STUDY ON THE FLEXURAL BEHAVIOUR OF CFRP-GRID REINFORCED CONCRETE ONE-WAY SLABS

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ABSTRACT

Because of many merits, such as high strength-to-weight ratio, fatigue resistance and especially anti-corrosion, the CFRP (Carbon Fibre Reinforced Polymer) becomes a good alternative to steel as the reinforcement in concrete components. This paper addresses the features and results of the FEM and experimental studies on the flexural behaviour of CFRP-grid reinforced concrete one-way slabs. For the FEM simulation analysis, series of CFRP-grid reinforced concrete one-way slabs with different beam depths and the steel counterparts were modelled in ABAQUS and their bending properties like load-displacement relationships, ultimate load capacities and crack behaviour were analysed and compared through numerical bending tests. For the verification experiment, the corresponding CFRP reinforced specimens were fabricated and the real bending tests were conducted on them. Both the FEM and experiment results show that the CFRP-grid reinforced concrete one-way slabs are superior in many aspects to their steel counterparts and their flexural performance can meet the requirement of the present construction industry.

KEYWORDS

CFRP, RC one-way slabs, flexural behaviour, FEM, experiment.

INTRODUCTION

Reinforced concrete slabs are the basic components in variety of structures and facilities. They are commonly utilized as roof, floor, platform, wall, foundation, pavement and many other structural forms, of which steel reinforcing has a long history owing to their effectiveness and economy as concrete reinforcement. However, when the slabs are exposed to aggressive environmental conditions like de-icing salts, industrial chemicals and combinations of moisture, the corrosion of steel reinforcement will occur, which accelerate the deterioration of slabs and the loss of their performance and serviceability, and finally, can probably lead to tremendous maintenance costs.

In addition to high strength-to-weight ratio and good fatigue resistance, another main advantage of CFRP (Carbon Fibre Reinforced Polymer) is the excellent corrosion resistance, which makes it advisable as a good alternative to steel in terms of concrete reinforcement. Furthermore, CFRP is much lighter than steel, and it will also largely decrease the thickness of concrete protective layers because of its corrosion resistance. Therefore, it is obvious that the CFRP reinforced concrete slabs can become much lighter and thus the costs of substructure and foundation will be lowered. All points described above show that the CFRP reinforcement concrete one-way slabs have a promising future.

In Germany, the research of using CFRP reinforcement into concrete components started in the late 1990’s (Deskovic et al. 1995, Pieplow 2006, Schilde et al. 2007, Curbach et al. 2009 and Schlaich et al. 2012). The forms of reinforcement can be CFRP-bar and/or CFRP-grid. Chair of Conceptual and Structural Design of TU Berlin cooperated with GINKGO Projektentwicklung GmbH to conduct a series of investigations on CFRP-grid reinforced concrete slabs. In this paper, the preliminary research results about the flexural behaviour of CFRP-grid reinforced concrete one-way slabs are presented. Firstly, the FEM comparative study between CFRP-grid reinforced concrete one-way slabs and the steel counterparts is introduced and the merits of CFRP-grid reinforced concrete one-way slabs are certified. Then, the experiment of the full-scale specimens is presented, so as to verify the outcome of the FEM research. Based on the results of both FEM and experiment, it is concluded that the CFRP-grid reinforced concrete one-way slabs could be a good alternative of the steel ones and the bending performance of these new slabs can meet the requirement of the present construction industry and they can be utilized in numerous projects of the GINKGO Projektentwicklung GmbH.
FINITE ELEMENT METHOD SIMULATION ANALYSIS

Specifications of Dimension and Reinforcement

The FEM simulation analysis aimed to compare the flexural behaviour of CFRP-grid reinforced concrete one-way slabs and their steel counterparts and figure out the potential advantages of these CFRP reinforced slabs in terms of bending. Therefore, specimens in the numerical bending test were divided into two groups, in which slabs with CFRP-grid reinforcement belonged to the Group A while slabs with steel-grid reinforcement were in the Group B. Each slab group included two slabs with different beam depths (100 mm or 140 mm), so as to study the effect of the beam depth. For comparison purposes, the beam depth and reinforcement ratio of the corresponding slabs from different groups were set to be the same.

The geometric and reinforcement details of the two slabs from the Group A are shown in Figure 1. Because of the superior anti-corrosion capacity of CFRP-grid, the thickness of concrete protective layer was set to be 5 mm. The dimension and property of the CFRP-grid utilized in the beams were from the SGL Sigratex Grid 600 (grid spacing: 12 mm × 18 mm; grid section: 102 mm²/m × 153 mm²/m), while those of the grid in the plate were from the SGL Sigratex Grid 250 (grid spacing: 17 mm × 18 mm; grid section: 49 mm²/m × 52 mm²/m).

![Figure 1. Geometric and reinforcement details of CFRP-grid reinforced slabs (unit: mm)](image)

The geometries and reinforcement details of the two steel-grid reinforced slabs are shown in Figure 2. They are similar to their CFRP counterparts, except that the steel-grids were arranged more closely and the plate was appropriately thickened due to the requirement of thicker protective layers (according to the DINEN 1992 (EC 2), the concrete protective layer was 20 mm thick). The cross section areas of steel grid were equal to those of the corresponding CFRP-grids in order to make the reinforcement ratio remain unchanged.

![Figure 2. Geometric and reinforcement details of steel-grid reinforced slabs (unit: mm)](image)

FEM Model in ABAQUS

The FEM models were built in the general FEM software ABAQUS. The loads were firstly acted at the rigid spreader beams and then transferred through cuboid cushions into the specimens. So every specimen was subjected to a four-point bending load at each rib. The longitudinal distance between supports at the slab ends was 1980 mm and the shear span was 590 mm, so the longitudinal distance between the two point loads was 800 mm. Based on the geometric and loading specifications, the diagrams of FEM model and CFRP (or steel) grid reinforcement are shown in Figure 3.

![Figure 3. FEM model and CFRP (or steel) grid reinforcement](image)

In the FEM models, the concrete parts were modelled by the C3D8R elements, which are 3-dimension 8-node reduced integration solid elements, and the concrete material properties came from the ABAQUS embedded
concrete damaged plasticity model, which is based on the modified Drucker–Prager strength hypothesis (Kmieck et al. 2011), with the concrete grade C30 \( (f_c = 32.4 \text{ MPa}, f_t = 1.78 \text{ MPa}, E = 30000 \text{ MPa} \) and tension stiffening was considered). Furthermore, the concrete damage index was defined (0 indicates no damage, 0 – 1 indicates partial damage and 1 indicates completely damage), so as to describe the crack behaviour of the slabs. The CFRP (or steel) grids were modelled by the T3D2 elements, which are 3-dimension 2-node truss elements. The CFRP mechanical properties were based on those of the SGL Sigmatex Grid \( (f_c = 1200 \text{ MPa and } E = 164000 \text{ MPa}) \). The steel mechanical properties came from the common steel grid \( (f_y = 210 \text{ MPa}, f_u = 230 \text{ MPa}, E = 210000 \text{ MPa and } \varepsilon_y = 0.1\%) \).

**Numerical Simulation Results**

In the numerical bending tests, every slab was loaded until the calculation diverged. The load-deflection curves, ultimate bearing capacities and crack behaviour were gained. The results and discussions are in the following.

1. The relationship of the load-deflection

   ![Image](image_url)

   **Figure 4.** The load-deflection curves of CFRP or steel reinforced concrete one-way slabs

   It can be seen from the Figure 4, the load-deflection curve of the CFRP concrete slabs are approximate linear, which shows the material linearity of the CFRP reinforcement, while the load-deflection curve of the steel concrete slabs are approximate double-linear including a long horizontal segment, which shows the non-linearity of the steel material. Moreover, the slope of the black curve (CFRP) is always larger than that of the red curve (steel) during the rising step, which indicates that the CFRP concrete slabs have greater stiffness than their steel counterparts. The reason is probably that CFRP reinforcement is closer to the bottom of the beam though the E-Modulus of CFRP is slightly lower than that of steel.

2. The comparison of ultimate bearing capacities

   ![Image](image_url)

   **Table 1.** The ultimate loads at CFRP or steel reinforced concrete one-way slabs

<table>
<thead>
<tr>
<th>Concentrated load at every rib</th>
<th>CFRP concrete slab</th>
<th>Steel concrete slab</th>
</tr>
</thead>
<tbody>
<tr>
<td>h = 100 mm</td>
<td>13 kN</td>
<td>4 kN</td>
</tr>
<tr>
<td>h = 140 mm</td>
<td>28 kN</td>
<td>11.5 kN</td>
</tr>
</tbody>
</table>

   It can be seen from the Table 1 that the ultimate bearing capacity of CFRP concrete slab is much higher than that of steel concrete slab with the same beam depth. It is mainly because the ultimate strength of CFRP reinforcements is much higher than that of steel reinforcements and they were also arranged closer to the bottom of the beam than their steel counterparts. The Table 1 also shows that increasing the beam depth can considerably increase the ultimate bearing capacity of the grid reinforced concrete one-way slab, no matter what kind of reinforcement material was used.

3. The comparison of the crack behaviour

   As mentioned before in this paper, the concrete damage index was defined to indicate the bending crack behaviour of these two types of concrete slabs. Compared with the crack conditions in the ultimate limit state, the cracks in the serviceability limit state usually merit more attention. Therefore, the tension crack behaviour of these two groups of slabs under the serviceability limit state is presented in this paper as follows. The definition of the serviceability limit state is accordance with the specification from the EC 2.
From the Figure 5 and Figure 6, it can be seen that the steel reinforced concrete slabs no matter \( h = 100 \) mm or \( h = 140 \) mm have bigger area of tensile cracks than the CFRP reinforced concrete slabs. Under the serviceability limit state (according to Euro Code 2), the concrete cracks appeared only at the ribs of the CFRP concrete slabs, while in their steel counterparts, the cracks appeared not only at the ribs but also at the plates. It shows that CFRP-grid reinforced concrete slabs have better crack control performance than their steel counterparts probably because they have much thinner concrete protective layers.

**BENDING EXPERIMENT VERIFICATION**

**Experimental Programme**

The above FEM research shows that the CFRP-grid reinforced concrete one-way slabs have many advantages compared with the steel counterparts in terms of flexural properties. However, the CFRP-grid reinforced concrete one-way slabs are the novel designs and only the FEM results are not enough to guarantee their practicability. Therefore, a series of bending tests were conducted on the real CFRP-grid reinforced concrete one-way slabs, so as to verify the results from the FEM simulation.

The specimens in the bending experiment consisted of four CFRP reinforced concrete slabs, which were classified into two groups according to the beam depth (100 mm or 140 mm). Every group contained two specimens, which had the same geometries and material properties as the corresponding numerical models. Their dimensions and reinforcement details can be seen in Figure 1. The used material properties are shown in the following Table 2.

<table>
<thead>
<tr>
<th>Material</th>
<th>Type</th>
<th>Compressive Strength ( f_c )</th>
<th>Tensile Strength ( f_t )</th>
<th>E-Modulus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>C30</td>
<td>32.1 MPa</td>
<td>-</td>
<td>30000 MPa</td>
</tr>
<tr>
<td>CFRP</td>
<td>SGL SigraTEX Grid</td>
<td>1066 Mpa</td>
<td>164000 Mpa</td>
<td></td>
</tr>
</tbody>
</table>

Same as the numerical tests, the specimens were simply supported at two ends of each rib. The loads were the four concentrated loads provided by two Hydraulic actuators. The locations of the loads were the same as in the numerical tests. The deflections at the middle point of each rib were measured by the displacement meters and were automatically recorded by the data acquisition system with the load values from each hydraulic actuator. The development of crack was recorded by photos and the width of crack was measured by crack ruler. Figure 7 shows the experiment setup and the instrumentation.
The load was applied in displacement control mode and every specimen was loaded to failure. During the loading, the load applier was paused or unloaded several times to control cracks and strains and also to facilitate taking notes.

**Experiment Results and Data Analysis**

(1) The load-deflection relationships

![Figure 8. The load-deflection curves of four specimens compared with FEM results](image)

It can be seen from the Figure 8 that the experimental results coincide well with the FEM results. The ultimate loads gained from the numerical test are slightly higher than those from the experiment.

(2) The crack behaviour

The crack development of these four specimens was similar. The Figure 9 shows the crack distribution on the back side of specimen 2 in both serviceability and ultimate limit state compared with FEM results.
As can be seen from the Figure 9, the crack development and distribution gained from the experiment are approximately consistent with the results from the FEM. In the serviceability limit state, the cracks only located at the rib region, especially between the loading points; in the ultimate limit state, the cracks distributed widely at the rib and plate and the transversal penetrating cracks appeared and caused the failure of the slabs. As observed from the experiment, the crack spacing and crack width were relatively small. This indicates that the CFRP-grid reinforcement can effectively control the cracks in the concrete one-way slabs.

CONCLUSIONS

Compared with the steel counterparts, the flexural behaviour of the CFRP-grid reinforced concrete one-way slabs with different beam depths were investigated through numerical and experimental methods. The conclusions of the study can be summarised as follows:

(1) In comparison with the steel-grid reinforced slabs, the CFRP-grid reinforced ones have higher bearing capacities in the ultimate limit state and better crack performance in the serviceability limit state. This is mainly because that the CFRP grids have much higher ultimate tensile strength and the concrete protective layers are considerably reduced due to the superior anti-corrosion ability of CFRP.

(2) The flexural performance of the CFRP-grid reinforced concrete one-way slabs can meet the requirement of the present construction industry. This was proved not only by the FEM numerical research but also by the verification bending experiment.

ACKNOWLEDGMENTS

This project was funded by the GINKGO Projektentwicklung GmbH of Dresden in Germany.

REFERENCES


