13 ± 0.24	2.05 ± 0.29	1.99 ± 0.33	2.04 ± 0.26
M40SF15	5.44 ± 0.45	2.35 ± 0.23	2.48 ± 0.26	2.55 ± 0.29	2.48 ± 0.32	2.09 ± 0.31	2.40 ± 0.21
M40SF20	5.58 ± 0.42	3.40 ± 0.48	3.73 ± 0.53	3.80 ± 0.34	3.68 ± 0.27	3.23 ± 0.55	3.62 ± 0.43
M40SF30	5.38 ± 0.42	4.04 ± 0.61	5.21 ± 0.65	5.54 ± 0.75	5.48 ± 0.75	3.89 ± 0.70	5.03 ± 0.61
M40SF45	5.47 ± 0.41	5.30 ± 0.77	6.70 ± 1.22	6.63 ± 1.55	6.53 ± 1.40	5.29 ± 0.84	6.33 ± 1.19

Table 5 SFRC classification
as per *fib Model Code 2010*

Concrete	Class	$f_{R,3k}/f_{R,1k}$	$f_{R,1k}/f_{Lk}$
M40SF10	2b	0.9	0.40
M40SF15	2c	1.0	0.42
M40SF20	2.5e	1.3	0.50
M40SF30	3e	1.4	0.61
M40SF45	4b	0.9	0.80

values. It can be seen that the values of $f_{eq,3}$ and $f_{R,4}$ are higher than $f_{eq,2}$ and $f_{R,1}$, respectively, which indicates that the energy absorption and post-cracking capacity increase at larger crack mouth openings, in the case of SFRC, especially at higher dosages.

Based on the data obtained, the FRC can be classified according to *fib Model Code 2010* in terms of the response at the serviceability limit state (represented by CMOD = 0.5 mm) and at the ultimate limit state (represented by CMOD = 2.5 mm). Note that, in order to take into account the effect of variability of the test specimens, characteristic values of the parameters are considered, i.e. $f_{R,1k}$ and $f_{R,3k}$. The class of the FRC is denoted with a number followed by a letter: the number is based on the value of $f_{R,1k}$ rounded off to the nearest 0.5 MPa and the letter depends on the ratio $f_{R,3k}/f_{R,1k}$ ratio, as follows:

a. if $0.5 < f_{R,3k}/f_{R,1k} \leq 0.7$
b. if $0.7 < f_{R,3k}/f_{R,1k} \leq 0.9$
c. if $0.9 < f_{R,3k}/f_{R,1k} \leq 1.1$
d. if $1.1 < f_{R,3k}/f_{R,1k} \leq 1.3$
e. if $f_{R,3k}/f_{R,1k} > 1.3$

The FRC is taken to be suitable and can be used at Ultimate Limit State (ULS) if the relationships given in Eqs. (4) and (5) are fulfilled, where f_{Lk} is the characteristic value of the LOP.

$$f_{R,1k}/f_{Lk} \geq 0.4 \tag{4}$$

$$f_{R,3k}/f_{R,1k} \geq 0.5 \tag{5}$$

The classification for the SFRCs tested based on the *fib Model Code2010*, as well as the ratios given in Eqs. (4) and (5) are shown in the Table 5. It can be observed that all the SFRCs considered here have satisfied the restrictions on the minimum residual strength, as given in Eqs. (4) and (5). This becomes relevant in structures with high degree of redundancy, especially when fibres completely replace conventional reinforcement, where a minimum redundancy level is required for the structural member.

4.4 Relationship Between Equivalent and Residual Flexural Tensile Strengths

A linear relationship was found to exist between the equivalent ($f_{eq,2}$ and $f_{eq,3}$) and residual strength parameters ($f_{R,1}$ and $f_{R,4}$), as shown in Figs. 8 and 9, confirming the observations of Barros et al. [7]. Further, the relationships between $f_{eq,2}$ and $f_{R,1}$

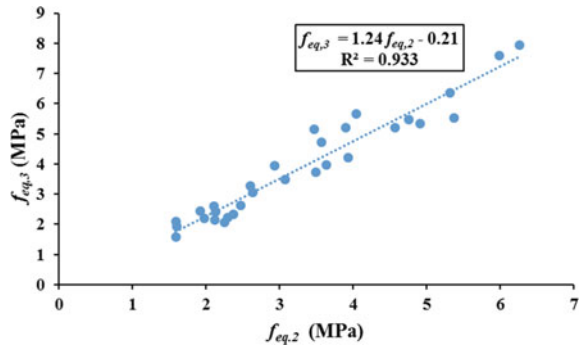**Fig. 8** Relationship between $f_{eq,2}$ and $f_{eq,3}$ of SFRC

$$f_{eq,3} = 1.24 f_{eq,2} - 0.21$$
$$R^2 = 0.933$$

Fig. 9 Relationship between $f_{R,1}$ and $f_{R,4}$ of SFRC

$$f_{R,4} = 1.40 f_{R,1} - 0.79$$
$$R^2 = 0.873$$
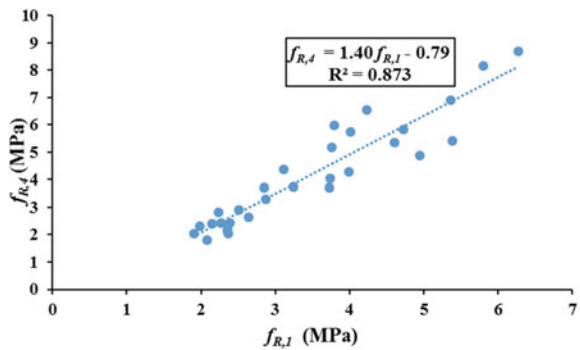
Fig. 10 Relationship between $f_{eq,2}$ and $f_{R,1}$ of SFRC

$$f_{R,1} = 0.92 f_{eq,2} + 0.42$$
$$R^2 = 0.99$$
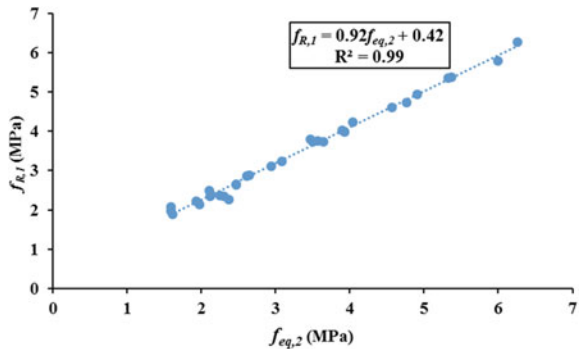
Fig. 11 Relationship between $f_{eq,3}$ and $f_{R,4}$ of SFRC

$$f_{R,4} = 1.064 f_{eq,2} - 0.09$$
$$R^2 = 0.97$$
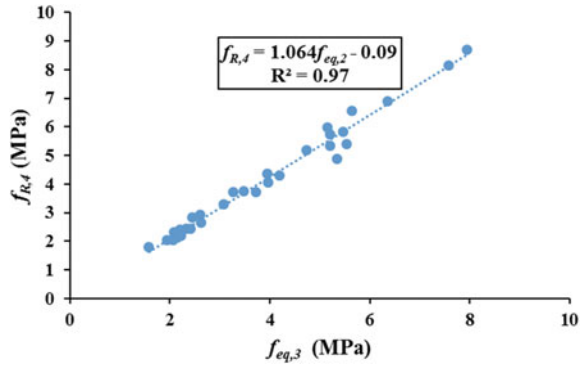
and between $f_{eq,3}$ and $f_{R,4}$ are represented in Figs. 10 and 11, with good correlation between two sets of parameters, as again obtained by Barros et al. [7].

The present study suggests that approximate values of f_{eq} or f_R can be obtained when the other has been reported.

5 Conclusions

The post-cracking behaviour SFRC was assessed using three-point bending tests on notched specimens for M40 grade of concrete. From the results obtained from the concrete mixes and fibre dosages considered here, the following conclusions can be drawn.

- From the load–CMOD behaviour and load–deflection behaviour of the SFRC from notched beam test, it can be concluded that at large crack openings, the hooked-ended steel fibres are efficient in enhancing the post-crack load-carrying capacity. This is reflected by the higher values seen for $f_{eq,3}$ and $f_{R,4}$ than for $f_{eq,2}$ and $f_{R,1}$.
- A good correlation exists between equivalent and residual flexural tensile strengths parameters of SFRC.

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