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Fatigue performance of orthogonally reinforced concrete slabs: Experimental investigation

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ABSTRACT

The fatigue performance of reinforced concrete slabs was investigated under clearly defined bending conditions with large scale tests. Two series of four tests exhibiting orthogonal reinforcement layouts at different orientations were subjected to constant force-amplitude cyclic loading. The reinforcement direction in the reference series of tests coincided with the direction of principal moment. In the second series of tests, a deviation of 45° between the principal moment and reinforcement direction was introduced. The effect of inclined reinforcing bars with respect to the principal moment direction on the fatigue strength of structural concrete slabs is described. Direct measurement of reinforcing steel strains enabled a characterisation of the redistribution of internal forces within the cross-section after failure of individual bars until global failure of the slab.

1. Introduction

The load-carrying capacity of the composite material *reinforced concrete* lies in the ability of the concrete to resist (primarily) compressive forces and of the reinforcement to resist tensile forces after cracking of the concrete. Research on reinforced concrete under the influence of fluctuating loads, however, indicates that the integrity of both materials as well as their interaction through bond [1] deteriorates under repeated loading. The *CEB* state of the art report [2] provides an insightful overview of previous work on this phenomenon of fatigue of structural concrete.

Concrete members subjected predominantly to cyclic flexural loading typically exhibit increases in the width of existing cracks through a progressive deterioration of bond; disproportionally large deflections result and failure ensues through rupture of individual reinforcing bars or spalling of the concrete in the flexural compressive zone [3]. This failure mode has been observed in numerous experimental investigations [4–6]. *Fehlmann* and *Vogel* [7] investigated the fatigue performance of a typical frame type bridge in a large-scale test with the prescribed fatigue load model according to the current Swiss standard [8]. Virtually no changes in the load-carrying response, apart from the formation of some new cracks, was observed during approximately 90% of the fatigue life. Fatigue damage to the structure remained mostly undetected by conventional methods until shortly before failure. Furthermore, some investigations have shown that concrete members subjected to cyclic loading can exhibit different failure modes to those predicted under static loading. *Chang* and *Kesler* [9] conducted a large number of tests on beams in which specimens failed in flexure under static loading and due to fatigue shear modes under cyclic loading. It is currently neither possible to establish the present state of damage in a structural concrete member, nor to predict the remaining fatigue life for future loads [7].

The deck slabs of concrete bridges have been identified to be susceptible to fatigue [10]. Slabs are in direct contact with the wheel loads of heavy vehicles and typically exhibit small ratios of own weight to live loads. A numerical investigation of the stress range in various bridge cross-sections under traffic loads indicates that particularly the transverse deck slab direction at the cantilevers and between the webs is fatigue critical in the absence of prestressing [11]. Due to the highly statically indeterminate nature of slabs and considerable capacity to redistribute stresses, loads are resisted through combinations of bending and torsional moments. Such bending action is typically resisted by layers of finely spaced reinforcing steel bars in an orthogonal layout. As a result, the direction of principal moment will deviate from the reinforcement directions under certain loading and support conditions. A scarcity of experimental data considering the fatigue performance of slabs under clearly defined combinations of bending and torsional moments prompted the tests described in the present paper.

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Nomenclature

A_{gt}	reinforcing steel strain at peak load
E_c	modulus of elasticity of concrete
E_s	modulus of elasticity of reinforcing steel
F	applied force
F_{act}	actuator force
$F_{\max}, F_{\min}$	maximum and minimum applied load during cyclic loading
G	own weight of loading yoke and rocker bearings in test setup
$M_{n,\max}, M_{n,\min}$	maximum and minimum bending moment in n-direction
N	number of load cycles
$N_{s,\mathrm{fat}}$	number of load cycles corresponding to nominal fatigue strength
N_u	maximum number of load cycles to failure
R	support reactions
SG 1…SG 7	strain gauges
c_{nom}	nominal concrete cover to the reinforcement
$f_{c,\mathrm{cube}}$	concrete cube compressive strength
f_{cc}	concrete cylinder compressive strength
f_{ct}	concrete tensile strength
$f_{su,\mathrm{stat}}$	static tensile strength of reinforcing steel
$f_{sy,\mathrm{stat}}$	static yield strength of reinforcing steel
g_{c0}, g_{m0}	own weight of specimens per unit length
h	height
m_1, m_2	principal moments per unit length
m_x, m_y	bending moments per unit length in the x- and y-directions
m_{xy}	torsional moment per unit length relative to x- and y-directions
u_1, u_2	concrete deformations on top surface and soffit in n-direction
w_1, w_2	midspan deflection at front and back surface of specimen
w_m	average midspan deflection
w_r	crack width
$\Delta\sigma_s$	reinforcing steel stress range
$\Delta\sigma_{s,\mathrm{fat}}, \Delta\sigma_{sd,\mathrm{fat}}$	nominal and design fatigue strength of reinforcing steel
ε_{cu}	concrete strain at peak load
ε_{su}	rupture strain of reinforcing steel
ε_{sv}	reinforcing steel strain at onset of strain-hardening
$\varepsilon_{sx}, \varepsilon_{sy}$	reinforcing steel strains in the x- and y-directions
ρ_x, ρ_y	geometric reinforcement content in the x- and y-directions
σ_1, σ_2	principal stresses
σ_n, σ_t	normal stresses in the n- and t-directions
σ_{sx}, σ_{sy}	reinforcing steel stress in the x- and y-directions
σ_x, σ_y	normal stresses in the x- and y-directions
φ_n	angle defining reinforcement direction
∅	diameter

An experimental campaign consisting of two series of four large-scale tests was carried out at the structural laboratory of ETH Zurich. Slab specimens were reinforced with standard profiled reinforcing steel bars in an orthogonal layout and tested under constant force-amplitude cyclic loading. Reinforcement layouts were investigated wherein (1) the principal moment and reinforcement direction coincide and (2) with the introduction of a 45° deviation between the principal moment and reinforcement directions. The primary objective was to investigate whether an inclination of reinforcing bars with respect to the principal moment/stress direction detrimentally influences the fatigue strength of reinforced concrete slabs. The redistribution of internal forces within the reinforcement after failure of individual bars was studied as well as the characterisation of development in response between fatigue failure of the first reinforcing bar and global failure of the slab.

2. Testing program

Two slab strips were constructed in each of the two series of tests with the reinforcement layouts indicated in Fig. 1. The tests of series A constituted the reference set in which only one layer of reinforcement was activated under bending action. Through a rotation of the orthogonal reinforcement layout by $\varphi_n = 45°$ with respect to the principal moment direction, both layers of reinforcement were activated in tension in the tests of series B. Specimens were subjected to a high level of constant amplitude cyclic loading in which the maximum load $F_{\max}$ resulted in a bending demand of approximately 65% of the theoretical yield moment. The minimum load $F_{\min}$ was defined such that the expected reinforcing steel stress range clearly exceeded the fatigue endurance limit of the reinforcement.

In the tests of series A, the orientation of the activated reinforcement in x-direction corresponded to the principal moment direction such that $m_x = m_1$ and $m_y = m_{xy} = 0$. In the tests of series B, the activated reinforcement in both the x- and y-directions deviated from the principal moment direction. This resulted in a combination of bending and torsional moments with respect to the reinforcement directions corresponding to $m_x = m_y = m_{xy} = 0.5 \cdot m_1$. These bending conditions are indicated graphically on Mohr's circle for bending and torsional moments in Fig. 1(c). Considering the tensile zone of each slab as an equivalent reinforced concrete membrane, see Fig. 1(b), allows a description of the corresponding stress states in the reinforcement and in the concrete between cracks as shown in Fig. 1(d). Flexural cracks in the concrete form perpendicular to the direction of the larger (tensile) principal stress. Hence, the concrete between cracks remains unstressed in the tests of series A and the principal stress at the crack is resisted exclusively by the reinforcement in x-direction such that $\sigma_1 = \sigma_{sxr} \cdot \rho_x$. Considering equilibrium at the cracks in the tests of series B indicates that the applied stress is resisted by both layers of reinforcement. The corresponding equilibrium condition results to $\sigma_1 = \sigma_{sxr} \cdot \rho_x = \sigma_{syr} \cdot \rho_y$.

3. Test specimens

The geometry and reinforcement layout of the specimens of series A and B are illustrated in Fig. 2. The test parameters, summarised in Table 1, are identical for both series with the exception of the direction of the flexural reinforcement φ_n with respect to the n-axis. Two orthogonally placed layers of reinforcement were provided in the flexural tensile zone at a spacing of 100 mm with a nominal concrete cover of $c_{\mathrm{nom}} = 20$ mm to the reinforcement. The orientation of the outer and inner layers of reinforcement corresponded to the x- and y-directions, respectively. All reinforcing bars activated in tension were ordered with end anchorages of the type ancoFIX®, see [13], in order to ensure a short bond development length within the edge regions of the specimen. The flexural compression zone remained unreinforced. Vertical shear reinforcement was provided between the supports and the cross-sections of load application in order to prevent a premature shear failure of the concrete.

The reinforcement for the specimens of series A consisted of 8 ∅ 12 mm bars placed parallel to the longitudinal or n-axis of the specimen in the outer layer with 26 ∅ 12 mm bars constituting the inner layer in the transverse direction (t-axis). The flexural reinforcement in the specimens of series B consisted of two layers of 22 ∅ 12 mm bars each, which were placed with deviations of −45° and 45° with respect to the specimen n-axis. An approximately isotropic reinforcement layout resulted in all specimens with geometric reinforcement contents of