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REHABILITATION OF REINFORCED CONCRETE SLAB USING ULTRA HIGH-PERFORMANCE CONCRETE AND FIBER REINFORCED POLYMER

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Abstract. Rehabilitation the flexural capacity of reinforced concrete structures has been the subject of many studies. However, there is currently limited research on repairing such structures using Ultra-High-Performance Concrete (UHPC) and the combination of UHPC with Fiber-Reinforced Polymer (FRP) materials. This article presents the results of an experimental study on the flexural behavior of 4 specimens: 1 specimen of reinforced concrete (RC), 1 specimen strengthened with FRP sheets, and 02 specimens with the same height as the RC specimen but with a replacement of 3 cm of the protective concrete layer with a UHPC layer, either bonded or not bonded to the existing concrete, with or without the reinforcement of FRP sheets. The experimental results of the 4-point bending tests indicate that, while maintaining the height of the RC specimen constant, replacing the protective concrete layer with a UHPC layer and incorporating FRP in the tension zone led to an increase of approximately 83.35% in flexural capacity, with the deflection at the failure stage rising by only 12.8%. This research opens up a new and promising direction for improving and extending the service life of RC bridges using UHPC and FRP.

Keywords: Ultra-High-Performance Concrete, four-point flexural test, flexural behavior.

1. INTRODUCTION

Reinforced Concrete (RC) bridge structures are commonly used in Vietnam and around the world. These structures resist the direct load from vehicle traffic and are simultaneously exposed to environmental factors such as moisture and the penetration of chloride ions. Over time, these RC structures will undergo deterioration and damage. Current methods for repairing cracks in bridge decks involve using epoxy injection or filling or patching cracks. In cases of more severe damage, such as concrete spalling or corrosion of steel reinforcement corrosion, the replacement of the concrete deck is often necessary. However, this replacement method requires an extended period of bridge closure to facilitate the demolition and pouring new concrete.

Due to its flat panel structure, the common approach for repairing and restoring the load-bearing capacity of reinforced concrete bridge decks often involves the use of Fiber-Reinforced Polymer (FRP) [1] or adhering steel plates [2] to supplement the steel reinforcement in the tension zone. Typically, a layer of normal concrete (NC) needs to be poured on top, connecting this layer to the existing bridge deck. However, the addition of a layer of normal concrete increases dead load without providing additional structural benefits. Therefore, the use of new materials for repair and strengthening to enhance the service life and ensure the load-bearing capacity of the RC bridge deck while reducing construction time is a significant scientific and practical concern.

Ultra-High-Performance Concrete (UHPC) has several outstanding mechanical features compared to conventional concrete, such as very high compressive strength (ranging from 120 MPa to 200 MPa), tensile strength, significant crack resistance (ranging from 8-12 MPa), and high resistance to corrosion due to its high density, resulting in low water permeability, low chloride ion permeability, etc., [3-5]. With these remarkable characteristics, UHPC is one of the solutions for replacing deteriorated and damaged protective concrete layers. This material has been applied in the repair and restoration of the load-bearing capacity of reinforced concrete bridge decks in some projects around the world, such as the bridge over the Morge River and the Chillon Bridge in Switzerland [5].

Another study by Haber et al [6] demonstrated the effectiveness of replacing the surface concrete layer with a 3 cm-thick UHPC layer on the bridge over the Morge River in Switzerland, as shown in Figure 1. After 10 years of service, the deterioration of the bottom of the RC deck did not significantly progress, primarily because the UHPC surface layer prevented the infiltration of environmental factors attacking this region. The effectiveness of UHPC overlays has been confirmed in several studies by authors such as Hoang [7], Liu [8] and El-Mandouh [9].

Fiber-Reinforced Polymer (FRP) sheets are commonly used for the repair and strengthening of steel-reinforced concrete structures [1]. Compared to the steel plate bonding solution, this approach has become quite popular in Vietnam over the past decade. FRP sheets have the advantage of being lightweight and easy to use. Several global studies have demonstrated the effectiveness of enhancing RC structures using this material [10]. However, the strengthening of reinforced concrete by combining a UHPC layer with FRP requires further experimentation.

Figure 1. Photo of the bridge over the Morge River in Switzerland after 10 years of retrofitting with 30 mm UHPC [6].

With the goal of repairing and restoring the load-bearing capacity of RC structures without increasing the dead load, this research assesses the flexural behavior of RC specimens repaired by combining a UHPC layer on the top surface with FRP sheets in the tension zone. The effectiveness of the reinforced specimens will be compared to a control RC specimen.

The outline of this paper is as follows. Section 2 presents the proprieties of materials, the dimensions and reinforcement details of specimen as well as the test set up. In section 3, the experimental results in terms of failure mode, midspan deflection, displacement relative between UHPC and NC are presented. A formula based on ACI 440.2R-17 to predict the flexural bending moment of this new repair method for RC structures is proposed in this section. Finally, some conclusions and perspectives are presented in section 4.

2. MATERIALS AND TEST PROCEDURES

2.1 Materials

UHPC used in this study includes the following main constituent materials with the following technical characteristics: Portland cement PC40; Quartz sand; Admixtures and fly ash; The steel fibers incorporated into the concrete have a tensile strength of over 2000 MPa, with a diameter of 0.2 mm and a length of 12 mm.The properties of this UHPC were investigated in our previous research [3], revealing an average compressive strength of 130 MPa and an average tensile strength of 9 MPa for the UHPC concrete specimens at 28 days. The conventional concrete used in the study has a compressive strength of f_c' = 35.8 MPa at 28 days of age.

The Fiber-Reinforced Polymer (FRP) sheet used in the study is the Tyfo SCH-41 sheet, with a sheet thickness of 1 mm when combined with epoxy adhesive. FRP has an ultimate tensile strength f_u of 986 MPa, a tensile modulus of elasticity of 95.8 GPa, and an elongation of 1.01%.

The types of steel reinforcement used include: steel reinforcement with 12 mm diameter in the tension zone; steel reinforcement with 12 mm diameter in the compression zone; and stirrups with a 6 mm diameter at the beam ends to prevent local failure in the bridge bearing area. The yielding stress of the steel reinforcement is 453 MPa.

2.2. Specimen test

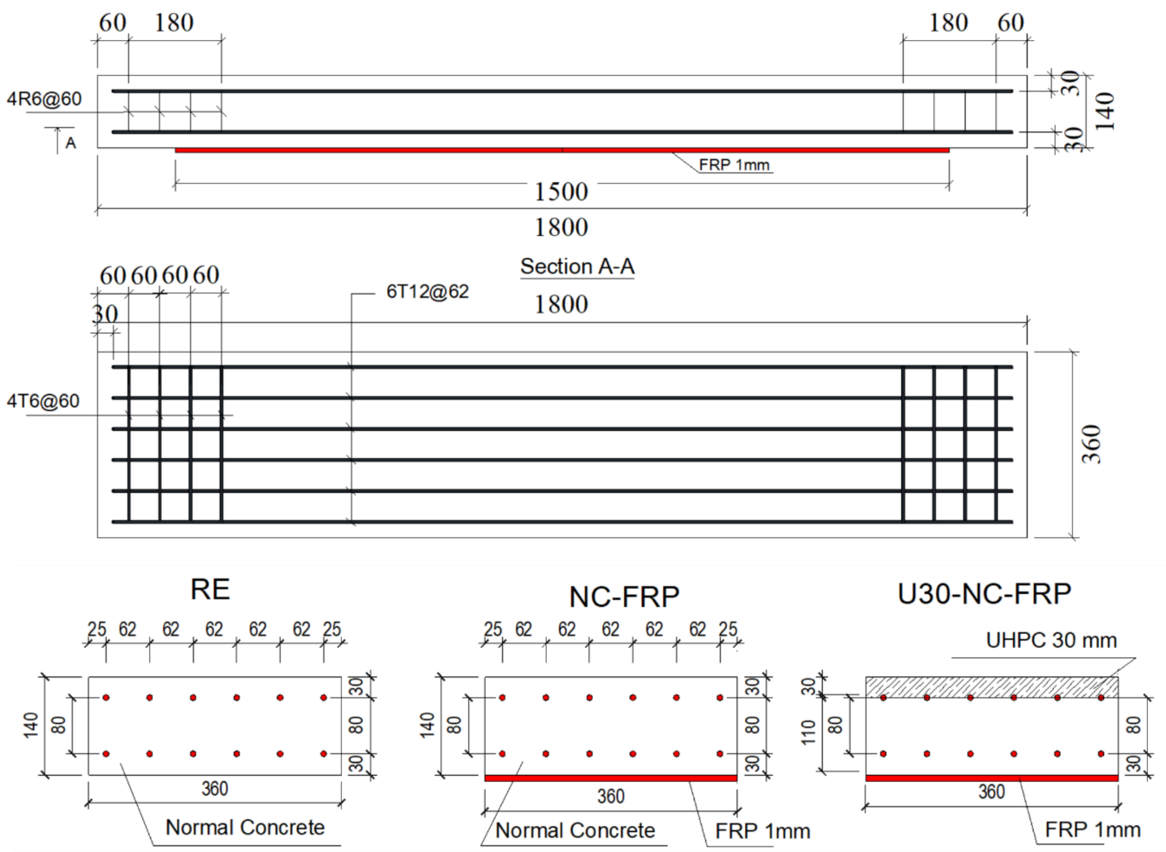


Figure 2. Dimension of specimen.

This experimental campaign was conducted on four test specimens: one of reinforced concrete (RC), another featuring RC strengthened with FRP sheets in the tension zone, and two specimens reinforced with FRP sheets, all with the same height as the RC specimen. The variation in these two includes the replacement of 3 cm of the protective concrete layer with a

UHPC layer—either bonded or not bonded to the existing concrete. The dimensions of the RC slabs specimens are as follows: length 1800 mm, width 360 mm, and height 140 mm, with a 30 mm cover concrete layer.

Meanwhile, the height of NC for the other two specimens is typically 110 mm. To assess the effect of the interaction between normal concrete and UHPC, one specimen has their surfaces roughened, and one specimen have steel dowel bars pre-installed (Figure 3). After three days casting, the normal concrete surface was roughened, and a 30 mm thick UHPC layer was cast in place (Figure 3 a,b). Arrangement of steel dowel bars pre-installed are displayed in Figure 3d. All specimens were covered with plastic film to prevent moisture loss and test was carried out after 28 days. The control specimen with steel-reinforced concrete is labeled NC, the specimen with added FRP sheet is labeled NC-FRP, and the specimens with 30 mm UHPC, both without anchorage and with anchorage to the RC deck, are labeled U30-0-NC-FRP and U30-NC-FRP, respectively.

The FRP sheet bonding process is carried out by first inverting the main beam and then preparing the surface by grinding large aggregate, applying Typo S epoxy adhesive for adhesion, and finally bonding the high-strength composite fiber sheet. The thickness of the sheet after bonding is 1 mm.

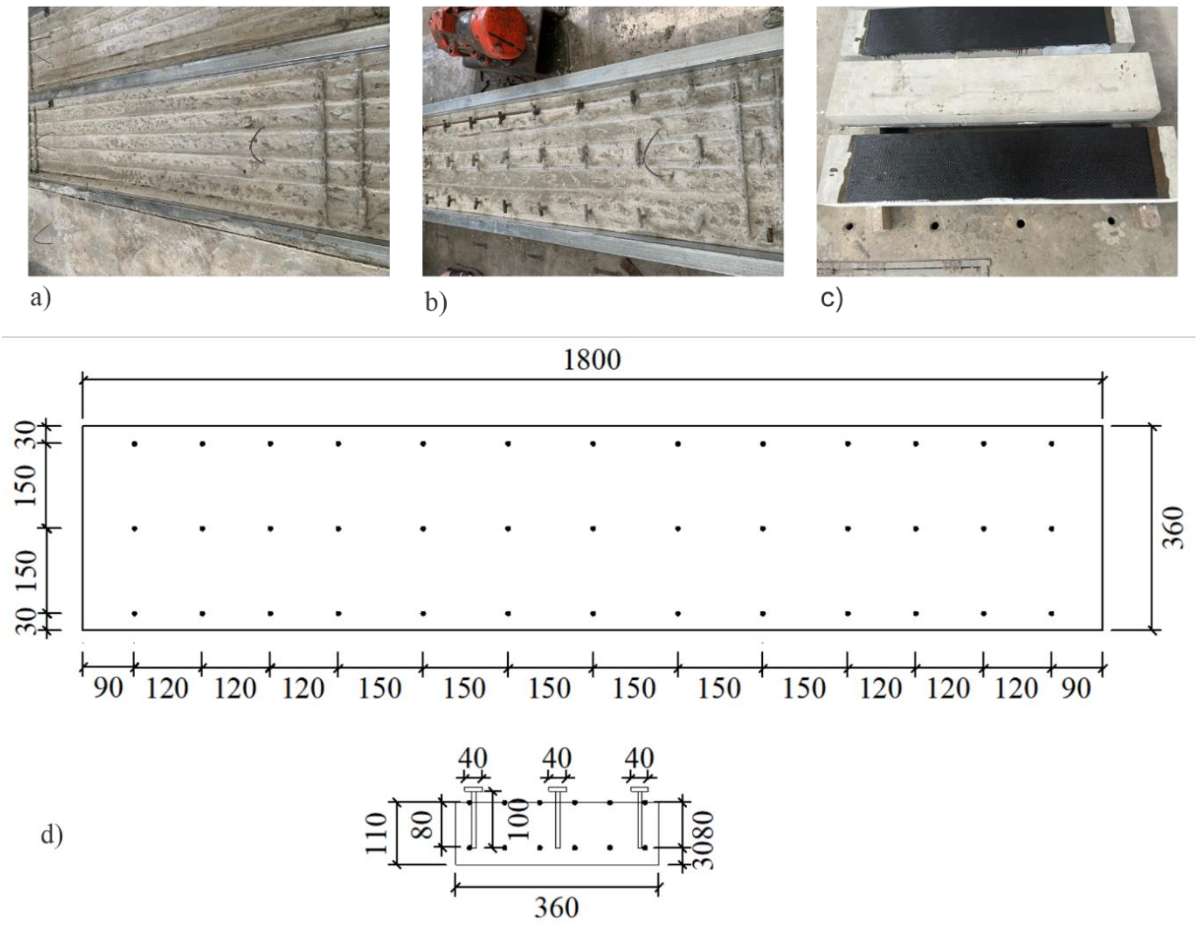
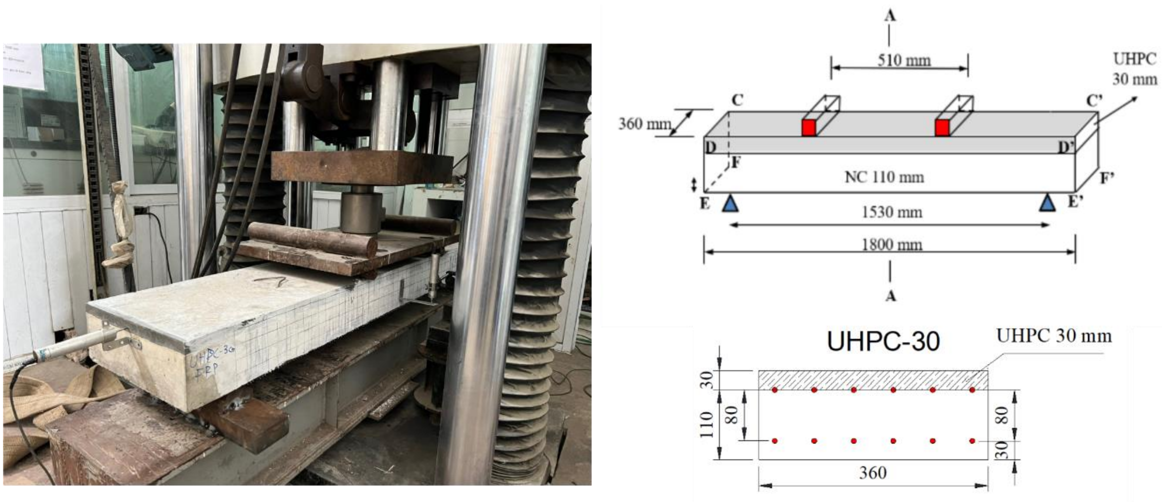


Figure 3. a) Specimen with surfaces roughened b) specimen with steel bars pre-installed, c) Specimen after bonding FRP d) Arrangement of steel steel dowel bars pre-installed.

2.3. Test procedure

The specimens were subjected to a four-point bending test (Figure 4.a). The distance between the two supports was 1530 mm. The four-point bending test was performed with a distance of 510 mm between the two loading points (Figure 4.b). The experiment was conducted with a loading rate of 0.1 kN/s. During the testing process, the deflection at the midspan was measured using a single linear variable differential transducer (LVDT). Additionally, the displacement between the two layers of normal concrete (RC) and UHPC was also measured using another LVDT. During the test, the sequence of crack formation and the corresponding applied load were recorded.



a) Test set up

b) Schema for four bending test

Figure 4. Four point bending test [11].

3. RESULTS AND DISCUSSION

3.1. Failure mode

The ultimate forces and failure modes of the 4 specimens are summarized in Table 1. The development of cracks corresponding to the applied load on the specimens is described in Figure 5.

Table 1. Summarized ultimate moments and failure modes of tested specimen

Specimen ID	P_u (kN)	M_u(kNm)	δ_u(mm)	Enhancement (%)	Failure mode
NC	148.4	37.83	15.65	-	Shear
NC-FRP	202.0	51.5	14.01	36.14	Debonding-Shear
U30-0-NC-FRP	187.3	47.77	12.68	26.28	Debonding-Shear
U30-NC-FRP	272	69.36	17.56	83.35	Debonding-Shear

Note:P_u: Ultimate force;M_u: Ultimate moment, δu: Midspan deflection at failure state.

The RC specimen (NC) was damaged when the ultimate moment M_u was reached at 37.83 kN.m, with a maximum deflection of 15.65 mm. The failure mode was attributed to shear (Figure 5a), characterized by the sudden and abrupt formation of a crack (brittle failure) and an inclined crack between the supports and loading points. This type of failure is common in specimens that typically lack stirrups (Figure 2).

a)NC

b) NC-FRP

c) U30-0-NC-FRP

d)U30-NC-FRP

Figure 5. Four point bending test.

The U30-0-NC-FRP specimen simulates a scenario where the deteriorated protective concrete layer of the structure is gradually removed over time, followed by the pouring of a 30 mm thick UHPC layer. The connection between the two concrete materials is solely through adhesion. The failure moment of this specimen was lower than that of the NC-FRP specimen, reaching 47.77 kN.m, with a deflection of only 12.68 mm. The brittle failure occurred abruptly when a separation between the UHPC and the regular concrete occurred, resulting in the failure of the specimen, similar to the RE specimen (refer to Figure 5c).

The U30-NC-FRP specimen is similar to the U30-0-NC-FRP specimen but includes the addition of steel anchors (anchorage) between the RC deck and the UHPC concrete. The interaction between the two types of concrete layers increased the ultimate failure moment of the specimen to Mu = 69.36 kN.m, and the ultimate deflection reached 17.56 mm. The ultimate bending moment increased by 83.35%, and the ultimate deflection increased by 12.8%. The failure of the specimen occurs after the debonding of the FRP sheet in the region near the supports, as described in Figure 5.d.

3.2. Mid-spans Deflection

Figure 6 shows the relationship between the bending moment applied to slab and the deflection of the beams at the midspan for different specimens. The results in Figure 6 indicate that in both cases, when there is no steel reinforcement connecting the UHPC layer and the RC deck, the behavior of the specimens is quite similar to the control specimen initially. However, afterwards, when there is a separation between the layers, the concrete specimen fails earlier than the control specimen.

The deflection of the U30-NC-FRP specimen at the failure stage reaches 17.56 mm, a minor increase compared to the deflection of the control specimen reinforced with an FRP sheet, which reaches 14.01 mm. The specimen without a connection between the UHPC and the RC deck fails earlier and only reaches a deflection of 12.68 mm. The failure mode of all these concrete specimens all involves the separation of the FRP layer and abrupt failure.

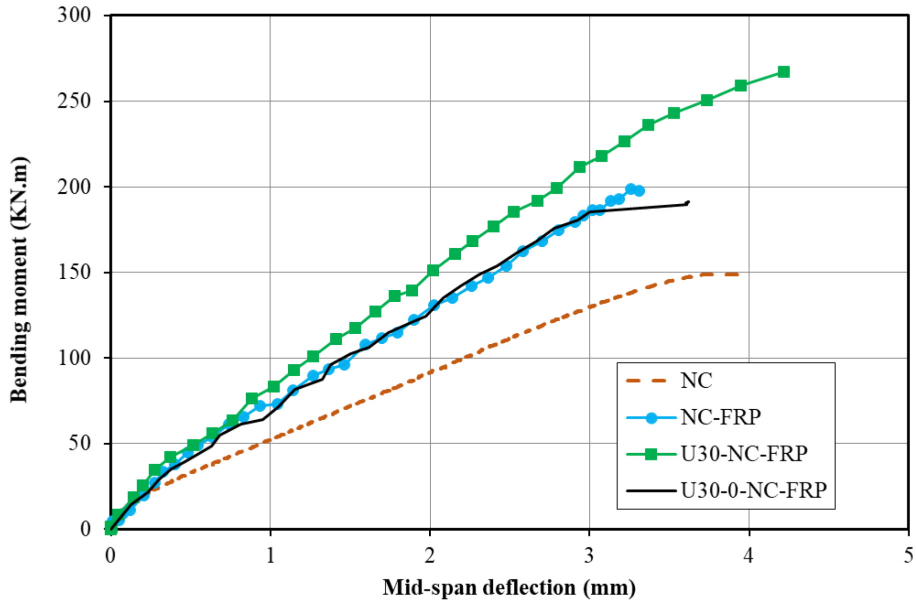


Figure 6. Bending moment applied to slab -midspan deflection curve

3.3 Relative displacement between UHPC and NC

The specimens with anchors connecting the concrete and UHPC layers show no displacement between the layers. However, for the specimens connected through adhesive bonding between the two layers, a phenomenon of slipping between the layers occurs. The maximum displacement measured at the failure stage is 0.22 mm.

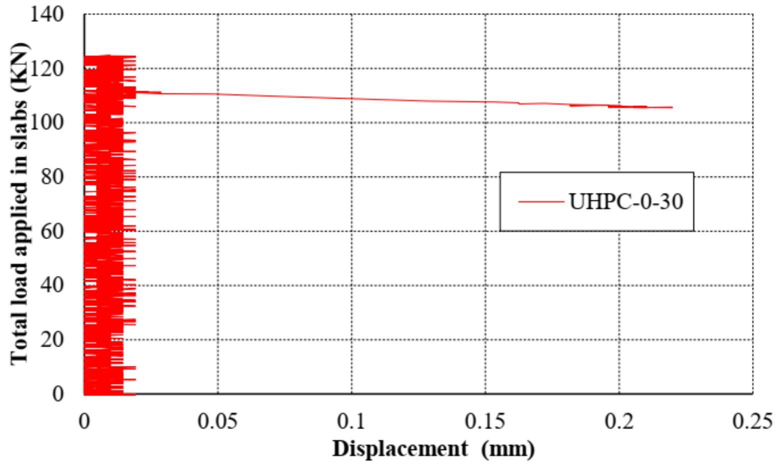


Figure 7. Total load applied in slab and relative displacement between UHPC and RC deck curve.

The other specimens do not exhibit excessive displacement between the UHPC and NC deck, indicating the effectiveness of the anchors between these two layers.

3.4 Prediction of flexural bending moment

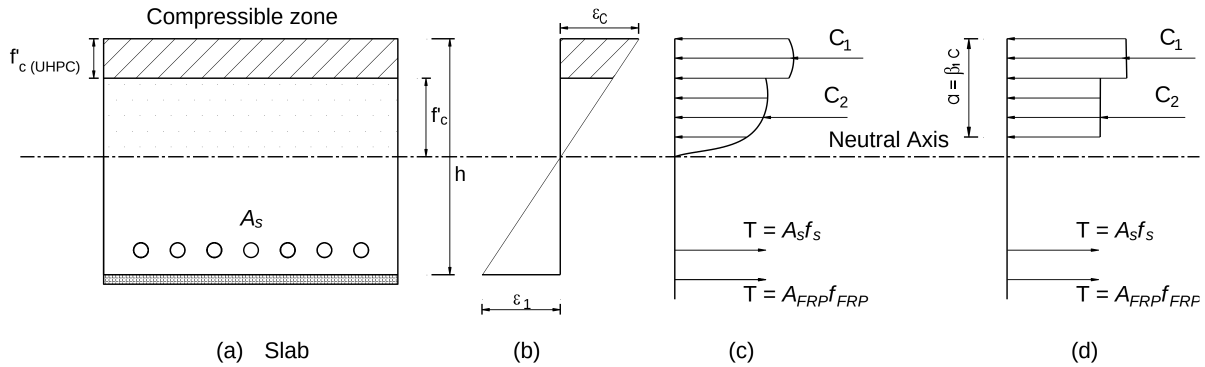


Figure 8. Calculation assumptions for the flexural strength of UHPC-NC-FRP.

In this section, a formula for predicting the flexural bending moment of a concrete deck slab is proposed. The slab consists of a UHPC layer in the compression zone, a layer of normal concrete, and a layer of FRP in the tension zone (Figure 8). Based on ACI 440.2R-17 [12], the flexural capacity of a concrete deck slab is calculated as follows:

$$M_n = A_s f_s\left(d_s - \frac{a}{2}\right) + 0.85 A_{FRP} f_{FRP}\left(h - \frac{a}{2}\right) \quad (1)$$

Where a is the height of the rectangular stress block, $a = \beta_1 c$ with c is the height of the compression zone of the section determined by the following formula:

$$c = \frac{A_s f_s + A_{FRP} f_{FRP}}{0{,}85 f_c' \beta_1 b + 0.85 f_{cUHPC}' \beta_{1UHPC} b} \quad (2)$$

Where: A_s is the areas of the steel reinforcement in the tension zones of the deck; A_{FRP} is the cross sectional area of FRP section. f_s is the yield tensile strengths of the steel reinforcement in the tension zones; f_c' is the compressive strength of the concrete; f_{cUHPC}' is the compressive strength of UHPC in the case of the U30 specimen; $\beta_1$is a coefficient dependent on the compressive strength, and b is the width of the cross-section. f_{FRP} is the tensile strength of FRP.

Table 2. Comparison of Experiment and prediction.

Specimen	$M_{u,exp}$ (kN)	$M_{u,prediction}$ (kN)	$M_{u,exp}/M_{u,prediction}$
NC-FRP	51.5	53.32	0.97
U30-0-NC-FRP	47.77	61.36	0.78
U30-NC-FRP	69.36	61.36	1.13

Except for the case of the U30-0-NC-FRP sample where the damage is caused by delamination between the UHPC layer and NC, the calculated results of the samples reinforced with FRP and combination of UHPC and FRP are quite consistent with experimental results. Therefore, for this structure, the use of ACI 440.2R-17 standards for calculations is entirely appropriate.

5. CONCLUSION

The paper presents the results of an experimental study on retrofitting the load-carrying capacity of regular reinforced concrete using combined UHPC and FRP, examining specimens of the same size and height. The experimental results demonstrate the effectiveness of replacing the 30 mm protective concrete layer with UHPC, incorporating anchors in the compression zone and applying FRP in the tension zone. This replacement increased the load-carrying capacity by approximately 83.35%, with the deflection at the failure stage increasing by only 12.8%.

Furthermore, the addition of the UHPC layer and FRP changed the failure characteristics of the RC deck from brittle shear failure to debonding and shear failure. However, in cases where there was no connection between the UHPC layer and the RC deck, a delamination phenomenon occurred, reducing the load-carrying capacity of the structure after replacement.

Finally, this research suggests that the use of ACI 400.2R-17 can predict the flexural strength of composite slabs. The study provides an additional solution for the repair and reinforcement of RC decks, utilizing a new material that is both highly impermeable and resistant to chloride ingress while enhancing the load-carrying capacity of the RC deck.

Further research will focus on analyzing the experimental behavior and structural modeling of the repaired RC deck with UHPC in the compression zone and FRP reinforcement in the tension zone with various configurations.

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