FRPRCS-14, Belfast - June 2019

Large-Scale Tests on the Structural and Deformation Behaviour of I-Beams with Carbon Reinforcement

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Abstract

The innovative composite material carbon-reinforced concrete allows the realisation of thin, high-performance components due to the high strength and corrosion resistance of the material. Applicable design concepts are necessary to accurately predict their structural and deformation behaviour. For this purpose, three precast carbon-reinforced concrete beams with I-profile were tested at the Institute of Structural Concrete (RWTH Aachen University). The specimens were tested upside-down using multiple hydraulic jacks in order to simulate realistic loading conditions. The beams were very slender, having a height of 90 cm, an upper and lower flange width of 20 cm and a web thickness of 5 cm. Their length was 8 m. Carbon bars were used as flexural reinforcement, whereas grids consisting of epoxy-impregnated carbon yarns were installed as shear reinforcement. The existing flexural models very accurately predict the test results of structural components with different types of non-metallic reinforcement, e.g. carbon bars and carbon grids. In this paper, the results of the experimental investigations regarding the ultimate limit state are presented.

Keywords: carbon reinforced concrete, textile reinforcement, deformation behaviour, bending behaviour, experiments, design concepts

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Introduction

To ensure the applicability of the high-performance composite material carbon concrete in practice, reliable methods for determining the ultimate capacity and the structural deformation in serviceability limit state are indispensable [1,2]. In practice, the ultimate limit state design of steel reinforced concrete for bending is done using a variation of the strain plane. The resulting forces in the reinforcement are then calculated using the elastic modulus for reinforcement steel. Since steel reinforcement bars in members with more than one reinforcement layer usually have the same bond characteristics throughout the layers, this is not necessarily the case for layers with non-metallic reinforcement, e.g. layers with carbon grids and carbon bars. Therefore, large-scale tests were carried out on three carbon concrete beams to check the applicability of common used design principles for beams with mixed carbon reinforcement, e.g. carbon grids and carbon bars. The results of the tests were compared with previously calculated values. Furthermore, finite element calculations were carried out, which also confirm the applicability of numerical methods. In the following article, the test setup, the preliminary design and the ultimate capacity are presented.

Materials

The reinforcement of the carbon concrete beams is made of three different materials (Figure 1). The longitudinal reinforcement consists of carbon bars with a core diameter of 9 mm and milled spiral notches to reach a sufficient bond behaviour (σ_{max} = 1,735 MPa, ε_u = 11.2 ‰). The shear reinforcement is formed by biaxial grid-shaped fabrics made of carbon fibres impregnated with epoxy resin (Roving). The ultimate strength in wrap direction (0°) is 3,221 MPa with an elongation of 13.2 ‰. Both flanges are connected with pre-formed textile grids made from carbon fibres in in the compression flange (σ_{max} = 3,221 MPa, ε_u = 13.2 ‰) and AR-glass fibres in the tension flange of the beams (σ_{max} = 1,311 MPa, ε_u = 18.5 ‰).

Figure 1: Reinforcement material: a) carbon bar, b) carbon grid, c) carbon form grid

The high-strength self-compacting concrete was tailored to the maximum grid size with a maximum grain size of 8 mm. The average maximum compressive strength of the concrete cylinder (d/h = 150/300 mm) after 28 days is 98.9 MPa. The corresponding modulus of elasticity was also determined from cylinder tests (d/h = 150/300 mm) with a mean value of 38.748 MPa after 28 days.

Test program

The three test specimens (Figure 2) were designed for bending tensile failure (beam FT01), i.e. a failure of the longitudinal reinforcement, failure of the concrete compression zone (beam FT02) and for investigation of a full splice in mid-span (beam FT03). This article focuses on the results of FT01.

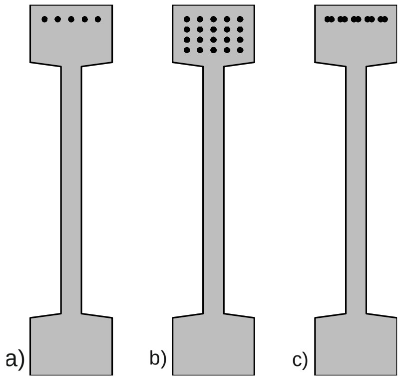
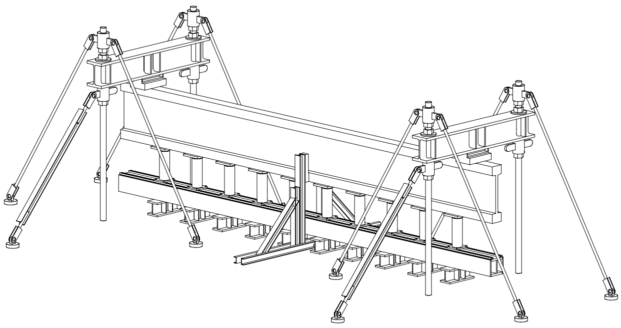


Figure 2: a) FT01, b) FT02, c) FT03

To ensure that the textile grid in the tension flange does not fail before the carbon bars, AR-glass grids are used in the tension flange. To predict the ultimate capacity of the beams, a simple iterative variation of the strain plane using the parabola rectangle diagram was performed. The ultimate moment is then calculated in accordance to the ultimate strength of the materials as it is commonly done with reinforced concrete members in bending. The geometrical parameters and reinforcement ratios were optimized to ensure an optimal utilization of reinforcement at serviceability limit state, defined here by the deflection of L/250 at mid-span.

Test Setup

The static system is chosen to be a simply supported beam with a uniformly distributed load (UDL). On both ends of the beam a roller bearing is installed. Due to this support construction, constraint forces can be neglected. In order to be able to apply a UD-load, an upside-down test setup was chosen (Figure 3). The load was applied with ten hydraulic jacks arranged equidistantly. This arrangement was chosen because the practical realization of two stiff support constructions is easier than the construction of a sufficiently rigid support for the hydraulic jacks. Each hydraulic jack was able to apply a maximum load of 590 kN. During the performed tests a load of only 200 - 250 kN was necessary, therefore the maximum load has not been reached. According to their data sheet the hydraulic jacks have a maximum lifting height about 250 mm. The bracings of the support constructions are to forward imperfection loads, which can occur during the test but also especially in the event of failure. Since the test specimens are slender, additional horizontal supports prevented a lateral buckling of the compression chord.

a) 

b) 

Figure 3: Test setup: a) isometric representation, b) photo

Test Results and Comparison

The specimens were tested under quasi-static load conditions with a loading rate of 10 kN/min. Due to stepwise loading, it was possible to mark the new cracks during each load stage. The load was then applied monotonic from a defined load stage up to failure. The load-deflection curve of FT01 is shown in Figure 4. FT02 and FT03 are not discussed in this article.
The primary failure was initiated by rupture of the longitudinal reinforcement bars after they reached their ultimate strain. Therefore, the failure mechanism can be classified as tension failure. As a consequence, the remaining longitudinal carbon fibres had to take account of the remaining loads. Immediately due to significant rising bond stresses which could not be anchored in the web with thin concrete cover, large-scale spallings occurred (marked in Figure 4). The calculated ultimate load was 697.7 kN (+ 1.9 % of the ultimate test load). This deviation is due to the fact that the material properties on which the calculation is based differ slightly from the actual values. However, a deviation of almost 2 % is a very accurate result.

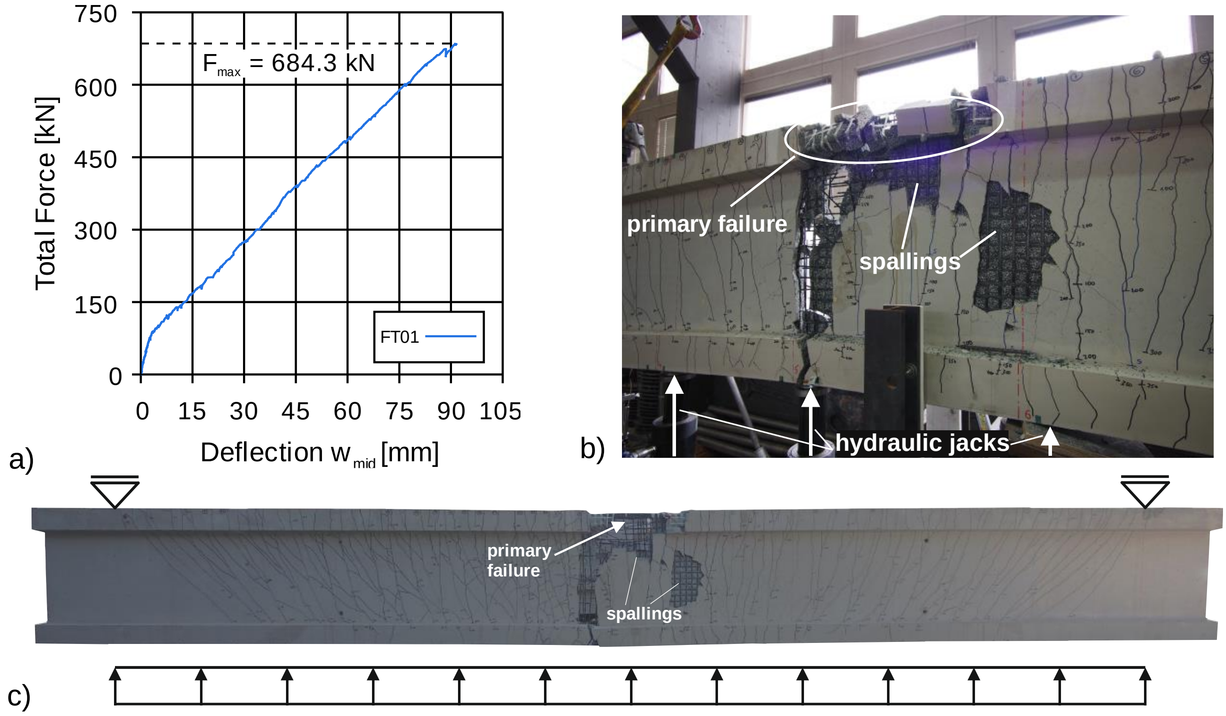


Figure 4: Results FT01: a) load-deformation curve, b) state of failure, c) longitudinal view

Further Investigations

Further investigations were carried out on deflection calculations according to [3] and on the numerical integration of a moment curvature diagram. Also nonlinear FE-Simulations using ABAQUS have been carried out giving very precise results.

Conclusions

The investigations showed that the calculation models very accurately predict the ultimate moment capacity of the beam. Using the material parameters from single yarn tensile tests [2], each roving has been considered in the ultimate moment capacity with respect to its belonging lever arms. Although the bond characteristics between the reinforcement materials differ, the forces in each roving could be calculated using Hooke's law. The advanced test setup using ten hydraulic jacks worked very well to reach realistic loading conditions with an UDL. Calculations on the deflection also gave very precise results but could not be discussed in this paper. The anchorage of the longitudinal and shear reinforcement did not fail before the ultimate state was reached [4]. Finally, it can be noted that the developed calculation models in the research project 'C³-V1.2' can be used to calculate the ultimate capacity of concrete members with different types of reinforcement.

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Acknowledgement
This work was supported by the German Federal Ministry of Education and Research (BMBF), project C³-V 1.2 (grant no. 03ZZ0312C). This support is gratefully acknowledged.