Construction and Building Materials 107 (2016) 138–156

Contents lists available at ScienceDirect

Construction and Building Materials

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

Proposal for the fatigue strength of concrete under cycles of compression

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HIGHLIGHTS

- The Dutch National Annex has to be corrected for concrete under compressive fatigue.
- New results for concrete compressive fatigue for high strength concrete are used.
- A database from the literature is compiled.
- Proposals for design and assessment are developed.

ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 4 January 2016
Accepted 5 January 2016
Available online 11 January 2016

Keywords:
Codes
Compression
Concrete
Database
Fatigue

ABSTRACT

The Dutch National Annex to Eurocode 2 deviates from Eurocode 2 for the Wöhler curve for concrete in compression, but has a discontinuity in the *S–N* curve for 1 million load cycles. Therefore, a new expression for concrete subjected to repeated loading is sought, which should be valid, yet not overly conservative, for high strength concrete. A database of experiments on high strength concrete tested in compressive fatigue is developed, and used to derive new expressions. Two new formulas are proposed: (1) for the assessment of the fatigue strength of existing structures, and (2) a simplified method for design.

1. Introduction

Fatigue is of importance for structures subjected to repetitive loading, such as bridges under traffic loads [12,33]. Fatigue cracking in concrete is not as easy and straightforward to determine as fatigue cracks in, for example, steel. As such, it is difficult to identify fatigue damage in concrete structures [2].

The maximum compressive stress in a concrete specimen can be subjected to decreases as the number of cycles of loading increases. When a concrete specimen (often a cylinder) is tested for compressive fatigue, the specimen is loaded between a lower and upper stress. These limits are expressed as a fraction of the concrete compressive strength, and can be written as $S_{min}f_{ck}$ and $S_{max}f_{ck}$. The values of S_{min} and S_{max} are dimensionless and between 0 and 1. The upper limit for S_{max} in experiments is typically 0.95 and S_{min} can be as low as 0.02.

One of the results of fatigue tests on concrete cylinders in compression is the so-called Wöhler-curve, or *S–N* curve. In this graph, a (linear) relation is found between the logarithm of the number of cycles to failure N and the maximum stress level S_{max} (for a given minimum stress level S_{min}). The *S–N* curve generally start at $S_{max} = 1.0$ and $\log N = 0$. Compared to experimental results, there is large scatter between the *S–N* curve and the experiments in the low-cycle fatigue range. From experiments, it is known that the *S–N* curve for concrete is approximately linear starting at 100 cycles [19]; for these ranges of large numbers of cycles the scatter between experiments and the curves becomes smaller.

The expression for concrete under compression subjected to cycles of loading from NEN-EN 1992-2+C1:2011 [3] is more conservative than previously used expressions in the Netherlands. In order not to create a major disruption with the Dutch bridge design practice, different expressions are given in the National Annex NEN-EN 1992-2+C1:2011/NB:2011 [5]. The *S–N* relationship given in the Dutch National Annex consists of two equations: the first branch is valid for $N \leqslant 10^6$ cycles and the second branch for $N > 10^6$ cycles. At 10^6 cycles, the equation from the Dutch National Annex coincides

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http://dx.doi.org/10.1016/j.conbuildmat.2016.01.007

List of notations

$f'_{b,rep,k}$	characteristic value of the uniaxial short term concrete compressive strength
$f'_{b,rep,v}$	characteristic value of the concrete compressive strength in the limit state of fatigue
$f'_{b,v}$	fatigue reference strength
$f_{c,cyl,mean}$	average measured value of the concrete cylinder compressive strength
f_{cd}	design concrete compressive strength
$f_{cd,fat}$	design fatigue strength
f_{ck}	characteristic concrete compressive strength
$f_{ck,fat}$	characteristic concrete compressive strength for the limit state of fatigue
$f_{c,mean,max}$	maximum measured concrete compressive strength
k_1	a factor from the Eurocode expression for fatigue
m	the number of cycles of constant amplitude
n_i	the number of cycles with a constant amplitude at interval i
s	a factor that depends on the strength class of the cement
t	the concrete age in days
t_0	the time of the start of the cyclic loading on the concrete
t_T	the concrete age in days, corrected for temperature
AVG	average value
CHAR	characteristic value based on a normal distribution
COV	coefficient of variation
$E_{cd,max,equ}$	the maximum compressive stress level
$E_{cd,min,equ}$	the minimum compressive stress level
$E_{cd,max,i}$	the maximum compressive stress level for the considered interval
$E_{cd,min,i}$	the minimum compressive stress level for the considered interval
N	number of load cycles
N_1	first part of the S–N curve in the *fib* Model Code
N_2	second part of the S–N curve in the *fib* Model Code
N_i	the number of cycles to failure with a constant amplitude at interval i
R	stress ratio
R_{equ}	stress ratio
R_i	stress ratio of the considered interval
R_i^*	the stress ratio for $S_{max,EC}$
S	fraction of compressive strength applied in load cycle
$S_{c,max}$	maximum fraction of compressive strength applied in load cycles
$S_{c,min}$	minimum fraction of compressive strength applied in load cycles
S_{max}	maximum fraction of strength applied in load cycles
$S_{max,EC}$	the value of S_{max} associated with 10^6 cycles
$S_{max,pred}$	the value of S_{max} from the proposed methods for a given number of cycles N
$S_{max,test-}$	the value for S_{max} in the experiments for a given number of cycles N
S_{min}	minimum fraction of strength applied in load cycles
STD	standard deviation
$T(\Delta t_i)$	temperature during time period Δt_i
Y	expression used in the fatigue formula of the *fib* Model Code
$\beta_{cc}(t_0)$	coefficient for the concrete strength at first load application
$\beta_{cc}(t)$	describes the strength development with time
$\beta_{c,sus}(t,t_0)$	factor for sustained loading
γ_m	partial factor for the material
γ_c	partial factor for concrete
$\gamma_{c,fat}$	partial factor for concrete in the limit state of fatigue
$\sigma'_{b,d,max}$	design value of the maximum compressive stress in the concrete $\sigma'_{b,d,min}$ design value of the minimum compressive stress in the concrete
$\sigma_{cd,max,equ}$	upper stress of the ultimate amplitude for N cycles
$\sigma_{cd,min,equ}$	lower stress of the ultimate amplitude for N cycles
$\sigma_{c,max}$	upper compressive stress of the ultimate amplitude for N cycles
$\sigma_{c,min}$	lower compressive stress of the ultimate amplitude for N cycles
Δt_i	number of days with temperature T

with the expression from the original Eurocode, with the exception in the definition of certain parameters. The transition between these two S–N curves at 10^6 cycles is not smooth, but instead causes a jump in the Wöhler-curve. Because of this anomaly in the current code provisions, it is necessary to propose a new expression for concrete under cycles of compressive loading. The goal was again to have an expression that is not overly conservative, and matches the Dutch design practice more closely. Moreover, the proposed expression should be valid, yet not overly conservative, for the classes of high strength concrete that have recently been introduced in the market. Therefore, recent test data on high strength concrete are used to verify the proposal developed for the Dutch National Annex to the Eurocode.

The proposal will be different for design (procedure in line with Eurocode requirements) and assessment (iterative procedure that gives more precise results for low-cycle fatigue). Existing bridges erected before 1990 were not verified for fatigue in the Netherlands. Nowadays verification of the fatigue strength of all bridges is required and an expression for fatigue verification for existing bridges which is not overly conservative needs to be derived in order to prevent the need for major structural changes in existing bridges. For these cases as well, understanding the fatigue behavior of high strength concrete is important, as material research [32] has shown that due to the ongoing hydration of the cement paste, high concrete strengths are obtained when cores are drilled from existing bridges.

2. Literature survey

2.1. Parameters affecting the fatigue strength

Several parameters influence the fatigue strength of concrete members in compression. The first parameter is the maximum and minimum stress levels in the applied cycles. If S_{min} is increased, the number of cycles to failure increases [2]. Sometimes the stress ratio $R = S_{min}/S_{max}$ is used to express the stress levels.

When fatigue testing is carried out, significant scatter is found on the number of cycles to failure N for given applied stresses. This scatter is caused by the variability of the concrete compressive strength [15]. It is thus necessary to test a number of specimens at each level of S_{max} to determine the S–N curve. What also needs to be kept in mind is that the load rate application in a static test is typically much slower than in fatigue testing, also influencing the results [2,28].

Variables such as water–cement ratio, cement content, amount of entrained air, curing conditions and age at loading do not seem to influence the fatigue strength. This conclusion was based on extensive experimental research for concrete compressive strengths up to 60 MPa [2].

Traditional fatigue tests are executed by cycling continuously between the minimum and maximum stress until failure. Some research studied the effect of rest periods [7,8]. This research indicated that recovery occurs during rest periods, increasing the