An advanced polymer composite and concrete slab system

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This paper reports on an investigation into the feasibility of a structural slab system comprising of a sheet of carbon fibre reinforced polymer (CFRP) in tension and concrete in compression. The CFRP serves as permanent formwork as well as tension reinforcement. It was found that the slab system performed satisfactorily at ultimate and serviceability limit states. A design for a slab for use in a typical building is presented.

Introduction

Advanced Polymer Composites (APCs) have a number of advantages over steel, such as high strength to weight ratio and corrosion resistance. Their light weight makes them easier and safer to handle on site. One way in which APCs may be used to reinforce concrete is by using bars as a direct replacement of steel reinforcement. However, this may not be the most efficient way to use these materials, which are expensive and may be better used in thin plate sections. An alternative way of using APC materials to reinforce concrete is as permanent formwork, on to which concrete is cast to form a composite section.

Design of the slab system

In a typical office building, the slabs are around 150mm depth and span 3m between the secondary beams. In this investigation the slab was modelled at approximately one-third scale, spanning one way with a 1m span and a thickness of 50mm. The design consisted of a corrugated CFRP profiled sheet that could be placed in position and used to support the weight of the wet concrete during the construction phase. At this stage of the project it was not economical to construct a specific mould with an optimum shape on which to lay up the CFRP. Therefore, a commercially available corrugated steel sheet was used as the mould. The cross-section of the slab is shown in figure 1.

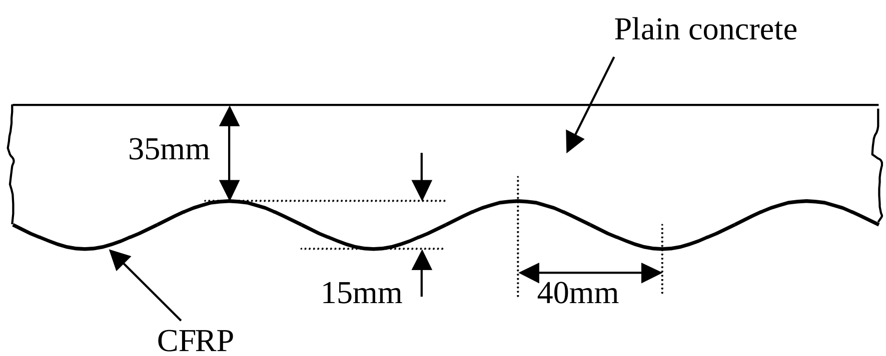

Figure 1. Cross-section of CFRP/concrete composite slab

For the design of the test specimen, the analysis of the slab cross-section was based on Engineer's small deflection bending theory. The stress-strain relationship of the concrete was assumed to be non-linear with the characteristic given in BS8110 [1].

The failure strain of concrete was taken as 0.0035. The CFRP was assumed to be linear elastic with a modulus of elasticity of 164 kN/mm^2 and a tensile strength of 860 N/mm^2. These data were obtained from a combination of manufacturer's data and previous tests on samples. The failure strain of the CFRP was calculated to be 0.0052. The corrugated shape of the CFRP was approximated as trapezoidal in order to simplify the analysis.

The analysis predicted the neutral axis at the ultimate limit state to be 19mm below the top surface of the concrete.

Construction of the slab system

The CFRP sheet was 0.5mm thick and consisted of high-strength carbon fibre fabric in an epoxy resin.

The concrete mix was designed in accordance with [2] to achieve a characteristic strength of 40 N/mm^2 at 28 days, using 10mm aggregate. Due to the lack of steel reinforcement, it was possible to use a low slump concrete with a target slump of 30-60mm, with a water-cement ratio of 0.42. Cube tests at 28 days confirmed the concrete strength to be 57 N/mm^2. Further cube tests at 4 months when the slab was tested in the laboratory showed that the concrete strength at that time was around 70 N/mm^2.

The bond between the CFRP and the concrete was formed by means of a two-part epoxy adhesive, which was applied to the surface of the cured CFRP sheet immediately before the wet concrete was poured.

Testing

The slab was set up as simply supported in the direction of the corrugations, with an effective span of 900mm. A concentrated load was applied in the centre of the slab, spread over an area of 150mm^2, as shown in figure 2.

During the test, load and deflection were measured. Strain gauges were attached on the top and bottom at a number of locations to measure bending strains in the major and minor directions of bending. More details of the instrumentation are given in [3].

Slab performance in testing

The graph of load against deflection measured close to the load is shown in figure 3. The graph shows the behaviour over the entire test. Following an elastic region in which an unload-reload loop was carried out, a peak load of 18.65kN was reached at point A in figure 3. At this point, a failure was observed in the transverse direction of bending, just to one side of the load, in which the profile of the CFRP layer straightened locally and debonded from the concrete over one corrugation, and a crack opened up in the concrete across the whole width of the slab.

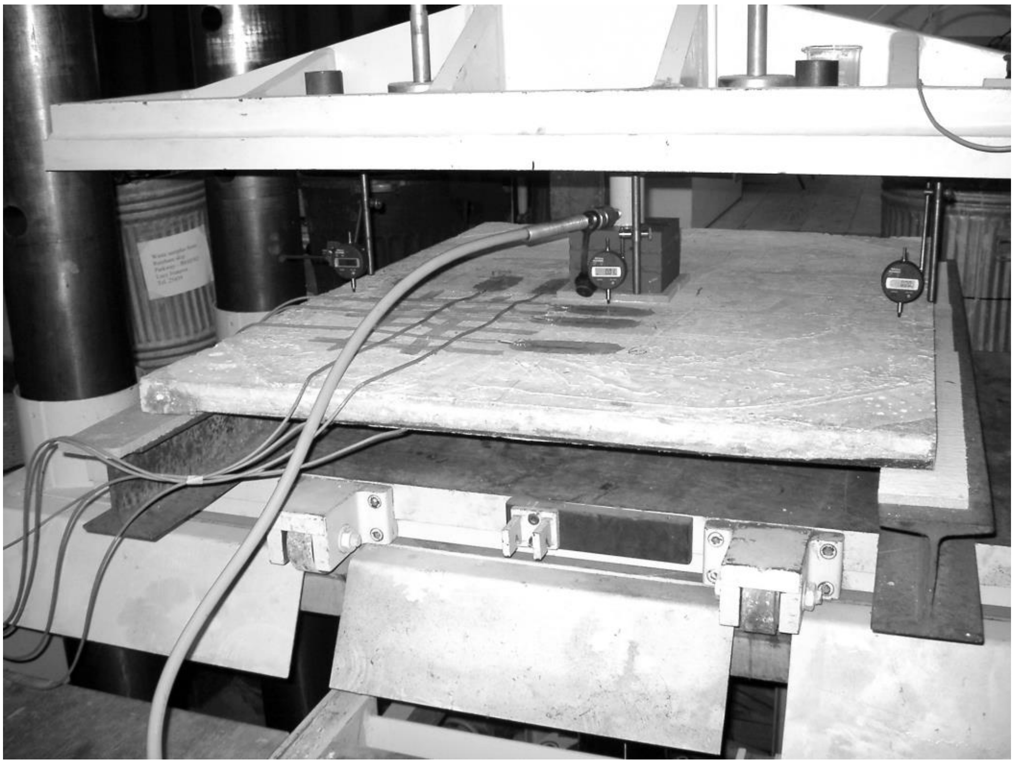

Figure 2. Slab arrangement for testing

Despite this crack, it was still possible to increase the load further and induce a failure in the major direction of bending. This occurred at a load of 19.5kN at point B in figures 3 and 4. Figure 4 shows that at this point the strain in the CFRP, in the major direction close to the load, had reached approximately 5000με. This is in good agreement with the expected tensile strain capacity of the CFRP. On unloading of the slab, a permanent deflection of 5mm was observed, as shown in figure 3.

The slab was reloaded and it was found that large deflections up to 25 mm were possible, with the formation of what appeared to be a plastic hinge across the entire width of the slab (figure 5). When the maximum concrete strain reached approximately 0.0035, crushing of the concrete was observed on the surface and the slab failed catastrophically by debonding of the concrete from the CFRP over one quarter of the slab.

The fact that, at the ultimate failure condition of the slab, both materials had reached their predicted failure strains indicates that the original analysis approach was reasonable.

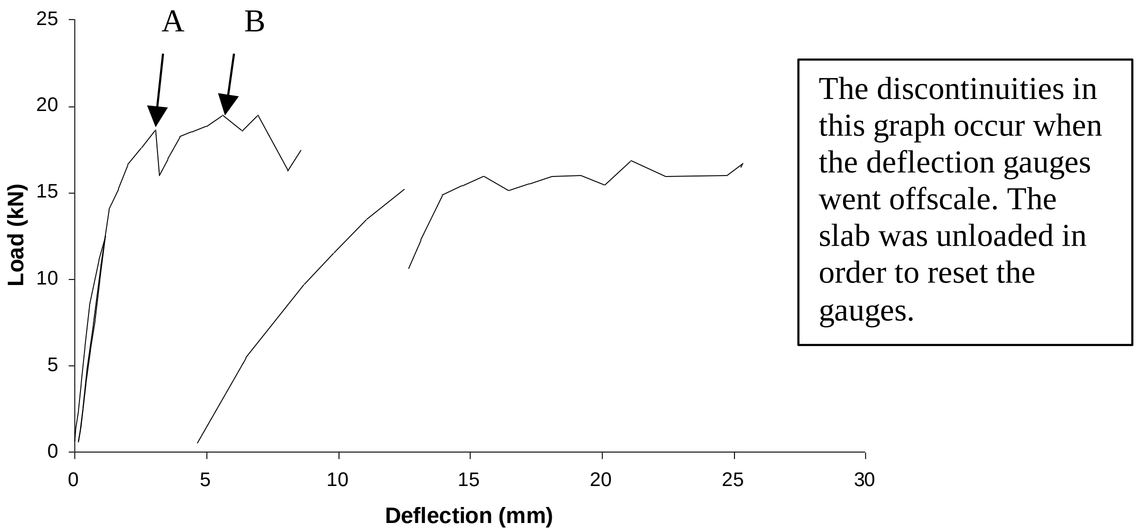

Figure 3. Load against deflection for the entire test

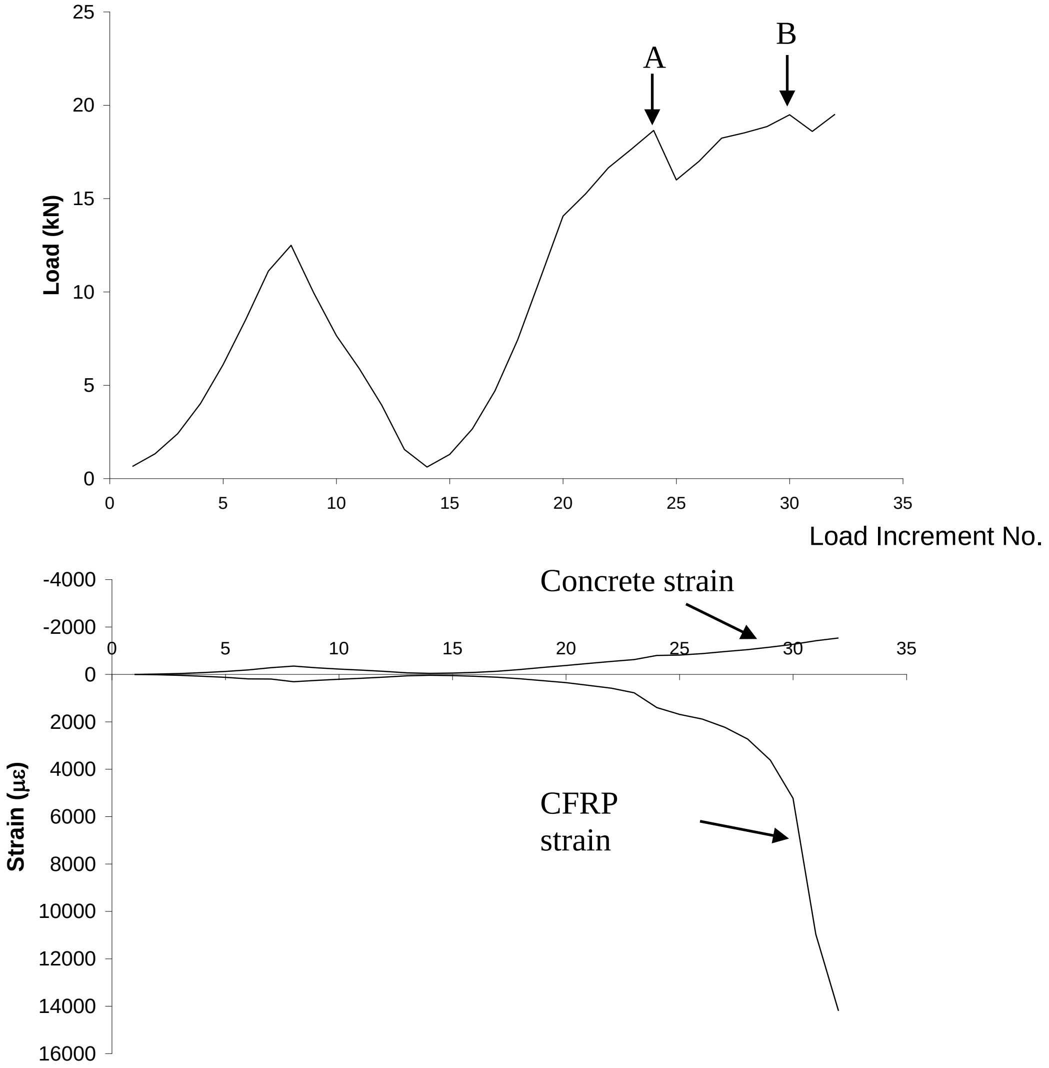

Figure 4. Variation of load and strain close to the centre of the slab

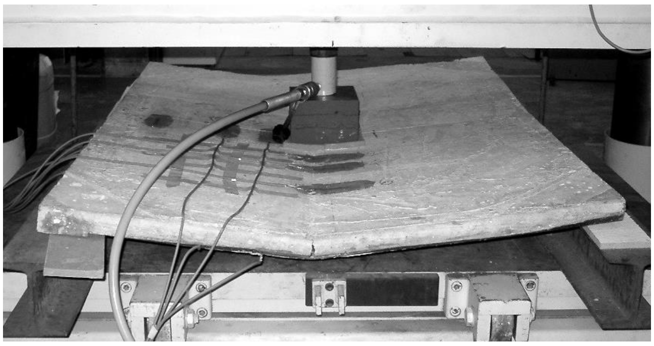

Figure 5. The ultimate failure condition of the slab

The neutral axis position was calculated from the strains in the top and bottom fibres of the cross-section. It was found that in the first part of the test, the neutral axis was at approximately mid depth, 25mm below the top of the section. It is reasonable to assume that the concrete was uncracked at this stage. As the test proceeded, the neutral axis rose gradually to about 10mm below the top when the ultimate load was reached. This was higher than predicted by the analysis. As acceptable data had been obtained for the modulus of elasticity of the CFRP and the strain in that material, at the ultimate load, was in accordance with predictions, the most likely explanation for the discrepancy between the neutral axis position and the predicted position lay with the stiffness assumed for the concrete. The cross-section was back-analysed with the initial modulus of elasticity of the concrete assumed to be $8000\sqrt{(f_{cu}/\gamma_m)}$ N/mm^2 (compared with $5500\sqrt{(f_{cu}/\gamma_m)}$ used in BS8110) and with f_{cu} taken as 70 N/mm^2 and γ_m as 1.0, and this resulted in reasonable agreement with the experimental observations of neutral axis position. Therefore, it appears that the concrete stiffness was higher than allowed in the design code.

A linear elastic finite element model using plate elements was constructed using a computer package. The relative bending stiffnesses in the major and minor directions were calculated to be 1:0.832. These were obtained using transformed sections, taking the modulus of elasticity of concrete to be $8000\sqrt{(f_{cu}/\gamma_m)}$ N/mm^2 . In the major direction the section was simplified to a trapezoidal shape and in the minor direction the average depth was used. The result for bending moment distribution through the slab in the finite element model was very close to the results observed during the experiment, both initially in the elastic region and after cracking.

Application

In order to investigate the application of this form of slab in a typical office building, a further design was carried out with a span of 3m, a dead load of 2.4kN/m^2 and an imposed load of 5kN/m^2 [4]. In order to satisfy the SLS deflection limit of span/250 [1], a slab with a depth of 100mm and a CFRP thickness of 0.7mm was required. This gave a deflection of 10.6mm and was well within ULS limits, with a bending moment capacity of 43.7kNm per metre width of slab.

Conclusions

A structural slab system was designed in which permanent formwork and tension reinforcement were provided by a thin CFRP corrugated sheet on to which concrete was poured. It was found that at the ultimate limit state, the predicted failure strains of the concrete and CFRP were reached. A successful bond between the CFRP and concrete was achieved by means of an adhesive that was applied to the CFRP prior to pouring the concrete. The slab proved capable of withstanding large plastic deformations. At the serviceability limit state, structural performance was satisfactory. A slab system with an overall depth of 100mm would be feasible in a typical office building.

Future Work

Creep was observed at each load increment during the test. Each time a further load increment was applied, the load instantaneously peaked and then relaxed before settling down to an approximately stable value. This creep was particularly obvious past the SLS limit, approaching the ultimate load. The primary cause of this is likely to be creep of the resin adhesive used to bond the concrete to the CFRP. Further research to investigate the effect of creep could involve applying a constant load to the slab representing the serviceability limit state and observing its behaviour over a long period. Ideally, this would be several days or weeks.

In practice, it would be necessary to provide a certain level of fire resistance to the slab. This would probably be achievable by using a fire resistant resin matrix in the CFRP. An example suitable for large-scale use in buildings would be a phenolic resin, which is relatively inexpensive [5]. Future work should include the construction of a slab using CFRP with a phenolic matrix. The structural performance under normal conditions and the fire resistance would need to be tested.

Acknowledgements

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