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FLEXURAL BEHAVIOR OF RC COMPOSITE BEAMS WITH ULTRAHIGH PERFORMANCE FIBER REINFORCED CONCRETE LAYER USING FINITE ELEMENT MODELING

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ABSTRACT: Engineers have investigated the use of various types of composite techniques on structural elements to obtain structural elements with high flexure capacity due to the need for higher strength structural materials and the need for large-span structures. The high compressive strength and deformation capacity of the Ultra-High-Performance Fiber Reinforced Concrete (UHPFRC) stimulated its utilization in the compression zone of composite beams to increase its flexural capacity. This study aimed to develop a three-dimensional finite element (FE) model using ANSYS software to scrutinize the flexural behavior of reinforced concrete composite beams with a UHPFRC layer in the top fiber zone and normal strength concrete (NSC) in the bottom zone subjected to flexural bending. The effect of the tensile reinforcement ratio and the thickness of the UHPFRC layer in the compression zone on the load capacity of composite beams has been investigated. The comparison of numerical analysis findings versus experimental data reported in the literature revealed that the results of the FE model were significantly close to the experimental results. It was noticed that the use of UHPFRC in the compressive zone of the composite beams had improved the flexural capacity of these beams. Additionally, the findings indicated that the optimal UHPFRC layer thickness was one-fifth of the beam height for beams with up to 3% tensile reinforcement and one-third of the beam height for beams with up to 5% tensile reinforcement.

Keywords: Finite element, Flexural behavior, Ultra-high-performance fiber reinforced concrete, RC composite beams, ANSYS

1. INTRODUCTION

The need for developing composite beams with higher flexural capacity as in long-span structures stimulated the use of UHPFRC to increase its flexural capacity due to its superior performance, durability, ductility, high compressive strength, tensile strength, and plastic deformation capacity when compared with NSC [1-3]. The UHPFRC is a composite material with a low water/cementitious materials ratio and with high percentages of steel fibers and micro silica. Many studies have been conducted on studying the structural performance of beams made with UHPFRC [4-10]. The increase in the percentage of fiber volume fraction in UHPFRC beams has increased its load-carrying of it. The utilization of UHPFRC beams with high reinforcement ratio has provided large ductility [5], while the utilization of a low reinforcement ratio has reduced the ductility, and the multiple micro-cracking and localized macro-cracking have characterized the cracking and failure pattern of UHPFRC beams [11,12]. Many studies have shown that incorporating fibers into UHPFRC can reduce or eliminate the need for shear reinforcement in beams [13-17]. The shear resistance of UHPFRC beams has increased as the percentage of fiber volume fraction increases. Also, the spacing limit between shear reinforcement in UHPFRC beams can be allowed to be 0.75d.

Many studies have been conducted on studying the behavior of beams made by composite use of UHPFRC and normal or high strength concrete [18-25]. The UHPFRC, in most cases, was used as a strengthening material for an existing beam. Different configurations of applying the UHPFRC layer in the strengthening of beams as applying the UHPFRC layer on the tension side, the compression side, or covering three sides were used. Adding the UHPFRC layer in the compression side has allowed the use of a high percentage of tensile reinforcement. The use of NSC in the tension side has helped in preventing brittle behavior caused by crack localization. The utilization of the UHPFRC layer for strengthening the NSC beam has significant positive developments in the load-carrying capacity. The effect of cyclic loading on the performance of reinforced concrete beams strengthened with the UHPFRC thin layer has been studied [26]. The use of the UHPFRC thin layer for retrofitting reinforced concrete flexural elements has improved its structural performance. The composite applications in reinforced concrete with a UHPFRC layer in the compressive side with low reinforcement ratios have been investigated [23,24]. However, UHPFRC's greater strength and deformation capability cannot be efficiently used in these composite applications. The flexural behavior of composite beams with UHPFRC layer in the compression side and NSC on the tension side and with high reinforcement ratios to acquire sufficient ductility tested under four-point loads has been investigated [1]. It was potential to increase the percentage of reinforcement in the tension zone up to 5% while reinforcement is not required in the compression zone.

This study investigates the structural behavior of composite beams with a layer of UHPRC located at the top of the compression zone and NSC in the tension zone, with emphasis on the load capacity and deflection at mid-span, to improve flexural capacity by determining the optimum effective thickness of UHPERC layer. For this purpose, finite element analysis is performed employing nonlinear FEA code (ANSYS R14.5) [27], which is verified by using experimental results obtained from the literature [1].

The reinforcement ratios of the study ranged from 1.8% to 5.0%, and the thicknesses of the UHPFRC layer in the compression side were one-fifth and one-third of the composite beam height. The tests of beams are carried out under the effect of 4-points loading. The study illustrated that the use of UHPFRC layer in the compressive side of the composite beams had allowed the use of high percentage tensile reinforcement in the beams up to 5% without using reinforcement in the compression side of the beam and significant improvements in ductility, flexural capacity and stiffness have been acquired when compared with the NSC beams. Hence, experimental results confirmed that the capacity and overall performance of composite beams with the UHPFRC layer in the compressive side was significantly improved compared with the NSC beams. In addition, the results from the analytical model were in good agreement with the experimental ones.

2. NUMERICAL MODEL

The FE models in this study were conducted to understand better the flexural performance of composite beams with the UHPFRC layer in the compression side. The proposed models were constructed utilizing the FEA software package ANSYS R14.5 [27] for the simulation of the flexural behavior of composite beams with UHPFRC layer in the compression zone of the beam were based on experimental results obtained from the literature [1]. With the addition of web reinforcement and friction between concrete surfaces, it has been possible to enhance the connection between the UHPFRC layer and NSC without the NSC sliding up to the failure load. The bond between the UHPFRC layer and the NSC was assumed perfect [24]. The results obtained from numerical analyses were verified with the experimental results from the literature, and the results of the nonlinear FE models have good agreements with experimental results.

Fig.1 and Table 1 show the cross-sectional dimensions and tensile reinforcement of the modeled composite beams with the UHPFRC layer in the compression zone. The composite beams are comprised of NSC in the tension zone and UHPFRC layer in the compression zone subjected to four-point bending tests. There were five ratios of the reinforcing steel in the tension zone and two different thicknesses of the UHPFRC layer in the compression zone of the composite beams.

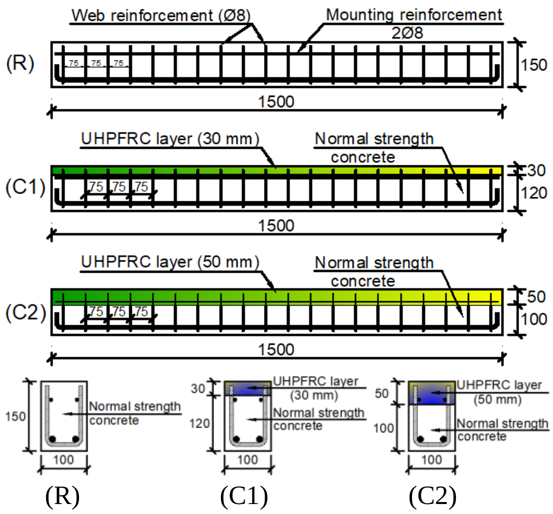


Fig.1 Details of the modeled composite beams (all dimensions are in mm)

Table 1 Geometric of the composite beams

Beam	Width (mm)	NSC thickness (mm)	UHPFRC thickness (mm)	Tension RFT
R1	100	150	0	2ϕ12
C11	100	120	30	2ϕ12
C21	100	100	50	2ϕ12
R2	100	150	0	2ϕ14
C12	100	120	30	2ϕ14
C22	100	100	50	2ϕ14
R3	100	150	0	2ϕ16
C13	100	120	30	2ϕ16
C23	100	100	50	2ϕ16
R4	100	150	0	2ϕ18
C14	100	120	30	2ϕ18
C24	100	100	50	2ϕ18
R5	100	150	0	2ϕ20
C15	100	120	30	2ϕ20
C25	100	100	50	2ϕ20

The stress-strain behavior of the reinforcing steel is illustrated in Fig.2 hereinafter. The reinforcing steel's Poisson's ratio and the modulus of elasticity were 0.3 and 200 GPa, respectively.

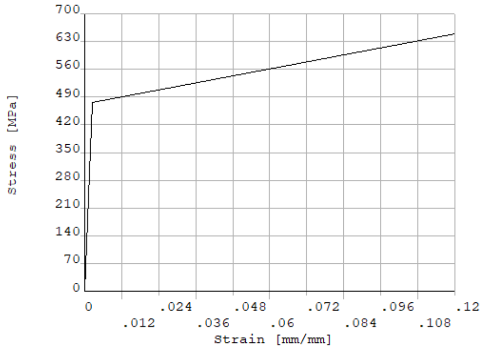


Fig.2 Stress-strain relationship for reinforcing steel

The concrete was accepted to be homogenous and, at first isotropic. The stress-strain relationship of concrete under uniaxial compression is shown in Fig.3 [24]. The used Poisson's ratio for the concrete was 0.2.

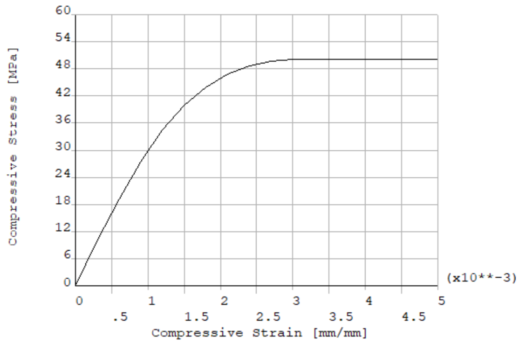


Fig.3 Compressive stress-strain relationship for concrete

The used uniaxial compressive stress-strain relationship for the UHPFRC layer is shown in Fig.4. The assumed Poisson's ratio for the UHPFRC was 0.22.

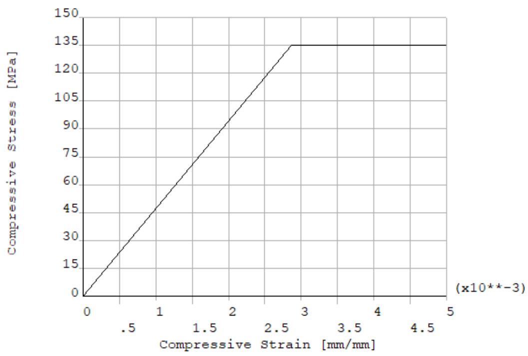


Fig.4 Compressive stress-strain for UHPFRC

The material properties of the tensile reinforcement and concrete in the proposed models as the yield strength of the reinforcement (f_y), the ultimate strength of the reinforcement (f_u), and the compressive strengths (f_c) at test day for NSC and UHPFRC were shown in Table 2.

Table 2 Beams' tension reinforcements properties and concrete strengths

Beam	f_y, MPa	f_u, MPa	f_c, MPa NSC	f_c, MPa UHPFRC
R1	475	631	50	---
C11	475	631	50	137
C21	475	631	50	137
R2	481	651	48	---
C12	481	651	48	132
C22	481	651	48	132
R3	487	688	52	---
C13	487	688	52	134
C23	487	688	52	134
R4	472	683	50	---
C14	472	683	50	136
C24	472	683	50	136
R5	480	661	49	---
C15	480	661	49	137
C25	480	661	49	137

Fig.5 shows the geometry, loading, and dimensions of the modeled composite beams. The self-weight of beam contribution was considered in the numerical models. The beam was simply supported on two supports. The length of the rectangular beam is 1500 mm, and its cross-section is 100 x 150 mm, the distance between the supports is 1400 mm, and the distance between the two-point load is 400 mm.

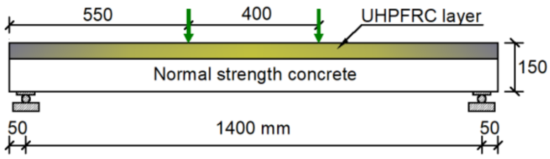


Fig.5 Geometry, loading, and beam dimensions

The numerical models were constructed using fine and coarse meshes, as shown in Fig.6. Three types of elements were used in the model construction: LINK 180 element for the representation of the reinforcing steel, SOLID 65 element for the representation of both NSC and UHPFRC, and SOLID 45 element for representation of supporting and loading plates as shown in Fig.7. The values for shear transfer coefficients for closed and open cracks were 1 and 0.2, respectively.

Nonlinear static analysis was performed in the modeling. The bond between the reinforcing steel element and the concrete element is assumed to be perfect. The boundary conditions at the supports were selected to represent the experimental conditions. The displacement control has been applied at the loading plates, and the applied loads have been recorded at each step which helps in obtaining the load-deflection curves for each composite beam.

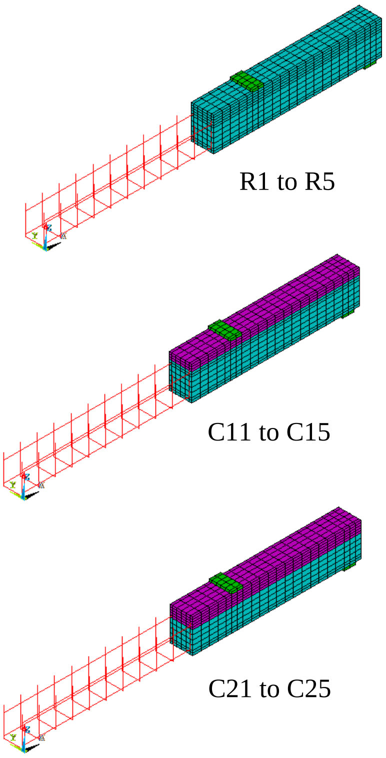


Fig.6 Finite element mesh, composite beams

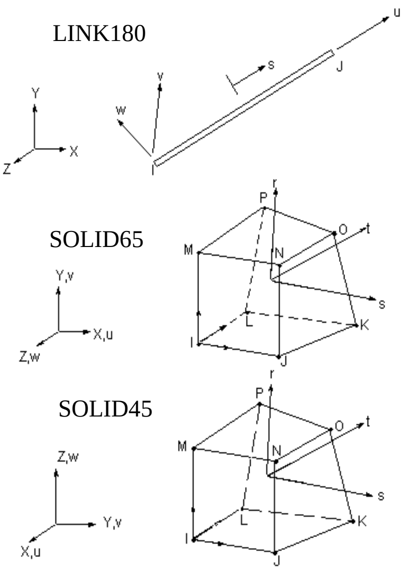


Fig.7 Geometry of elements (FE model)

3. VALIDATION OF THE NUMERICAL MODELS

Load-deflection curves for composite beams were derived using FE models and compared to experimental values to verify the numerical models. The comparisons have been made between numerical results and experimental results from literature using peak load (P_{max}), yield load (P_y), and yield deflection (Δ_y). Fig.8 shows the load-deflection curves from the numerical models and the experimental results for beams (R1, C11, and C21). Fig.9 shows the load-deflection curves from the numerical models and the experimental results for beams (R2, C12, and C22). Fig.10 shows the load-deflection curves from the numerical models and the experimental results for beams (R3, C13, and C23). Fig.11 illustrates the load-deflection curves for beams derived from computer models and the experimental data (R4, C14, and C24). Fig.12 illustrates the load-deflection curves for beams derived from computer models and the experimental data (R5, C15, and C25). When the load-deflection curves generated by the finite element models are compared to the experimental findings, a good match is seen.

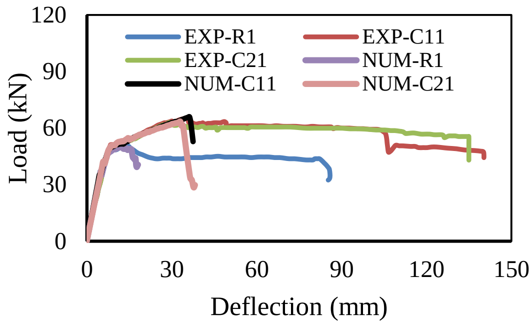


Fig.8 FE and Experimental Results (R1-C11-C21)

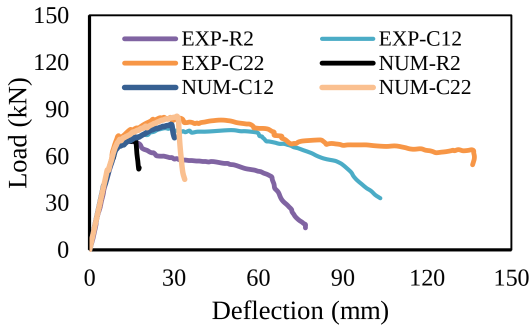


Fig.9 FE and Experimental Results (R2-C12-C22)

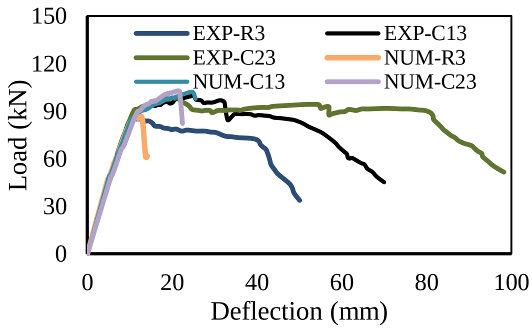


Fig.10 FE and Experimental Results (R3-C13-C23)

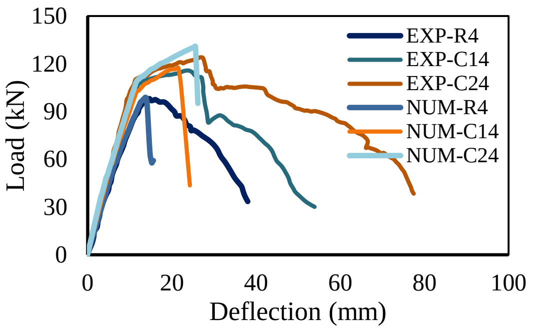


Fig.11 FE and Experimental Results (R4-C14-C24)

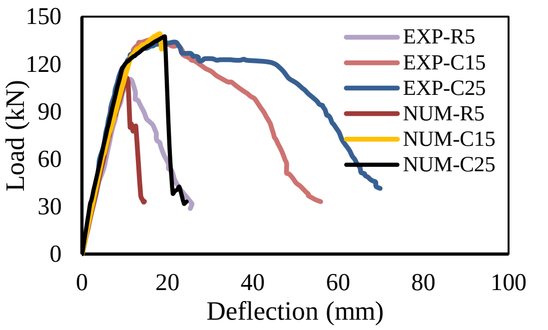


Fig.12 FE and Experimental Results (R5-C15-C25)

The comparison between the values of yield loads, P_y that are obtained from numerical models, and the experimental values are shown in Fig.13. The maximum difference between results was 4.28% for beams without UHPFRC layer, and the differences were 4.11% and 3.36% for specimens with a UHPFRC layer of thickness of 30 and 50 mm, respectively.

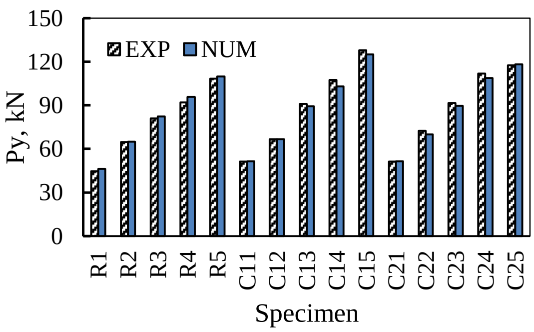


Fig.13 FE and Experimental Results (P_y)

Fig.14 shows the mid-span deflections, Δ_y for both numerical models and experimental results. The maximum difference between results was 5.90% for beams without UHPFRC layer, and the differences were 5.04% and 3.06% for specimens with a UHPFRC layer of thickness of 30 and 50 mm, respectively.

It is clear from Fig.15 that the maximum difference in the Peak load, P_{max} between numerical models, and experimental results were 2.59% for beams without a UHPFRC layer, and the differences were 2.64% and 4.52% for specimens with a UHPFRC layer of thickness 30 and 50 mm, respectively. The finite element models revealed higher peak loads than the experimentally reported tests, except for the model of beam C21.

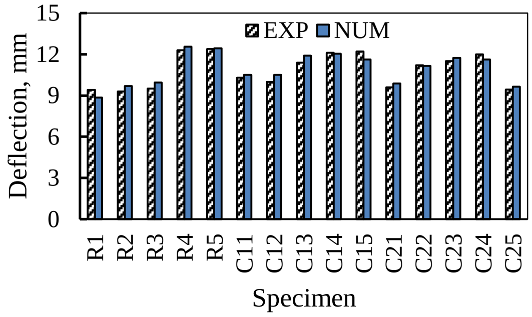


Fig.14 FE and Experimental Results (Δ_y)

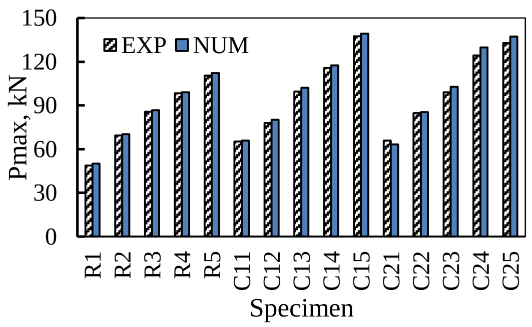


Fig.15 FE and Experimental Results (P_{max})

Fig.16 shows the deformed shape and the crack pattern for the composite beams. The numerical models have presented similar results to the experimental ones. These comparisons have indicated a good agreement between the numerical and the experimental results. That confirms that the numerical models have been validated.

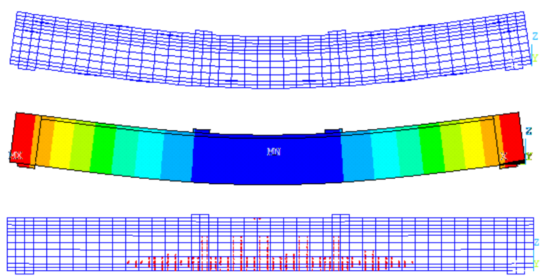


Fig.16 Deformed shape and crack pattern

4. PARAMETRIC STUDY

The developed finite element models demonstrated their ability to accurately simulate the flexural behavior of composite beams that had a UHPFRC layer in the compression zone. The prior study only required two thicknesses of the UHPFRC layer in the compression zone, which was a significant saving. They accounted for one-fifth and one-third of the overall height of the beam, respectively. The flexural behavior of composite beams was investigated using the validated finite element model that was developed. The model was used to investigate the effect of the reinforcement ratio and the thickness of the UHPFRC layer in the compression zone on the flexural behavior of composite beams. The details of beams used in the parametric study are shown in Fig.17.

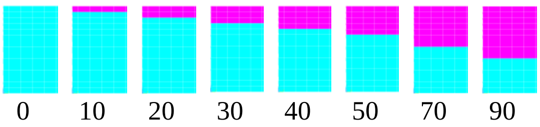


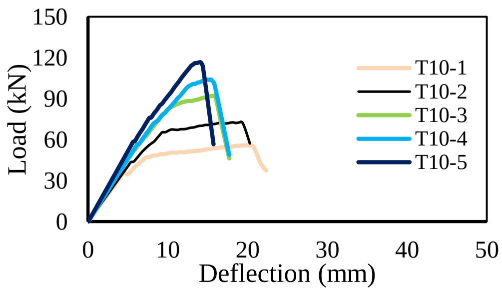
Fig.17 Details of the composite beams (mm)

The reinforcement ratios are ranged between 1.8% and 5.0%, and the thicknesses of the UHPFRC layer are ranged between 6.6% and 60% of the total height of the composite beam. The compressive strengths of NSC and UHPFRC were 48 MPa and 137 MPa, respectively.

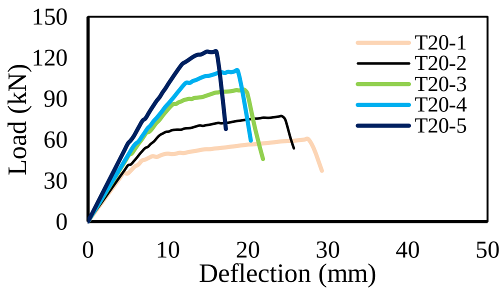
5. RESULTS AND DISCUSSION

All numerical models have been constructed using the finite element software ANSYS. Fig.18 shows the load-deflection curves for composite beams with different percentages of tensile reinforcement and different thicknesses of the UHPFRC layer in the compression zone of the composite beams based on the numerical analysis. It can be seen that the increase in the tensile reinforcement ratio in the composite beam has increased peak load.

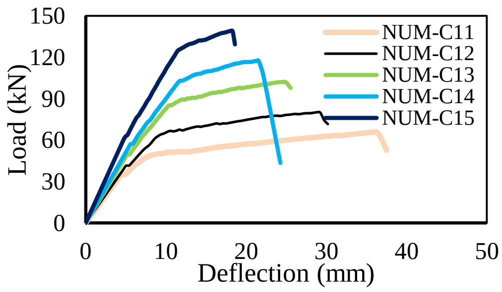
Fig. 19 shows the effect of variation in the thickness of the UHPFRC layer and the tensile reinforcement ratios on the peak load of the composite beams. The increase in the thickness of the UHPFRC layer in the composite beams has increased the peak load.



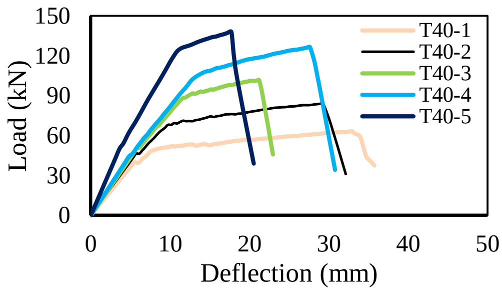
(a) UHPFRC thickness = 10 mm



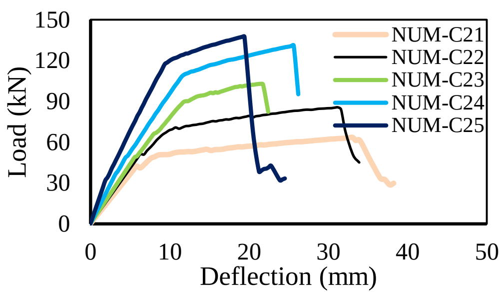
(b) UHPFRC thickness = 20 mm



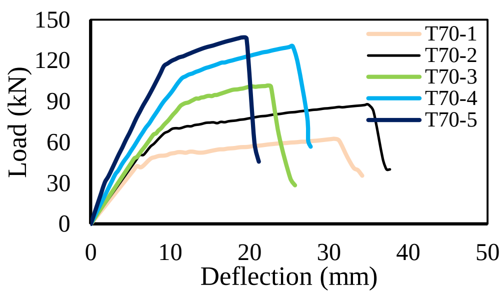
(c) UHPFRC thickness = 30 mm



(d) UHPFRC thickness = 40 mm



(e) UHPFRC thickness = 50 mm



(f) UHPFRC thickness = 70 mm

Fig.18 Load-deflection curves at mid of span at various thicknesses of UHPFRC layer (FE models)

It can be seen that an increase in the thickness of the UHPFRC layer up to 20% of the total height of the composite beam increases the peak load for tensile reinforcement ratios up to 3%. This is also true for reinforcement ratios up to 5%. When the thickness of the UHPFRC layer is increased to one-third of its total height, the peak load for reinforcement ratios of up to 5% goes up.

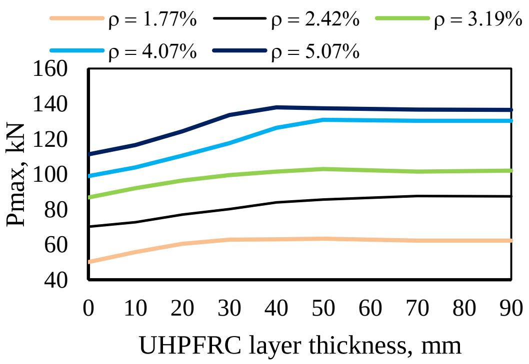


Fig.19 Effect of the thickness of UHPFRC layer and the tensile reinforcement ratio on the peak load

6. CONCLUSION

Based on the analytical results, using a UHPFRC layer in the compression zone of composite beams has improved its flexural capacity. The increase in the tensile reinforcement ratio allows an increase in the ductility of the beam. The optimum percentage of the height of the UHPFRC layer was one-fifth of the total height of the composite beam for tensile reinforcement ratios up to 3% and one-third of the total height of the composite beam for tensile reinforcement ratios up to 5%. The increase in the thickness of UHPFRC to more than one-third of the total height of the composite beam does not affect the capacity of the composite beam. The simulation of composite beams with a UHPFRC layer in the compression zone and NSC in the tension zone utilizing FE analysis in the ANSYS R14.5 program is quite well since the predicted mode of failure, peak loads, yield loads, and yield displacements were close to those obtained from experimental results from the literature.

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