International Journal of Fatigue 70 (2015) 342–350

Contents lists available at ScienceDirect

International Journal of Fatigue

journal homepage: www.elsevier.com/locate/ijfatigue

Effect of the loading frequency on the compressive fatigue behavior of plain and fiber reinforced concrete

Arthur Medeiros [a,b], Xiaoxin Zhang [a,*], Gonzalo Ruiz [a], Rena C. Yu [a], Marta de Souza Lima Velasco [b]

[a] ETSI de Caminos, Canales y Puertos, Universidad de Castilla-La Mancha (UCLM), Avenida Camilo José Cela S/N, 13071 Ciudad Real, Spain
[b] Department of Civil Engineering, Pontifical Catholic University of Rio de Janeiro (PUC-Rio), 22451-900 Rio de Janeiro, Brazil

ARTICLE INFO

Article history:
Received 8 March 2014
Received in revised form 11 August 2014
Accepted 13 August 2014
Available online 23 August 2014

Keywords:
Fatigue
Compression
Fiber-reinforced concrete
Loading frequency

ABSTRACT

This paper presents the recent experimental results aimed at disclosing the loading frequency effect on the fatigue behavior of a plain concrete and two types of fiber-reinforced concrete, using polypropylene and steel fibers. Compressive fatigue tests were conducted on 123 cubic specimens (100 mm in edge length). Four different loading frequencies, 4 Hz, 1 Hz, 1/4 Hz and 1/16 Hz, were employed. The maximum stress applied on the specimen was 85% of its compressive strength and the stress ratio was kept constant as 0.3. The results show that the loading frequency effect on the fatigue behavior of the plain concrete is pronounced. The fatigue life (the number of cycles to failure) at lower frequencies is less than that at higher frequencies. However, the fibers do improve the fatigue behavior significantly under low loading frequencies. Such trend can be attributed to the effectiveness of the fibers in bridging cracks, and thus inhibiting the crack extension under cyclic loads.

1. Introduction

Since the beginning of research work on the fatigue behavior of concrete, numerous experiments have been conducted to study the influence of different fatigue parameters [1–18]. These parameters are either set by fatigue test conditions, such as the minimum stress σ_{min}, the maximum stress σ_{max} and the loading frequency f, or determined by material properties, for instance, the static material strength σ_c, which can be the compressive strength f_c or the tensile strength f_t, or any other critical stress defined accordingly. Other parameters include the stress ratio R, defined as $\sigma_{min}/\sigma_{max}$, or the stress level S, defined as σ_{max}/σ_c.

Regarding the effect of loading frequency f on the fatigue life N (the number of cycles resisted before failure) of plain concrete, the first studies [1,2] show that when f was between 4.5 Hz and 7.5 Hz, the loading frequency had slight effect on the fatigue life, however, when f was less than 0.16 Hz, the fatigue life was reduced. Some other researchers [6,10] suggested that the loading frequency had minor influence on the fatigue life when the loading frequency was between 1 Hz and 15 Hz, and the maximum stress S_{max} was less than 75% f_c. After that, it was shown that when S_{max} was greater than 75% f_c, the loading frequency had a significant influence on N [19], a reduction of the frequency by a factor 100 resulted in shortening of N by a factor of 10 to 30.

The classical fatigue equation [7] has evolved accordingly to illustrate the role of some common fatigue test parameters:

$$\frac{S_{max}}{\sigma_c} = 1 - (1 - R)\beta \log N \tag{1}$$

where β is a material parameter. The same relation was confirmed for fatigue strength of concrete in compression and in tension for splitting tests of cubes [11,12]. Even though the influence of loading frequency (or time) has been observed as early as in 1960 [5] and confirmed in the 1970s [8,9,20], it was not considered analytically until Hsu [13] modified Eq. (1) by including the loading frequency. He put forward two models accounting for the fatigue life, namely a model considering low-cycle fatigue ($N < 10^3$) for structures subjected to earthquake, which is expressed below as Eq. (2); the other one took high-cycle fatigue ($10^3 < N < 10^7$) into account for airport pavements, bridges and highways, shown below as Eq. (3), where T is the period of the repeated loads ($T = 1/f$):

$$\frac{S_{max}}{\sigma_c} = 1 - 0.0662(1 - 0.556R)\log N - 0.0294\log T \tag{2}$$

$$\frac{S_{max}}{\sigma_c} = 1.20 - 0.20R - 0.133(1 - 0.779R)\log N - 0.053(1 - 0.445R)\log T \tag{3}$$

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* Corresponding author. Tel.: +34 926 295 300x3261; fax: +34 926 295 391.
E-mail addresses: xiaoxin.zhang@uclm.es, zhangxiaoxinhrb@gmail.com (X. Zhang).

http://dx.doi.org/10.1016/j.ijfatigue.2014.08.005
0142-1123/

Another model was developed by Furtak [14] containing a frequency influence coefficient C_f as described in Eq. (4):

$$\frac{S_{max}}{\sigma_c} = CN^{-A}(1 + BR\log N)C_f \tag{4}$$

$$C_f = 1 + a(1 - bR)\log f \tag{5}$$

where A, B, C, a and b are adjusting parameters and, C_f is determined by Eq. (5).

An improvement on the previous equation was performed by Zhang et al. [16], including reversal stress besides the loading frequency as expressed in the Eq. (6):

$$\frac{S_{max}}{\sigma_c} = (ab^{-\log f} + c)[1 - (1 - R')\beta\log N] \tag{6}$$

Recently, Saucedo et al. [21] developed a probabilistic fatigue model for concrete and fiber-reinforced concrete (FRC), which took into account the effect of loading frequency, see Eq. (7). The model is based on the initial probabilistic distribution of compressive strength, i.e., on the distribution of the specimens broken at the first cycle in quasi-static compressive tests. The model also needs two series of tests at different frequencies to fit its parameters. The fatigue life is estimated as follows:

$$N(PF, \sigma_{max}, f, R) = \left\{ \frac{\lambda\sqrt[k]{-\ln(1 - PF)}}{\sigma_{max}\left[\frac{\dot{\sigma}_0}{2f(1-R)\sigma_{max}}\right]^{0.014\exp(\gamma f)} - \sigma_{min0}} \right\}^{\frac{1}{[b+c\ln(1+f)](1-R)}} \tag{7}$$

where $\sigma_{min0,}k, \lambda$ are parameters related with the initial Weibull distribution of compressive strength. b, c, γ can be fitted by two different fatigue loading conditions with varied frequencies. PF is the probability of failure. $\dot{\sigma}_0$ represents the stress rate of the characterization tests.

Plotting the loading frequency versus the number of cycles to failure according to Eqs. (2)–(6), Fig. 1 was obtained for $S_{max}/\sigma_c = 0.75$ and $R = 0.1$. The model of Saucedo et al. is not plotted in the graph because it is related with the initial distribution of compressive strength, rather than a single value of σ_c. Besides, it fits the actual materials sensitiveness to the frequency since two series of results at different frequencies are required to obtain the parameters.

From Fig. 1, it can be observed that the fatigue life decreases with a decrease in loading frequency. Note that, however, these equations were obtained based solely on the plain concrete fatigue tests. Regarding the fatigue behavior of FRC in compression, the available work is rather limited [22–26]. Furthermore, the effect of loading frequency has not been considered so far.

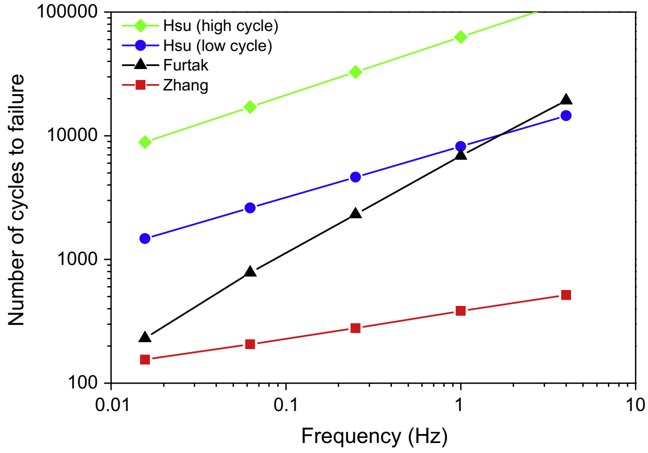

Fig. 1. Number of cycles to failure – frequency by adopting different models.

Thus, in order to evaluate the effect of the loading frequency on the compressive fatigue behavior of plain concrete and FRC with steel and polypropylene fibers, several series of compressive fatigue tests at various frequencies were performed as a part of a longer study [27]. The results show that the loading frequency effect on the fatigue behavior of the plain concrete is pronounced. However, for the fiber-reinforced concretes the fatigue life under low loading frequencies approaches that under high loading frequencies. Furthermore, a comparison among different fatigue models is also presented.

The rest of this paper is structured as follows: the material characterization is given in Section 2, Section 3 describes the fatigue tests and results which are discussed regarding the fatigue life and the strain history. Finally, relevant conclusions are drawn in Section 4.

2. Material characterization

Three types of concrete were made of the same matrix, using ASTM type I cement 52.5R, sand size no greater than 4 mm, siliceous gravel aggregate of 12 mm maximum size and superplasticizer (Glenium C-355). The mixing proportions by weight were 1:0.35:1.89:2.17:0.014 (cement: water: sand: siliceous gravel: plasticizer).

Different types of fiber and the fiber content are as follows:

- Concrete 1 (C1): plain concrete without fibers.
- Concrete 2 (C2): polypropylene fiber reinforced concrete; corrugated polypropylene fibers, 40 mm in length, rectangular cross section (0.50 mm × 1.30 mm), aspect ratio 62, fiber volume ratio 0.56% (5 kg/m^3).
- Concrete 3 (C3): steel fiber reinforced concrete; hooked end steel fibers, 35 mm in length, 0.55 mm in diameter, aspect ratio 64, fiber volume ratio 0.64% (50 kg/m^3).

The tests were divided in twelve series: three types of concrete and four loading frequencies. For each type of concrete, 40 cubic specimens (100 mm in edge length) were assigned for the fatigue tests and 6 cubes were tested to measure the quasi-static compressive strength at the stress rate 0.2 MPa/s. The 100 mm cubes were cut from prismatic specimens with dimensions 100 mm × 100 mm × 450 mm, the loading direction on the cubes was always perpendicular to the longitudinal axis of the prism.

In order to obtain the mechanical properties, eight 300 mm × 150 mm (height × diameter) standard cylinders were cast, four of them were tested at 28 days, the rest at around one year, following ASTM C39 and C469 Standards. Table 1 provides the quasi-static compressive strength f_c, elastic modulus E and Poissońs ratio v at both ages, moreover, corresponding standard deviations are shown in the table.

3. Fatigue tests

The compressive and fatigue tests were performed through a servo-hydraulic testing machine, cubes (edge length 100 mm) were used as shown in Fig. 2. The displacement between two steel platens was measured by two LVDTs (Linear Variable Differential Transducer).

The load control was applied for the fatigue tests with a sine signal as shown in Fig. 3, where S_{min}, S_m and S_a are the minimum stress, mean stress and stress amplitude, respectively.

The maximum stress S_{max} applied on the cubic specimen was 85% of the cubic strength f_c, the stress ratio $R = S_{min}/S_{max}$ was set