12th International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-12
B.L.A. Pichler, Ch. Hellmich, P. Preinstorfer (Eds)

https://doi.org/10.21012/FC12.1187
MS02-1:3

FATIGUE DAMAGE ASSESSMENT OF CONCRETE USING WIDE-RANGE EXPERIMENTAL DATA

PETR MIARKA[*♦], JOSÉ D. RIOS[†], STANISLAV SEITL[*♦], VLASTIMIL BÍLEK[▼] AND HÉCTOR CIFUENTES[†]

[*]Institute of Physics of Materials, Czech Academy of Sciences,
Žižkova 22, 616 00 Brno, Czech Republic
e-mail: miark@ipm.cz, www.ipm.cz

[♦]Brno University of Technology, Faculty of Civil Engineering,
Veveří 331/95, 602 00 Brno, Czech Republic

[†]Department of Continuum Mechanics and Structural Analysis, Escuela Técnica Superior de Ingeniería,
Universidad de Sevilla,
Camino de los Descubrimientos s/n, 41092, Seville, Spain
e-mail: congress@framcos.org, www.framcos.org

[▼]VŠB — Technical University of Ostrava, Faculty of Civil Engineering,
Ludvíka Podéště 1875/17, 708 00 Ostrava-Poruba, Czech Republic

Key words: Fatigue, Concrete, S-N field, Cycling loading

Abstract: This contribution focusses on the fatigue damage assessment of concrete samples using wide-range experimental data. Within this study, the concrete samples were tested under various loading conditions: static fracture, low-cycle and high cycle fatigue. This allowed us to obtain static load-CMOD, S-N curves for fatigue lifetime assessment, and mainly CMOD-N curves showing the stiffness degradation at high-cycle fatigue load regime. The low-cycle fatigue resistance is assessed from stepwise load-CMOD curves with increasing CMOD value every step, allowing to analyse damage growth between each load cycle. This study investigates the fatigue resistance of concrete samples by combining all of these experimental data and could provide useful recommendation for structural design.

1 INTRODUCTION

Concrete structures form an essential part of the local and global infrastructure, and their lifespan is usually measured in decades. Many structures such as highway and railroad bridges, railway sleepers, offshore structures are exposed to repeated load and fails due to fatigue rupture of concrete [1].

The fatigue tests of plain concrete material tested in [2][3][4][5] and the results provide valuable information to the community of structural engineers and helped to improve structural safety. Furthermore, fatigue design of a structure is considered for the ultimate limit state (ULS), while the serviceability limit state (SLS) is missing, i.e., the assessment of the crack width w_c, crack length l and deflection δ. This missing SLS fatigue consideration in standards may lead to an unoptimized structure, which may eventually result in a visible damage of load-bearing structural components.

This contribution focuses on the damage assessment of fatigue failure with the whole range of fatigue regimes, i.e. low-cycle to high-cycle. The results of experimental tests are presented in form of S-N curve, load-CMOD curve, damage-CMOD curve and are providing useful information for future structural design.

2 THEORETICAL BACKGROUND

For assessment of fatigue lifetime is the most-commonly used S-N curve, which relates applied stress S to total number of load cycles N. It is then assessed by Basquin's power law [6] in following form:

$$S = A \cdot N^B \tag{1}$$

where A is the static strength and B is the degradation of the mechanical properties under the cyclic load.

However, the S-N curve finds useful application for the concrete structures with more than 1×10^4 loading cycles often recognised as a high-cycle fatigue (HCF) region. The HCF region is often document by low damage occurrence in the tested samples. For this reason, it is of the most interest to capture early damage propagation leading to major lifetime reductions.

Standard fracture behaviour is obtained from static fracture tests with a result of post-peak non-linear behaviour with softening branch documented by load-CMOD curve. From such test one can obtain values of work of fracture W_f and fracture energy G_f together with a value of $\mathrm{CMOD_{IC}}$ at $P = P_{max}$. Such value can indicate deformation needed to rupture the sample.

Low-cycle behaviour is obtained from cyclic test with step-wise increasing CMOD values of upper and lower levels with a result with information of post-peak loading and unloading behaviour. Such test can be used to characterise dissipative mechanisms associated with concrete strength degradation under cyclic loading. This is documented by a degradation of unloading stiffness, which is defined by the value of damage δ. The damage parameter δ can be calculated as follows:

$$\delta = (1 - \frac{E_i}{E_o}), \tag{2}$$

where E_0 is the initial elastic stiffness and E_i is the current unloading stiffness at each point of P-CMOD curve.

3 EXPERIMENTAL DETAILS

3.1 Test geometry and test setup

Three-point bending set-up using beam with rectangular cross-section was selected with dimension of L = 240 mm, B = 40 mm, a_0 = 8 mm ~ 24 mm and W = 80 mm – See Figure 1.

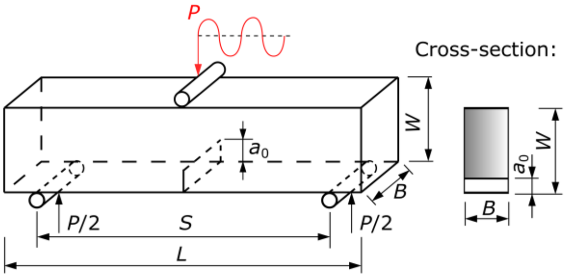

Figure 1: Dimension of samples used for static and fatigue experimental tests.

Concrete samples were tested under static, cyclic and monotonic loading conditions using servo-hydraulic testing rig Instron 8872 with a maximum load capacity 25 kN. Static and cyclic test were performed under a CMOD controlled regime, while monotonic tests were done with a testing frequency of 10Hz. The sample mounted in testing machine is presented in Figure 2.

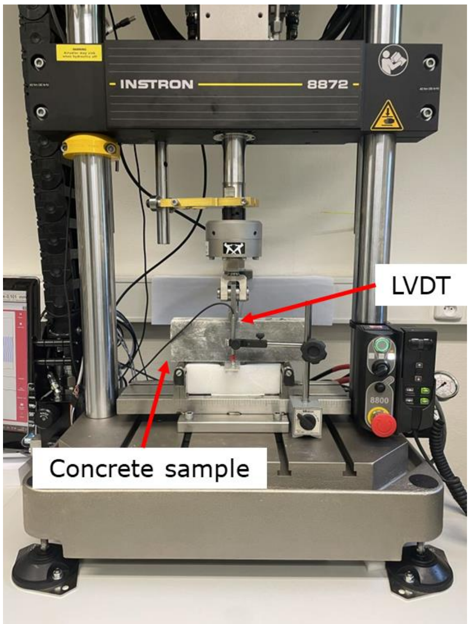

Figure 2: Dimension of samples used for static and fatigue experimental tests.

3.2 Material

Within this study ordinary Portland cement (OPC) was selected as a binder. OPC was mixed with three fractions of natural aggregates: sand 0/4 mm, granite 4/8 mm and granite 8/22 mm. A constant dosage of polycarboxylate superplasticizer Glenium 300 (BASF, Germany) was added to the mixture to achieve good workability. The water to cement ration w/c was 0.3. The mixture composition per 1 m^3 is shown in Table 1.

Table 1: Mixture composition per 1m^3.

CEM I 42.5R [kg]	Water [kg]	Superplasticizer [kg]
450	135	9
Sand 0/4 [kg]	Granite 4/8 [kg]	Granite 8/22 [kg]
866	290	740

In order to characterise concrete behaviour static compressive strength f_c, static flexural strength f_{ct} and modulus of elasticity E were measured at various age. Measured mechanical properties are presented in Table 2.

Table 2: Measured mechanical properties at various age.

Age [days]	1	28	91	365
f_c [MPa]	49.9 ± 0.5	91.5 ± 4.3	90.4 ± 4	109.6 ± 1.0
f_{ct} [MPa]	-	8.1 ± 0.4	9.3 ± 1.1	10.2 ± 0.7
E [GPa]	-	44.2 ± 1.6	44.7 ± 1.6	46,6 ± 1.3

The measured mechanical properties document the homogeneous material behaviour with relatively small dispersion of measured strengths and young's modulus E.

3.3 Loading scenarios

In order to comprehensively characterise fracture behaviour of concrete and tackle down the fatigue crack growth, we have selected following loading cases under which the material was tested.

In total three loading cases were selected: a) static fracture with CMOD increasing during the test, b) cyclic with CMOD increasing and decreasing every load step and c) monotonic cyclic with defined maximum and minimum force $P_{\max}$ and $P_{\min}$, respectively. The selected load cases are presented in Figure 3.

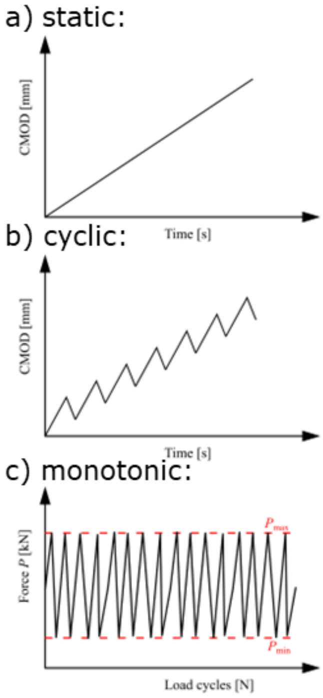

Figure 3: Used load cases in the experimental study.

All three load cases provide different yet valuable information on the damage mechanisms in concrete sample.

4 RESULTS AND DISCCUSSION

We begin the damage assessment with fracture tests performed on a sample with relative notch ratio a/W of 0.3 according to RILEM recommendations [7]. The measured P-CMOD curve is presented in Figure 4.

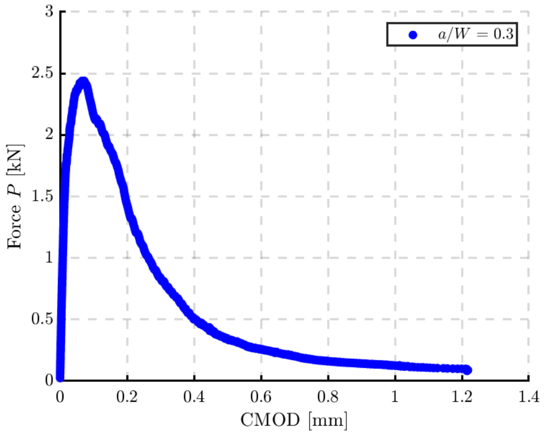

Figure 4: Results of static fracture test.

The obtained data served in the assessment of the size independent fracture energy G_F as proposed by Karihaloo [8] and to hinge model proposed by Abdalla [9] for constitute cohesive σ-w law assessment. The results of static fracture tests allow to compare fracture behaviour with other concrete materials.

We continue our damage assessment with the results of cyclic tests see Figure 5.

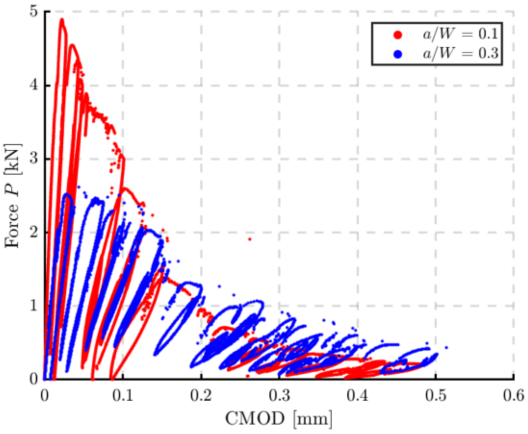

Figure 5: Results of cyclic load test for two notch depths.

In total ten load cycles were performed for two different relative notch depths a/W = 0.1 and 0.3. The longer initial notch depth was chosen to reduce the brittleness of the material and allow test to be performed in full length.

Such cyclic test relates damage progress to applied CMOD [10]. The damage parameter was calculated according to Eq. (2), and the result are shown in Figure 6.

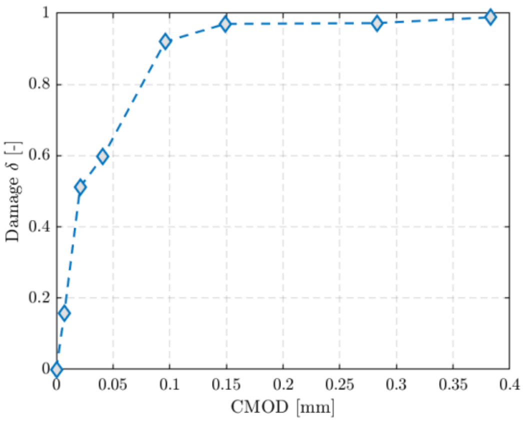

Figure 6: Damage propagation obtained from cyclic test.

The damage-CMOD or δ-CMOD curve shows rapid damage progress after reaching value of 0.05 mm for which the damage δ is nearly 60%. If this value is compared to CMOD at $P_{\max}$ 0.1 mm obtained from static fracture test, the cyclic CMOD is half of this value and already evincing 60% of damage. This has serious practical implications.

The results of monotonic fatigue tests are presented as S-N curve in Figure 7.

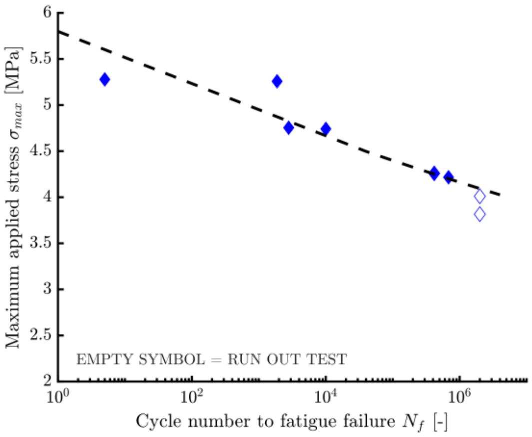

Figure 7: Measured S-N curve.

The runout of the test was set to 2×10^6 loading cycles. When reaching this load cycle limit, the test was interrupted and we set the applied stress as the fatigue limit.

Moreover, the S-N curve can be used to obtain determined coefficients of Basquin's power law, and the results of least square fitting are presented in following equation:

$$S = 5.799 \cdot N^{-0.024} \tag{3}$$

The power coefficient B is in this case -0.024, which agrees with the previously obtained experimental values ranging from -0.015 to -0.040. The Eq. (3) could be used to predict remaining fatigue life and helps to indicate failure of the specimen and links the result to the static strength.

12 CONCLUSIONS

The experimental results presented in this paper provide comparison of various load cases with different damage mechanisms in concrete material. The results provide valuable information for structural design and contribute to increase structural safety of load bearing concrete structures.

ACKNOWLEDGEMENTS

This paper was created as a part of project No.CZ.02.01.01/00/22_008/0004631 Materials and technologies for sustainable development within the OP JAK Program financed by the European Union and from the state budget of the Czech Republic as well as the financial support from the Czech Science Foundation under project no. 25-15755S. José D. Ríos wishes to express his gratitude to the Universidad de Sevilla for the financial support provided for the completion of a research stay at Brno University of Technology, under grant SOL2024-29846 from the VII Plan de Investigación y Transferencia. The results presented in this paper were completed during this stay.

DATA AVAILABILITY

The data used in this study is available at: https://doi.org/10.5281/zenodo.14629558

REFERENCES

[1] Lee M.K. and Barr B.I.G., 2004. An overview of the fatigue behaviour of plain and fibre reinforced concrete. *Cem. and Conc.Comp.*, **26**:299-305.

[2] Bazant Z.P., Schell W.F., 1993. Fatigue fracture of high-strength concrete and size effect. *ACI Mater. J.*, **90**:472.

[3] Miarka P., Seitl S., Bílek V. and Cifuentes Bulte H., 2022. Assessment of fatigue resistance of concrete: S-N curves to the Paris law curves. *Constr. and Build. Mat.*, **341**:127811.

[4] Korte S., Boel V., De Corte W. and De Schutter G., 2014. Behaviour of fatigue loaded self-compacting concrete compared to vibrated concrete *Struc. Conc.*, 15 (2014), pp. 575-589.

[5] Ríos J.D., Cifuentes H., Yu R.C. and Ruiz G., 2017. Probabilistic Flexural Fatigue in Plain and Fiber-Reinforced Concrete. *Materials*, **10**:767.

[6] Basquin O.H., 1910. The exponential law of endurance tests. *Am. Soc. for Test. and Mat. Proc.*, **10**:625-630.

[7] RILEM-TCM85, 1985. Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams *Mater. Struct.*, **18**(4):287-290.

[8] Muralidhara S., Prasad B.K.R., Eskandari H., and Karihaloo B.L., 2010. Fracture process zone size and true fracture energy of concrete using acoustic emission. *Constr. and Build. Mat.*, **24**:479-486.

[9] Abdalla H.M. and Karihaloo B.L., 2004. A method for constructing the bilinear tension softening diagram of concrete corresponding to its true fracture energy *Mag. Concr. Res.*, **56**(10):597-604.

[10] Baktheer, A. and Becks, H., 2021. Fracture mechanics based interpretation of the load sequence effect in the flexural fatigue behavior of concrete using digital image correlation. *Constr. and Build. Mat.*, **307**:124817.