Flexural Performance of Reinforced Concrete (RC) Beam Strengthened by UHPC Layer

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Research Article

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Abstract

Reinforced concrete (RC) structures may be subjected to an increase in load, severe environmental attack, and other factors that may lead to deterioration. Strengthening/repair techniques are typically used to upgrade the strength or enhance the durability which extends the service life of the structures. In the current study, the behavior of reinforced concrete beam strengthening by the UHPC layer with/without construction joints was investigated. The effect of the steel/GFRP bars across the construction joints was also performed and the results were compared with control specimens. The results indicate that the inclusion of UHPC layers at the tensile side of the RC beams significantly increased their stiffness and delayed the crack initiation. Meanwhile, the presence of the construction joint in the UHPC overlay decreased the efficiency of the strengthening method. Furthermore, utilizing steel/GFRP bar in UHPC overlay across the construction joints showed a significant increase in loading carrying capacity and had a significant effect on the modes of failure. The results also demonstrated that the UHPC overlay experienced a sufficient bond to concrete as no separation was observed.

1. Introduction

Concrete structures are prone to deterioration due to ageing, e.g., exposure to severe environments causing corrosion of steel reinforcement, natural and human-made extreme events such as earthquakes, vehicular impacts, fire exposure etc., or simply due to changes in design codes or changes in use [1]. Rehabilitation of damaged concrete structures to meet the current codes’ requirements and strengthening existing concrete structures to carry higher permissible loads appear to be a more cost-effective and appealing option than demolishing and rebuilding[2][3]. Several methods have traditionally been used to repair and strengthen reinforced concrete structures, such as reinforced concrete jacketing, epoxy bonding steel plates, external post-tensioning, and externally bonding carbon fibre-reinforced polymer [4][5]. Despite their effectiveness in achieving strengthening goals and improving strength and durability, these methods have some drawbacks. For example, using concrete jacketing increases the weight and size of the structural element, while using steel plate technique increases the risk of corrosion, fire resistance and debonding. On the other hand, ageing adhesion materials at the interface and fire resistance represent a challenge when using FRP strengthening technique [6][5].

Ultra-high performance concrete (UHPC) is a relatively new building material with great compressive and tensile strength and excellent durability, making it an ideal material for strengthening/rehabilitation [7]. UHPC has superior mechanical properties, including a compressive strength at least 120 MPa [8], sustainable post-cracking tensile strength exceeding 5 MPa[9], high energy absorption capacity, and low permeability, shrinkage and creep [10]. The first attempt that used UHPC material to strengthen reinforced concrete structures was in Switzerland and North America [11]. In recent years, numerous experimental and simulation studies have been conducted to explore the flexural behaviour of reinforced concrete beams strengthened by the UHPC layer taking into consideration many variables, such as the overlay thickness, the reinforcement ratio in the overlay, and other aspects.
Paschalis et al. [12] indicated that the UHPC layer used in strengthening reinforced concrete beams is a promising technique based on experimental results. A large increase in stiffness was noted with a slight increase in ultimate load due to strengthening the RC beam by the UHPC layer. In comparison, the ultimate load capacity increased significantly (90%) when the steel rebar reinforced the UHPC layer. Al-Osta et al. [13] investigated different techniques to glue the UHPC layer on the reinforced concrete beam. The first one was by sandblasting RC beams surfaces and casting UHPC in situ. The other was by bonding prefabricated UHPC strips to the RC using epoxy adhesive. Both techniques showed an overall better performance. The results showed that no significant difference in the results for flexural testing of strengthened beams was observed based on variations in interface preparation technique. The addition of a steel reinforcing bar in the UHPC layer was found to be significant to improve the ultimate load and stiffness of the strengthened member [4][14]. The cracking and flexural resistance of the strengthened beams with the reinforced UHPC layer toughened by the placement of steel wire mesh was further improved [15]. Tanarslan [16] investigated the reinforced concrete beams' behaviour that were strengthened with prefabricated UHPC laminates. Different applied UHPC laminates were tested to determine which method is more effective for the flexural strengthening of RC beams. It was found that UHPC laminate usage is an effective technique to enhance RC beams' behaviour and load carrying capacity and can be preferred to strengthen deteriorated structures.

According to the author's knowledge, most experimental and numerical studies in this field extend the UHPC layer beyond the support. This is not the same as what would be done at a practical construction site. The present study aims to investigate the flexural behaviour of reinforced concrete beam strengthening by the UHPC layer extending to the face of the beam supports representing the face of the column. On the other hand, the study investigates the effect of construction joints in the UHPC layer.

2. Experimental Work

Seven full-scale RC simply supported beams were tested to investigate the flexural performance of RC beams strengthened by a UHPC overlay. The specimens were designed based on ACI 318 [17]. The beam geometry was 2000 mm in clear span with a rectangular cross-section having a depth of 200 mm and a width of 150 mm. The beam was reinforced with Ø 12 mm at both the top and bottom. On the other hand, Ø 6 mm @ 85 mm was used as shear reinforcement to ensure the specimens were controlled by flexural failure. Figure 1 presents the geometry and reinforcement detail of tested specimens. The key variables were UHPC overlay, UHPC reinforcement type and location of the construction joint.

2.1 Material properties

Ready-mix was used to casting the RC specimens. The concrete compressive strength target was 35 Mpa. On the other hand, many trial mixes were conducted to produce ultra-high performance concrete (UHPC) with acceptable hardening and fresh properties. Table 1 presents the mix proportion used to produce UHPC material. A percentage of 2% per volume copper-coated steel fibres with a length of 13 mm, a diameter of 0.2 mm, and tensile strength of 3005 MPa (as per the manufacturer data sheet) was
used to prepare the UHPC mixture. Table 2 shows the hardening mechanical properties and testing method for both normal strength concrete (NSC) and UHPC.

Deformed steel bars of diameters 6 mm and 10 mm were used to construct the RC specimens, while a glass fibre reinforced bar (GFRP) of diameter 10 mm was used to reinforce the UHPC overlay. Table 3 presents the mechanical properties of steel and GFRP bars. Figure 2 shows the test procedure for the hardening and fresh properties of concrete.

Table 1
The mix preparation of UHPC.

<table>
<thead>
<tr>
<th>Cement (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>Silica fume (kg/m³)</th>
<th>water/binder (%)</th>
<th>SP/binder (%)</th>
<th>Steel fiber (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>950</td>
<td>1050</td>
<td>190</td>
<td>15</td>
<td>3.5</td>
<td>157 (2%/m³)</td>
</tr>
</tbody>
</table>

*a pass from sieve 0.6 mm.

Table 2
Mechanical properties for both types of concrete.

| Normal concrete | | | |
|-----------------|-----------------|-----------------|
| **Type of test** | **Test method** | **Average value** |
| Compressive strength (cube) | BS 1881 – 115[18] | 38.28 Mpa (30.6Mpa)* |
| Indirect tensile test-modulus of rupture($f_r$) | ASTM C78/C78M[19] | 5.14 MPa |
| Indirect tensile test-splitting tensile strength ($f_t$) | ASTM C 496/C 496M[20] | 3.22 MPa |

<table>
<thead>
<tr>
<th>UHPC</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive strength (cube)</td>
<td>ASTM C109/109M[21]</td>
<td>137.3b MPa</td>
</tr>
<tr>
<td>Indirect tensile test-modulus of rupture($f_r$)</td>
<td>ASTM C78/C78M[19]</td>
<td>18.23 MPa</td>
</tr>
<tr>
<td>Indirect tensile test-splitting tensile strength ($f_t$)</td>
<td>ASTM C 496/C 496M[20]</td>
<td>13.82 Pa</td>
</tr>
</tbody>
</table>
This value represents cylinder compressive strength, the cube strength is equivalent to cylinder strength based on [22][23].

<table>
<thead>
<tr>
<th>Diameter (mm)</th>
<th>Material type</th>
<th>fy (MPa)</th>
<th>fu (MPa)</th>
<th>E&lt;sup&gt;a&lt;/sup&gt; (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>steel</td>
<td>600.5</td>
<td>656.63</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>Steel</td>
<td>420</td>
<td>520</td>
<td>200</td>
</tr>
<tr>
<td>10&lt;sup&gt;b&lt;/sup&gt;</td>
<td>GFRP</td>
<td>---</td>
<td>827</td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> assumed value, <sup>b</sup> as per manufacturer datasheet

### 2.2 Test matrix

Figure 3 shows the detail of the tested specimens. The first specimen serves as a control specimen labelled (C). The other specimens are labelled by three parts. The first part (OS) refers to the overlay strengthening layer. The second part represents the type of reinforcement in the UHPC layer, where (N) refers to no reinforcement, (R) refers to steel rebar reinforcement and (G) refers to GFRP reinforcement. The third part represents the location of the vertical joint, where (0.5) refers to a mid-span construction joint, (0.33) refers to a construction joint at the third span and (0) represents no joint. All UHPC overlays having a thickness of 50 mm.

### 2.3 Preparation of tested specimens

Figure 4 illustrates the procedure of casting and strengthening the tested specimens. The reinforcement was assembled first, and then it was placed in the wooden moulds. Before pouring the concrete into the mould, a retarder was sprayed on the base of the mould to prevent the tension surface of strengthening specimens from setting too quickly. After 24 hours of casting, the tension surface of specimens was washed off with a high-pressure water jet to expose the aggregate. This method was used to rough the tension side, which was decided to strengthen by UHPC overlay. The specimens were left under curing for 28 days. After that, the tension surface was cleaned with water jetting, and then vacuum air was used to dry the surface. A special mould was installed on the tension surface to casting the UHPC layer. Before casting the UHPC layer, epoxy bonding agent (Netobond EP) was applied evenly across the whole surface of normal concrete and left for about 2 hours as per recommendations of the manufacturer. Finally, UHPC layer of thickness 50 mm was cast based on the configuration mentioned in the previous section and then left to cure for about 28 days.

### 2.4 Test method

Figure 5 illustrates the test setup and arrangement of tested beams. The four-point bending test setup was conducted for all tests. The clear distance between two supports of the beams was 2000 mm. Each beam was loaded to failure with two concentrated loads separated by a distance of 400 mm. The test
was terminated when the applied load dropped rapidly. A 500 kN hydraulic jack with a loading rate of 0.5 kN/sec. was used to apply the load. A load cell with a capacity of 300 kN was utilized to measure the applied load. The vertical mid-span displacement was measured using a linear variable differential transducer (LVDT). In addition, three horizontal LVDT was attached on the surface side of normal concrete in one hand and on the UHPC layer on the other hand to record the relative slip between the UHPC layer and the normal concrete beam.

3. The Experimental Results And Discussion

3.1 Crack pattern and failure mode

The first visible crack appeared in the control specimen (C) at load level 12 kN under the point load. As the load increased, a new flexural crack developed along the beam. When the load level reached 25 kN, the cracks developed from mid to high section of the beam and widened. Finally, the area between the two-point load was crushed at 63 kN, and the load dropped slowly. As expected, the specimen failed in flexural mode, as shown in Fig. 6 (a). Strengthening the specimen using unreinforced UHPC layer (OSN0) delays the appearance of the first crack, increases the stiffness, and increases the ultimate load by about 11%. The first visible crack appears at load level 25 kN. As the load increases, an additional crack is generated but less than what was observed in control specimens. The UHPC overlay shows multi hair cracks along with the UHPC layer. The presence of a construction joint in the unreinforced UHPC layer (OSN0.5) makes the UHPC overlay has no effect despite the slight increase in stiffness. In this case, the first crack noted at 9 kN in the interface of the construction joint. No significant cracks were observed in the UHPC overlay until the final stage. With increasing the applied load, the first crack propagates horizontally 20 mm away from the interface between the UHPC and normal concrete and then behaves similarly to the control specimen. On the other hand, utilizing steel reinforcement or GFRP reinforcement in the UHPC overlay improves the performance of the strengthening technique by increasing the load-bearing capacity, stiffness and eliminating the cracking width as well as the flexural crack distributed along the span. The first crack was observed at the joint interface. The flexural crack was generated along the strengthened beam at a distance equal to 100 mm. Immediately after the collapse, a shear crack developed at the ends of the strengthening layer, followed by brittle failure due to concrete cover separation, as shown in Figure (6). The overlay separation formed through the NSC, away from the interface between UHPC and NSC. The failure happened before developing the full capacity of the reinforced UHPC overlay in spite of the perfect bond between the NSC and UHPC overlay. However, most previous research extended the overlay over the support, and this should provide anchorage and prevent the concrete form separation. In practice, this is not true. Thus care should be taken when using this technique in strengthening by providing mechanical anchorage at the ends of UHPC overlay or using CFRP warp to prevent brittle failure.

3.2 Load-deflection response
Figure 7 illustrates the load-deflection response of all tested specimens. As shown in Fig. 7, all strengthened specimens show an increase in the load-bearing capacity and stiffness. The specimen OSN0.5 shows similar behaviour to the control specimen with increased stiffness. In comparison, the other strengthened specimens show similar behaviour until about 45 kN. The result indicated that reinforcing the UHPC overlay by both steel bar/GFRP improves the overall behaviour and diminishes the effect of the construction joint in the UHPC overlay. It is clearly shown that a sudden failure controls the specimens strengthened with reinforced UHPC overlay through concrete cover separation due to the high bond stresses concentration at the ends of the UHPC layer. The separation was generated 20 mm away from the bonding interface due to the perfect bond between the NSC and UHPC overlay.

Constructing the joint in the third span showed better performance than that in mid-span despite it being under the combined effect of shear and moment. The load-bearing capacity increased about 11.7% for the specimens strengthened by UHPC overlay with a construction joint at the third span rather than mid-span for both steel bar and GFRP reinforcing cases. Moreover, utilizing GFRP in reinforcing UHPC overlay shows an increase in the load-bearing capacity of about 7.8% with respect to that reinforced with a steel bar for both mid-span and third-span construction joint cases. This is may be due to the compatibility between the UHPC and GFRP because they have a similar modulus of elasticity. However, specimens with UHPC overlay reinforced by steel bar show more rapid failure than others. Finally, Table 4 presents the main experimental results. The percentage of increase in ultimate load (Pu) compared to the control specimen is represented by the value between the brackets in the column of ultimate load (Pu).
Table 4  
experimental results and observations

<table>
<thead>
<tr>
<th>Specimens ID</th>
<th>First crack load (kN)</th>
<th>$P_{u}$ (kN)</th>
<th>$\Delta_{y}$ (mm)</th>
<th>$\Delta_{u}$ (mm)</th>
<th>Ductility (%)</th>
<th>Energy absorption (kN:mm)</th>
<th>Stiffness (kN/mm)</th>
<th>Failure mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>12</td>
<td>63.437</td>
<td>15.2</td>
<td>33.58</td>
<td>2.2</td>
<td>1598.68</td>
<td>4.2</td>
<td>Flexural</td>
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<td></td>
<td></td>
<td>(15.2)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSN0</td>
<td>25</td>
<td>70.431</td>
<td>9.5</td>
<td>12.66</td>
<td>1.33</td>
<td>608.14</td>
<td>7.57</td>
<td>Flexural</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(11.1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSN1/2</td>
<td>9</td>
<td>66.772</td>
<td>13.2</td>
<td>26.1</td>
<td>1.98</td>
<td>1237.14</td>
<td>5.06</td>
<td>Flexural</td>
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<tr>
<td></td>
<td></td>
<td>(5.25)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>OSR1/2</td>
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<td>74.32</td>
<td>6.1</td>
<td>8.92</td>
<td>1.44</td>
<td>375.50</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>(17.15)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>OSR1/3</td>
<td>25</td>
<td>83.05</td>
<td>8.5</td>
<td>9.93</td>
<td>1.17</td>
<td>475.67</td>
<td>9.77</td>
<td>Concrete cover separation</td>
</tr>
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<td></td>
<td>(30.92)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OSG1/2</td>
<td>13</td>
<td>80.171</td>
<td>10.1</td>
<td>12.56</td>
<td>1.25</td>
<td>596.91</td>
<td>7.28</td>
<td>Concrete cover separation</td>
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<td></td>
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<td>(26.4)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>OSG1/3</td>
<td>17.7</td>
<td>89.506</td>
<td>12.2</td>
<td>14.14</td>
<td>1.17</td>
<td>777.34</td>
<td>7.27</td>
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<td></td>
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</tr>
</tbody>
</table>

### 3.3 Ductility

Ductility, defined as the capacity to undergo inelastic deformation before failure, not only provides a warning before ultimate failure but also minimizes dynamic load demand by increasing energy dissipation and reducing damage [24]. The ductility index was defined as the ratio of ultimate displacement to the yielding displacement [25]. The ultimate displacement ($\Delta_{u}$) was corresponding to the ultimate load. On the other hand ($\Delta_{y}$) was calculated based on Park [26]. Figure 8 presents the component of the ductility index. In the present study, the ductility of strengthened beams reflects the reserved load-carrying capacity from the yield point to the ultimate load-carrying capacity. Table 4 presents the ductility index of the tested specimens. The ductility index of all specimens were less than the control specimen (c), as shown in Fig. 9. There are mainly two reasons, first, the generation of multiple main cracks in the tensile zone of the control specimen (as shown in Fig. 6), making the deflection at the ultimate load higher, thus giving a high ductility index. The strengthened beams have a higher tensile strength at the tension face, and only one main crack developed in the UHPC overlay resulting in less deformation. The second reason is that the strengthened specimens with reinforced
UHPC overlay failed suddenly by concrete cover separation at the ends of the layer due to high stress concentration before reaching its full capacity.

### 3.3 Stiffness

This study calculated the initial stiffness for the strengthened beam and compared it with the control specimen. The initial stiffness was estimated by using the secant of the force versus displacement relationship passing through the point at which the applied force reaches 75% of the ultimate load [27], as shown in Fig. 9. The overall results of the initial stiffness are listed in Table 4. The value between brackets represents the increase in stiffness with respect to the control specimen. Table 4 shows that all the strengthened specimens show an increase in the initial stiffness compared with control specimens. The specimen with UHPC overlay (OSN0) shows 80% increase in initial stiffness as shown in Fig. 10, whereas the presence of the construction joint in the UHPC overlay reduces the initial stiffness significantly. On the other hand, reinforcing the UHPC overlay by steel rebar shows an increase in initial stiffness by about 121% and 132% for both OSR1/2 and OSR1/3, respectively. This is due to the high stiffness of the steel rebar. While the beam strengthened by UHPC overlay reinforced by GFRP bar show results approximately similar to OSN0, this may be due to the modulus of elasticity of GFRP bar equivalent to that of UHPC.

### 3.4 Energy absorption capacity

The energy absorption capacity of the concrete specimen may be estimated as the area contained by the load-displacement curve up to its ultimate state, reflecting the energy absorption that might be sustained before exhibiting a substantial decline in load bearing capacity [28]. Previous studies indicated that energy absorption capacity is the most appropriate indicator of concrete buildings not only for its structural reaction against the seismic motion but also for concrete structures that must resist the impact load generated by accidents or terrorist attacks [28]. As a result of increasing concerns regarding public and structural safety in recent decades, the energy absorption capacity of sensitive and important infrastructure or objects having a high risk potential needs to be seriously considered [29][30]. Table 4 presents the energy absorption of the tested specimens. The energy absorption of all specimens were less than the control specimen (c), as shown in the Fig. 11, due to sudden failure before it reached full capacity because of concrete cover separation.

### 3.5 Slip at the interface in structural tests

As mentioned in section 2.5, two LVDTs were used to record the slip between the normal concrete and UHPC overlay. No significant slip was recorded at the interface between the normal concrete and UHPC. Figure 12 presents the relation between the slip and the applied load. Based on the Fig. 12 and experimental observation, the perfect bond between the two types of concrete is clear. The specimens strengthened by UHPC overlay reinforced by steel /GFRP bar filed due to concrete cover separation at 20 mm away from the interface inside of normal concrete, as shown in Fig. 6.
4. Conclusions

This paper presents the results of an experimental study to investigate the flexural behaviour of RC beam strengthened with a UHPC overlayer. The following conclusions may be drawn regarding the outcome of the study:

1. The inclusion of UHPC layers at the tensile side of the RC beams significantly increased their stiffness while delaying the onset of cracks.
2. The presence of the construction joint in the UHPC overlay decreases the efficiency of the strengthening method.
3. The beam strengthened with unreinforced UHPC overlay shows a slight load-bearing capacity increase. However, adding steel bar/GFRP bar to the UHPC overlay shows a significant increase in loading bearing capacity despite the presence of the construction joint in the UHPC overlay.
4. Using construction joint in the UHPC overlay at the third span shows better performance than that at mid-span.
5. As the UHPC overlay is reinforced with steel bar/GFRP bar, the mode of failure changes to brittle failure due to concrete cover separation. This is not observed in the previous experimental research because they extend the UHPC overlay beyond the support, which prevents the concrete cover separation. Thus, care should be taken when using this strengthening technique by fixing the ends of overlay with mechanical anchorage or confining with CFRP laminate warp.
6. Finally, the bond between the UHPC and NSC was very effective, and no significant slip at the interface was recorded.

Declarations

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1

Detail and geometry of tested

![Figure 1](image1.png)

Figure 2

Test method for NSC and UHPC concrete

![Figure 2](image2.png)
The other two specimens (OSR0.5 and OSR0.33) were similar in details shown above but with steel rebar rather than GFRP in the UHPC overlay.

**Figure 3**

details of strengthening specimens
Figure 4

The procedure of casting and strengthening the tested specimens
Figure 5

The test setup and arrangement of tested beams.
Figure 6

Failure mode of tested specimens
Figure 7

Load-deflection curve for tested specimens
**Figure 8**

Determination procedures of initial stiffness
Figure 9

Experimental ductility factors
Figure 10

The initial stiffness
Figure 11

Energy absorption capacity

Figure 12

Slip at the interface