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Comparison of Existing Experimental and Finite Element Models to Predict the Behavior of Ultra High-Performance Concrete (UHPRC) Beams

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الملخص العربى :

اجرى العديد من الباحثون التجارب العمليه على منشاءات بالحجم الطبيعى للوصول الى اسس التصميم المناسب لهذة العناصر مع انه كان من الممكن ان يقوموا باجراء تلك التجارب باستخدام طريقه النمازج الحسابيه حيث ان هذة النمازج اثبتت قدرتها على القيام بنمزجه مثاليه لجميع خصائص المواد كالخرسانه وحديد التسليح. لذلك الهدف من هذه الدراسه هوا القيام باعداد نموزج حسابى يتم التحقق من مطابقته عن طريق المقارنه مع بعض التجارب العمليه السابقه لاستخدامه فى التنبوء بسلوك الكمرات الخرسانيه المدعمه بشرائح الخرسانه فائقه المقاومه فى اتجاه الضغط .

ABSTRACT

Researchers have carried out experimental models for large-scale structural members to establish design processes that can be simplified by using an alternative method. In this method the concrete material model accessible in finite element (FE) packages is validated using a limited number of material and structural member tests. Therefore, the objective of this study is to investigate the efficacy and validate of the well-known existing experimental model in studing the behavior of large-scale structural members made up of UHPFRC beams. Experimental results from the literature [3&14] were used to validate the proposed model for predicting the flexural behavior, ultimate load, and deformation of strengthened UHPRC beams. The comparison showed the FE model was able to predict the behavior of the tested beams with a high degree of accuracy, including load deflection curves, ultimate capacity, and cause of failure. This model was used as a reference point since it was able to accurately predict the behavior of UHPRC specimens with different geometries, loading conditions, and reinforcing features with good accuracy. The model was then used as a guideline for a parametric study on beams to evaluate the existing analytical method. The aim of this study is to investigate the applicability of strengthening

simple beams and beams with cantilevers with the UHPC layer on the compression side using finite element model. The results show a good capability of the numerical models to predict the overall the flexural behavior, ultimate load and deformation of strengthened UHPRC beams.

KEYWORDS: Numerical, Strengthening Beams in compression, UHPFRC, Finite element modeling, and ABAQUS.

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INTRODUCTION

Recently, after the Egyptian government issued the reconciliation law on the facilities, some problems appeared in the concrete structures, as it led to the citizens rushing to modify the residential facilities into commercial ones to achieve more gains. Accordingly, the presence of some unsafe structural elements such as reinforced concrete columns, beams, and slabs will be noted . There is strengthened work required to match the new live load, but unfortunately, there is difficulty in strengthening it on the tension side. Therefore, the study was carried out on the strengthening of reinforced concrete beams using Ultra High Concrete (UHPC) with different thicknesses on the compression side. k. Hibal [1] Investigated fifteen full scale reinforced concrete beams composite with variable thickness of UHPFRC (3, 5 and10 cm) placed in tension side. Additional bars were placed in half a layer of UHPFRC with thickness 5 and 10 cm. The reinforcement ratio corresponds to 2% of the UHPFRC cross-section. All beams were tested until failure to demonstrate the performance and structural behavior of composite “UHPFRC-concrete” beams in bending. The test results showed that the increase of UHPFRC layer increased the maximum capacity and improved deformation compared with a normal concrete beam. Also, the use of reinforcement bars in UHPFRC layer exhibited a higher apparent magnitude of hardening and cracks were less pronounced. T. Noshiravani and E. Brühwiler [2] investigated the effect of UHPFRC as an additional layer on tensile side of reinforced concrete cantilever beam. The results observed the beams strengthened with UHPFRC layer fail in flexure at a force that is 2.0 to 2.8 times higher than the control of RC beams and improvement in capacity and deformation. O. T. Tsioulou &et al [3] tested ten RC beams strengthened with a concrete layer to investigate the flexural behavior and the interface slip value. Three techniques were used to strengthened RC beams. The first technique, additional concrete layer in tension side along the whole beam length, another technique additional concrete layer in tension side but did not extend to the supports of the beam. The last technique additional concrete layer in compression side along the whole beam length. The results were obvious that the techniques have a good effect on the stiffness and the ultimate capacity of the beams. Otherwise, the worst technique was strengthening with a partial length concrete layer. Moreover, the beams were strengthened with additional concrete layer in compression side give very small slip value (almost zero) while, the beams strengthened with additional concrete layer in tension side give very high slip value.

P.R. Prem & et al [4] presented the flexural behavior of damaged RC beams strengthened with UHPFRC overlay. The UHPFRC overlay was added on the tension face on the beam with epoxy mortar. The results showed a significant increase in load carrying capacity and ductility in the RC beams strengthened with UHPFRC overlay.

A.P. Lampropoulos &et al [5] studied experimental and numerical model to investigate the efficiency of strengthening of existing beams using UHPFRC layers. The UHPFRC layers with 50 mm thickness were used at different locations in compression side, tension side and three side jacket as U section. Results showed that the additional RC layer in compression side did not need of steel connectors as it behaved almost monolithically. The results indicated that the addition of UHPFRC layer in the tension and in the compression side had almost the same effect to the yield and ultimate moment since an increment of almost about 30% was observed in both cases. While, the addition of a three-side jacket resulted to significant increment of both yield and ultimate moments about (160–180%). Overall, all beams were strengthened in tension side, compression side and three sides jacket could increase the ultimate flexural strength and decrese deformations. M. N. Isa [6] developed and investigated the behavior of reinforced concrete beams strengthened with UHPFRC jackets in different configurations. Two concepts were used to apply the UHPFRC jackets. The first concept applying by sandblasting the concrete beams surfaces and casting UHPFRC in situ around the desired surfaces. While, another concept applying the prefabricated UHPFRC strips to beams surfaces using epoxy adhesive. Test results showed that casting fresh UHPFRC around the beam showed higher bond strength under compression and shear. While the beams strengthened with prefabricated UHPFRC strips bonded with epoxy adhesive shows higher bond strength in tension. Overall great enhancement in regarding crack propagation, stiffness and failure load for all types of strengthening technique and configuration was observed. M. Safdar &et al [7] investigated the flexural behavior of RC beams retrofitted with varying thicknesses of UHPFRC layer in tension and compression zone. The results showed that the ultimate flexural strength of RC beams repaired with UHPFRC layer in tension and compression zone were increased with the increase in UHPFRC layer thickness. Also, the results showed UHPFRC improves stiffness and delays the formation of localized cracks, thus improving the resistance and durability of repaired beams. M. Singh &et al [8] presented the experimental investigation on the flexure behavior of UHPFRC beams reinforced with conventional steel bar reinforcement. The numerical models were developed to predict the flexural behavior of the UHPFRC beams. Numerical models were developed and validated with the test results of the beams for which the concrete damaged plasticity. The stems indicated an excellent capability of the numerical models to predict the overall load deflection behavior of the UHPFRC beams. M.A. Al-Osta &et al [9] Two different strengthening techniques of UHPFRC were used to investigated the flexural behavior of RC beams. The first technique was cast in situ after sandblasting beams. While the anther technique was precast UHPFRC plates and attached it with epoxy primer. The test results showed that there was no considerable difference in the results of the two strengthening techniques. Also, the failure load, crack propagation and stiffness indicated significant positive developments resulting from the two strengthening techniques. H.M. Tanarslan &et al [10] presented the results of an experimental study to investigate the potential usage of epoxied and mechanically anchored UHPFRC laminates with and without internal reinforcements to strengthen flexural deficient RC beams. The results showed that UHPFRC laminate usage, especially in the case of anchorage, was an effective technique to improve the load carrying capacity of RC beams. Moreover, it was observed that adding reinforcing bars into the laminates could improve the efficiency of the applied method remarkably. A. R. Murthy &et al [11] examined the performance of RC beams retrofitted with a thin ultra-high strength concrete UHSC strip after they had been subjected to several levels of damage. From the results it was found that the damaged reinforced concrete beams can be successfully strengthened and rehabilitated by using a thin precast UHSC strip adhesively bonded to the prepared tensile surface of damaged beams. M. Shafieifar &et al [12] tested several small-scale beams were constructed to evaluate the flexural behavior and ultimate moment capacity of the UHPRC beams. The results obtained from the experiments were then used to validate the Finite Element (FE) mode. Whenever numerical and experimental results are compared, it is clear that the proposed numerical model can reasonably predict the structural behavior of UHPRC beams. Finally, the verified FE model was used as a benchmark for comparing existing analytical approaches to calculating the moment capacity of UHPC beams. S. A. Paschalis &et al [13] Investigated full scale (RC) beams strengthened with UHPFRC layers with and without steel bars to evaluate flexural strengthening and interface characteristics between UHPFRC and concrete through push-off tests. Furthermore, a finite element analysis was performed, and important parameters of the evaluated approach were studied. Finally, the results of this study showed that strengthening with UHPFRC layers is a successful technique, since the performance of the strengthened components increased in all of the situations studied.

Y. Zhang &et al [14] Studied thirteen the same RC beams strengthened with UHPRC layer to determine the flexural behavior, crack resistance, ultimate load , deflection and mode of failure. The results indicate that the cracking and flexural behavior of the RC beams enhanced by the UHPRC layer were greatly improved as compared to the un-strengthened RC beam. With the addition of steel wire mesh, the strengthened beam also showed the most noticeable improvement in cracking and flexural resistance. Flexural resistance was observed in the strengthened beam with the addition of steel wire mesh. K. Turker, I. B. Torun [15] The investigated RC beams have an UHPFRC layer on the compression side and a Normal Strength Concrete NSC layer on the tensile side, with a variable tensile reinforcement ratio (ranging from 1.8% to 5.0%).On the compression side, two different thicknesses of UHPFRC layer were applied (one-fifth of the beam height/one-third of the beam height). The flexural characteristics of the composite beams (ductility, capacity, and stiffness) were evaluated by comparing them to pure NSC beams in four-point bending tests (control beams). The study found that without using compression reinforcement, it was possible to increase the tensile reinforcement ratio of composite beams by up to 5%. In addition, a UHPFRC layer thickness of one-third of the beam height was suitable for overall flexural behavior in this type of composite beam.

The goal of this study is to evaluate an existing experimental model for calculating the flexural behavior, ultimate load, and deformation of reinforced UHPRC beams. The FE model is verified using the results of these experimental tests. The material characteristics of UHPRC beams utilized in this model were derived from those used in recent research [3&14]. The finite element model was able to estimate the behavior of the tested beams with a high degree of accuracy, including load-deflection curves, ultimate load capacity, and mode of failure. This model has been used as a reference because it accurately predicted the behavior of UHPRC beams with different geometries, loading conditions, and reinforcing details. It was then used as a benchmark in a parametric study on large-scale beams to estimate overall efficiency. The aim of this study is to investigate the applicability of strengthening simple beams and beams with cantilevers with the UHPC layer on the compression side.

Finite Element Analysis

Finite element (FE) models are one approach for predicting the behavior of UHPFRC beams. ABAQUS [16], a finite element programme, offers numerous concrete models. For the purpose of this research, concrete and UHPFRC were both simulated using a model of concrete damage plasticity. However, ABAQUS included two more concrete damage plasticity (CDP) models.

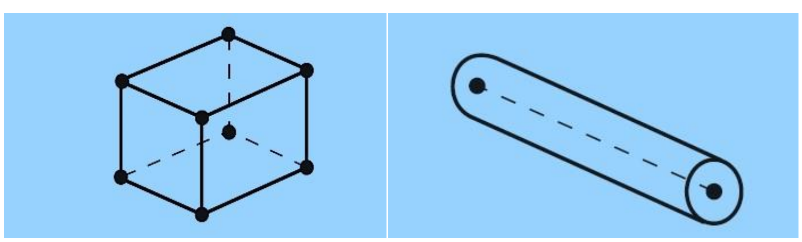
The (CDP)model was used in this work because it can represent the complicated nonlinear features of concrete and UHPFRC when considering compression or tension softening behavior. The UHPFRC performance in tension and compression was estimated to be multilinear stress-strain with uniformly distributed fiber effects. Table 1 presents all of the CDP modelling parameters used in the study. In addition, as shown in Table 2, the recruited material specifications of steel reinforcement bars used to model the steel reinforcing bars. For the concrete and UHPFRC models shown in Figure 1-a, the 3-D solid continuum element C3D8R is used. Steel reinforcement is modelled using the T3D2 element as separate truss components with steel material properties and cross-sections, as displayed in Fig 1-b. The reinforcement is inserted into the concrete using an ABAQUS constraint termed the Embedded Region. To divide the simulated RC beams into fine elements, a mesh size of 25 mm 25 mm was suggested. The suggested small mesh was necessary to get accurate findings that were consistent with the experimental response at the failure load and failure pattern levels, as illustrated in Figure 2.

Table1 The employed material parameters of Concrete and UHPRC for the FEM computation which set according to the results of the experimental results

	Elastic parameter			
	Young's modulus	Poisson's ratio	Compression strength $f_c/$(MPa)	Tensile strength f_{ct}(MPa)
Concrete	23500	0.2	25	2.77
UHPRC	46000	0.22	126	12
	Concrete Damage Plasticity (CDP) Parameters			
Concrete and UHPRC	Dilation angle	Eccentricity ($\mathbf{f_{co}/f_{bo}}$)	K	Viscosity parameter
	36 0.1	1.167	0.667	0

Table 2 The recruited material specifications of steel reinforcement bars for the FEM simulation

	Elastic parameter	
Young's modulus (MPa)		200000
Poisson's ratio		0.30
	Plastic parameter	
Diameter (mm)	Yield stress	Plastic Strain
6 mm	240	0
8 mm	360	0
10 mm	525	0



(a) 3D Continuum element (C3D8R) (b) Truss element (T3D2)

Figure 1 Adopted element models for concrete and reinforcement [16]

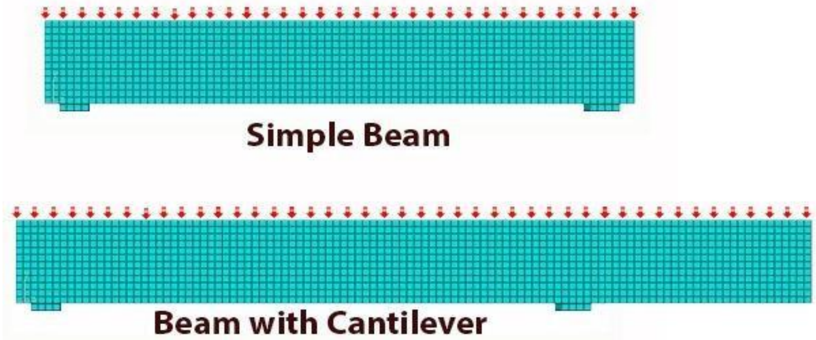


Figure 2 Geometry, Loading and boundary conditions in ABAQUS

Finite element model validation

The experimental test results of O. T. Tsioulou et al 2013 [3] and Y. Zhang et al 2020[14] have been used to compare the finite element method results. The validation was done by comparing the flexural behavior, ultimate load, and deformation.

O. T. Tsioulou & et al [3]

The three beams adapted from O. T. Tsioulou & et al [3] contained of reinforced 2Φ12 in tension side and cross section 150x250x2200 mm. One beam, O1, was used as control beam, while the others beam T1 and C1 were strengthened by adding a new concrete layer of 50 mm thickness at tensions and compression side respectively. Figure 3 shows the addition of a concrete layer along the full length of the beam. In case of beam strengthened with concrete layer in tension was reinforced with 2Φ12 on the tensile side and compression side without reinforcement. Figure 4 showed the test setup and all beams have concrete compressive strengths around 39.5(MPa)

The load deflection curves for the beam's comparison experimental load capacity and finite element predicted load capacity performed by O. T. Tsioulou et al [3]. Figure 5 shows a comparison of the load versus deflection at mid-span of the control beam O_1 and the two types of strengthened beams T_1&C_1. As shown in figure 6, the strengthened beams T_1&C_1 had a

higher capacity than the control beam O1. When the two strengthening techniques of beams were compared, the tensile side strengthening beams T_1 gave a much higher increase in strength than compressive side strengthening beams C_1. In addition, failure has been formed of vertical separation between the original beam and the additional strengthened layer. This failure is obvious as a sudden reduction of the load value. Moreover, the bending cracks propagated along the interface of beam strengthened with additional layer in tension side more than strengthened beam in compression side.

Y. Zhang& et al [14].

The three beams adapted by Y. Zhang& et al [14] had a cross section of 200x300x2250 mm and were reinforced 3Φ16 on the tension side and 2Φ10 on the compression side. The additional UHPRC layer, with a depth of 50 mm and a width of 200 mm, was cast along the entire length of the RC beams at tension side. One RC beam I-C was used as a control beam without strengthening. The second beam UC was strengthened by adding a UHPRC layer reinforced with one-layer Φ10 @ 53mm in the longitudinal direction and Φ10 @ 150mm in the transverse direction as shown in figure 7. The last beam S-UC was strengthened by adding a UHPRC layer reinforced with steel wire mesh Φ10. The test setup shown in figure 8 and the mechanical properties of NSC and UHPC of all beams were 145 (MPa) and 164 (MPa) respectively. Figure 9 shows a comparison of the load versus mid-span deflection curves of the control beam I-C and the two types of strengthened beams UC & S-UC. In general, the initial stiffness of the beams I–C is slightly higher than that of the UC during the elastic stage. However, after the I–C beam cracked, the stiffness of beam UC gradually increased and became greater than that of the I–C beam, with the stiffness increase becoming more apparent as the load increased. After reaching the ultimate load, the decreases and the deflection increases. At the comparison zone, the beams I–C were suddenly destroyed by crushing. However, the strengthened beam UC& S-UC appear a long descending branch after the ultimate load reaches. When compared to the control beam I–C, the strengthened beams with additional UHPRC layers UC & S-UC improved flexural performance and increased ultimate load capacity by about three times. Comparing the load-strain curves in Figure10&11 showed that the strain in main steel of beam UC & S-UC are clearly lower than that of the I–C at the same load level. Overall, the tensile stress of the main steel in the strengthened beam was reduced and the resulting cracking resistance was improved with the UHPRC layer toughened by different strategies. In general, the higher the strain on the top surface under the same load of the RC layer as well as on the bottom surface of the beam is strengthened with the UHPRC layer. Furthermore, when subjected to the same load, the compressive strain of NSC and the tensile strain of UHPRC in the strengthened beams toughened through the steel wire mesh. These comparisons show that developed FEM offer acceptable simulation models on the strains developed in both compression and tension steel. The strengthened beam with the additional UHPRC layer containing steel wire mesh demonstrated the greatest improvement in cracking and flexural resistance. Above all, the proposed finite element method could give a quite accurate prediction for the behaviors of reinforced concrete beams strengthened with UHPRC layer.

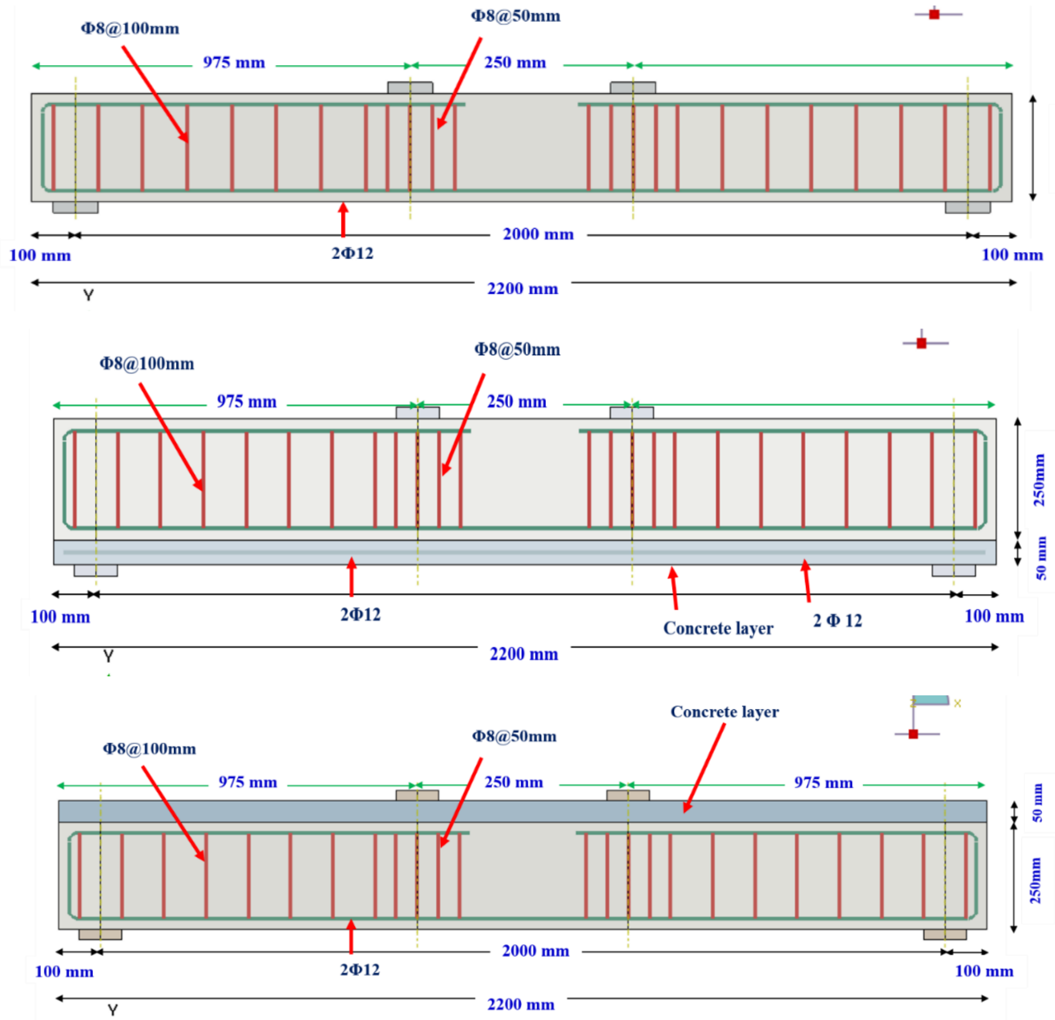


Figure 3 Geometry of experimental specimens and reinforcement details (control beam O1, Strengthened beam in tension T1, and Strengthened beam in compression C1) [3]

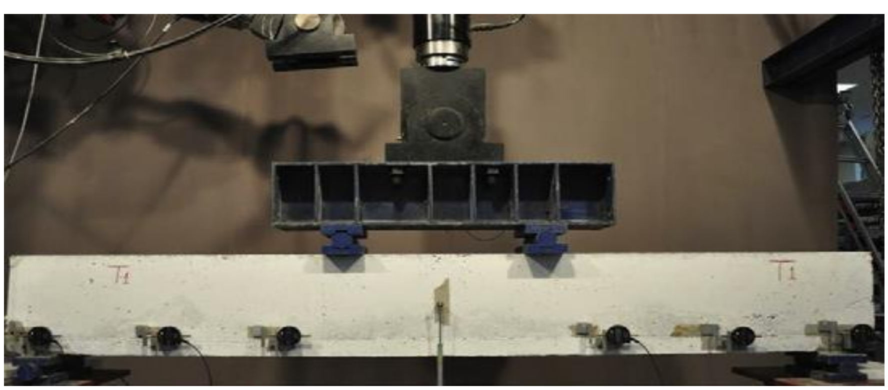


Figure 4 Experimental set up for beams [3]

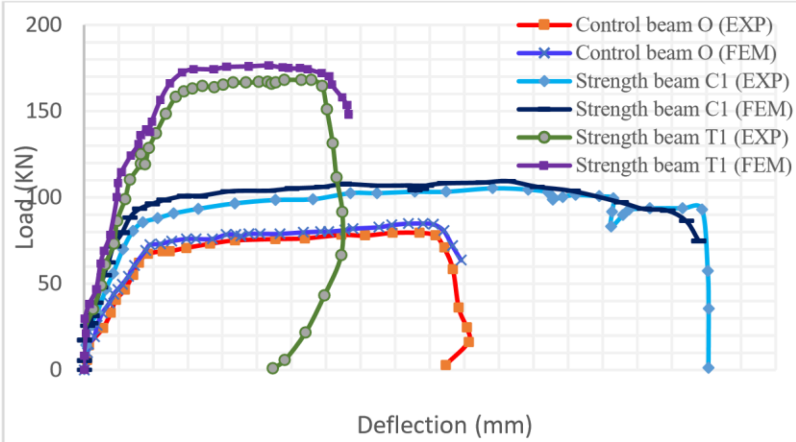


Figure 5 Load against deflection curve comparisons between (EXP [3]& FEM)

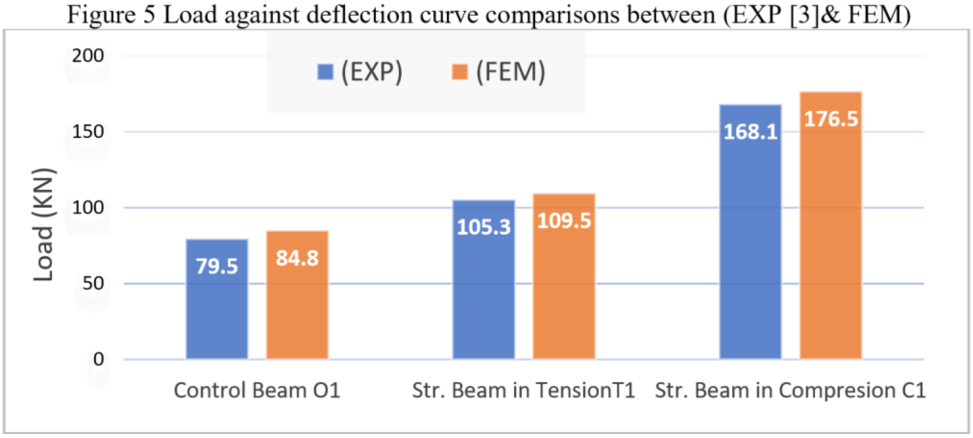


Figure 6 comparisons between ultimate loads failure (EXP [3] & FEM)

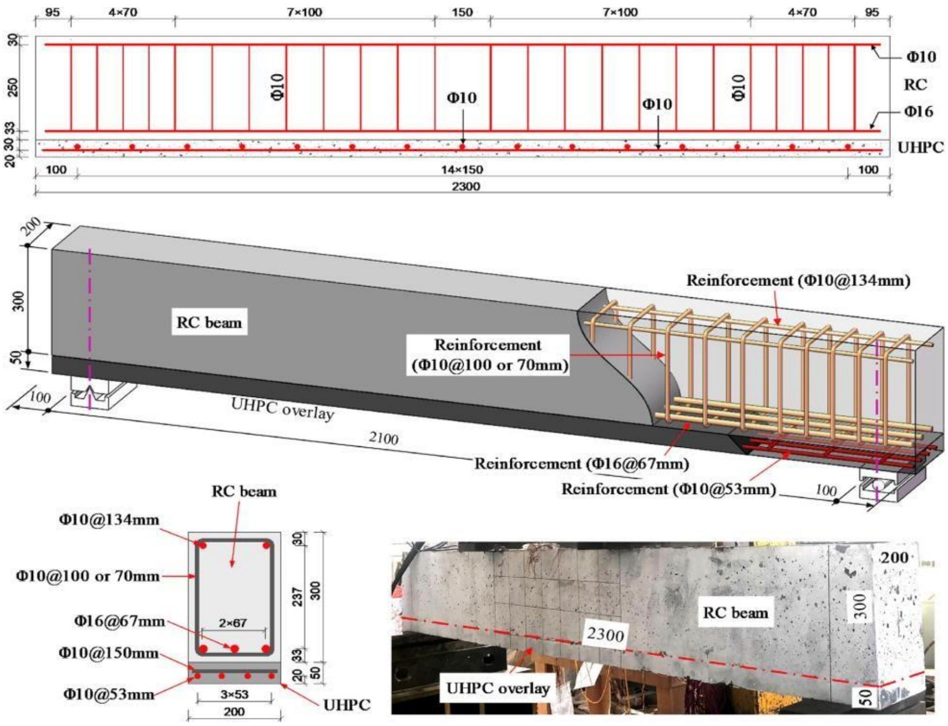


Figure 7 Geometry of experimental specimens and reinforcement details [14]

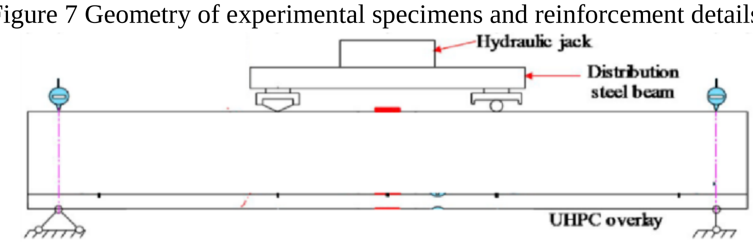


Figure 8 Experimental test set up [14]

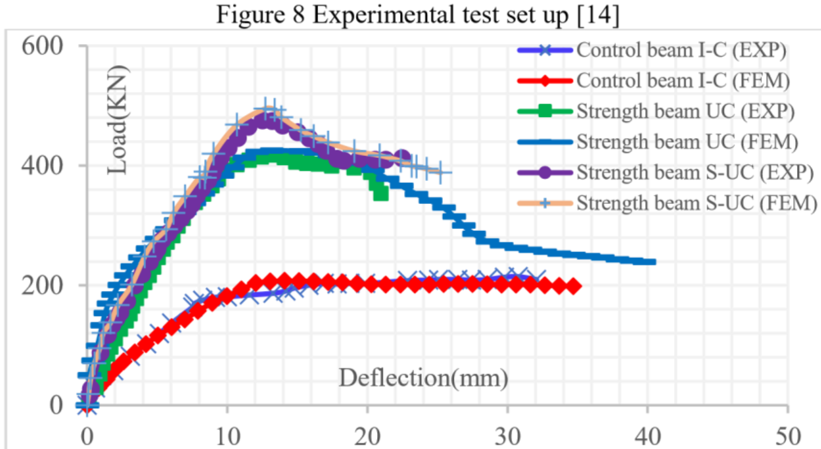


Figure 9 Load - deflection curve comparisons between (EXP [14]& FEM)

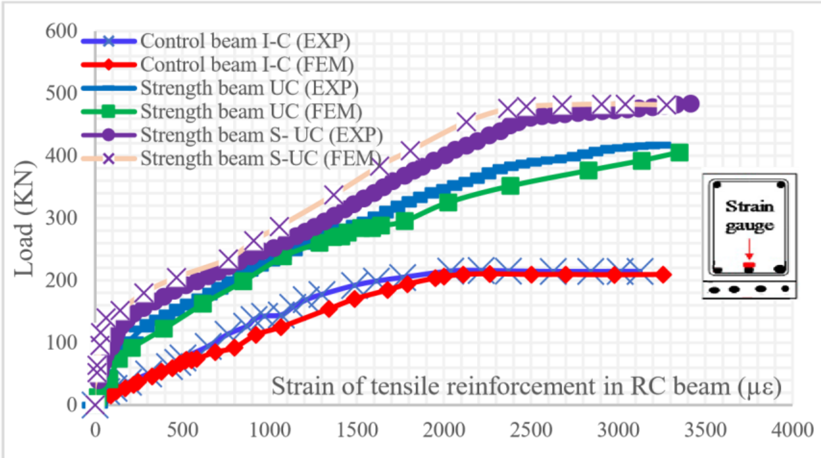


Figure 10 comparisons between (EXP [14]& FEM) Load-tensile reinforcement strain curves in RC beam

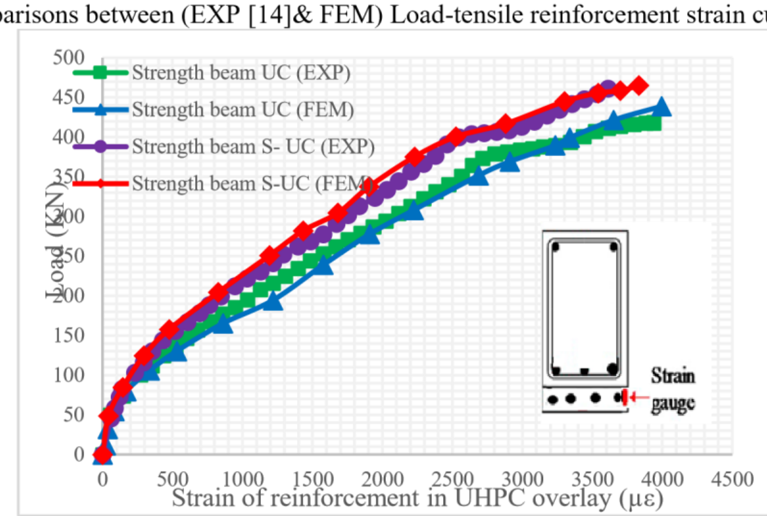


Figure 11 comparisons between (EXP [14]& FEM) Load-tensile reinforcement strain curves in UHPC beam

Parametric Studies

Using a validated finite element model, parametric studies were performed to conduct a thorough investigation study on the beams' need for strength using the UHPC layer on the compression side.

Analysis was performed on two group of nonlinear finite element models. Group1, contain five simple beams (B) with cross-section 120x300x2000 mm and reinforced with 3Φ10 on the tension side, 2Φ8 on the compression side and two branches Φ 6 mm stirrups @ 150 mm as shown in Figure 12. Group2, contain five beams with cantilever (BC) having the same previous section and reinforcement while the additional cantilever a as shown in Figure13. Table 3 showing the details of different cases of parametric studies, the

Parameters selected in this study include two types of beams (group1& group2); simply supported beam and beam with cantilever on one side.

Group 1 simple beams; One of theme as control beam and three beam (B-C30, B-C50 and BC70) strengthened with additional layer in compression side with thickness (30, 50 and 70) mm as shown in figure 14. while the final beam (B-C50&S) strengthened with additional layer

50 reinforced with 2Φ10 as shown in figure 15.

Group 2 beam with cantilever; One of theme as control beam and three beam (BC-C30, BCC50 and BC-C70) strengthened with additional layer in compression side with thickness (30, 50 and 70) mm as shown in figure 16. while the final beam (BC-C50&S) strengthened with additional layer 50 reinforced with 2Φ10 as shown in figure 17.

Table 3 Details of different cases of parametric studies.

Group Name	Specimen Code	Thickness of UHPC plate in compression side	reinforcement
Group (1)	Control simple beam	-	-
	B -C30	30 mm	No reinforcement
	B -C50	50 mm	No reinforcement
	B -C70	70 mm	No reinforcement
	B -C50&S	50 mm	Reinforcement with 2Φ10
Group (2)	Control beam with cantilever	-	-
	BC -C30	30 mm	No reinforcement
	BC -C50	50 mm	No reinforcement
	BC -C70	70 mm	No reinforcement
	BC -C50&S	50 mm	Reinforcement with 2Φ10

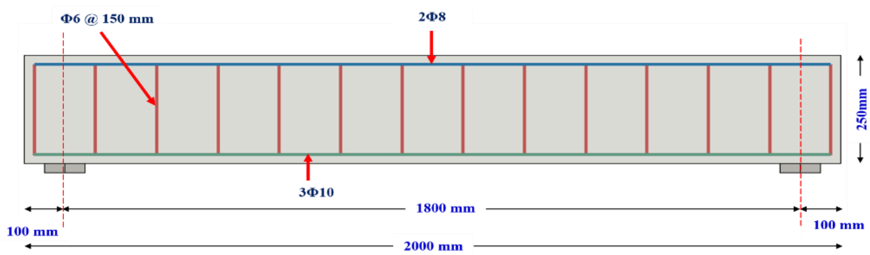


Figure 12 Geometry and reinforcement details of simple beam (B).

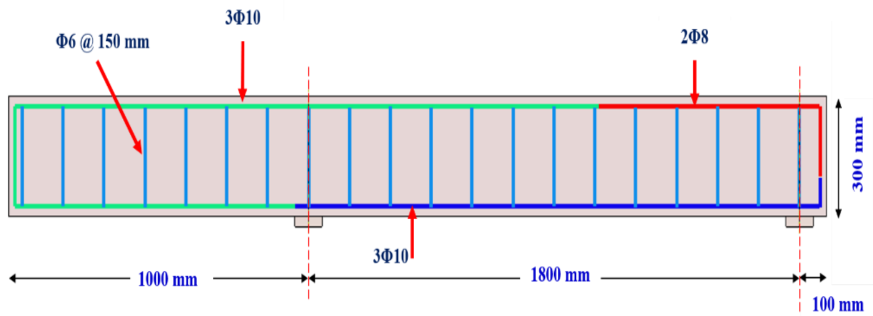


Figure 13 Geometry and reinforcement details of beam with cantilever (BC).

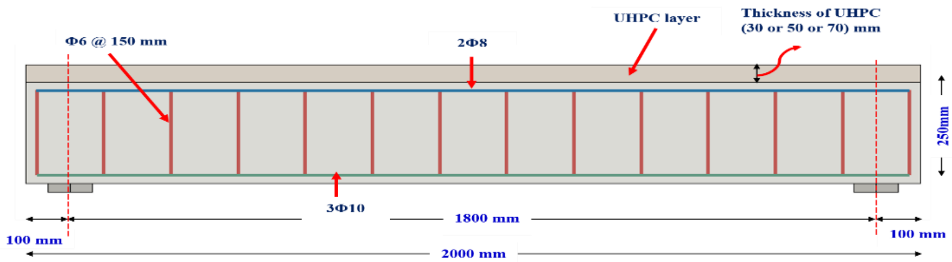


Figure 14 Geometry and reinforcement details of simple beam and strengthened with additional UHPC layer (BC30, B-C50 and B-C70).

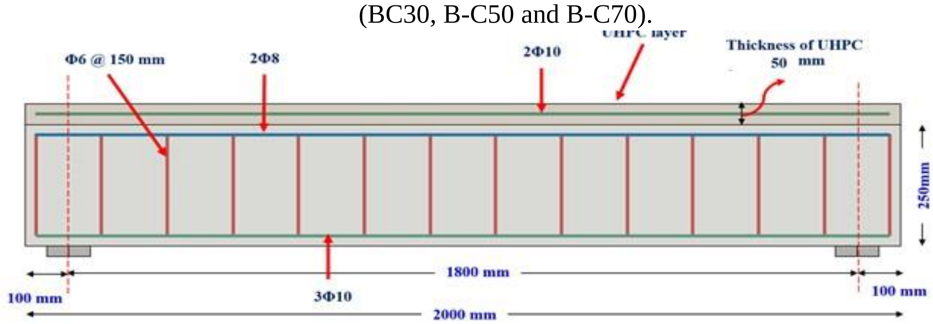


Figure 15 Geometry and reinforcement details of simple beam and strengthened with additional UHPC layer (B-C50 &S)

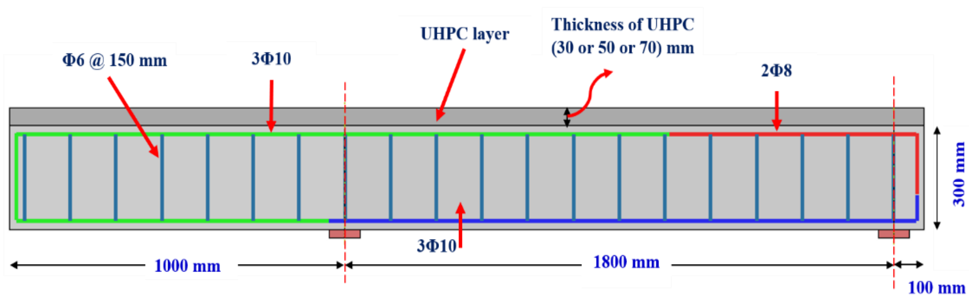


Figure 16 Geometry and reinforcement details of beam with cantilever and strengthened with additional UHPC layer (BC-C30, BC-C50 and BC-C70).

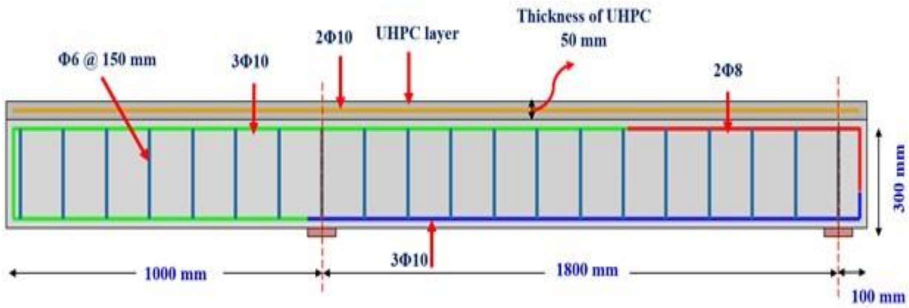


Figure 17 Geometry and reinforcement details of beam with cantilever and strengthened with additional UHPRC layer (BC-C50 &S)

Ultimate Loads

Figure18 shows the maximum failure loads obtained from FEM analysis displayed as follows: Group 1 (simple beam): The beams were strengthened with UHPC layers (30, 50, and 70 mm) in compression side, resulting in increases in ultimate failure loads of 17%, 26.5%, and 46%, respectively, over the control beam. While the use of steel reinforcement in the beam (B-C50 & S) was strengthened with a 50mm UHPC layer, no load increase was observed when compared to the beam (B-C50) without steel reinforcement.

Group 2 (beam with cantilever): The beams were strengthened with UHPC layers (30, 50, and 70 mm) in compression side, resulting in increases in ultimate failure loads of 38.8%, 69.7%, and 70.8%, respectively, over the control beam. Also, the use of steel reinforcement in the beam (BC-C50 & S) was strengthened with a 50mm UHPC layer, the load increase was observed when compared to the beam (BC-C50) without steel reinforcement.

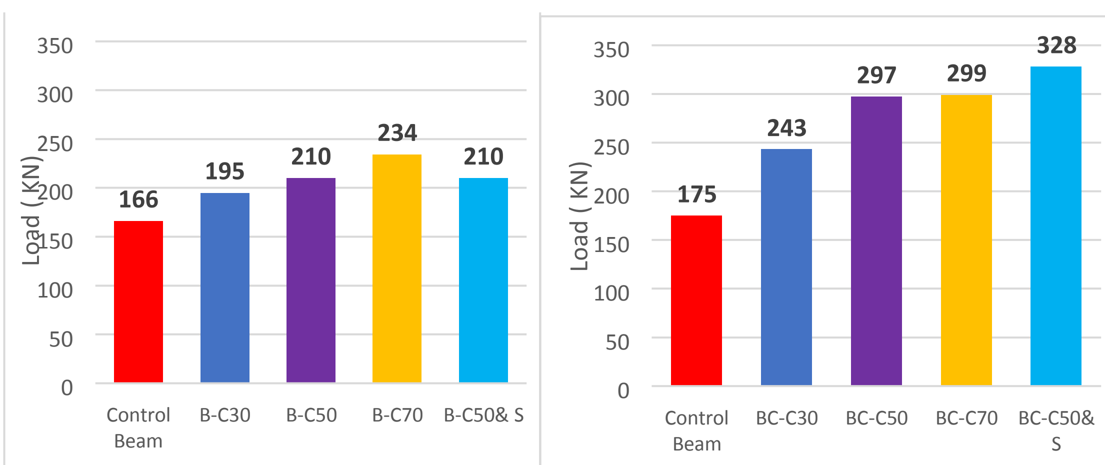


Figure 18 Ultimate loads failure for group 1 (simple beam) and group2 (beam with cantilever)

Load-deflection curves

Figure 19 displays the load versus deflection curves for group 1 with varying thickness of UHPC layers (30, 50 and 70) mm (simple beam). It can be seen that, all the beams were strengthened with a UHPC layer on the compression side showing the same trend and behavior compared with the control beam, with an increase in ultimate loads and enhancement in deformation. However, the additional steel bar in the UHPC layer with a 50mm thickness did not increase load or enhance behavior. Also, it is found that the strengthened beam with larger UHPC thickness has more ductile than the beam with smaller UHPC thickness.

Figure 20 displays the load versus deflection curves for group2 (beam with cantilever). It showed the same result as the group 1, but it showed a more significant improvement because of the presence of the UHPC layer in the tension side in relation to the cantilever, also, the additional steel bar in the UHPC layer with a 50mm thickness had small increase load or enhance behavior.

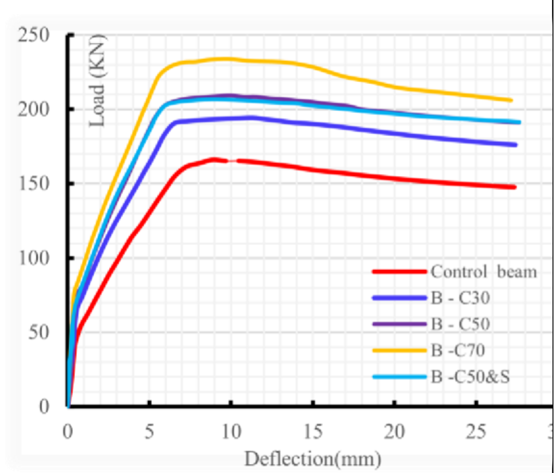


Figure 19 load-deflection curves at mid- span for group 1 (simple beam).

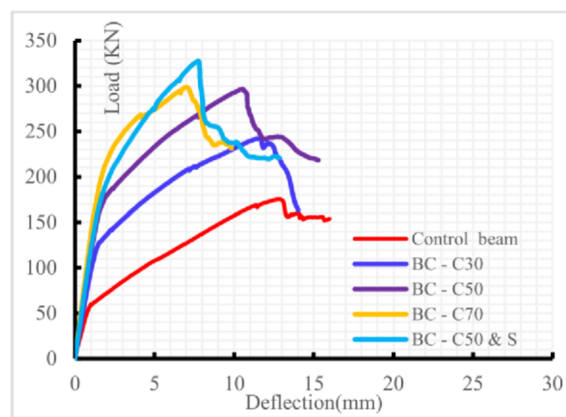


Figure 20 load-deflection curves at cantilever edge for group 2 (beam with cantilever).

4.3 Load Strain Behaviors

Figures 21 and 22 depicted the load-strain relationships of tensile steel reinforcements at the mid-span of group 1 (simple beam) and the edge of the cantilever beam in group 2.

Figure 21 Group 1 (simple beam): The load-strain relationships of tensile steel reinforcements at mid-span have the same trend and show an increase slightly with an increase in the thickness of the UHPC layer (30, 50, and 70 mm). While the use of steel reinforcement in the UHPC layer is not effective in the load-strain curve.

Figure 22, group 2 (beam with cantilever): The load-strain relationships of the tensile steel reinforcements at the edge of the cantilever beam have the same trend and show a greatly increased with the increase in the thickness of the UHPC layer (30, 50, and 70 mm). In addition, steel reinforcement in the UHPC layer has proven to be more effective in load-strain curves.

Failure Mode

Figure 23 shows the failure modes for group 1(simple beam) and group 2 (beam with cantilever0 displayed as follows:

Group 1(simple beam): It shows that all beams failed in flexure mode at the mid-span. The first crack started at the tension side of the beams. As loads increased, one vertical crack was observed along the beam depth until failure. The beams were strengthened with UHPC layers (30 and 50 mm) on the compression side, which delayed the first crack, but as loads increased, the vertical crack was observed along the beam depth until failure. While the beam was strengthened with the UHPC layer, 70 mm showed cracks at the tension side and yielding of steel.

Group 2 (beam with cantilever): all beam failures occurred due to shear failure at the interface of support on the cantilever as shown in figure 23. The use of the UHPC layer (30 and 50 mm) can enhance the crack pattern and change the crack position from cantilever to the beam.

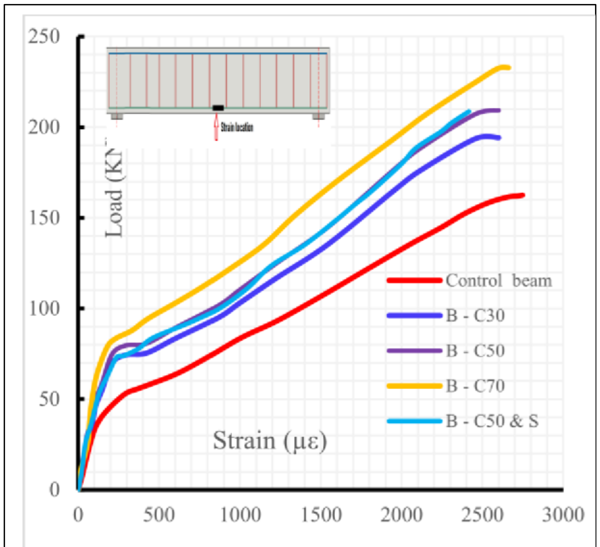


Figure 21 Load -strain curves at steel bar in tension side group 1 (simple beam).

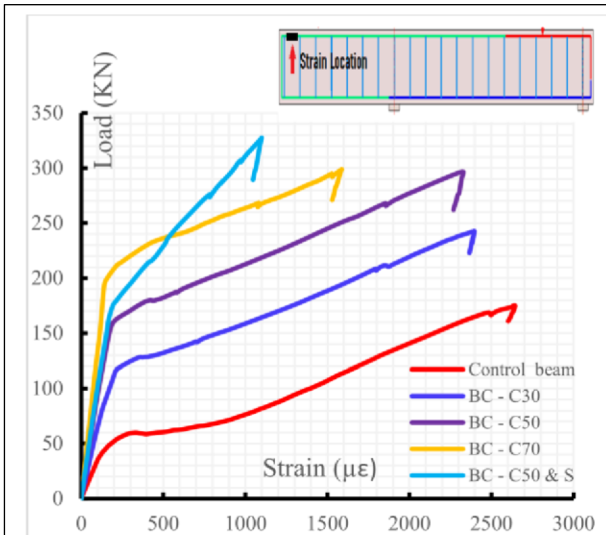


Fig ure 22 Load-strain curves at steel bar in tension side at cantilever edge group 2 (beam with cantilever).

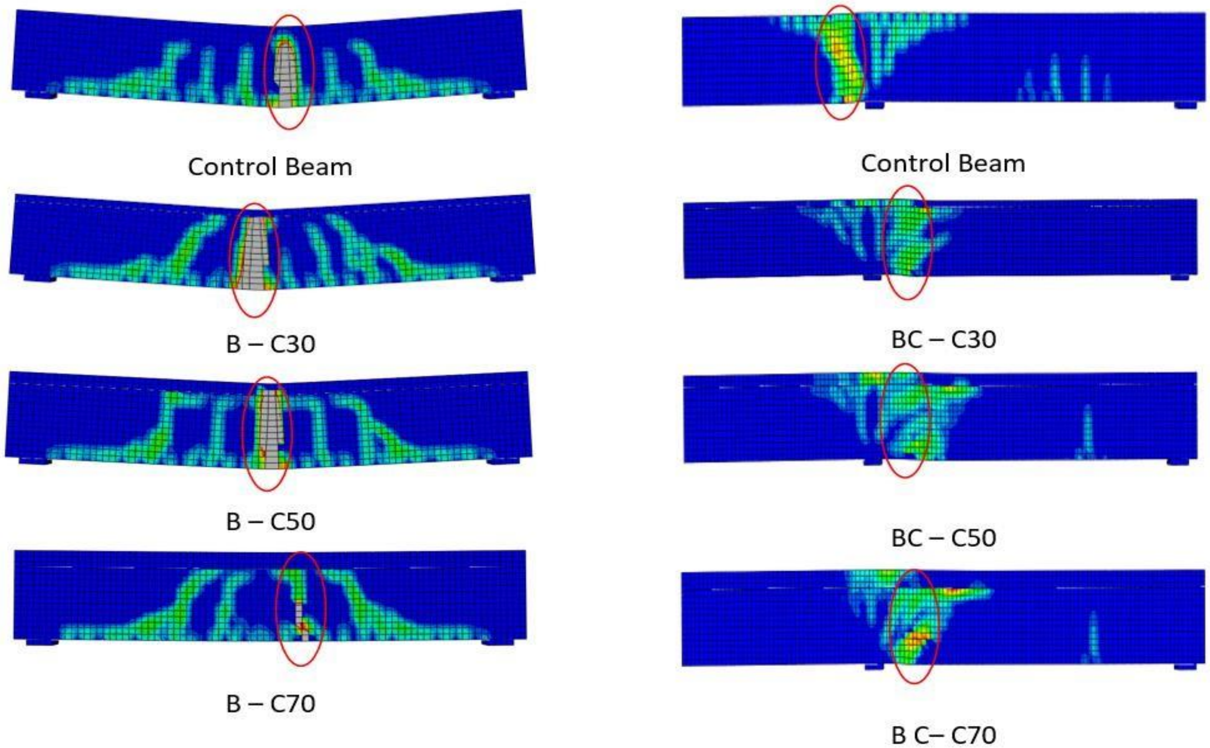


Figure 23 Failure Mode for group 1 (simple beam) and group2 (beam with cantilever)

Conclusions

The nonlinear finite element method for reinforced concrete beams was established, which was verified by existing experimental results. Comparative analyses of simple beams and cantilever beams strengthened with varying thicknesses of additional UHPC layer on the compression side. The following conclusions can be drawn.

- The results of the study show that strengthening with UHPC layers is a promising technology, since the performance of the strengthened reinforced concrete beams increased in all of the situations studied.
- The ultimate failure loads of simple beams increased from 17% up to 46% with the increase in the thickness of the additional UHPC layer.
- The ultimate failure loads of the beam with cantilever increased from 38.8% up to 70.8% with the increase in the thickness of the additional UHPC layer.
- The addition of steel reinforcement to the UHPC layer had more effect on the beams strengthened at the tension side. while having no effect on compression-side reinforced beams strengthened with varying thicknesses of additional UHPC layer on the compression side.

- The increase thickness of the additional UHPC layer improve the deflection value of simple beam up to 23%. Also improve the deflection value of beam with cantilever up to 54%.
- The strengthening beams on the compression side can be used when it is not possible to strengthen on the tension side, considering that it is not as effective as strengthening on the tension side.

Based on the above, the strengthened beam with the additional UHPRC layer showed the greatest improvement in cracking and flexural resistance. Thus, the finite element method could provide a reasonably accurate prediction of the behavior of reinforced concrete beams reinforced with an UHPRC layer.

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