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QUASI-CONTINUOUS STRAIN MEASUREMENT WITH DISTRIBUTED FIBRE OPTIC SENSORS IN REINFORCEMENT BARS AND EXTERNALLY BONDED CFRP STRIPS AT CONCRETE SLABS – EXPERIMENT AND MODELLING

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Abstract
Externally bonded carbon fibre reinforced polymers (CFRP) are widely used for the strengthening of reinforced concrete components. The knowledge of the strain distribution between embedded and externally bonded reinforcements is a prerequisite for analysing the load-bearing behaviour of reinforced concrete components strengthened in this way.
In this paper, the strain distribution between embedded steel reinforcements and externally bonded CFRP of RC beams is investigated experimentally and numerically. In order to describe the bond behaviour of the embedded and the externally bonded reinforcements, experimental investigations are carried out on reinforced concrete slabs. Distributed fibre optic sensors and strain gauges are used for the measurement of the reinforcement strains. By using state-of-the-art fibre optic measurement systems, the strain distribution of both steel and CFRP reinforcement is recorded along the entire lengths of the specimens during four-point bending tests.
Due to the different bond characteristics of the reinforcement types, the strain distribution cannot be calculated by presuming a plane strain distribution based on the Euler-Bernoulli beam theory. For the computation, an analytical approach is used taking the different bond-stress-slip behaviour of the embedded and externally bonded reinforcement into account.

Keywords: CFRP, RC beam, bond, distributed sensing, fibre optic sensor.

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Introduction

Reinforced concrete structures are often exposed to aging phenomena, material fatigue and environmental conditions. Externally bonded reinforcement (EBR) made of carbon fibre reinforced plastics (CFRP) ensures an increase in both, load capacity and service life of the building structures. The performance of this strengthening method is greatly affected by the bond behaviour between the EBR and the concrete surface. The description of the bond behaviour necessitates detailed knowledge of the strain distribution of the reinforcement types. In experimental tests, strain distribution is usually measured using conventional electrical resistance strain gauges. However, the positioning of the discrete measurement points is a crucial point. Due to the limited sensing locations of the discrete sensors, monitoring of local incidents, as cracks or large strain gradient is rather difficult.
In this paper, the strain distribution between embedded steel reinforcement and externally bonded CFRP of RC Beams is investigated on specimens without pre-fabricated cracks. Distributed fibre optic sensors are used for the measurement of the reinforcement strains.

Experimental Tests

Test Setup

Four reinforced concrete slabs are tested in a four-point bending static loading test, as shown in Figure 1. The test specimens have a length l = 1.4 m, a width b = 30 cm and a height h = 15 cm. The externally bonded CFRP strips have a length l_L = 1.2 m and a cross section A_L of 1.4 x 50 mm^2 and the steel bars have a diameter d_S = 10 mm. The thickness of the concrete cover is set to 20 mm. The experimental tests are performed in a hydraulic testing machine, where the load is applied with a constant displacement rate of 0.008 mm/s until debonding failure of the EBR.
The quasi-continuous strain measurement of the embedded reinforcement bar and the externally bonded CFRP strip are carried out by using a single distributed fibre optic sensor along the entire lengths of the reinforcement types. The sensor fibre is attached in a 1 x 1 mm^2 notch on the bottom side of the steel rebar. The notch is created by removing the lower longitudinal rib of the steel rebar, whereas the transverse ribs remained unaffected, in order to maintain the bond behaviour of the embedded reinforcement. The CFRP strain is measured with the same strain sensor, which is mounted onto the exterior surface of the EBR. The fibre optic sensor is covered with an additional layer of epoxy resin in order to ensure protection and enhance the bond between the sensor and the surfaces.

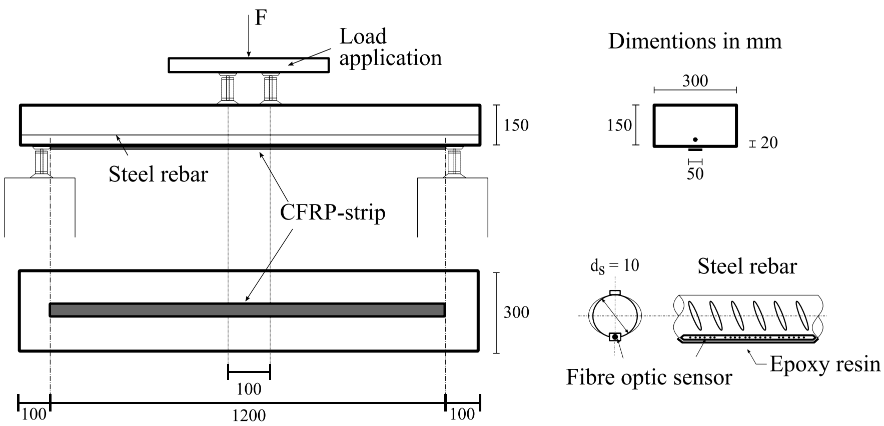

Figure 1: Experimental setup for four-point bending test

Materials

The experimental tests are carried out with CFRP strips with an elastic modulus E_L of 170,000 N/mm². The adhesive is a cold cured two-component epoxy resin and the thickness of the adhesive layer is set to 2 mm.
The specimen for the four-point bending tests is made of concrete with a strength class C 40/50 according to EN 206. The compressive strength f_{cm} is determined in compressive tests on sample cubes with an edge length of 150 mm after 28 days to 60.2 N/mm². The bond strength by pull-out at the surface $f_{ctm,surf}$ is measured corresponding to EN 1542 to 3.30 N/mm². The interior reinforcement steel is a B 500 B according to DIN 488-1 with a yield stress f_{yd} = 500 N/mm² and an elastic modulus E_s = 200,000 N/mm².
The adhesive used for mounting the fibre sensor onto the reinforcement surfaces is a one-component cyanolacrylate. An additional layer of a two-component epoxy resin with rapid cure time is used to cover the sensor.

Measurement Method

In the experimental tests, high-resolution distributed sensing technology based on back-scattered Rayleigh signals is used for the strain measurements of the reinforcement types. The optical distributed sensor interrogator *LUNA ODiSI-B,* which is based on Optical Frequency Domain Reflectometry (ODFR), is used to interrogate the scattered light signal in the bare fibre. The recorded sum signal of the Rayleigh scattering is processed with a Fast Fourier Transformation (FFT) to generate a highly reproducible amplitude distribution, a characteristic "fingerprint", which is used to evaluate the strain distribution of the embedded and the externally bonded reinforcement [1].
By using the respective measurement system, distributed strain measurements with 1.28 mm spatial resolution over the entire length of the reinforcement types could be achieved.

Test Results and Simulation

Failure Mode

During the four-point bending test, the initial flexural crack appeared at the midspan of the RC slab at 15.0 kN. With increasing load, new flexural cracks propagate toward the support. Upon reaching the ultimate load at 50.5 kN, a sudden intermediate crack (IC) debonding failure between the adhesive and the concrete surface was observed.

Strain Distribution

The measured strain distribution of the internal and external reinforcement at selected measurement time points of one slab are shown in Figure 2. The progression of the quasi-continuous strain distribution can be observed at several stages during the experimental test. The distinctive spikes in the steel strains (middle stage, right graph) at 36.3 kN clearly indicate the positions of the flexural cracks. The plastic deformation of the steel rebar (late stage, right graph) upon reaching ultimate load is also recorded at the midspan of the specimen.

Modelling Method

The measured strain distribution can be determined with the numerical model from Zehetmaier (2006) [2]. The analytical approach allows a recalculation of the strain distribution between embedded steel rebar and externally bonded reinforcement with consideration of the different bond-slip behaviour of the reinforcement types under static loading. However, for design applications Zehemaier has developed a simplified engineering approach using the bond coefficient δ_{Lk} for the calculation of the CFRP strain ε_L assuming a plane state ε_L^{II}. The recalculated strain distribution with the engineering approach according to Zehetmaier with the bond coefficient δ_{Lk} are also shown in the Figure 2.

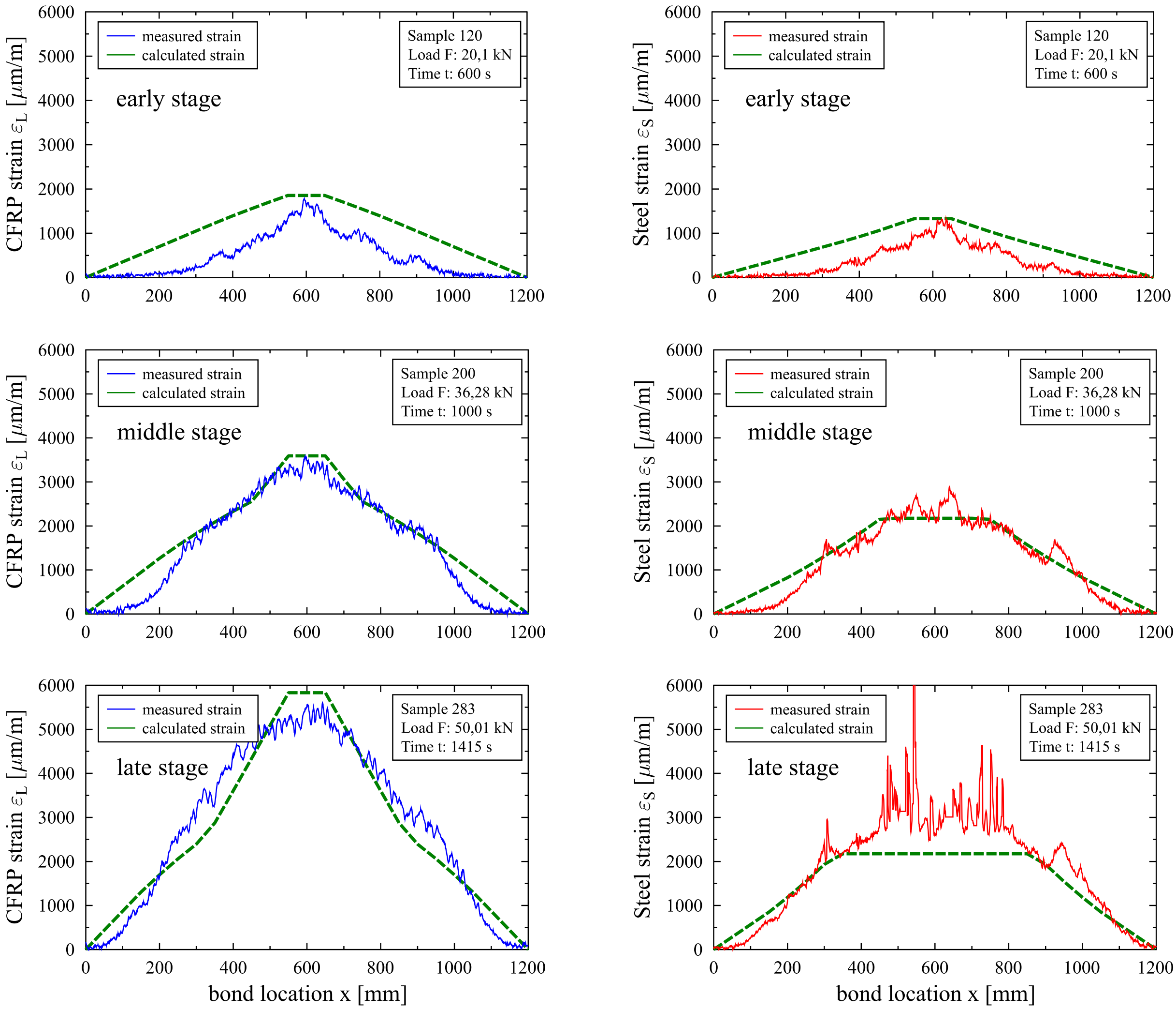

Figure 2: Measured and calculated strain distribution during four-point bending test C

Conclusion

The experimental investigation demonstrates the quasi-continuous strain measurement with distributed fibre optic sensors. The progress of the strain distribution can be observed in four-point bending tests on specimens without pre-fabricated cracks. Local incidents in the strain distribution, as cracks and debonding zone of the CFRP are recorded along the entire length. The calculated strain development with the modelling method above shows satisfactory results at the later stages. At early stages (below 2 ‰), the calculated CFRP strain shows significant deviations. For a precise calculation especially at early stages, concrete tensile strength and tensions stiffening effects have to be considered in the modelling method.

References

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