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PARAMETRIC STUDIES OF RC BEAMS STRENGTHENED IN SHEAR WITH UHPFRC PLATES

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ABSTRACT

External bonding of ultra-high performance fiber reinforced concrete (UHPFRC) plates to reinforced concrete (RC) beams has been found to be an effective technique for shear strengthening. In order to obtain a clear understanding of shear strength of RC beams strengthened with UHPFRC, a numerical finite element model has been developed using the finite element package Abaqus/standard. The proposed model was verified and used to investigate crucial parameters of the examined technique. Parameters, which are mainly related to the design of this technique, such as effect of shear span to depth ratio, effect of UHPFRC plates' thickness, effect of the UHPFRC plates' reinforcement ratio, effect of the individual contribution of longitudinal side strengthening, and effect of the UHPFRC compressive strength on mechanical performance of RC beams strengthened in shear with prefabricated UHPFRC plates have been analyzed in the proposed research. The investigation resulted in a number of important conclusions reflecting the effects of the studied parameters on the behavior of the strengthened beams.

Keywords: UHPFRC, Prefabricated Plates, Shear, Reinforced Concrete, Finite Element Model.

1. INTRODUCTION

Several methods are available for strengthening or rehabilitation of existing concrete structures. Reinforced concrete jacketing, epoxy bonding steel plates, external post-tensioning, and externally bonding carbon fiber-reinforced polymer (CFRP) are some of the preferred methods for the strengthening process [1-4]. Despite the efficiency of these methods, it still have several disadvantages such as the difficulty of installation, the heaviness of applied strengthening material, disturbing the household during application, and some durability problems (corrosion risk, lack of fire resistance). Recent researches in construction materials technology have developed new cementitious composites such as ultra-high performance fiber reinforced concrete (UHPFRC). It is a cementitious composite with outstanding mechanical and durability properties.

Different researches have focused on the improvement of the mechanical properties of UHPFRC [5-6]. They concluded that the performance of UHPFRC is highly affected by the amount of fibers in the mixture. Also, fracture parameters including cohesive stress and fracture energy are significantly influenced by the fiber content: higher cohesive stress and fracture energy were achieved with higher fiber content.

The performance of composite RC-UHPFRC beams subjected to bending and shear in a cantilever beam setup was investigated by Noshiravani and Bruhwiler [7]. For this investigation the UHPFRC layer was cast at the tensile side of the beams. The span length, the ratio and the type of the reinforcement were variable. From the experimental results it was found that most of the beams failed due to a flexural failure at a force of 2 to 2.8 higher than the resistance of the control specimens. The medium span specimens on the other hand, which had a low shear reinforcement, failed with a shear-flexural crack.

Gomes et al. [8] and Ruano et al [9] found a significant increase in the shear strength by increasing fibre dosages. Besides that, in fibre reinforced concrete beams, the deformation was not localized in a single crack, which led to a considerable improvement of the beam ductility.

Guo and Wang [10] presented an experimental study on the behavior of shear connectors in UHPFRC-NSC composite structure. A new experimental installation (The NSC block is laid on the supporting deck, and the higher UHPFRC block is cantilever, meanwhile the top side of the NSC block is constrained.) is applied. A modified formula is proposed to calculate the load carrying capacity of shear connector. The experimental results are in good agreement with the calculated results.
Although previous researchers have studied the shear strengthening of RC beams using UHPFRC composites [7-10], different parameters affect the behavior of such elements are still lacking in literature. This paper develops a numerical parametric study to show effect of shear span to depth ratio, UHPFRC plates' thickness, UHPFRC plates' reinforcement ratio, strengthening individual longitudinal side, and UHPFRC compressive strength on the shear strength of RC beams strengthened in shear with UHPFRC plates.

2. FINITE ELEMENT MODEL

This section produce a finite element model (FEM) able to simulate numerically the behavior of RC beams strengthened in shear with prefabricated UHPFRC plates. The proposed FEM validated against the experimental results proposed by Sakr et al. [11] to specify its accuracy. Additionally, crucial parameters which have not been investigated experimentally was investigated.

2.1 Finite Element Model Construction

The finite element analysis software ABAQUS Hibbitt [12] has been used to construct the numerical model. The concrete damage plasticity model has been used to model the concrete and UHPFRC behavior, due to its ability to represent the inelastic properties of both of concrete and UHPFRC. The reinforcing steel was assumed to be an elastic-perfectly material and identical in tension and compression. The surface based cohesive behavior is used to model the behavior of the adhesive layer in order to allow for the debonding failure mode.
An eight-node linear brick, reduced integration, hourglass control element (C3D8R) was used to model both of the concrete and UHPFRC while a two-node linear 3D truss (T3D2) element was used to model the steel bars and stirrups. Fine mesh consisting of elements with maximum area of 1.0 cm^2 is used because a finer mesh does not show significant differences in results. The two supports was modeled as hinged and roller supports. The relation between the concrete and the steel reinforcement was assumed to be full bonded modeled by the embedded region constraint. Geometrical model used for the finite element model of the control beam C-S is depicted in Fig. 1.

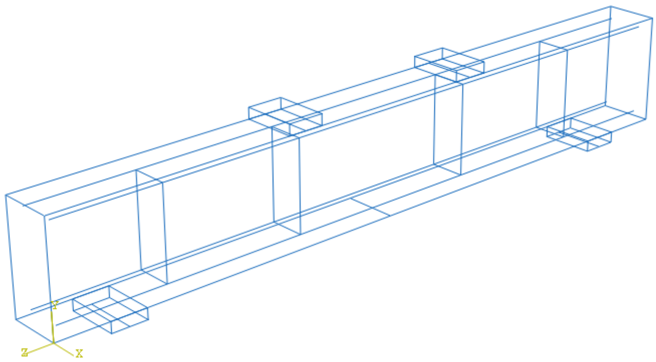


Fig.1: Geometrical Model Used for the Finite Element Model of the Control Beam (C-S)

2.2 Finite Element Model Validation

Table 1: Comparison between the experimental and numerical maximum load of the tested beams

Specimen	P_{FEM} (kN)	P_{EXP} (kN)	P_{FEM} / P_{EXP}
C-S	112	115	0.97
ST-1S	152	153	0.99
ST-1S-R	247	252	0.98
ST-2S	271	281	0.96
ST-2S-R	327	331	0.98

Table 1 shows that the ratio between the numerical (P_{FEM}) and the experimental (P_{EXP}) maximum loads ranges from 0.97 to 0.99, which considers acceptable accuracy. While Fig. 2 appears that the numerical load deflection curves of the tested beams are in a good manner with the experimental results.

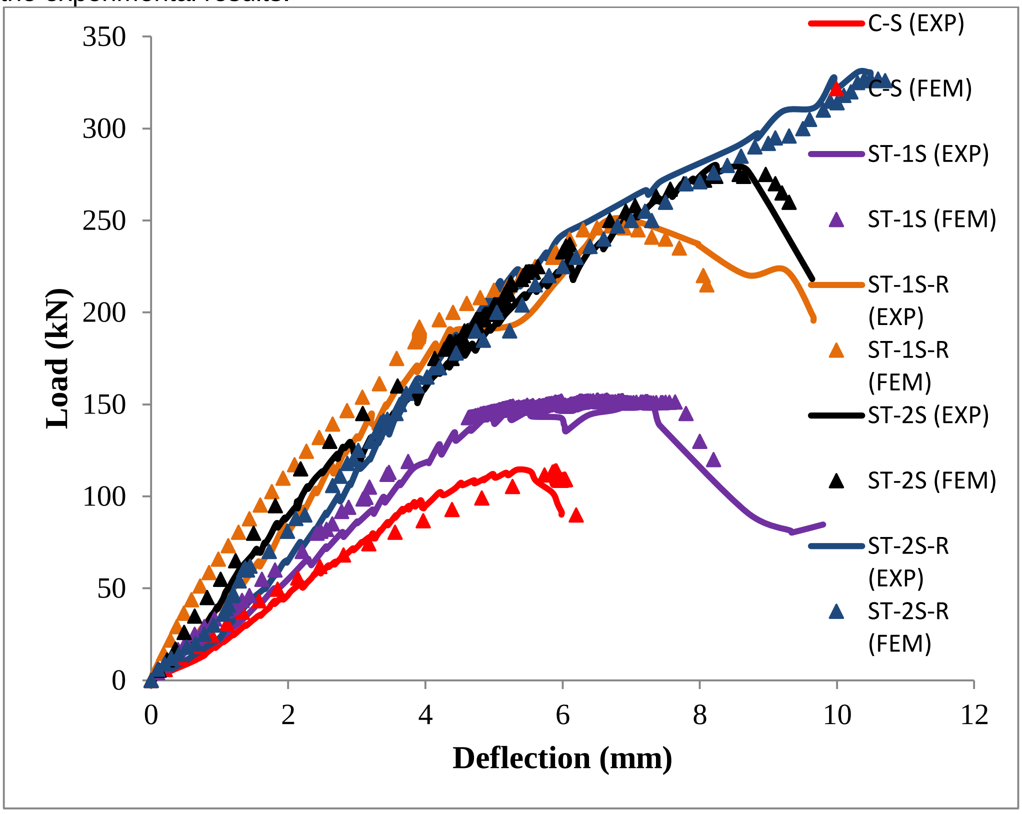


Fig. 2: Experimental Versus Finite Element Load–Deflection Curves for the Tested Beams

3. PARAMETRIC STUDY USING THE FINITE ELEMENT MODEL

3.1 Effect of Shear Span to Depth Ratio

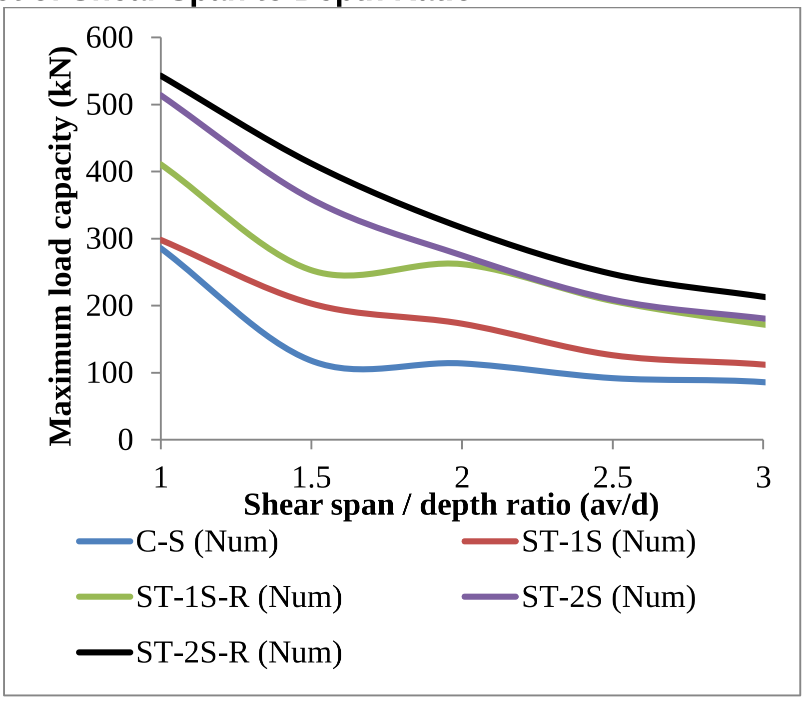


Fig.3: Maximum Load Capacity for the RC Beams with Various Shear Span/Depth Ratios

Table 2: Results of the RC beams with various shear span/depth ratios

Specimen	a_v / d ratio	Numerical maximum load capacity P_u (kN)
C-S	1	286
	1.5	118
	2	114
	2.5	92
	3	86
	3.5	61
ST-1S	1	298
	1.5	203
	2	173
	2.5	126
	3	112
	3.5	89
ST-1S-R	1	411
	1.5	253
	2	262
	2.5	207
	3	172
	3.5	145
ST-2S	1	514
	1.5	359
	2	275
	2.5	209
	3	181
	3.5	156
ST-2S-R	1	543
	1.5	412
	2	316
	2.5	247
	3	213
	3.5	181

Although shear span to depth ratio is a very important factor on the shear behavior of RC beams whether strengthened or not, there is a lack of studies providing a complete picture of behavior for the shear-strengthened beam covering a wide range of shear span to depth ratios. This section focuses on the effect of the shear span to depth ratio , (a_v/d) where a_v and d are respectively the length of the shear span and the effective depth of a concrete beam, on the shear performances of RC beams strengthened with prefabricated UHPFRC plates. To study the strengthening effect for RC beams (C-S, ST-1S, ST-1S-R, ST-2S, ST-2S-R) a wide range of shear span to depth ratios from 1.0 to 3.5 at 0.5 intervals will be considered.
The maximum load capacities of the analyzed twenty-four RC beams are shown in Table 2 and plotted in Fig. 3, in order to reveal the effect of shear span to depth ratio on the shear behavior of RC beams strengthened with UHPFRC plates. According to the proposed numerical results it can concluded that the value of the RC beams' shear capacity is clearly dependent on the shear span to depth ratio.

3.2 Effect of UHPFRC Plates' Thickness

The thickness of the prefabricated UHPFRC plates considers one of the main factors that affect the strength and the stiffness of the strengthening material, so the second parameter is the effect of UHPFRC plates' thickness (t, cm) on the maximum load capacity (P_u, kN). To study the strengthening effect for RC beams (ST-1S, ST-1S-R, ST-2S, ST-2S-R) a wide range of UHPFRC plates' thickness from 1.0 to 6.0 cm at 1 cm intervals will be considered. Shear span to depth ratio considered to be equal to 2.0 equivalent to the value used in the experimental program.

The maximum load capacities of the twenty-four RC beams analyzed are shown in Table 3. The maximum load capacity increases as the UHPFRC thickness increases. According to the FE simulation results in Table 3, when the ratio of the UHPFRC thickness to the width of beam ST-1S is less than or equal to 0.2, tensile rupture failure of the UHPFRC occurs. If this ratio is greater than 0.2, debonding failure occurs. To differentiate between debonding and rupture failure modes of beam ST-2S, UHPFRC thickness to the beam width ratio varied slightly to become 0.27 instead of 0.2 in case of beam ST-1S. Additionally from the same table, it is found that the UHPFRC thickness to the beam width ratio do not change the failure mode of both of ST-1S-R and ST-2S-R beams due to the presence of the steel anchors.

Table 3: Results of the RC beams with various thicknesses

Specimen	t (cm)	Maximum load capacity P_u (kN)	Failure mode
ST-1S	1	130	Rupture
	2	136	Rupture
	3	152	Rupture
	4	158	Debonding
	5	163	Debonding
	6	173	Debonding
ST-1S-R	1	213	Shear-Flexural Failure
	2	220	Shear-Flexural Failure
	3	229	Shear-Flexural Failure
	4	239	Shear-Flexural Failure
	5	246	Shear-Flexural Failure
	6	262	Shear-Flexural Failure
ST-2S	1	233	Rupture
	2	254	Rupture
	3	275	Rupture
	4	295	Rupture
	5	317	Debonding
	6	333	Debonding
ST-2S-R	1	260	Flexural Failure
	2	290	Flexural Failure
	3	316	Flexural Failure
	4	336	Flexural Failure
	5	350	Flexural Failure
	6	370	Flexural Failure

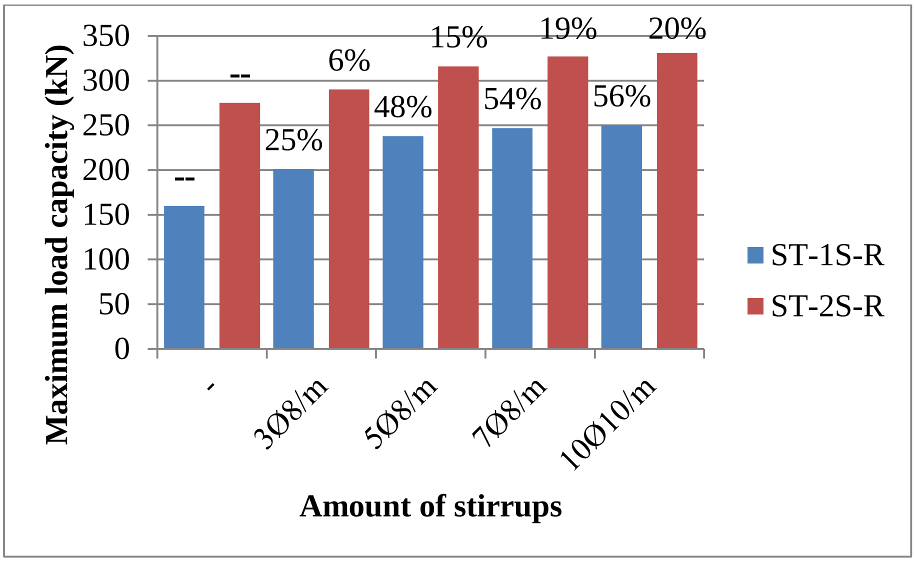
3.3 Effect of UHPFRC Plates' Reinforcement Ratio

The third parameter is the effect of UHPFRC plates' reinforcement ratio on the behavior of RC beams strengthened with UHPFRC. To study the effect of UHPFRC plates' reinforcement ratio a wide range of strengthened RC beams ST-1S-R and ST-2S-R were analyzed as shown in Table 4. Shear span to depth ratio and UHPFRC plates thicknesses' considered equal to the value used in the experimental program.

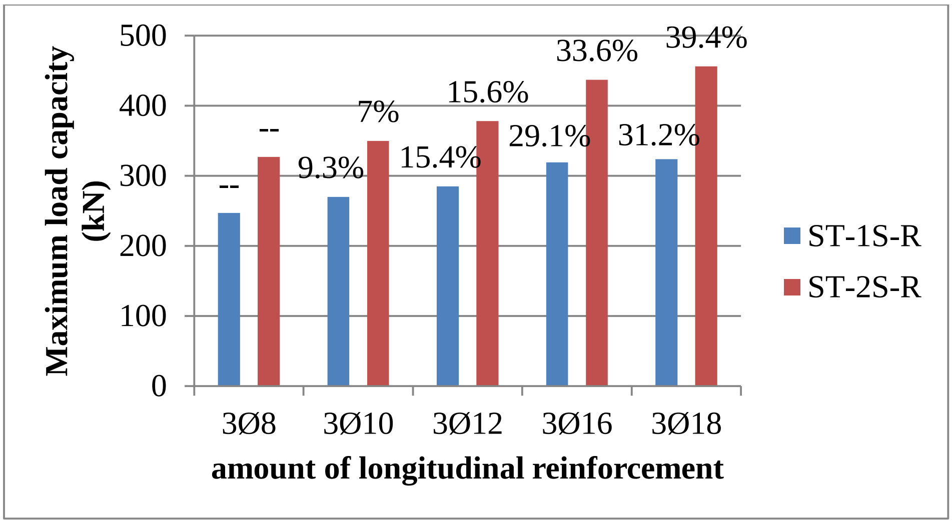
Table 4: Results of the RC beams with various UHPFRC plates' reinforcement ratio

Specimen	*Longitudinal reinforcement ratio (As/Ac %)*	*transversal reinforcement (Ast/Ac %)*	*Maximum load capacity P_u (kN)*
ST-1S-R	3Ø8 (0.84)	-	160
		3Ø8/m (0.84)	201
		5Ø8/m (1.4)	238
		7Ø8/m (1.96)	247
		10Ø10/m (4.36)	250
ST-2S-R	3Ø8 (1.68)	-	275
		3Ø8/m (1.68)	290
		5Ø8/m (2.8)	316
		7Ø8/m (3.92)	327
		10Ø10/m (8.72)	331
ST-1S-R	3Ø8 (0.84)	7Ø8/m (1.96)	247
	3Ø10 (1.31)		270
	3Ø12 (1.88)		285
	3Ø16 (3.35)		319
	3Ø18 (4.24)		324
ST-2S-R	3Ø8 (1.68)	7Ø8/m (3.92)	327
	3Ø10 (2.62)		350
	3Ø12 (3.76)		378
	3Ø16 (6.7)		437
	3Ø18 (8.48)		456

Results shown in Table 4 confirm the experimental result that indicates the ability of UHPFRC plates to change the failure mode of the strengthened RC beams from sudden brittle failure to ductile failure mode. Scanning of the tabulated results refer to by increasing the stirrups ratio within the UHPFRC plates in both of ST-1S-R and ST-2S-R beams increased the maximum load capacity till debonding and rupture occurred for beams ST-1S-R and ST-2S-R at amount of stirrups equal to 7Ø8/m, respectively. By increasing, the amount of stirrups the maximum load capacity did not significantly affected. On the other side, the maximum load capacity of beams ST-1S-R and ST-2S-R increased by 32% and 40%, respectively, in case of using 3Ø18 longitudinal reinforcement instead of 3Ø8 as shown in Fig. 4.



(*a*)

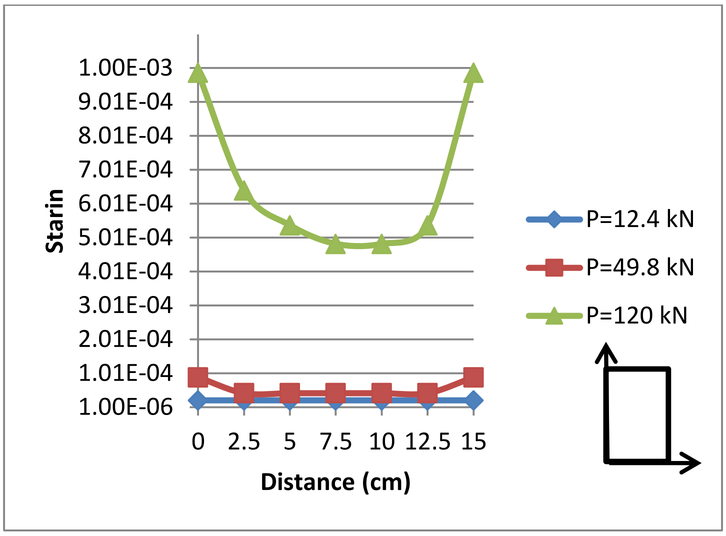


(*b*)

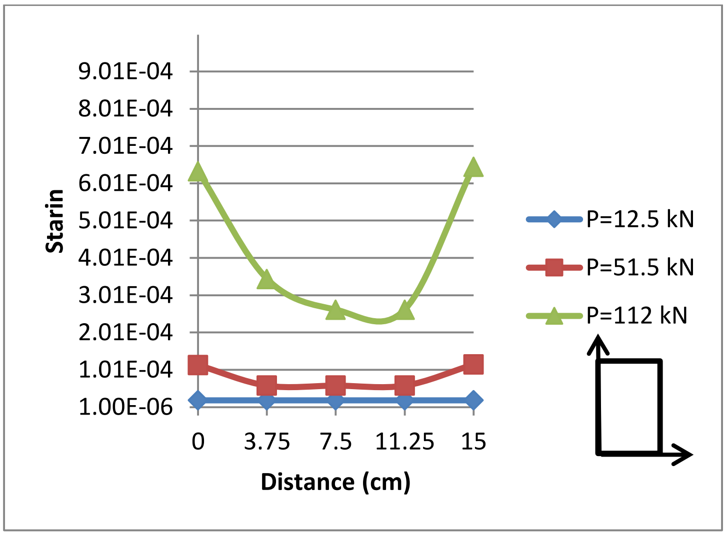
Fig. 4: Maximum Load Capacity For The Strengthened RC Beams With Various UHPFRC Plates' Reinforcement Ratios: a) Longitudinal Steel 3Ø8, b) Stirrups 7Ø8/m

3.4 Effect Of The Individual Contribution Of Longitudinal Side Strengthening

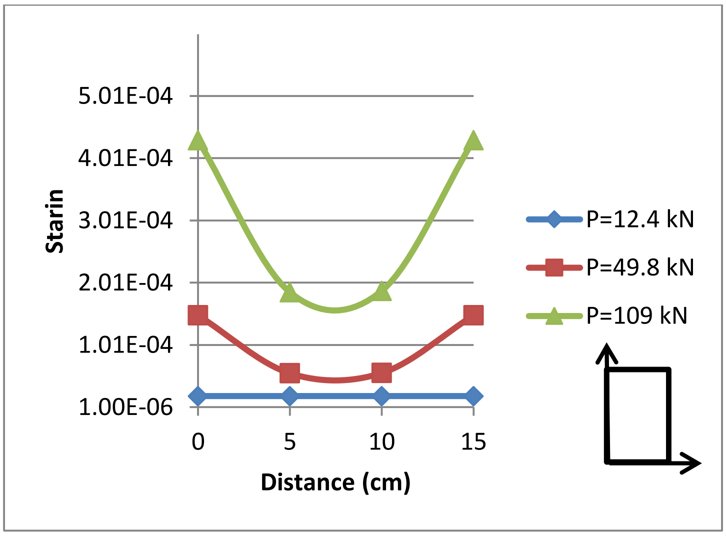
The experimental program showed that strengthening one side of the RC beams revealed the efficiency of the UHPFRC material to prevent the diagonal shear crack from appearing on the strengthened surface, which was obvious on the non-strengthened surface. The current section aims to plot the strain distribution on the beam width to explain the difference in failure mode occurred on the two sides of the RC beam. Beams C-S, ST-2S, and ST-1S were considered and results have been depicted in Fig. 5, Fig. 6 and Fig. 7, respectively.



***(a)* mesh size 2.5 cm**

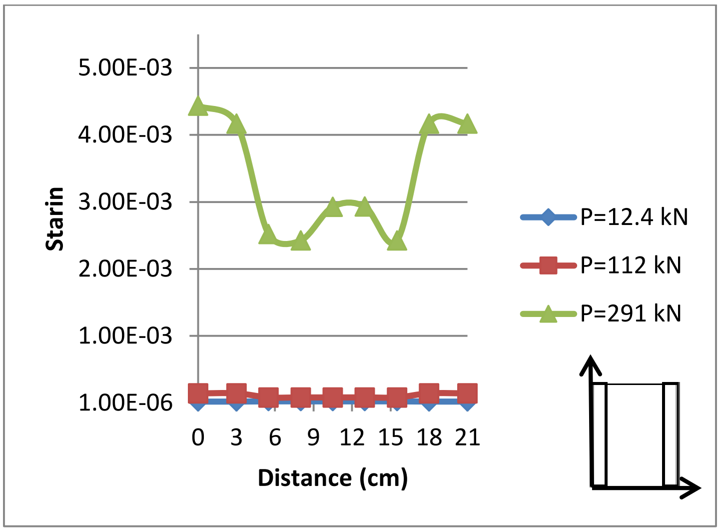


***(b)* mesh size 3.75 cm**

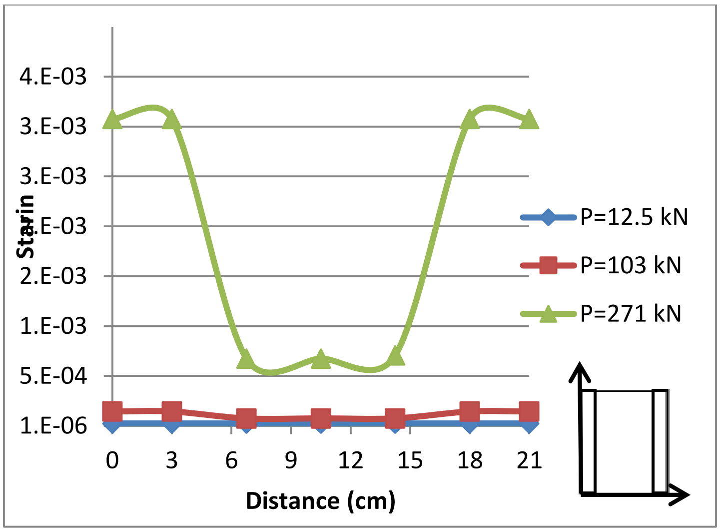


***(c)* mesh size 5 cm**

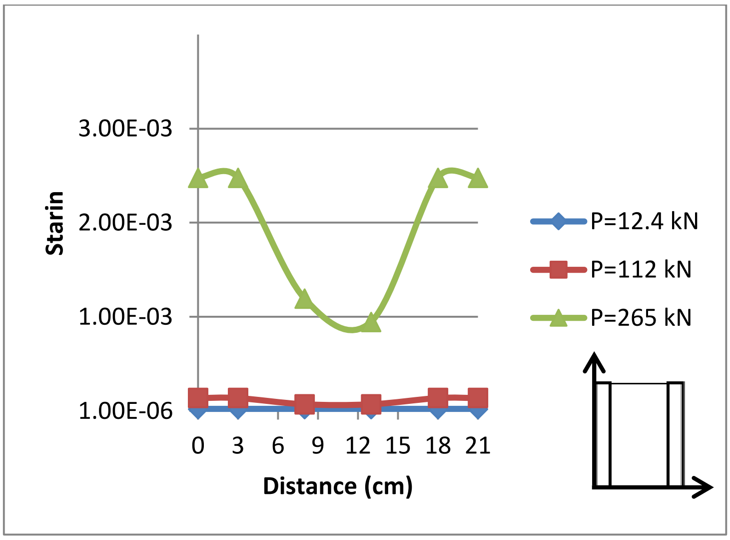
Fig. 5: Strain Distribution On The Control Beam C-S Width At Different Loads



***(a)* mesh size 2.5 cm**

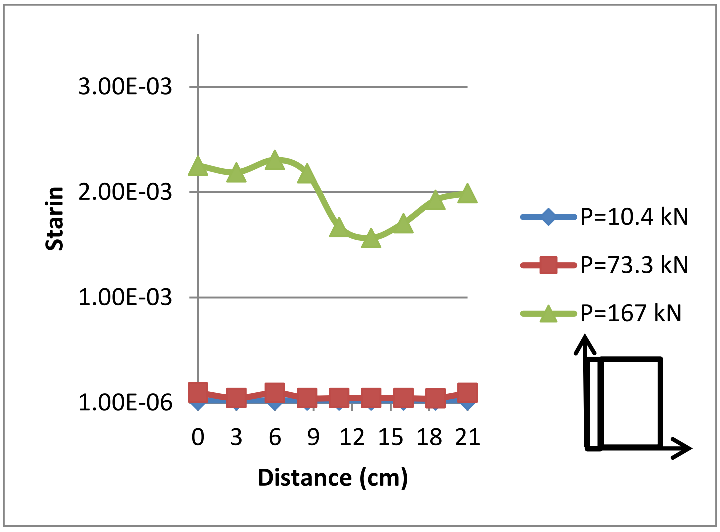


***(b)* mesh size 3.75 cm**

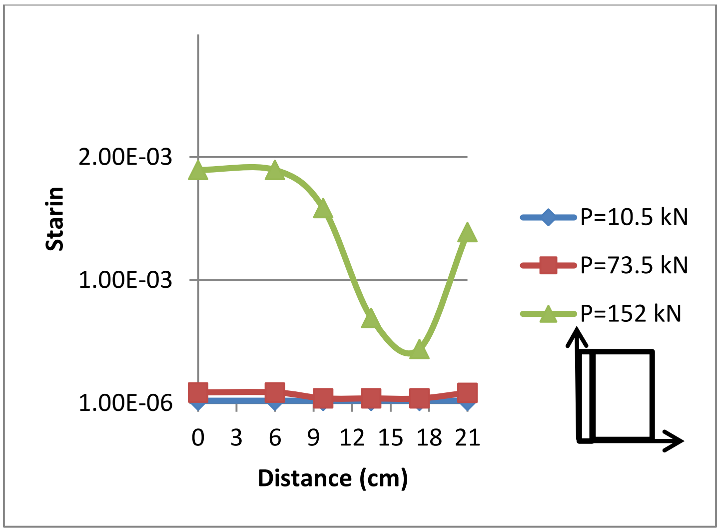


***(c)* mesh size 5 cm**

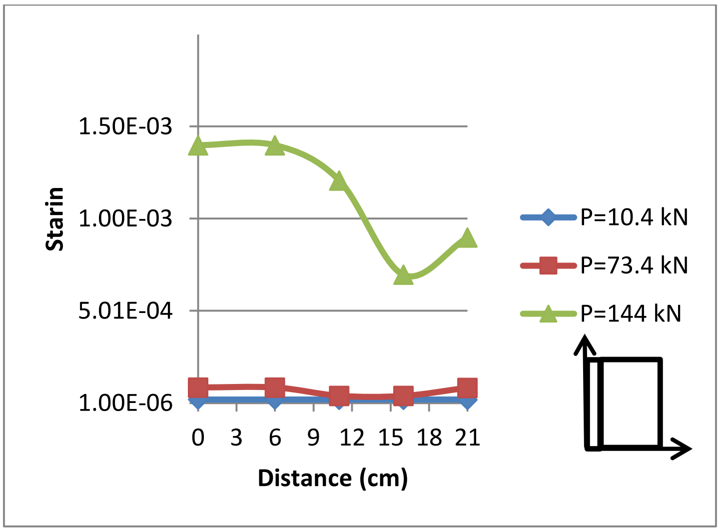
Fig. 6: Strain Distribution On The Strengthened Beam ST-2S Width At Different Loads



(a) **mesh size 2.5 cm**



(b) **mesh size 3.75 cm**



(c) **mesh size 5 cm**

Fig. 7: Strain Distribution On The Strengthened Beam ST-1S Width At Different Loads

The strain distribution over the beams' widths show uniform strain distribution before cracking load. As the load increase the strain increase in the beginning and the end of the beam where cracks started to grow. In addition, the same figures show that the strain value changed when the mesh size differed, this affects the numerical maximum load capacity. Therefore, it is important to verify the mesh size with an experimental program. The proposed charts agree well with experimental failure modes. Strain of beam ST-2S reaches the rupture strain, which indicate rupture of the UHPFRC plate. While the lower strain of beam ST-1S indicate debonding of the UHPFRC plate.

3.5 Effect Of The UHPFRC Compressive Strength

The compressive strength of the UHPFRC not only affects the tensile properties but also the cost of the mix. This section studies the effect of the compressive strength on the performance of the strengthened beam with a constant tensile strength. Beams (ST-1S, ST-1S-R, ST-2S, ST-2S-R) with a wide range of UHPFRC plates' compressive strength will be analyzed and results have been depicted in Table 5. The same table shows that the compressive strength of the prefabricated UHPFRC plates does not affect the maximum load capacity of the strengthened beams. Therefore, if the UHPFRC mix had had a high tensile strength with relatively low compressive strength, designers would have reached to significant increasing in the load carrying capacity with a relatively low cost.

Table 5: Results of the RC beams with various UHPFRC plates' compressive strength

Specimen	*UHPFRC compressive strength MPa*	*UHPFRC tensile strength MPa*	*Maximum load capacity P_u (kN)*
ST-1S	135	11.50	152
	110		152
	90		152
	70		152
ST-1S-R	135	11.50	247
	110		247
	90		247
	70		247
ST-2S	135	11.50	271
	110		271
	90		271
	70		271
ST-2S-R	135	11.50	327
	110		327
	90		327
	70		327

CONCLUSIONS

Parametric study of the shear behavior of RC beams strengthened with prefabricated UHPFRC plates using numerical investigation has been carried out. From the results of the present study it is possible to conclude that:

1. Value of the RC beams' shear capacity is clearly dependent on the shear span to depth ratio. For safe design, the a_v/d ratio should be explicitly considered in the design equations.
2. The ratio of the UHPFRC thickness to the width of the strengthened beams controls the failure mode; whether rupture or debonding. Presence of the steel anchors could prevent the debonding failure mode.
3. The maximum load capacity of beams ST-1S-R and ST-2S-R increased by 32% and 40%, respectively, in case of using 3Ø18 longitudinal reinforcement instead of 3Ø8.
4. The mesh size value could control the maximum load capacity of the tested beams consequently it is important to be verified against an experimental program before the construction of the finite element model.
5. If the UHPFRC mix had had a high tensile strength with relatively low compressive strength, designers would have reached to significant increasing in the load carrying capacity with a relatively low cost.

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