Materials and Structures
DOI 10.1617/s11527-015-0727-y

ORIGINAL ARTICLE

Creep behaviour of cracked steel and macro-synthetic fibre reinforced concrete

R. Zerbino · D. H. Monetti · G. Giaccio

Received: 30 December 2014 / Accepted: 5 October 2015

Abstract The study of creep behaviour of fibre concrete in cracked conditions is nowadays one of the main subjects of interest; many research groups in the world are working on this matter and the development of test methods and the definition of parameters for its characterization becomes an urgent necessity. This paper explores the use of different types and levels of long term bending loads and compares the creep rates of fibre reinforced concretes (FRC) incorporating steel and two macro-synthetic fibres. Tests arrangements with three and four point loadings were used. An initial crack width of 0.5 mm was adopted. It was verified that the creep rate clearly increases in macro-synthetic FRC and that the application of loading–unloading cycles does not imply significant changes in the creep rate when compared to permanent loads of similar magnitude. After creep tests the remaining residual bending capacity of FRC is considerable. Similar creep behaviour was observed by using three or four point loading configuration.

R. Zerbino (✉) · D. H. Monetti · G. Giaccio
Civil Engineering Department UNLP, Calle 1 y 47,
La Plata B1900TAG, Pcia de Buenos Aires, Argentina
e-mail: zerbino@ing.unlp.edu.ar

R. Zerbino
CONICET, La Plata, Argentina

G. Giaccio
CIC, La Plata, Argentina

Published online: 12 October 2015

Keywords Fibre reinforced concrete · Creep behaviour · Steel fibres · Macro-synthetic fibres · Crack opening rate

Abbreviations

f_c'	Compressive strength
f_L	First-peak flexural strength
f_{R1}	Residual flexural strength at 0.5 mm
f_{R2}	Residual flexural strength at 1.5 mm
f_{R3}	Residual flexural strength at 2.5 mm
f_{R4}	Residual flexural strength at 3.5 mm
f_{final}	Stress at the end of initial cracking (before unloading)
$CMOD_{max}$	Maximum crack mouth opening displacement in bending test
$CMOD_{res}$	Residual crack mouth opening displacement after unloading
f_{maxC}	Maximum stress applied during creep tests
COD	Crack opening displacement during creep test
COD rate	Crack opening displacement rate under permanent loads
$CR_{30\text{–}90}$	Crack opening rate between 30 and 90 days under loading
f_{MP}	Maximum flexural stress after creep tests
f_{R1P}	Residual flexural strength at 0.5 mm after creep tests
f_{R2P}	Residual flexural strength at 1.5 mm after creep tests

f_{R3P} Residual flexural strength at 2.5 mm after creep tests

f_{R4P} Residual flexural strength at 3.5 mm after creep tests

1 Introduction

Important advances have been achieved over the past decades regarding the residual strength characterization and applications of fibre reinforced concrete (FRC). The recent *fib* Model Code 2010 [7] includes specific sections for the design of FRC elements. In addition, new types of non-metallic fibres have been developed.

In many applications fibres have been incorporated in concrete in order to improve the service life of the structures, considering their benefits in crack control. Studying the combined use of conventional steel bar reinforcement and fibres, several authors found that the addition of steel fibres considerably reduces the deferred deformations under sustained loads and the cracks widths with a positive effect on the durability of concrete, mainly in aggressive environments; in addition, only a few changes on the residual resistance were found [5, 9–12].

The study of creep behaviour of cracked FRC and the conditions for a stable residual response represent a key point of interest, since serviceability of the material will depend on its capacity to transfer the sustained stresses through the fibres and the stability of the cracks. The results of creep tests are especially significant for elements reinforced solely with fibres that tend to present cracks in service state. Slabs-on-grade, shotcrete for ground control, and tunnel segments appear as frequent structural applications where the creep in cracked state should be considered.

The creep response is particularly relevant in the case of synthetic macrofibres. Nevertheless, there are no standard test methods and there is limited information on the long term behaviour of cracked FRC elements under load, with only few reports dealing with the subject, mainly on steel FRC [1–3, 8, 13, 14].

However, it is encouraging that many papers were presented during the last RILEM BEFIB 2012 Conference in Guimaraes, Portugal, and more than 15 research groups in the world are working on the subject. In 2014, the RILEM Technical Committee "Creep behaviour on cracked sections in FRC" was created. The objectives of this committee include to compile results into mechanisms of creep behaviour of FRC, to propose test methods and parameters for characterization, and to analyze the variables that act on the creep (i.e. composition and properties of concrete, dosage and type of fibres, stress level).

This paper studies the creep behaviour of cracked beams with the aim of analyzing variables involved in the testing methodology and criteria for the evaluation of creep performance; FRC incorporating steel and macro-synthetic fibres were tested and compared.

2 Experimental program

The experimental program explores some variables related to the creep testing method as the stress levels where stable tests can be performed, the effect of using three point or four point bending setup on the creep test results and the benefits that loading–unloading cycles could report in reducing the testing time when compared to permanent loads. In addition, the use of creep rate as a criterion for the analysis of creep performance is applied.

Four Series of FRC (named S1, M2, M3 and S4) incorporating steel and macro-synthetic fibres were studied. The responses of different fibres can be observed when comparing Series S1, M2 and M3, while the effect of the loading configuration can be analyzed comparing Series S1 and S4. As it was mentioned, the slabs on grade are a typical case where the influence of creep at cracks or joints is manifested. The selected concretes incorporate three well known fibres of proved performance and are representative of this type of application.

2.1 Testing procedures

Twelve beams of 150 × 150 × 600 mm and four standard cylinders of 150 × 300 mm were cast with each FRC. The specimens were cured in moist room, and after that they were placed for 2 or 3 weeks in laboratory environment to minimize the variations in strength during long term tests. Table 1 presents a scheme that summarizes the testing program.

The beams of each FRC were separated in two groups. To characterize FRC bending behaviour, a first group of three beams (named "a–c") was tested as

Table 1 Testing program

Specimens conditioning and testing steps				Measured parameters
Moist curing + exposure in laboratory environment				
FRC characterization: complete EN14651 bending tests (3 beams, a–c)				f_L, f_{R1}, f_{R2}, f_{R3}, f_{R4}
Compressive tests on cylinders				f'_c
Precracking process up to 0.5 mm COMD (9 beams, d–l)				f_L, f_{R1}
Creep tests	Series 1	3 PB	permanent loads (3 beams, a–c)	Load—COD
	Series 1–3	3 PB	permanent loads (6 beams, d–i)	
			loading–unloading events (3 beams, j–l)	
	Series 4	4 PB	permanent loads (3 beams, d–f)	
			loading–unloading events (6 beams, g–l)	
FRC residual properties (beams that did not failed during creep tests)				f_{MP}, f_{R1P}, f_{R2P}, f_{R3P}, f_{R4P}

indicated in the EN 14651 Standard [6] (3-point bending, 500 mm span, 25 mm notch). The crack mouth opening displacement (CMOD) was used as the control signal of a closed-loop servo-hydraulic system, through a clip gage placed at 1 mm from the bottom of the beam. The first-peak strength (f_L) and the residual flexural strengths at 0.5, 1.5, 2.5 and 3.5 mm of CMOD (f_{R1}, f_{R2}, f_{R3} and f_{R4}, respectively) were calculated.

A second group of nine beams (named "d"–"l") was used for creep tests. The creep procedure includes a pre-cracking process, the creep test itself and finally, a bending test to evaluate the residual strength properties after creep. To induce the cracks in concrete and considering that the residual stress f_{R1} is used for the verification of SLS (7), each beam was loaded until a CMOD of 0.5 mm was achieved. The first-peak stress (f_L) and the residual stress f_{R1} were calculated to characterize and compare the performance of these beams.

The creep setup and testing methodology was similar to that used by Arango et al. [1] where three beams are loaded together in each frame. However, three point bending setup, the same as the used by EN 14651 standard, was adopted (Series S1, M2 and M3). In order to compare the results obtained with three point or four point bending setup, in Series S4 (a FRC similar to S1) four point bending setup was used. Figure 1 shows a scheme of both loading configurations. The crack opening displacement during creep test (COD) was measured with a mechanical dial gage placed at the level of the tensile side of the beams.

The frames were placed in a closed room with temperature control. Previous to the measurements it was verified that the room remained for more than 3 h at 21 ± 2 °C.

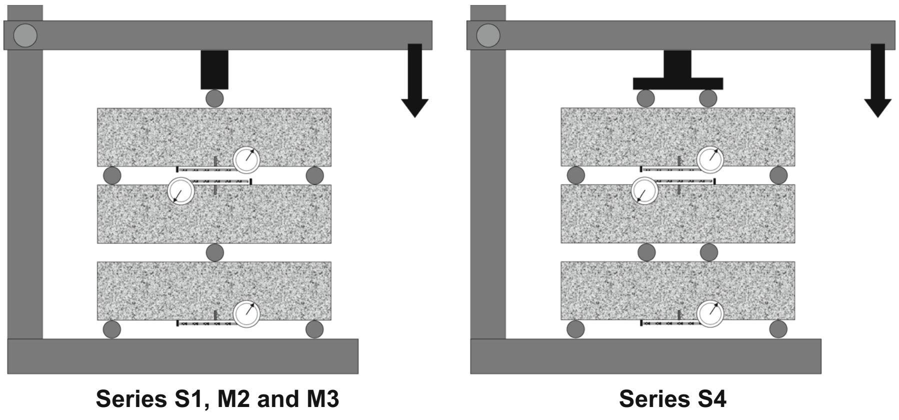

Fig. 1 Scheme of creep frames and load configuration

To analyze the conditions for stable creep development different sustained stress levels were applied on sets of three beams, the highest up to 70 % f_{R1} and the lowest up to 50 % f_{R1}. These stress levels were selected considering that the beams were pre-cracked up to 0.5 mm and that previous researches on steel FRC indicate that the creep deformations are not significant for stresses lower than 50 % of the residual stresses f_{R3} or f_{R4} [3, 13].

On other set of beams static loading–unloading events (cycles) were applied to analyze if the creep rate varies with respect to that measured under permanent loads; in this case maximum stresses of near 70 % f_{R1} and two cycles per week were applied.

In all frames, the beam with the lowest f_{R1} of the set was placed at the top and the beam with the greatest residual capacity at the bottom. At the beginning of the creep tests a brief period at low stresses was adopted in order to avoid undesired movements in the supports and the consistency of the COD measurements. In many cases, when the specimens showed stable creep behaviour for many weeks, the stresses were increased with the aim to observe its influence on the creep rate.

During long term loading some beams failed, some beams underwent very high deformations and others remained stable preserving bearing capacity. After the creep test the beams that did not failed were removed from the frames and they were monotonically loaded (standard test velocity) up to failure to evaluate their remaining strength capacity; the maximum stress after creep tests (f_{MP}), and the residual flexural strengths at 0.5, 1.5, 2.5 and 3.5 mm of CMOD (f_{R1P}, f_{R2P}, f_{R3P} and f_{R4P}, respectively) were calculated.

2.2 Fibres and FRC characteristics

Four concrete Series were done; Series S1 and S4 were prepared with 30 kg/m^3 of a hooked end steel fibre, while Series M2 and M3 incorporate 3 kg/m^3 of two different and widely used macro-synthetic fibres. Figure 2 shows the fibres used.

The selected FRC, including the type and content of fibres, are representative of fibre concretes frequently used in the construction of slabs-on-grade.

The base concrete materials and mixture proportions were very similar in all cases, varying only the cement type and the dosages of chemical admixtures; a polycarboxylate superplasticizer was used to produce

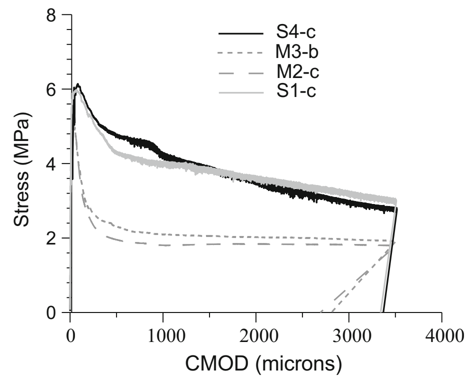

Fig. 3 Stress versus crack opening curves in bending (EN14651 standard)

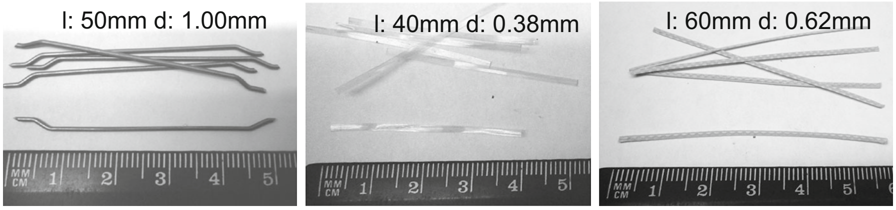

Fig. 2 Used fibres (*left* series S1 and S4; *centre* series M2; *right* series M3)

Table 2 Compressive and flexural strengths of FRC

FRC	Compressive strength (MPa)	Flexural tensile strengths (MPa)				
		f_L	f_{R1}	f_{R2}	f_{R3}	f_{R4}
S1	42.6	5.7	3.7	3.3	2.9	2.6
M2	53.1	5.6	2.0	1.9	1.8	1.8
M3	53.2	5.5	2.1	1.8	1.9	1.9
S4	42.1	5.5	4.1	3.6	3.1	2.7

Table 3 Strength and residual properties during initial cracking and after creep tests

Beam	Pre-cracking tests				Residual parameters after creep tests					
	f_L (MPa)	f_{R1} (MPa)	$CMOD_{max}$ (μm)	$CMOD_{res}$ (μm)	Fibre density (fib/cm^2)	f_{MP} (MPa)	f_{R1P} (MPa)	f_{R2P} (MPa)	f_{R3P} (MPa)	f_{R4P} (MPa)
S1-d	5.0	4.1	506	366	0.34	4.6	4.4	4.4	3.9	3.5
S1-e	5.3	4.5	507	377	0.31	5.6	4.9	5.2	4.6	4.0
S1-f	5.5	4.5	506	372	0.33	5.1	5.0	4.3	3.7	3.3
S1-g	4.7	3.1	507	375	0.37	4.1	4.0	3.8	3.7	3.4
S1-h	4.7	3.7	501	363	0.30	5.2	4.8	4.9	4.3	4.0
S1-i	5.5	4.1	508	365	0.27	5.6	5.4	5.0	4.5	4.0
S1-j	5.5	4.6	506	385	0.38	6.0	5.4	5.8	5.0	4.4
S1-k	6.0	5.0	530	398	0.39	6.4	6.0	5.8	4.4	3.7
S1-l	5.6	4.7	506	370	0.29	5.6	5.3	5.3	4.6	4.0
M2-d	5.0	2.0	503	320	–	–	–	–	–	–
M2-e	5.0	1.9	554	369	–	–	–	–	–	–
M2-f	5.8	1.9	504	320	–	–	–	–	–	–
M2-g	5.0	2.0	505	310	–	1.7	1.5	1.7	1.7	1.7
M2-h	5.3	2.0	602	371	–	–	–	–	–	–
M2-i	5.1	2.1	504	316	–	1.2	0.2	1.1	1.1	1.1
M2-j	5.3	2.1	504	316	–	1.4	1.1	1.3	1.4	1.4
M2-k	5.5	2.1	504	320	–	1.7	1.5	1.7	1.7	1.7
M2-l	5.3	2.2	504	316	–	1.4	1.0	1.3	1.3	1.3
M3-d	5.7	2.1	507	326	–	–	–	–	–	–
M3-e	5.3	2.5	507	296	–	1.6	1.1	1.6	1.6	1.5
M3-f	5.6	2.5	506	300	–	–	–	–	–	–
M3-g	4.8	1.5	508	313	–	1.5	1.4	1.5	1.5	1.5
M3-h	4.8	1.5	504	336	–	1.2	1.2	1.2	1.2	1.2
M3-i	5.0	1.6	505	314	–	1.7	1.5	1.6	1.7	1.7
M3-j	5.1	1.7	506	322	–	1.1	0.7	1.1	1.1	1.1
M3-k	4.9	1.8	508	298	–	1.6	1.2	1.6	1.5	1.4
M3-l	4.7	1.8	507	312	–	1.2	0.6	1.1	1.1	1.1
S4-d	5.0	3.7	517	376	0.28	4.9	4.0	4.9	4.5	4.1
S4-e	4.9	3.8	510	400	0.35	5.3	4.9	5.1	4.9	4.1
S4-f	5.0	4.0	526	391	0.31	5.0	4.9	4.7	4.2	3.9
S4-g	6.4	3.6	514	378	0.25	4.0	3.5	3.7	3.8	3.7
S4-h	4.9	3.6	504	414	0.24	4.7	4.1	4.4	4.1	3.6
S4-i	4.9	3.6	510	403	0.25	4.6	4.1	4.3	3.9	3.2
S4-j	4.9	4.0	507	376	0.28	5.2	5.2	5.2	4.8	4.5
S4-k	5.2	4.1	518	368	0.35	4.9	4.6	4.4	4.2	3.8
S4-l	5.3	4.6	573	441	0.38	6.7	5.6	6.5	5.7	5.0

FRC with slumps equal to 55 ± 10 mm. All FRC incorporated 360 kg/m^3 of cement, 1000 kg/m^3 of 19 mm maximum size granitic crushed tone as coarse aggregate, and 900 kg/m^3 of natural siliceous sand as fine aggregate. The water/cement ratios were 0.40 in FRC S1, M2 and M3 and 0.42 in S4.

Concrete S1 was prepared with ordinary portland cement similar to CEM I type. The specimens were cured in moist room during 28 days and then they remained in the laboratory. Tests on FRC S1 started at 50 days; the compressive strength and the mean results of the three beams (S1-a, S1-b and S1-c) tested in accordance to EN14651 standard are presented in Table 2. According to the Model Code 2010 [7] concrete S1 can be classified as a FRC type 3b.

In Series M2 and M3 ordinary portland cement similar to CEM IV type was used; again the specimens were moist cured during 28 days and then remained in the laboratory. The initial testing ages were 46 and 50 days, these FRC can be classified as type 2c and type 2b, respectively. Tests results are given in Table 2.

Finally, and considering that high early strength cement was used, in Series S4 the specimens were moist cured during 7 days and then stored in laboratory for 2 weeks. In S4 the initial testing age was 21 days. FRC S4, that showed a residual behaviour very similar to FRC S1 as expected (Table 2), can be classified as type 4b.

Figure 3 shows the stress versus CMOD curves obtained from bending tests performed in accordance to EN14651 on three prisms of each concrete. It is represented the curve corresponding to the specimen closer to the mean behaviour. Typical responses for the used contents of steel and macro-synthetic fibres are verified. Note that the post-peak response of S1 and S4 are very similar, as expected; these FRC will be used to compare creep tests performed under four point and three point loading configurations. Regarding macro-synthetic FRC, under static short term loads, M2 and M3 present similar residual capacity with flat post-cracking response, lightly lower in the case of M2.

3 Test results and discussion

Table 3 shows the mechanical properties (f_L and f_{R1}) measured during the pre-cracking process of the beams used for creep tests (named "d"–"l"); the maximum crack mouth opening displacement ($CMOD_{max}$) and the residual crack mouth opening displacement after unloading ($CMOD_{res}$) are also included. It must be noted that the individual results of f_L and f_{R1} are in accordance with the mean values measured on standard tests of beams "a–c".

Table 3 also shows, for the beams that did not fail during long term loading, the residual properties in bending after creep tests and, in Series S1 and S4, the fibre density measured on the fracture zone at the end of the study.

3.1 Creep tests results

In Series S1, high long term stresses of near 70 % f_{R1} were applied on beams S1-d–S1-f, while on beams S1-g to S1-i lower long term stresses of near 50 % f_{R1} were used. On beams S1-j to S1-l loading–unloading cycles with a maximum stress of near 70 % f_{R1} were applied. No COD recording was done on specimens S1-d and S1-g. Figure 4 shows the COD versus time curves of each beam of Series S1; as a reference, the

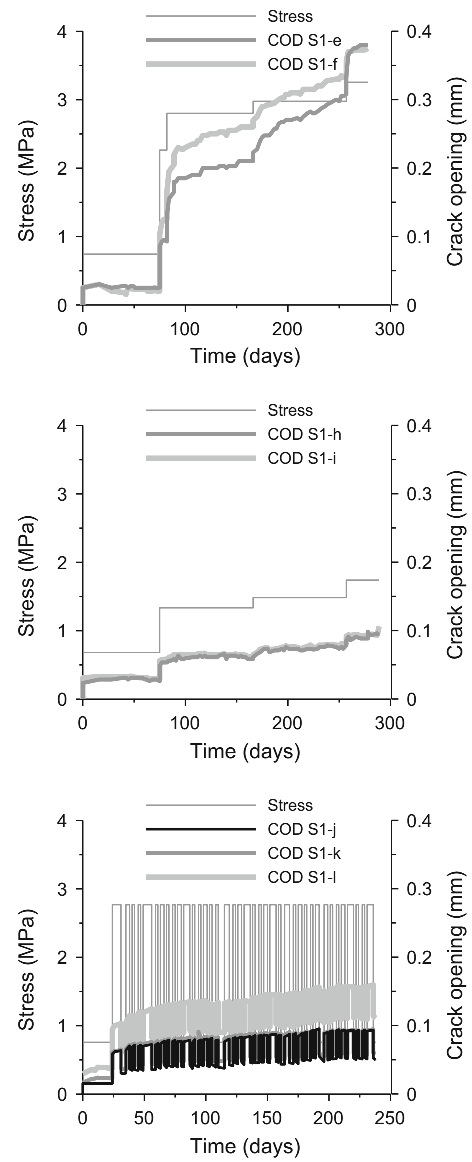

Fig. 4 Creep tests. Series S1

stress versus time curves corresponding to the central beam of each frame are also plotted.

Table 4 shows the load history of each specimen including the position of the beam in the frame, the nominal stress (considering the uncracked section) in absolute values and as a percentage of the f_{R1} of each specimen, the loading period and the COD rate calculated as a chord considering the differed crack openings during the lapse of loading. In the case of cyclic loadings the COD rate was calculated from the measurements at maximum stresses. As expected, the COD rate increases as the load applied increases. It is interesting to note that, contrary to what was expected, in the case of loading–unloading events the crack openings are lower when compared to the deformations (COD) measured under permanent loads.

Table 4 and Fig. 4 show stable creep behaviour, characterized by moderate increases in COD over the time, in the beams of Series S1 cracked up to 0.5 mm when stresses lower than 70 % of f_{R1} are applied.

In Series S1 creep tests on the three beams cracked up to 3.5 mm used for FRC characterization (S1-a to S1-c) were also made. Table 4 shows that the

Table 4 Series S1. Creep tests

Beam and frame position	Applied stress		Time under load	COD rate
	(MPa)	(% of f_{R1})	(days)	(mm/year)
S1-e middle	0.7	17	0–75	<0.01
	2.3	51	75–82	0.39
	2.8	63	93–166	0.13
	3.0	66	166–257	0.34
	3.3	73	257–278	0.78
S1-f bottom	0.8	18	0–75	<0.01
	2.4	54	75–82	1.17
	3.0	66	93–166	0.17
	3.1	70	166–257	0.26
	3.4	77	257–278	0.30
S1-h middle	0.7	18	0–75	0.01
	1.3	36	75–166	0.04
	1.5	40	166–257	0.07
	1.7	47	257–289	0.09
S1-i bottom	0.8	19	0–75	<0.01
	1.4	34	75–166	0.02
	1.5	38	166–257	0.07
	1.8	44	257–289	0.17
S1-j top	0.6	13	7–24	<0.01
	2.6	57	24–236	0.05
S1-k middle	0.8	15	7–24	0.01
	2.8	56	24–236	0.04
S1-l bottom	0.8	17	7–24	0.05
	3.1	66	24–236	0.08
	(MPa)	(% of f_{R4})	(days)	(mm/year)
S1-a top	0.7	30	0–85	0.07
	2.0	83	85–89	34.5
S1-b middle	0.7	31	0–85	0.34
	2.1	94	85–89	19.2
S1-c bottom	0.9	28	0–85	0.08
	2.2	73	85–89	1.41

specimens remain stable for stresses near 30 % of f_{R4} and for stresses higher than 70 % f_{R4} the COD rate drastically increases.

Table 5 shows the load history of each specimen of Series M2 and Fig. 5 the COD versus time and stress versus time curves. Again, the experimental program included three beams (M2-d to M2-f) at high long term stresses of near 70 % f_{R1}, other three beams at lower long term stresses of near 50 % f_{R1} (M2-g to M2-i), and loading–unloading events on the last three beams (M2-j to M2-l). No COD recording was done on specimen M2-d. Nevertheless, and although relative stable conditions were found for stresses lower than 50 % f_{R1}, some beams failed when the load was increased. In the case of cyclic loadings and after only a few days, very high COD rates were observed, mainly in M2-j and M2-l and, for that reason the beams were unloaded with the aim of evaluating their remaining residual capacity. The COD—time curves corresponding to beams M2-g to M2-i show a "secondary and tertiary creep period", resembling the typical shape of creep curves; those beams were unloaded when they achieved very high COD rates.

Table 6 shows the load history of each specimen of Series M3 and Fig. 6 the COD versus time and stress versus time curves. Again, long term stresses of near 70 % f_{R1} (beams M3-d to M3-f), of near 50 % f_{R1} (beams M3-g to M3-i), and cyclic loading–unloading events on beams M3-j to M3-l were used. As it happened in Series M2, stable conditions were found for stresses lower than 50 % f_{R1}, but it must be noted that beams M3-g to M3-i never showed a "tertiary type" creep response. The COD rates were clearly lower than those measured in Series M2. These beams

Table 5 Series M2. Creep tests

Beam and frame position	Applied stress		Time under load	COD rate
	(MPa)	(% of f_{R1})	(days)	(mm/year)
M2-e middle	0.6	34	0–24	0.75
	1.1	58	24–26	Failure
M2-f bottom	0.7	39	0–24	0.02
	1.2	65	24–26	102
m2-g top	0.6	31	0–12	0.46
	0.9	47	12–150	0.68
	0.9	47	150–285	0.99
M2-h middle	0.7	35	0–12	0.88
	1.0	51	12–80	12.7
			80–100	Failure
M2-i bottom	0.7	35	0–12	0.91
	1.0	50	12–90	8.0
			90–120	18.2
			120	Unloaded
M2-j top	0.6	30	0–17	1.6
	1.1	51	17–24	8.3
	1.5	70	24–33	59
			35	Unloaded
M2-k middle	0.5	26	0–17	1.6
	1.0	46	17–24	9.8
	1.3	64	24–33	15.3
			35	Unloaded
M2-l bottom	0.7	33	0–17	1.9
	1.1	53	17–24	13.2
	1.5	71	24–33	90
			35	Unloaded

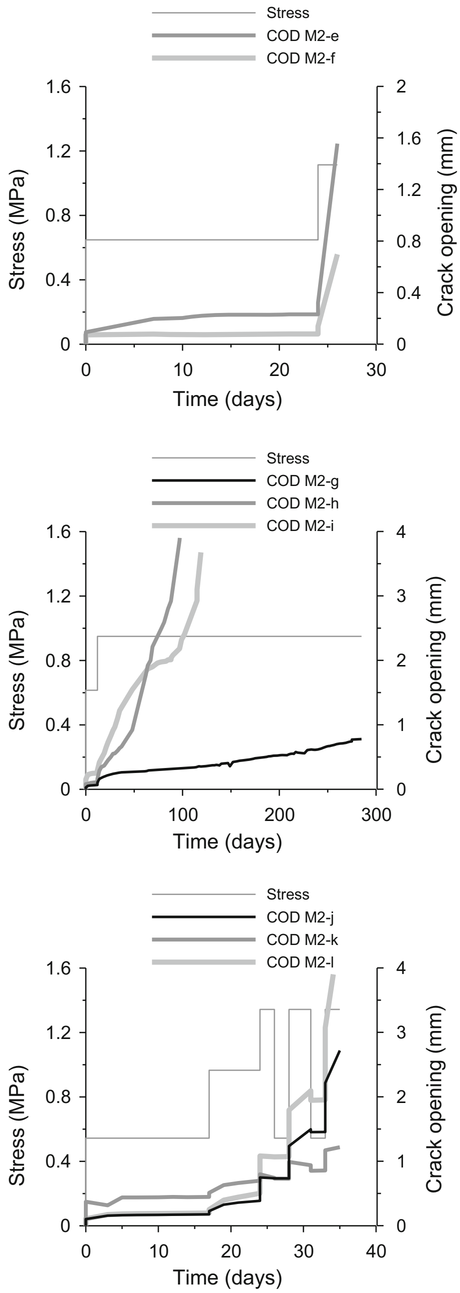

Fig. 5 Creep tests. Series M2

showed a stable behaviour, they remained loaded for more than 7 months and then they were unloaded.

Beams M3-d to M3-f remained very stable for stresses of near 30 % f_{R1}, when the load was increased up to 2.3 MPa beam M3-d failed (note that the stress was higher than the f_{R1} of this beam), and the companion beams M3-e and M3-f were unloaded. Regarding loading–unloading events, beams M3-j to M3-l also showed a very stable response for stresses of near 40 % f_{R1}, when the load was increased up to 80 % f_{R1} (1.3 MPa) beam M3-j failed, the companion beams were loaded again and were able to carry out similar stress level but showing significant COD rates, over 8 mm/year. After a few days they were unloaded in order to evaluate their residual bending properties.

Regarding the testing method used, consisting of placing three beams in each frame, the three point bending setup has the advantage that it is the same configuration used during pre-cracking and later bending tests. On the other hand, the use of the four point loading configuration makes it easier the arrangement of the specimens in the frame and it enhances the stability of the creep test. To compare the creep test results using three or four point configurations FRC S4 (equivalent to FRC S1) was tested. Table 7 shows the load history and Fig. 7 the COD versus time and stress versus time curves.

Long term stresses of near 70 % f_{R1} were applied in beams S4-d to S4-f, but they were previously loaded during nearly 90 days at long term stresses of near 50 % f_{R1}. On the rest of the beams (S4-g to S4-i, and S4-j to S4-l) loading–unloading events were applied, firstly with a maximum nominal stress of near 50 % f_{R1} (for 3 months) and later the maximum stress was increased up to near 70 % f_{R1}. None of these beams showed unstable creep behaviour and, as expected, the COD rate increases as the applied load increases, but it was always lower than 1 mm/year.

The concept of creep rate (COD rate) is a useful tool for the analysis of the creep behaviour of cracked FRC; the effects of type of loading, test configuration, stress levels or type of fibres will be analyzed based on this concept.

Considering the definition of the creep COD rate and the typical variation of COD rate with time, many tests showed that after 30 days under loading a clear decrease in COD rate takes place and, if stable conditions occur, no significant variations for different lapses under loading should be expected. However, it is clear that in order to compare the COD rate of different FRC, the results corresponding to very short loading periods could be uncertain. A definition of a creep rate calculated from the chord between 30 and 90 days ($CR_{30–90}$) represents a good alternative. The last column in Table 7 includes the values of $CR_{30–90}$ of Series S4. As expected, the values are lower than

Table 6 Series M3. Creep tests

Beam and frame position	Applied stress		Time under load	COD rate
	(MPa)	(% of f_{R1})	(days)	(mm/year)
M3-d top	0.7	34	0–10	2.0
	2.3	109	10–12	106
	2.3		14	Failure
M3-e middle	0.7	28	0–10	1.4
	2.0	83	10–12	24.1
			14	Unloaded
M3-f bottom	0.7	30	0–10	1.6
	2.1	82	10–12	11.9
			14	Unloaded
M3-g top	0.6	44	0–10	2.7
	0.6	44	10–228	0.12
M3-h middle	0.7	48	0–10	4.2
	0.7	48	10–228	0.31
M3-i bottom	0.7	46	0–10	4.7
	0.7	46	10–228	0.18
M3-j top	0.6	37	0–14	2.6
	1.3	80	14–18	Failure
M3-k middle	0.7	37	0–14	0.90
	1.3	76	14–18	M3-j failed
	1.3	76	18–35	9.9
	1.3	76	35–42	Unloaded
M3-l bottom	0.7	41	0–14	0.50
	1.4	79	14–18	M3-j failed
	1.4	79	18–35	8.8
	1.4	79	35–42	Unloaded

those calculated over the complete loading period but, as Fig. 8 shows, there is a good correlation between both COD rates. Finally, although the use of COD rates calculated in very short periods under loading could lead to assume a very high velocity that is not real for stable conditions (secondary creep), it reflects the instability of the creep process when the values are very high, i.e. greater than 1 mm/year for steel FRC or greater than 5 mm/year for macro-synthetic FRC. It must be noted that the mentioned values are indicated only for comparative purposes and new and systematic researches must be developed in the future, using a testing method clearly defined, to establish COD rates criteria. Finally, and although the main creep mechanism involved in cracked FRC is fibre pull-out, the exposure conditions could affect the results and the comparison with other authors' work. During the lapse of the tests (more than 2 years), the relative humidity and the temperature were registered, with minimums and maximums equal to 60 and 80 % for the humidity and 12 and 28 °C for the temperature. However, previous to COD measurements the room was acclimatized more than 3 h at 21 ± 2 °C.

3.2 Effect of the long term loads on the creep rate

The creep or COD rate increases as the stress increases, as expected, but for each FRC there is a stress level where an unstable behaviour characterized by a strong increase in crack growth starts.

In Series S1 for small initial CMOD (0.5 mm) the increment in COD is accelerated when the stresses exceeded 0.60 f_{R1}. An increasing tendency was also observed in the beams that were severely damaged previous to creep tests (CMOD 3.5 mm), but in this case this was true even for very low stresses ($\sim$0.30 f_{R4}). The results of Series S4 are coherent with those of the beams cracked up to 0.5 mm of Series S1, the COD

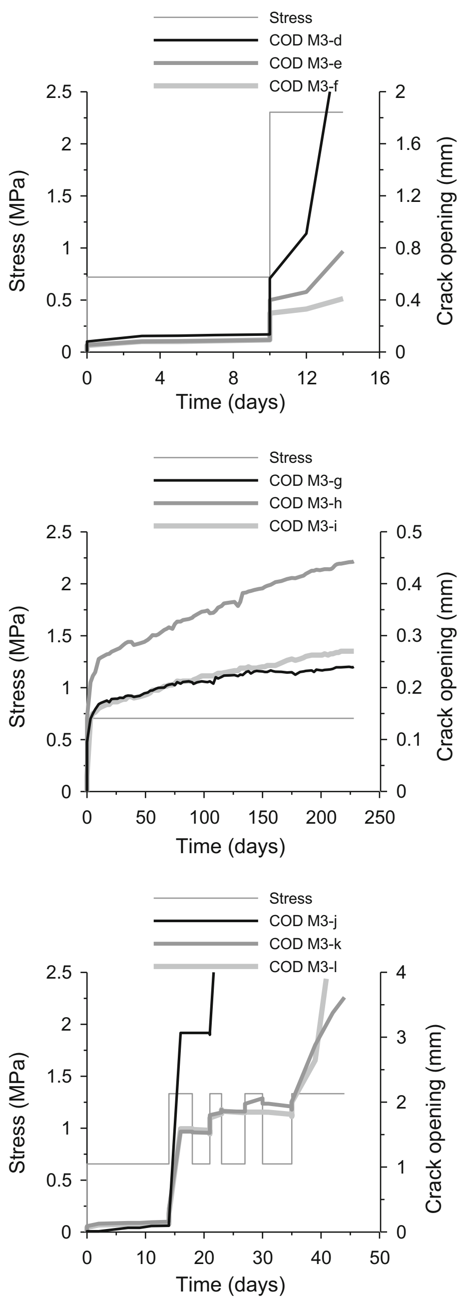

Fig. 6 Creep tests. Series M3

velocities are very low for stresses lower than 0.5 f_{R1}, and increase when the applied stress achieves near 0.7 f_{R1}.

In Series M2 the COD rate increases are significantly higher than in the previous case. When the stresses exceeded approximately 0.50 f_{R1} the increments in COD rate are very important. Similar conclusions can be drawn from Series M3, but in this case the COD rate increment appears at higher stresses. Some differences in the responses observed in Series M2 and M3 could be attributed to a greater pull-out strength measured with fibres M3 [4].

Figure 9 compares the variation in COD rates with the applied stress for each FRC; the stresses are expressed as the value relative to f_{final} (f_{R1} for beams cracked up to 0.5 mm or f_{R4} for beams cracked up to 3.5 mm). It can be seen that Series S1 and Series S4 (continuous lines) present the same tendency indicating that both loading configurations lead to similar responses. It is also evident that the creep rate increased in the specimens of Series 1 pre-cracked up to 3.5 mm (dotted line). The figure clearly shows that the creep rate can significantly increase in the case of macro-synthetic FRC (dashed lines), with variations that can be of an order of magnitude. However, great differences can be expected when different types of macro-synthetic fibres are considered. Besides the high COD rates measured when macro-synthetic fibres are added it is very interesting to note that their residual capacity was not significantly affected as it can be seen as follows.

3.3 Effect of the long term loads on the residual capacity

The beams that did not fail during creep tests, were removed from the frames and tested according to the general guidelines of EN 14651. Table 3 reports the residual properties measured in bending after the creep tests.

In Series S1 the beams were removed after nearly 10 months long term loading. Their residual properties are even greater than those measured on the reference beams (see Sect. 2.2) indicating that the long term loads had no significant effects on the residual strength capacity of the FRC, but with the consequent increases in crack openings. Similar conclusions can be extracted when the residual properties of Series S4 are analyzed.

Considering macro-synthetic FRC M2 and M3, again no great effects on the residual capacity (only small decreases) appear when comparing the reference beams and the post creep bending tests; although the cracks openings clearly grew the residual stresses were always higher than 1 MPa, which is over 20 % of the f_L.

Table 7 Series S4. Creep tests

Beam and frame position	Applied stress (MPa)	Applied stress (% of f_{R1})	Time under load (days)	COD rate (mm/year)	CR_{30-90} (mm/year)
S4-d top	0.4	23	0–7		
	1.3	49	7–11		
	1.8	49	11–126	0.11	0.03
	2.8	75	126–238	0.64	0.39
S4-e middle	0.4	11	0–7		
	1.3	35	7–11		
	1.8	48	11–126	0.09	0.03
	2.7	73	126–238	0.29	0.21
S4-f bottom	0.5	12	0–7		
	1.4	33	7–11		
	1.8	45	11–126	0.07	0.03
	2.7	67	126–238	0.08	0.04
S4-g top	0.4	12	0–7		
	1.1	30	7–11		
	1.7	46	11–126	0.10	0.05
	2.6	71	126–238	0.54	0.33
S4-h middle	0.5	13	0–7		
	1.1	32	7–11		
	1.7	48	11–126	0.03	<0.01
	2.6	73	126–238	0.38	0.22
S4-i bottom	0.5	14	0–7		
	1.2	32	7–11		
	1.7	48	11–126	0.11	0.05
	2.6	72	126–238	0.43	0.28
S4-j top	1.4	36	0–4		
	2.1	52	4–119	0.10	0.04
	3.1	76	119–231	0.46	0.37
S4-k middle	1.4	34	0–4		
	2.0	49	4–119	0.10	0.05
	3.0	72	119–231	0.60	0.39
S4-l bottom	1.5	33	0–4		
	2.1	46	4–119	0.12	0.06
	3.1	67	119–231	0.49	0.39

Figure 10 represents the maximum bending strength after sustained loads (f_{MP}) as a function of the maximum stress applied during creep test (f_{maxC}, see Table 3). Considering the variability among the samples, the residual capacity after the creep process was expressed as a relative value of the initial f_{R1} of each beam (f_{MP}/f_{R1}). In the case of steel FRC it can be seen that in Series S1, although the values of f_{MP}/f_{R1} decrease with the increasing f_{maxC}, as was expected, there were no significant changes in the residual capacity of the beams and only a quite uniform decreasing tendency appears, regardless the type of load applied. Although the range of f_{maxC} applied in Series S4 was not too extended, the f_{MP}/f_{R1} ratios are comparable (between 1 and 1.5) and similar conclusions can be drawn when four point loading configuration was applied.

In macro-synthetic FRC the f_{MP}/f_{R1} ratios are smaller (between 0.5 and 1) and lightly lower in Series M2 than in Series M3. In the last case, contrary

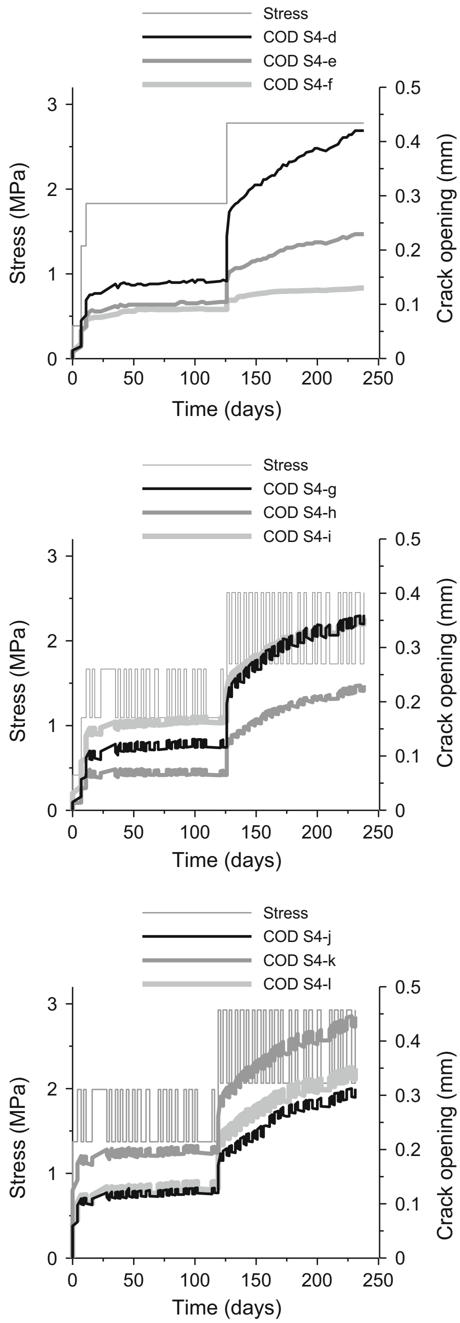

Fig. 7 Creep tests. Series S4

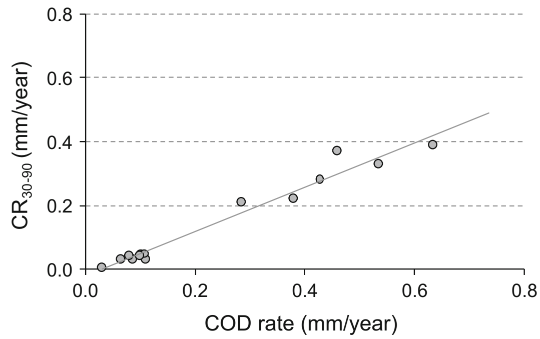

Fig. 8 $CR_{30–90}$ (chord between 30 and 90 days) versus COD rate (chord along the complete period)

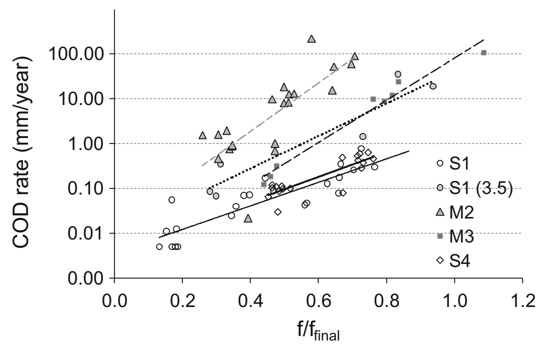

Fig. 9 Effect of long term loading level on the creep rate of the different FRC

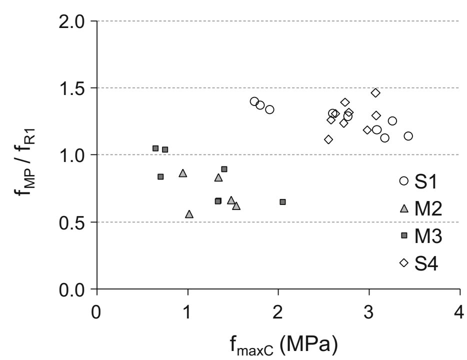

Fig. 10 Effect of long term loading level on the residual strength capacity

to M2 FRC, the differences in the maximum stresses applied during creep tests were significant. In both cases the tendency is similar; there were no significant changes in the residual capacity of the beams when low stresses were applied, and loading–unloading events produced lower effects than the application of similar permanent loads.

4 Conclusions

This paper discusses the effects of stress levels, type and configuration of loads on the creep behaviour of cracked FRC. The responses of concretes incorporating steel and macro-synthetic fibres are considered. The main conclusions are pointed as follows:

- The use of three or four point loading configuration in bending does not affect creep tests results in terms of the COD rate or the stress levels where a stable creep behaviour takes place, being the later much easier.
- The use of loading–unloading cycles does not contribute to the reduction of testing time and, for a given maximum stress, the obtained results were similar to those obtained with permanent stresses of the same value.
- The COD rate is an interesting tool to evaluate cracked FRC long term behaviour and to define a stability criterion. Based on the results obtained, it is recommended to consider the application of sustained loads for periods in the order of 90 days; the calculation of the creep rate between 30 and 90 days represents a good alternative. However, more systematic studies for the definition of a method to calculate the COD rate appear as future necessity.
- Concretes incorporating macro-synthetic fibres presented higher creep deformations and higher creep rate than steel FRC; variations in creep rate in an order of magnitude were measured.
- The studied steel FRC showed stable behaviour for long term stresses lower than 60 % of f_{R1}. In the macro-synthetic FRC this yield value decreased and great differences between both macro-synthetic fibres studied were found.
- The changes in the residual properties of concretes, after creep tests, were not very important, even though there were great deformations. Only a quite uniform decreasing tendency appears, regardless the type of load applied. Although the changes were greater in these macro-synthetic FRC than in steel FRC, it must be highlighted that for so large COD the remaining residual loading capacity is considerable.

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