Fatigue and fracture parameters of various glass fiber cement based composites

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1 Introduction

The search for construction materials with enhanced properties such as strength, ductility, toughness and durability has lead to an increasing interest in materials like fiber concrete and high-performance concrete. The limited knowledge about the long-term behavior or the effects of repeated loading on the properties of these materials has caused a growing interest on the fatigue performance of concrete. Examples of such cyclic loads include machine vibration, sea waves, wind action, automobile traffic etc. Additionally, reliable data are needed for the calibration of accurate models capable of predicting the fatigue behavior of structural concrete.

The use of fiber reinforced concretes (FRC) has increased in building structures because the reinforced fibers in concrete may improve the toughness, flexural strength, tensile strength, impact strength as well as the failure mode of the concrete.

During the past three decades, a number of works pertaining to experimental and analytical methods for evaluating the strength characteristics of FRC have been published under varied specimen types, fiber types, fiber contents, curing time and testing methods [1, 2, 3].

Fatigue loading is usually divided into three categories i.e. low-cycle, high-cycle loading and super-high-cycle fatigue [1]. It is supposed here that the studied materials are intended for using in high-cycle fatigue region. The paper continues and develops the previous study of co-authors [4, 5].

The aim of the paper is to present selected fatigue and fracture mechanics parameters of advanced building materials marked here as BS 080405 and HD 080326. The experimental measurements were made at two levels. The first one was a static measurement and its results are represented by values of effective fracture toughness of the material. The second level is connected with high-cycle fatigue – Wöhler curves of both study materials were determined. The obtained experimental results are compared with literature data.

2. Materials, equipment and test procedure

The experimental test program has been carried out at the Laboratory of Civil Engineering Faculty of Brno University of Technology in Czech Republic. Both static and fatigue tests were carried out in laboratories where temperature and relative humidity values did not undergo significant fluctuations. The controlled values for temperature and relative humidity were 22±2 °C and 50%, respectively.

2.1 Materials

The tested specimens were prepared from mixtures of which the compositions are presented in Table 1. Two types of fibers were used: (i) "BS" Special combination of polypropylene and polyethylene, properties of fibers were as follows – tensile strength 610 MPa, modulus of elasticity 5.2 GPa, diameter 0.48 mm, length 55 mm, and (ii) "HD" Alkali-resistant glass fibers (glass with high content of zirconium oxide), tensile strength 3500 MPa, modulus of elasticity 73 GPa, diameter 14 μm, length 12 mm.

Table 1 Composition of mixtures

Component [Unit]	*BS 080405*	*HD 080326*
CEM I 42.5 R Mokra [kg/m^3]	850	1000
Sand, 0/4 mm [kg/m^3]	1350	940
Water [kg/m^3]	197	280
Stachement 2060 superplasticizer [kg/m^3]	12	15
Polymer fibers BS 55 mm [kg/m^3]	2.5	–
Glass fibers HD 12 mm [kg/m^3]	–	6

2.2 Test methods

The experimental data are carried out from the three-point bending (3PB) tests. Fig. 1 shows the geometry of the 3PB specimens; dimensions were L=400, S=300, W=100 and thickness =100 mm. The initial notch was made by a diamond saw that fabricated the 2–2.5 mm wide notches with controlled notch profiles and orientation. The numerical study of the influence of the shape of a saw-cut notch on experimental results is shown in [6]. In this study 3PB specimens with notch to width a_n/W ratios of about (i) 0.33 were produced for subsequent static tests, and (ii) 0.10 were produced for subsequent fatigue crack growth testing.

The static tests were carried out in a testing machine made by the Zwick/Roell Company. The deflection control was used; the loading rate was 0.05 mm/min. During tests load–deflection diagrams were recorded, see Fig. 2. Effective fracture toughness was evaluated using the Effective Crack Model [7, 8]. This model combines linear elastic fracture mechanics and the crack length approach.

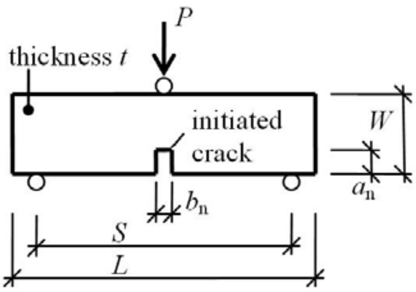

Fig. 1 Schematic of a three-point bend (3PB) specimen geometry

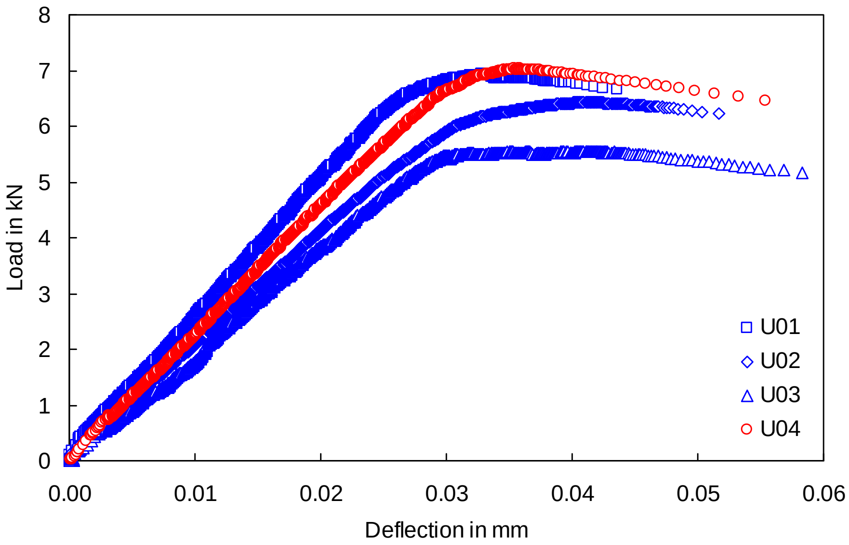

Fig. 2 Load–deflection diagram of selected specimens under 3PB static test

The fatigue crack growth experiments (Wöhler curves) were carried out in a computer-controlled servo hydraulic testing machine (INOVA–U2). Fatigue testing was conducted under load control. The stress ratio R=0.1 was selected to avoid shifting of the beams with cycling while generating stresses that could be considered representative of dead loads in beams. The load frequency used for all repeated-load tests was approximately 10 Hz. Along with data points, the analytical expressions for the curves in the following form were obtained through linear regression $S=a\times\log N+b$, where S is stress amplitude, N is number of cycles and a, b are the material parameters.

3 Results

3.1 Results from static tests

Experimental static load–deflection curves (*l*–*d* diagrams) were used and selected diagrams are displayed in Fig. 2. Every curve was assessed separately, and the variability of the effective fracture toughness is described by the estimation of the first two statistical moments (mean value and standard deviation) – see Table 2.

Table 2 Results of static fracture tests

Specimen	*Value [MPa.m$^{1/2}$]*	*Mean Value [MPa.m$^{1/2}$]*	*Standard Deviation [MPa.m$^{1/2}$] (COV [%])*
BS080405_U01	1.190	1.161	0.086 (7.4)
BS080405_U02	1.229		
BS080405_U03	1.064		
HD080326_U04	1.194	–	–

3.2 Results from fatigue tests

The results of the fatigue tests for study materials are presented in Figs. 3 and 4. The tested materials are loaded in the range of high-cycle fatigue; therefore an upper limit on the number of cycles to be applied was selected as 2 million cycles. The test was terminated when the failure of the specimen occurred or the upper limit of loading cycles was reached, whichever occurred first.

The results of the fatigue tests under varying maximum bending stress level are summarized in Fig. 3 where maximum bending stress in the fatigue experiment is plotted against the logarithm of number of cycles to failure. Along with data points, the analytical expressions for the curves (in the form $\sigma_f = a \times \log N + b$) were obtained through linear regression. The regression equation and the regression coefficient (R^2 is index of dispersion) for the present tested materials are:

BS 080504 $\log N = 5.84 \times \sigma_f^{-0.0333}$ and $R^2 = 0.74$,
HD 080326 $\log N = 6.98 \times \sigma_f^{-0.027}$ and $R^2 = 0.92$.

Finally, let's compare the linear regression lines for the present and the literature results taken from [1], where authors provide an overview of recent developments in study of the fatigue behavior of plain and fiber reinforced concrete. They consider three types of concrete – plain and reinforced by steel fiber with 0.5% and 1% fiber content.

The results of these tests are recorded in a Wöhler diagram, see Fig. 4 where on one axis the normalized stresses ($S_n = \sigma_f / \sigma_s$; σ_f–the values of fatigue loading stress and σ_s–values of static maximal stress) is given and on the other axis the numbers of cycles until failure on log scale are presented. The Wöhler curves coefficients for analytical expression in the form $S_n = a \times \log N + b$ are presented in Table 3; the last column are values of indexes of dispersion R^2.

It can be seen that for small values of N, the σ_f–N curves tend to converge to σ_f values that are greater than the static value $N=1$. This is mainly because the compressive strength used as a reference was obtained from the static tests in which the loading rate is much lower than that of the fatigue tests.

In Fig. 4, the results for each beam type are shown in the normalized form, obtained by dividing the value in Fig. 3 with the corresponding average static flexural strength for the same batch of specimens. Comparison between S_n–N curves for: plain concrete, SFRC (0.5% and 1.0% fiber content) from [1] and presented results for BS 080405 and HD 080326 is shown.

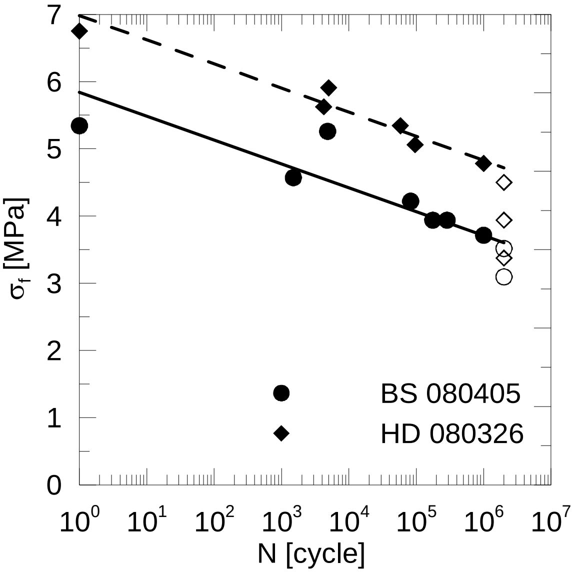

Fig. 3 S–N diagrams for BS 0804005 and HD 080326 materials

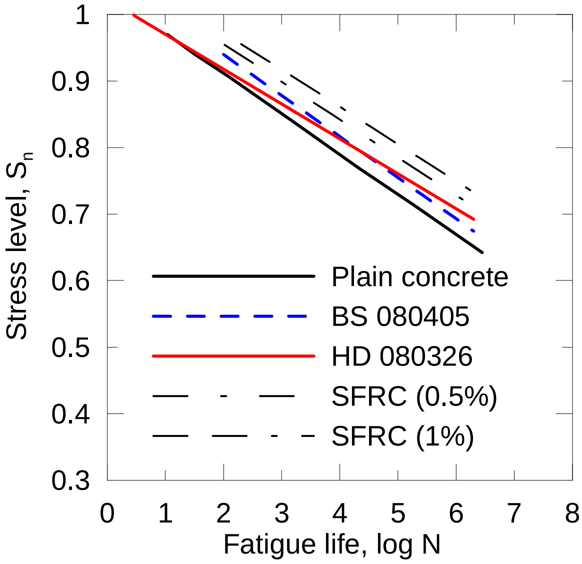

Fig. 4 Comparison between S_n–N curves for plain concrete, SFRC (0.5% and 1.0% fiber content) from [1] and presented results for BS 080405 and HD 080326

The benefit derived from the addition of fibers appears to be significant. It can be seen that the improvement of fatigue life due to fiber content increase from 0% to 0.2% and is comparable with improvement due to increase of fiber content from 0.5% to 1% in Table 3. Note that the fatigue test data of material BS 080405 show considerable variability – probably because length of fibers –, the fatigue test data of HD 080326 has the relatively low variability.

Table 3 Coefficients of S_n–N curves and indexes of dispersion

Material	*a and b in the fatigue equation*		R^2
	a	*b*	
Plain concrete	-0.0606	1.0327	0.72
BS 080405	-0.0617	1.0632	0.74
HD 080326	-0.0524	1.0343	0.92
SFRC (0.5%)	-0.0575	1.0727	0.60
SFRC (1%)	-0.0559	1.0854	0.73

4. Conclusions

Selected fatigue and fracture mechanics parameters of advanced building materials BS 080405 and HD 080326 were studied and fracture toughness and S–N curves were experimentally determined. The obtained experimental results pointed out some of the most relevant characteristics of the behavior of fiber cement based composites under monotonic/static and fatigue loading necessary for application in civil engineering industry.

The key to the success of improving the fatigue life of concrete with the addition of fibers seems to be related with the distribution of the fibers in concrete. In fact, if the fibers are not well dispersed in concrete, the addition of fibers may have a detrimental effect on the fatigue life of fiber cement based composites.

It can be concluded that for utilization of the material under dynamic loading HD 080326 composite is preferable.

Acknowledgment

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