Creep Testing Methodologies and Results Interpretation

Nicola Buratti and Claudio Mazzotti

Abstract This paper presents a literature review on the main testing methodologies used to investigate the long-term behaviour of cracked FRC elements. Various tests methods such as pull-out tests, uniaxial tension tests, beam bending tests, and plate bending tests are illustrated and discussed. The paper originates from a round table held during the FRC-CREEP 2016 workshop.

Keywords FRC · Creep · Testing · Pull-out · Uniaxial tension · Bending · Plate

1 Introduction

Many studies have contributed to a better characterization of short-term mechanical performances of FRCs and have led to the definition minimum performance requirements and design guidelines. On the other hand, a proper knowledge of the long–term behaviour of SFRCs (Steel Fibre Reinforced Concretes) and MSFRCs (Macro-synthetic Fibre Reinforced Concretes) has not yet been achieved.

Kurtz and Balaguru [1] tested the long-term performance of cracked beams made of concrete reinforced with polypropylene and nylon short-fibres. Creep failure occurred when the stress level was higher than a certain percentage of the failure load under short-term monotonic testing, measured using the Average Residual Strength (ARS) as defined by ASTM C1399 [2]. Bernard [3] investigated the time dependent behaviour of cracked FRC round panels reinforced with either steel or MS fibres. The load applied during long-term tests was defined according to the actual residual tensile-strength measured in the pre-cracking tests. Post-crack creep coefficients were relatively insensitive to load ratio for the SFRC and for one of the two MSFRCs while for the second MSFRC the creep coefficient was sensitive to the load ratio. MacKay and Trottier [4] described the results of experimental tests comparing the behaviour of one SFRC and one MSFRC under long terms loads.

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They concluded that, at similar loading levels, cracked MSFRCs could experience creep coefficients larger than SFRCs by a factor two. Kusterle [5] tested one SFRC and three different MSFRCs. For each mix six beams were cast and tested in four-point bending. The beams were pre-cracked up to a mid-span deflection of 1.75 mm. A sustained load ranging from 50 to 60 % of the strength at 1.75 mm was applied. Kusterle concluded that MSFRCs had large long-term deformations and that a maximum creep load ratio of 50 % seemed to be the maximum for obtaining good long-term performance. SFRCS were able to sustain larger loads (60 %). Failures were observed when the load level was increased to 75–80 %. Zerbino and Barragán [6] studied the creep behaviour of SFRC cracked beams subjected to long-term loading. The beams were pre-cracked up to crack openings spanning from 0.2 and 3.5 mm. For small crack-openings at the beginning of long-term tests stable responses were obtained during 18 months, even when applying stress levels equal to the final stress level reached at the end of the initial cracking tests. A stable response could be observed for a pre-crack of 0.5 mm. However, for load ratios of 0.96 relatively high crack-opening rates were found, indicating the possibility of the initiation of creep failure. When the loads were further increased, a quick failure was observed in these cases. When creep rupture took place, a three-stage creep response was observed. García-Tengua et al. [7] tested 31 SFRC specimens in four-point bending [8] in order to investigate the effects of various parameters on creep in cracked conditions by means of multiple linear regression. They concluded that the load-ratio had an effect on flexural creep response and that the extent of this effect depends on fibre slenderness and fibre dosage. Zhao et al. [9, 10] carried out an experimental program to investigate the long-term behaviour of SFRCS under uniaxial tensile loads by testing cylindrical specimens, pre-cracked up to either 0.05 or 0.2 mm crack openings. The time-dependent crack opening observed was almost at the same level of instantaneous crack opening after 3 months loading at around 30 % of cracking strength. They also concluded that the damage due to debonding at the fibre/matrix interface was not increasing with creep deformation at the loading level of 30 %, even though the irreversible part almost doubled during the creep loading. Babafemi and Boshoff [11] investigated the time-dependent behaviour of a MSFRC under long-term uniaxial tensile loading. Prismatic specimens were pre-cracked up to 0.5 mm using a displacement control machine. Babafemi and Boshoff observed that the MSFRC showed significant crack widening over time under sustained uniaxial tensile loads. Even at loads as low as 30 % of the post-peak resistance, the time-dependent crack widening did not stabilize after 8 months. Tensile creep failure occurred within 10 days for specimens loaded at 60 % of the post-peak resistance and within less than a day for a 70 % loaded specimen. Average fibre counts on the cracked face of MSFRC were found to influence the time-dependent behaviour. Higher fibre counts resulted in lower time-dependent CMOD and vice versa. Babafemi and Boshoff also performed single fibre long-term pull-out tests observing that specimens loaded at 50 % of the quasi-static capacity pulled out over time. Time-dependent crack widening under sustained loading was identified to be caused by two mechanisms: time-dependent fibre pull-out and time-dependent fibre creep. Buratti and Mazzotti found that temperature influences the creep deformation rates in particular on MSFRCs [12].

This paper presents the most widely experimental techniques used to evaluate creep deformations in cracked FRC sections, as discussed during a round table held during the 1st International RILEM Workshop on creep behaviour in cracked section of Fibre Reinforced Concrete, Valencia, Spain.

2 Pull-Out Tests

Pull-out tests have been used by various researchers in order to understand the bond between fibres and concrete. Most of the studies available in the literature concern the short term behaviour of steel fibres [13–19] but it is possible to find also studies on polymeric fibres [20–24].

To the authors knowledge the only experimental results published based on long-term pull out tests are those by Babafemi and Boshoff [11] and Nieuwoudt et al. [25], who used test setup in which the sustained load was applied to single fibres bonded in concrete using free hanging weights. The pull-out displacement was measured optically by taking digital images with a microscope.

Pull-out tests are attractive because they might allow a better understanding of the bond behaviour, even though using information on the long-term behaviour obtained from these tests in order to predict the behaviour of cross sections might be complicated by random fibre orientation and anchorage lengths.

3 Uniaxial Tension Tests

Van Mier and van Vliet [26] provide an overview on uniaxial tension tests procedures on quasi-brittle materials in general. The heterogeneity of these materials leads to various issues such as the need of large specimens, and the development of secondary flexural moments, causing redistribution of stresses. The experience of uniaxial tension tests on FRCs is in general limited. Plizzari et al. [27, 28] used uniaxial tension tests in order to investigate the behaviour of Steel Fibre Reinforced Concretes (SFRCs) under cyclic loads. Li et al. [29] investigated the uniaxial behaviour of SFRC and Macro Synthetic Fibre Reinforced Concrete (MSFRC) specimens with fibre volume fractions from 2 to 6 %. RILEM TC-162 [30] issued guidelines for uniaxial tension tests based on notched cylindrical specimens and fixed end plates. These guidelines were then used in a round robin test program [31, 32] after which it was concluded that significant differences resulted from different testing labs. The authors suggested that they could be due to different stiffness in the setups. A large variability of the results was observed and was suggested that it was due to material variation, even if it was not possible to analyse whether the small cross section size of the cylinders played an important role. In spite of some difficulties encountered during test executions the authors concluded that the uniaxial test was robust. Using the same experimental setup Barragán et al. [33] performed a parametric study on specimens containing steel fibres and analysed the effects of various parameters such as the depth of the notch and the slenderness of the cylinders. They also investigated the effect of fibre orientation by considering cast and cored specimens, these later being cored from prims in different directions with respect to the prims axis. They concluded that specimens are to be cored in order to obtain representative fibre orientations, especially if they are to be compared with bending tests. This was confirmed also by Zhao et al. [10] and Buratti and Mazzotti [34].

Zerguini and Rossi [35] carried out uniaxial tension tests on SFRCS considering notched cylindrical specimens with different diameters (68, 100, and 150 mm) in order to investigate the sensitivity of test results to this parameter. Fibre dosages from 54 to 100 kg/m^3 where used. The authors concluded that no significant dependence of either the average post-cracking energy in uniaxial tension or the dispersion relative to this characteristic with respect to specimen dimension could be identified, although it should be noticed that high fibre dosages were used. Sorelli et al. [36] carried out tests with freely rotating platens on prismatic specimens.

The literature on long-terms uniaxial tension tests is even more limited. Zhao et al. [10] performed uniaxial creep tests on notched cylinders. The setup used was composed of stiff steel plates epoxied at the ends of the cylinders which were connected by three loading bars used both to apply and to measure (using strain gauges) the tension force. The load was then applied by turning the fastening bolts on the loading bars. During the pre-cracking phase, the three loading bolds were fastened in such a way that the crack opening, which was measured using LVDTs in three positions at 120° around the circumference, was as uniform as possible. After pre-cracking the specimens were then tested under long-term loads using a lever based system. In this phase of the tests the rotation of the specimen ends was not blocked. Babafemi and Boshoff [11] carried out uniaxial tension tests on notched MSFRC prismatic specimens. Pre cracking was carried out in displacement control and then the specimens were loaded using a lever system. Buratti and Mazzotti [34] proposed a test procedure on notched cylinders on which the specimen ends are allowed to rotate, both in the pre-cracking and in the long-term test phase, by means of a spherical joint. During the pre-cracking phase, the authors identified specimens with anomalous rotations (e.g. parts in compression) which were then not used for long-term tests [37]. Long-term tests were then carried out on a chain of three specimens loaded using a lever frame (Fig. 1).

In all the cases cited above the typical testing procedure can be summarized as follows (see Fig. 2). The specimen if first pre-cracked up to a defined crack-opening (O-A) at which the residual strength f_R is measured. The average crack opening is normally considered to quantify the crack opening. Then the specimen it is unloaded (A-B) and transferred to the long-term testing frame. Since pre-cracking is normally carried out at very low crack opening rates, and therefore creep deformations develop during this stage, delayed deformations are in part recovered in the

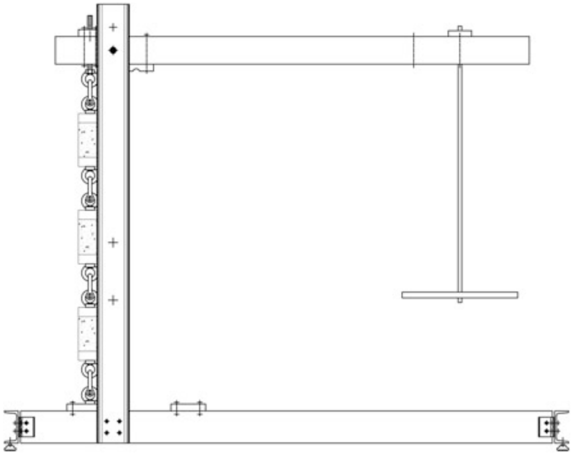

Fig. 1 Experimental setup used by the authors for long-term uniaxial tension tests [37]

unloaded state (B-C). There is yet no agreement in the scientific community on the significance of these deformations and on whether they should be monitored. The specimen is then reloaded up to a fraction of the residual stress measured during pre-cracking (C-D), $\sigma_C = \alpha f_R$, where α indicates the creep load ratio. The time t_L in Fig. 2 indicates the reloading time which should be as short as possible, in order to limit the interference between instantaneous and creep deformations. During the long-term tests deformations will increase at a constant load (D-E). At the end of the long term test the specimen is unloaded (E-F) and part of the long-term deformation is recovered (F-G). Finally, the specimen might be reloaded to failure in a short term test (G-H). It is worth noticing that tertiary creep (leading to failure) might be observed during the long-term tests. These tests are normally carried out in controlled environmental conditions.

In the authors' opinion, even though testing protocols exist for short term tests [38], long term tests present some specific problems. In fact, during long-term tests it is in general not possible to block the rotation of the specimen ends. If specimens are pre-cracked using fixed ends an inconsistent behaviour might be observed during long-terms tests, because of different secondary moments. Furthermore, very large rotations can occur during the long-term tests, leading in some case to compression forces in a portion part of the cracked section. This is more likely to occur when the number of fibres crossing the crack surfaces is limited [34, 37]. Buratti and Mazzotti also observed that uniaxial tension tests, because of the small cross-section size of the specimens, tend to exhibit, on FRCs with low fibre dosages, a scatter of the results which is much higher that bending tests.

Uniaxial tension test, even if more complicated to carry out than bending tests (see Sect. 4), are, to the Authors' opinion an interesting option because, if properly executed, they allow to study the average long term behaviour in tension and therefore their interpretation is more straightforward with respect to bending tests (see Sect. 4).

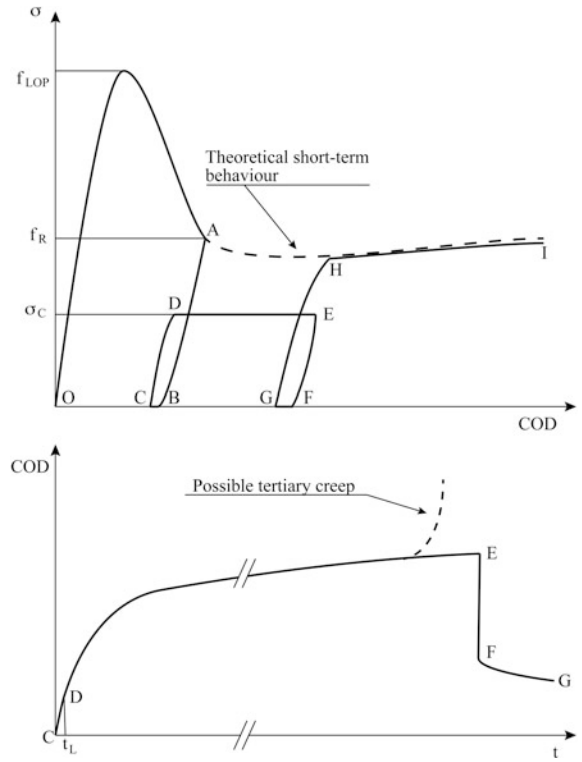

Fig. 2 Typical behaviour observed, in a softening FRC, in long-term tests in cracked conditions, in terms of nominal-stress versus crack opening (*top panel*) and crack opening versus time. COD indicates the general crack opening displacement and might correspond to either CMOD, CTOD or other parameters depending on the test setup

4 Bending Tests

4.1 Test Setup

Bending tests are by far the most widely used in order to evaluate creep deformations in cracked conditions. The testing procedure is normally similar to the one described in Sect. 3 with reference to uniaxial tests (see Fig. 2). The main difference is, of course, the crack opening or deformation measure being used in the pre-cracking and long-terms testing phases (e.g. CMOD, CTOD or mid-span displacement). Typical setups make use of lever systems in order to maintain constant loads for the whole duration of the tests [8]. Figure 3 shows the setup used by the Authors and derived from [8]. Daviau-Desnoyers et al. [39] adapted a hydraulic loading frame for creep tests in order to perform long-term bending tests. Kurtz and Balaguru [1] used a setup in which clamped specimens are loaded by a lever in a cantilever behaviour. Buratti and Mazzotti [12] carried out tests using 200 cm long beams with free hanging weights in a four-point bending setup. In the literature it is possible to find examples of tests on individual specimens and of tests on piles of specimens (normally 3) stacked one on top of each other (e.g. [5, 8, 40]). In this case the load on the specimens is obviously larger at the bottom of the pile, but

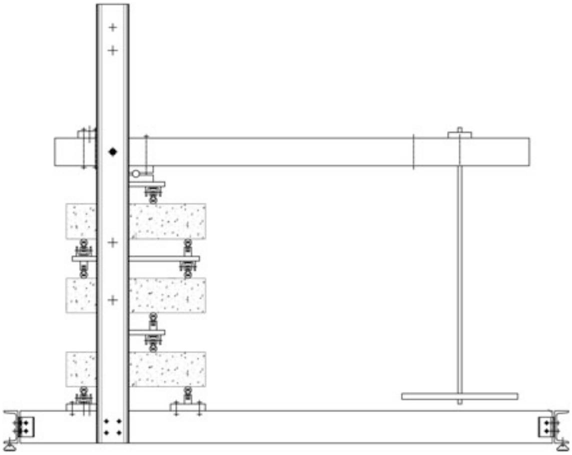

Fig. 3 Experimental setup used by the authors for long-term bending test [37]

often specimens can be ordered in such a way that the ratio of applied force versus residual strength at pre-cracking is constant. This is typically easier on MSFRC specimens because of smaller variability in the post peak behaviour.

In most of the tests published notched specimens were used [4, 6–8, 12, 40, 41] but examples of tests on un-notched specimens can be found in the literature [1, 5]. The most typical setup adopted while testing staked specimens is four-point bending, for obvious stability advantages. One of the shortcoming of this setup is that it is not consistent with the short-term testing procedure proposed by RILEM [42] which is typically used in the pre-cracking stage. However, Zerbino et al. [41] showed that 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 stable creep behaviour takes place.

In the literature concerning long-term bending test there is not yet agreement on the extent to which some parameters might influence the test results. The Creep load ratio (see Sect. 3) is very often set to 50 % of the residual strength measured at the end of pre-cracking. Many results seem to indicate that creep load ratios between 60 and 70 % might represent an upper limit to the long-term load (see Sect. 1). Defining the load ratio as a percentage of the residual strength at one point might be non-representative for FRCs with strong softening or hardening behaviour. In these cases, in fact, the ratio of creep load versus actual residual strength during the long-term tests might change significantly because of the long-term crack opening. Other criteria were used by some researchers (e.g. [1]) but they are very limited in the literature on the topic. Another important parameter is the crack opening used in the pre-cracking stage, which controls the damage level at the beginning of the long-term tests. According to the previous considerations on the load ratio it might be important to consider, together with the serviceability behaviour, the shape of the stress crack opening curve in the post-peak region in order to define this parameter. Other factors that affect the long term behaviour are environmental conditions, i.e. temperature and relative humidity. Buratti and Mazzotti [12] found that moderate temperature variations could trigger tertiary creep failures in MSFRC specimens. Another factor on which there is no wide agreement in the literature is the minimum test duration. Zerbino et al. [41] suggested that the duration should be around 90 days and proposed to use the 30–90 days crack opening rate, defined as the secant of the COD versus time curve from 30 to 90 days, as synthetic parameter for characterizing the behaviour of different FRCs. Comparing the durations published bending tests of FRCs with typical creep tests in compression these latter are much longer, if fact they have normally a duration of at least 6–12 months. Test duration might be critical because Kusterle observed tertiary creep failures after years of testing [43]. Zerbino et al. [41] found that performing loading-unloading cycles does not contribute to the reduction of testing time. Daviau-Desnoyers et al. [39] performed loading-unloading cycles during long-term tests in order to evaluate the progression of damage based on the observed compliance of the specimens.

Finally, another point on which different authors adopted different approaches is related to the deformation parameters to be measured during the tests. Typical examples are CMOD, CTOD and mid-span deflection. Relationships among those parameters (in particular crack opening and deflection) for long-term loads are not yet fully defined and therefore it might be complicated to compare tests in which different parameters were used. As an example, the creep coefficient in terms of mid-span deflection is normally larger than the one in terms of CMOD [12] because the former deformation parameter is affected not only by the delayed behaviour of the cracked cross-section but also by the creep of the un-cracked parts of the specimen.

4.2 *Interpretation of Results*

Most of the research results published until now provided a phenomenological description of the long-term behaviour of FRC elements in cracked conditions and identified some significant parameters. Analytical models were used to provide a description of the long-term behaviour ad it was shown that functions that are normally used to describe creep in compression can properly represent creep in bending [3, 44].

Detailed interpretation of results from long-term bending tests is still an open problem. In fact, the behaviour of the specimen, either in terms of CMOD or in terms of mid-span deflection, is affected by both the creep concrete matrix and the creep of the cracked part. This latter is the result on different phenomena that interact and whose individual contributions have not been yet clearly defined: creep of the concrete matrix in tension, creep of the fibre-to-concrete bond, micro-cracking [45], and, as far as MS fibres are concerned, creep of the fibres [46]. Concerning this latter contribution, it is worth noticing that currently there are no minimum requirements for MS fibres in terms of creep deformation.

In order to introduce creep in design it is mandatory to separate the tension behaviour from the one in compression. A viable approach seems to be constituted by inverse analysis. Buratti and Mazzotti [47], for example, proposed to derive compression creep form specific tests and to use a fibre based-model to provide a phenomenological description of the creep in tensions (using an equivalent continuum model). This model was then used to estimate creep in tension using an inverse analysis procedure on long-term flexural data. The model is being further extended using data from uniaxial tension tests for defining the creep model for the portion of the cross section in tension.

5 Plate Tests

Long-terms tests on circular plates were proposed by Bernard [3] with the aim of characterizing creep deformations in cracked conditions for fibre reinforced shotcrete elements. Recently long term tests on square panes have been proposed by Larive et al. [48]. The interpretation of the results of these tests presents complications similar to those discussed in Sect. 4.2, which in this case are increased by the static redundancy of the specimens and by the presence of multiple cracks. Furthermore, more complex experimental setups are typically required. Alternative testing procedures proposed by Ciancio et al. are being investigated by the Authors to this aim [49, 50].

6 Conclusions

A significant deal of research has been focused, in recent years, on the characterization the long-term behaviour of FRC elements in cracked conditions. Even if different researchers are converging on similar testing protocols the following main conclusions can be drawn from the literature review presented by the present paper:

- standard testing protocols, and relationship among main deformation parameters, need to be developed in order to allow and easier comparison of results and to facilitate discussion among researchers.
- The extent to which parameters such as creep load ratio, crack opening at the beginning of the long-term test, temperature and relative humidity influence the behaviour of FRCs has not yet been fully defined.
- Chemical, physical and mechanical phenomena governing creep of FRCs in cracked conditions have no yet been fully understood.
- The conditions for the onset of tertiary creep have not been yet fully understood.
- Inverse analysis procedures are most probably required for the interpretation of long-term bending tests.

– Prediction models for FRC creep in cracked conditions and in particular for tensile creep are not yet available but are needed if these phenomena are to be included in design.

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