Construction and Building Materials 155 (2017) 463–474

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

# Experimental investigation on the behaviour of reinforced concrete slabs strengthened with ultra-high performance concrete

Yin Hor [a], Wee Teo [b,*], Shirai Kazutaka [c]

[a] Graduate School of Engineering, Hokkaido University, Kita 13, Nishi 8, Sapporo 060-8628, Japan
[b] School of Energy, Geoscience, Infrastructure and Society (EGIS), Heriot Watt University Malaysia, Jalan Venna P5/2, Precinct 5, 62200 Putrajaya, Malaysia
[c] Faculty of Engineering, Hokkaido University, Kita 13, Nishi 8, Sapporo 060-8628, Japan

## HIGHLIGHTS

- UHPC is an excellent material suitable for strengthening concrete structures.
- Rehabilitated slabs show ductile failure mode with extensive deflection hardening.
- Retrofitted slabs show enhanced ultimate strength and stiffness.
- Thickness of UHPC layer is of great importance in determining the performance.
- Reinforced UHPC layer performs effectively, provided full bond development occurs.

## ARTICLE INFO

*Article history:*
Received 20 April 2017
Received in revised form 27 July 2017
Accepted 15 August 2017

*Keywords:*
Composite UHPC-concrete slabs
UHPC overlay
Rehabilitation
Structural behaviour
Shear capacity
Ductility

## ABSTRACT

Nine rectangular specimens were tested to investigate the behaviour of composite reinforced concrete (RC) slabs strengthened with ultra-high performance concrete (UHPC). The specimens were two series with various UHPC strengthening configurations. The first, a rehabilitation series, tested UHPC as patch material for repairing deteriorated concrete structures. The second, a UHPC overlay series, was used to retrofit soffits of RC members. The results showed that using the rehabilitation series, the UHPC reduced diagonal cracking and developed more flexural cracks as compared to RC slabs with no UHPC strengthening. The UHPC exhibited excellent energy absorption with extensive deflection hardening and ductility during the post cracking range. In the UHPC overlay series, each slab showed diagonal shear cracks and debonding modes. The UHPC overlay delayed the development of shear cracking. As the overlay thickness increased, the ultimate load increased; but the tendency for the UHPC to undergo fracture failure also increased.



## 1. Introduction

Ultra-high performance concrete (UHPC) is an advancement in concrete technology. It is a mix of reactive powder concrete (RPC) with steel fibres, which was firstly developed by Richard and Cheyrezy [1]. Typically, UHPC offers high compressive strength of from 150 to 200 MPa without heat curing [2]. In addition, UHPC or ultra-high performance fibre reinforced concrete (UHPFRC) exhibits excellent mechanical properties such as durability [3–5], low permeability [5,6] and energy absorption [7–11]. Therefore, UHPC is often used in protective structures, as non-penetrable coverings and in elements that must be durable against aggressive environments and severe loadings such as earthquakes, impacts or blasts.

Due to its superior properties, many researchers have expounded on the structural responses of UHPC members. Graybeal [12] conducted full-scale tests of UHPC bridge girders with different overall spans and shear spans. Voo et al. [13] conducted many structural UHPC tests. Their results showed that UHPC significantly improves ductile behaviour. Furthermore, Yang et al. [14] and Yoo et al. [15] reported how the longitudinal steel ratio affects UHPC beams. Their studies demonstrated that the rebar and steel fibres effectively control crack width and ductility.

Recently, UHPC has been considered as a potential tool in the challenge of retrofitting or repairing existing reinforced concrete (RC) members. Concepts for using UHPC to strengthen parts of structures where the outstanding properties of UHPC could be fully exploited have been proposed by Brühwiler and Denarie [5]. To

* Corresponding author.
*E-mail addresses:* yin_hor@yahoo.com (Y. Hor), t.wee@hw.ac.uk (W. Teo), shirai.kazutaka@eng.hokudai.ac.jp (S. Kazutaka).

http://dx.doi.org/10.1016/j.conbuildmat.2017.08.077
0950-0618/

validate the concepts, four unique full-scale site applications were discussed. Their findings were very encouraging. The use of UHPC has shown great potential and UHPC development is mature for use in either cast in-situ or precast applications using conventional standard concreting equipment.

To observe the performance of UHPC strengthening, some experimental studies that combine UHPC and RC have been carried out [16–21]. Oesterlee [16], Habel et al. [17] and Noshiravani and Brühwiler [18] evaluated the behaviour of RC members strengthened with UHPC overlays when subjected to bending. The results showed that UHPC overlays enhance the structural performance in terms of ultimate loads, stiffness and cracking behaviour. Zohrevand et al. [19] reported the use of UHPC within critical punching shear area of the RC slabs. It was shown that the partial use of UHPC improves the shear capacity and significantly influences cracking patterns in punching shear area compared to the reference RC slab. Another investigation was carried out by Alaee and Karihaloo [20] using CARDIFRC, a type of UHPC, to strengthen RC beams. Strips of CARDIFRC were attached to RC members using epoxy adhesive. The maximum load carried by the strengthened beams was equal to or higher than that of the RC beams, but the load-deflection curves showed softening behaviour after reaching the maximum force. In addition, Kim et al. [21] tested RC beams repaired with the conventional ductile fibre reinforced cementitious composite (DFRCC). Two thicknesses of DFRCC for the concrete cover thickness and twice the cover thickness were adopted in their study. Results mainly showed that DFRCC delays the bond interface failure between DRFCC and the original RC beams. However, DFRCC has lower mechanical properties, especially load bearing capacity compared to UHPC.

Owing to the novel properties of UHPC, however, the behaviour of composite members influenced by a UHPC layer strengthening has not yet been fully clarified. In particular, the number of studies in the literature on composite members that include overlays onto which an additional UHPC overlay is applied to existing RC members is very limited. More importantly, there are published studies of tests on UHPC overlay modes, but to the best of the authors' knowledge, as yet there are no publish reports on rehabilitation schemes in which UHPC is used to repair deteriorated concrete. Therefore, more experimental work in this area is definitely needed.

The purpose of this study is to further understand the structural behaviour of composite UHPC-concrete slabs. To accomplish the objective, tests on various UHPC strengthening configurations applied in the tensile zone of RC slabs were conducted. New experimental features of rehabilitation strengthening modes and UHPC overlay modes are described. The experimental program, including details of the test parameters and equipment setup is described in Section 2. In Section 3, the mechanical properties of UHPC materials are provided. The test results and discussion are presented in Section 4, focusing on the mechanical behaviour of load-deflection relationships, longitudinal steel strain, cracking development and failure modes. Section 5 summarises the research conclusions with recommendation of future research.

## 2. Experimental program

### 2.1. Description of test specimens and parameters

This experimental study used nine rectangular concrete slabs with various composite UHPC-concrete configurations. Two test series with distinct composite configurations were adopted. The first series used UHPC as rehabilitate material. It is labelled RE. The second, where UHPC is used as a retrofit material in overlays, is labelled OV. The RE series consisted of five slabs, while the OV series used four. Each slab was 1600 mm long with a clear span of 1200 mm. They were tested under a three-point load condition, as shown in Fig. 1. Full details of the various composite UHPC-concrete configurations adopted for the two series are illustrated in Fig. 2.

The RE series consisted of five slabs with 300 mm wide by 100 mm high cross sections. This series was designed to investigate the use of UHPC applied in the tension zone as patch material for repair and rehabilitation of structural members. Often in practice, deteriorated concrete will be removed and high performance repair materials applied to the concrete substrate. In this series, different UHPC thicknesses were considered in order to reflect different extents of deterioration and repair. The slab specimens were designated according to the thickness of the UHPC applied to the concrete substrate. For example, slab specimen RE-32 featured a slab with deteriorated concrete removed and rehabilitated with a 32 mm thick layer of UHPC. All slabs in the RE series had five T12 mm diameter high tensile steel bars (5T12) at the top and bottom. No transverse shear reinforcement was provided, but to avoid anchorage failure at the end supports, three R6 mm diameter mild steel links were installed. Details of the reinforcement are shown in Figs. 1 and 2.

The OV series consisted of four slabs with similar cross-sectional dimensions as the RE series, but with different additional UHPC overlays strengthening the tension zone. Two thicknesses of UHPC overlay were considered, 25 mm and 50 mm. Two slab specimens of each overlay thickness were prepared. One was not reinforced, while the other had five T10 mm diameter high tensile steel bars as longitudinal reinforcement (5T10). The slab specimens were designated according to the thickness of UHPC overlay and longitudinal steel reinforcement. Slab specimens with a UHPC overlay and longitudinal reinforcement are denoted by "a". For example, slab specimen OV-50a had a 50 mm thick UHPC overlay and was reinforced with 5T10 longitudinal reinforcement. Geometric and reinforcement details of the experimental specimens are summarised in Table 1.

The slab specimens for both series were prepared in two stages. First, the normal strength concrete (NSC) was cast, then the UHPC was mixed and cast onto the concrete substrate. The NSC was supplied by a local ready-mix supplier. Six 100 mm standard cubes and six 100 by 200 mm standard cylinders were prepared for compressive strength testing. All the slabs, cubes and cylinders were cured under identical conditions: under ambient temperature covered with wet hessian for 7 days followed by dry open air for the remainder of the period until the day of testing (day 28). The average compressive strength of the NSC at 28 days was 33 MPa for the cubes and 23 MPa for the cylinders.

After the NSC hardened, the top surface of the concrete was purposely roughened in order to create a good bonding surface for UHPC layer. This was done using chisel and hammer randomly throughout the NSC substrate. Before casting of UHPC, the surface of the concrete substrate was moistened for 10 min and wiped dry with a cloth. Unlike the NSC, UHPC was prepared manually in the laboratory. Because of the quantities, three separate UHPC mixes were prepared for the two series. Details of the UHPC mix proportions and mechanical properties are given in Tables 2 and 3. Fig. 3 shows the preparation of the slab specimens before and after casting of the UHPC layers.

### 2.2. Test setup and instrumentation

All slab specimens were simply supported and subjected to the three-point load configuration shown in Fig. 1. Each slab had a clear span of 1200 mm and carried a concentrated load at mid-span, applied at a loading rate of 0.1 kN/s. The shear span between the supports and load point is 600 mm, corresponding to a shear span-to-effective depth ratio (a/d) of 8.11 for slabs without UHPC overlays. Two types of instrumentation were used, linear variable differential transducers (LVDTs) to measure vertical mid-span deflection and electrical resistance strain gauges to measure internal longitudinal reinforcement steel strain. Fig. 4 shows a slab specimen with instrumentation ready for testing.

Two LVDTs were installed on each slab underneath the slab soffit at mid-span. The vertical deflections were plotted based on the average of the two LVDTs. For the slab specimens of the RE series, two strain gauges were installed at the mid-span of the bottom longitudinal reinforcement. For slabs OV-25a and OV-50a in the OV series, besides the two strain gauges on the bottom longitudinal reinforcements of the concrete substrate, two additional strain gauges were attached to their longitudinal reinforcements in the UHPC layer. Details of the positions of the strain gauges are shown in Fig. 1.

KYOWA waterproof strain gauges of 5 mm gauge length were used. Before a gauge was attached, the steel rebar was ground to a slightly flat surface for ease of gauge placement. The ground surface was then polished with sand paper and cleaned with acetone solvent before attaching the gauges using cement glue. To prevent strain gauge damage during concreting, all gauges were protected with an extra layer of silicone. Fig. 5 shows the placement of a waterproof strain gauge on the bottom longitudinal reinforcement before being protected with silicone.

## 3. UHPC material

The design strength of the UHPC in this study was targeted at 150 MPa. Several trial mixes were attempted. The mix proportion and constituents chosen for use in this study as a result of these trials are shown in Table 2. To obtain the rheology and mechanical properties of the UHPC mix, compressive strength testing, three-