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Flexural creep of steel fiber reinforced concrete in the cracked state

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HIGHLIGHTS

- Fiber slenderness and content modify effect of load ratio on SFRC flexural creep.
- Fiber length does not have a significant effect on SFRC flexural creep.
- Increasing fiber slenderness leads to reduced creep strains.
- Creep control, fibers: no high amounts required, slender fibers is the best choice.

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ABSTRACT

This paper aims at assessing the effect of a number of variables on flexural creep of steel fiber reinforced concrete in its cracked state, namely: fiber geometry (slenderness and length), fiber content, concrete compressive strength, maximum aggregate size, and flexural load. Notched prismatic specimens have been subjected to sustained flexural loads for 90 days following a test setup and methodology developed by the authors. Several experimental outputs have been measured: initial crack width, crack width at 90 days, and crack opening rates and creep coefficients at 14, 30, and 90 days. Multiple linear regression has been applied to relate these creep parameters to the variables considered. Semi-empirical equations have been obtained for these parameters. Statistical inference has been applied to identify the variables that have a statistically significant effect on SFRC flexural creep response. Fiber slenderness and fiber content have been found to significantly modify the effect that load ratio has on flexural creep response of SFRC.

1. Introduction

The evolution of strains and crack openings through time is fundamental for the durability of concrete structures. Time-dependent phenomena such as shrinkage and creep must be taken into account besides instantaneous strains and cracking [1,2].

Creep refers to the tendency of materials to develop increasing strains through time when they are subjected to a sustained load. As a result, deflection or elongation values tend to increase through time in relation to the initial strain, i.e. right after the load is applied. Codes for structural concrete consider compressive creep of concrete within the usual ranges in service conditions. On the contrary, tensile creep of either concrete or reinforcing bars is not usually considered. However, in the case of concrete structures, their long-term performance is basically affected by the behavior of cracked concrete [3].

Steel Fiber Reinforced Concrete (SFRC hereafter) members are designed in most applications to take advantage of SFRC differential features with respect to conventional concrete: when SFRC is brought to perform in the cracked state, cracks are under control and residual strength provides the structural member with further load-bearing capacity. There is no reason to expect differences between SFRC and conventional concrete regarding compressive creep. Any difference in terms of flexural creep behavior between SFRC and conventional concrete is related to the possibility of creep phenomena in the cracked zone of the section. Therefore the relationship between tensile creep and flexural creep of SFRC has attracted attention in recent studies [4]. Tensile creep of SFRC has been studied by some authors [5], but is not possible to easily extend their conclusions to flexural creep behavior.

Flexural creep of SFRC in the cracked state and the role that different factors play in creep behavior are quite understudied topics within the general field of SFRC mechanical properties. There are relatively few publications directly related to flexural creep behavior of pre-cracked SFRC beams, and therefore every contribution is a step further [2]. The need of developments in the understanding of tensile and flexural creep behavior of SFRC is motivated by

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several purposes, mainly: to improve the prediction of cracking and the stress evaluation in prestressed members [6].

There is a considerable consensus in relation to the main sources of SFRC time-dependent flexural strains [7]: creep in the compression zone, time-dependent bond strains between concrete and fibers sewing cracks, and creep of the fibers material. However, there are some discrepancies among experimental results concerning the effect of fibers on tensile and flexural creep which call for further research, as observed by Garas et al. [8]. While several authors have found out that fibers reduce creep and shrinkage [1,2,8,9], other studies have concluded that hooked-end steel fibers increase tensile creep [6].

Therefore, and considering that fibers contribution to load-bearing capacity is mainly related to flexural response in the cracked state, it is very important to evaluate how the material keeps crack opening values low enough so as to guarantee reinforcement effectiveness [10].

However, most of the studies on FRC flexural creep have compared the role of plastic or glass fibers to that of steel fibers, not focusing on the effect of steel fibers themselves. When some of these papers and reports [10–15] are brought together, the following general aspects arise:

- There is a variety of test setups and methodologies. Considering that SFRCs mechanical properties usually show considerable scatter, the lack of a standardized methodology contributes to uncertainty concerning SFRC creep behavior. An attempt to develop a consistent methodology based on a creep test setup for pre-cracked FRC specimens was needed.
- Most of the times the goal is not to characterize SFRC flexural creep but to compare the effect of steel fibers to that of synthetic fibers.
- Most studies limit their scope to one mix design, one type of steel fiber, or certain fiber content. In these cases, it is not considered how the variation of these parameters may affect SFRC creep behavior.
- In relation to the values considered for the stress/strength ratio, it is usual to consider different values. However, the way they are selected and the criteria this selection is based upon is not usually the same.
- There is an important heterogeneity concerning testing procedures and experimental approach. This leads to important differences between studies concerning several aspects, for instance: how load is applied to specimens, whether they are notched or not.

The aforementioned general aspects motivated two major goals for the research to be carried out. Firstly, to propose a general, standard-like methodology to study flexural creep of concrete. And second, to study the case of pre-cracked SFRC members in a comprehensive fashion, analyzing the effect of several parameters simultaneously.

In relation to the first aspect, the authors have made an effort to develop a test setup and methodology which have been extensively described elsewhere [16]. The test setup and methodology proposed in [16] is susceptible of standardisation and can be used: (a) to analyze creep behavior under some given conditions (for a determined concrete mix design, load level, etc.), and (b) to characterize the effect of particular fiber types and/or dosages under standard conditions (materials, concrete mix design, fiber concrete, pre-cracking level, load). This way creep of concrete is studied in standard-like conditions so that future results can be easily compared. This is the methodology that has been followed in the experimental program reported herein. It is based on a structural test, where creep occurs in bending. This creep test has two major advantages: it is easier to perform and control than the direct tension test, and it can be directly correlated to the bending test as used for SFRC characterization (EN 14651). As compressive creep and tensile creep can occur simultaneously in the section, results may be affected by creep in the compressed zone of mid-span section if the derived peak compressive stress is close to concrete compressive strength. As a result, it is not easy to dissemble the contributions of both phenomena on flexural creep. In spite of this, further developments in the interpretation of the phenomena converging in flexural creep response as obtained from this test are very interesting, as well as their possible implementation in codes, but these aspects fall out of the scope of this paper.

2. Objectives and scope

The major purpose of this research was to analyze the effect that different variables have on SFRC response to sustained flexural loads in the cracked state.

These variables have been selected to represent both SFRC composition and the load applied. Accordingly, different types of hooked-end steel fibers (in terms of length and slenderness), fiber contents, and concrete mix designs have been considered. A number of prismatic specimens have been produced and subjected to different sustained flexural loads covering usual values of these parameters in real applications.

Several creep parameters have been analyzed. The analysis of experimental results has followed a rigorous, statistical approach to assess the significance of the variables considered. The result is therefore a unified perspective on the relative contribution of the variables considered to flexural creep response of SFRC in the cracked state. This perspective offers a further conceptualization of the phenomenon under study.

3. Methodology and experimental outputs

3.1. The creep test

Prismatic 150 × 150 × 600 mm specimens have been produced, notched, pre-cracked, and then tested under flexural loads sustained for 90 days in agreement with the creep test setup and methodology developed by the authors [16]. An overview of this methodology is given in Fig. 1.

In a first stage, specimens are pre-cracked: each specimen is notched and loaded according to a four-point scheme based on the standard bending test [17,18], with a 450 mm span between supports, until a crack mouth opening displacement (CMOD hereafter) of 0.50 mm is reached. The load corresponding to this crack width, *Fw*, is retained and the specimen is then totally unloaded.

Pre-cracked specimens are reloaded and subjected to sustained load conditions according to the test setup shown in Fig. 2 (for dimensions and further details see [16]). Specimens are tested in columns of three to rationalize the requirements of time and space. The creep frame and all its components, in particular loading members and supports, have been conceived to be stiff enough to avoid undesirable, abrupt movements as well as friction in supports in order not to interfere the development of creep strains. This, together with the gravity loading on top of the specimens column (by means of a counterweight applied through a lever arm), guarantees the application of a constant load. This way all three specimens are loaded according to the four-point bending test and the load is kept constant for a determined lapse of time. In the case of this research, this timespan was 90 days, since the largest part of time-dependent strains occurs within the first 2 months [6].

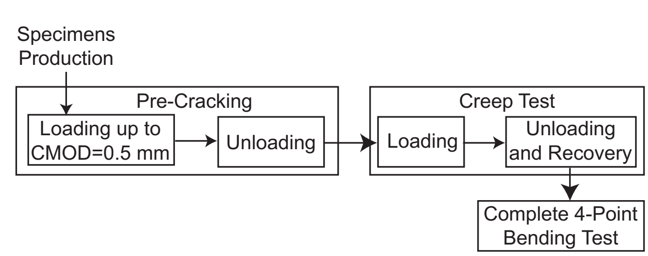

Fig. 1. General testing procedure.