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Numerical Study of Bond Stress-Slip Relationship in Large Scale Reactive Powder Concrete Beams

Abstract*-As the reactive powder concrete (RPC) represents one of the ultra-high performance concrete types that recently used in public works and in the presence of several attempts that aims to examine the behavior of RPC, this work aims to theoretically study the bond stress between RPC and steel bars and the corresponding slip for large reactive powder concrete beams by using finite element models done by ANSYS 16.1 software. Where, these numerical models were verified through several comparisons between their results, and the experimental one from previous work, in which good agreement were achieved. The effects of several parameters on the bond stress were studied, the parameters include concrete compressive strength, and steel fibers content, bar diameter, length of the developed bar and concrete cover thickness.*

Keywords*- reactive powder concrete, bond strength, slip, large-scale beam, finite element*

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1. Introduction

RPC represents one of the recent developed types of ultra-high performance concrete usually recognized by high strength, high durability, high density and its very fine components due to the absences of course aggregate plus the addition of the steel fibers in most times. The reinforced concrete members usually consist of concrete and steel reinforcement and must work as one unit in order to allow stresses transformation through the member under loading, this system is controlled by the bond mechanisms which in turn depending on three components the chemical adhesive, the friction and the mechanical interlock between concrete and the steel reinforcing bars. However providing of suitable development length is very necessary to prevent slip between concrete and steel. Previous works like Shima [1] investigate the bond stress between concrete and steel bars and establish a formula to predict the bond strength based on bar diameter, slip and other parameters, Ikki and Kiyomiya [2] modified the formula established by Shima [1] by adding two coefficients for concrete stress condition and steel bar direction, Darwin et al. [3] and Darwin [4] study the development length with corresponding to the concrete cover, diameter of the bars being developed and the effect of transvers reinforcement, while Al-Dabbous [5] study the bond strength and the development length for beams made with high strength concrete and derived a formula to estimate the bond stress, also, Hadi [6] study the bond of steel with high strength concrete cylinders by pull out tests.

2. Aim of This Work

This work aims to study the behavior of RPC beams that failed by anchorage loss by using finite element software ANSYS 16.1. The effect of parameters; RPC compressive strength, content of steel fibers, size of the tension steel bar, length of development, concrete cover and the spacing of transvers reinforcement have been studied on the maximum carrying load, deflection at mid span, bond stress between RPC and reinforcement, notches slip and concrete strain at compression side. Where, comparisons were made for both experimental and numerical results, in addition to the numerical examination of the extended parameters.

3. Bond Mechanisms

Generally, in case of reinforced concrete (RC) flexural members, the flexural compressive forces are resisted by concrete; on the other hand the flexural tensile forces are resisted by the steel bars. For this reason, a force transfer between the two materials is needed, and this force can be defined by the bond stress. In which, for design purposes no slippage of the steel reinforcement is assumed related to the surrounding concrete. Where, concrete and steel bars must behave as one unit, if slippage allowed, steel bars may pull out from the surrounding concrete and RC

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member will behave like plain concrete with no steel reinforcing bars, and leading to a sudden failure after the appearance of the cracks [7, 8]. This bond between these two materials mainly depending on the chemical adhesion, friction based on steel reinforcing bars roughness and the bearing acting on the steel bars deformations. This bond stress can be calculated using Eq. (1):

$$\mu = \frac{f_s \cdot d_b}{4\ l_d} \qquad (1)$$

In Which

μ= bond stress, MPa.

f_s= stress in longitudinal steel bars, MPa.

d_b= diameter of steel bar being developed, mm.

l_d= length of steel bar being developed, mm.

4. Finite Element

Finite element method (FEM) usually described as a numerical method that used to find the approximate solutions for differential and integral equations, this method is widely applicable in engineering problems. While, ANSYS that refers to ANalysis SYStem, and is defined as software with general purposes which is used to simulate the interaction of structural, physics, fluid mechanics, thermal and many other problems [9]. In this study, by using ANSYS 16.1 the behavior of large scale RPC beams failed by anchorage loss were simulated.

I. Element types

As the targets beams consist of RPC and steel reinforcing bars, element SOLID65 and LINK180 have been used to simulate RPC and steel bars respectively. The SOLID65 is a 3-D eight nodes element usually used to simulate concrete, while the bar LINK180 is defined with two nodes, a 3-D element used in modeling trusses, cables, links, springs, etc. in addition to these two elements, element SOLID185 has been used to model the steel plates used with loading points.

II. Real constants

In order to model the RPC beams experimentally studied by previous work of Eyad Kadhem et al. [10] real constants inputs in modeling process were provided as used in the experimental tested beams. For element SOLID65 the steel fibers were defined as material number 2 as submersed rebar, where the volumetric ratio of steel bars must be entered, see Table 1. For element LINK180, reinforcing steel bars cross sectional area should be entered as real constants required Table 2. While, SOLID185 no need for real constants inputs.

III. Material properties

For element SOLID65 both linear elastic and nonlinear inelastic data have been entered like modulus of elasticity and Poisson's ratio for both reactive powder concrete and steel fibers, also concrete compressive strength and the splitting tensile strength were entered. Element LINK180, needs for steel modulus of elasticity, Poisson's ratio and steel yield strength to be entered. Similarly, element SOLID185 is needed for the modulus of elasticity of steel and Poisson's ratio.

Table 1: Real constants element SOLID 65

Set number of real constant	Material number	Steel fibers volumetric ratio	Rebar		
			1	2	3
1	2	0%	0	0	0
		1%	0.00333	0.00333	0.00333
		1.5%	0.005	0.005	0.005
		2%	0.00667	0.00667	0.00667

Table 2: Real constants element LINK 180

Real constant set number	**Diameter of Steel bar (mm)**	**Steel bar area (mm^2)**
2	16	201.062
	20	314.159
	25	490.874
3	12	113.097
4	8	50.265

5. Case study

This work aims to numerically study the bond between RPC and steel reinforcing bars in large-scale beams, based on previous experimental work provided by Eyad Kadhem et al. [10]. The RPC beams cross section is equal to 200 × 300 mm^2 and 2000 mm in length, all beams were provided by two notches 100 mm × 80 mm on the width of the beam in order to allow slip recording, Figure 1 shows one of the beams tested by Eyad Kadhem et al. [10], Figure 2 illustrates beam geometry and test setup and Table 3 summarizes the parameters of these beams. Steel reinforcement with main single tension bar were used with different sizes, transvers reinforcement of 12 mm in diameter and two bars with 8 mm used in compression zone to hold the stirrups.

Figure 1: Beam after failure by Eyad Kadhem et al. [10]

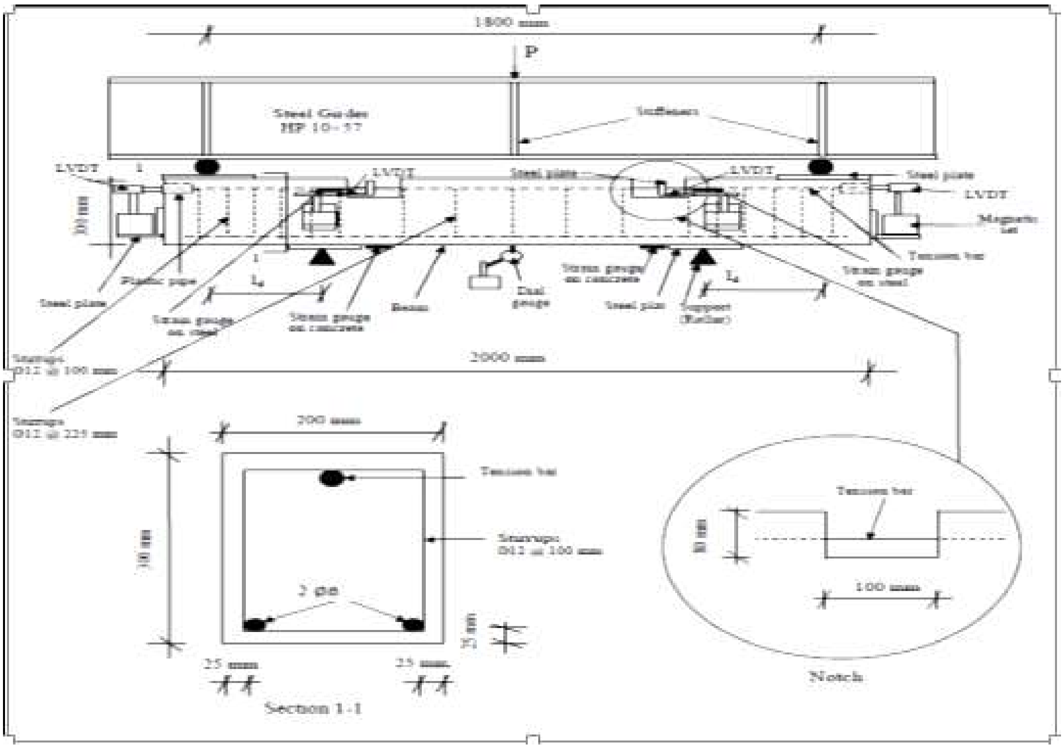

Figure 2: Beam test setup and geometry [10]

Table 3: Beams details and description [10]

Parameter set	Beam designation	Mixes	F_c (MPa)	V_f (%)	d_b (mm)	I_d (mm)	Concert cover
Control group (set 0)	B1-S0-R	M1-70	70	1	20	250	40
Set 1	B2-S1-80	M2-80	80	1	20	250	40
	B3-S1-90	M3-90	90	1	20	250	40
Set 2	B4-S2-0	M4-0	70	0	20	250	40
	B5-S2-1.5	M5-1.5	70	1.5	20	250	40
	B6-S2-2	M6-2	70	2	20	250	40
Set 3	B7-S3-16	M1-70	70	1	16	250	40
	B8-S3-25	M1-70	70	1	25	250	40
Set 4	B9-S4-200	M1-70	70	1	20	250	40
	B10-S4-300	M1-70	70	1	20	300	40
Set 5	B11-S5-25	M1-70	70	1	20	250	25
	B12-S5-50	M1-70	70	1	20	250	50

All beams were tested under two points monotonic load up to failure, where all beams (except one) failed by anchorage loss. Measurements such as maximum load, load at first crack, slip at two positions (notches and beams ends) and strain in both steel bars and concrete were measured. Depending on the strain found in reinforcing bars, Eq. (1) has been used to find the bond stress between the two materials.

6. Discussion of Finite element results

The RPC beams that tested by Eyad Kadhem et al. [10] have been modeled and analyzed by using ANSYS 16.1, and their numerical results were examined and compared with the experimental one.

As SOLID 65 is described as a three dimensional brick element, the used dimensions is 10, 25 and 25 mm, at X, Y and Z directions respectively, where these dimensions provided the best convergence for both results. While dimensions of the used elements related to LINK180 were forced to follow the node dimensions that belongs to element SOLID65. In order to model the bond stress between RPC and steel bars, the stresses in the steel bars were detected by ANSYS 16.1 at time when failure occurred due to anchorage loss (bond failure), in which these stresses were measured at the zone of maximum moment as same as measured in the experimental tests [10]. These stresses were used in Eq. (1) to establish the bond stress.

The numerical model for beam B1-S0-R is shown in Figure 3 as example for all modeled beams, as all tested beams by Eyad Kadhem et al. [10] were modeled in this work. Table 4 summarized the experimental results [10] and the numerical results obtained in this work, in which the agreement ratio between them includes the load-upward deflection at mid span, slip-bond stress and RPC compression strain-bond stress relationships.

As all tested beams were numerically modeled in this work, comparisons of experimental and numerical results were made, in order to check the validity of these models and to theoretically investigate (numerically study) the behavior of RPC beams failed with anchorage loss. The experimental and numerical results of B1-S0-R are chosen to be illustrated as example for all the modeled beams. Figure 4, Figure 5 and Figure 6, illustrate the load versus mid span deflection, notch slip versus bond stress and bond stress versus concrete compressive strain relationships respectively. The results listed in Table 4 provide that the best convergence be given by the beam ultimate load with agreement ratio of 94.99%, in addition a remarkable agreement was found with ratio of 88.36%, 90.32%, 90.75%, and 93.28% for deflection at mid span, notch slip, strength and strain of concrete respectively.

Figure 7 and Figure 8 show that maximum stresses in concrete are concentrated above and around the main tension-reinforcing bar, which is lead to concrete crush followed by anchorage loss failure.

Figure 9 illustrates the concentrated cracks above and around main steel bar at the notch due to slip action between RPC and steel bar. Figure 10 shows the cracks patterns occurred at the maximum load, where, most cracks were found to be concentrated at the beam top face at position of tension stresses. Concrete cracks, colored green and blue represent the second and the third cracks appeared and concentrated at top face of the beam along with the main tension steel bar as a result of relative slip, in which when bond strength fail between these two materials anchorage loss occurred. Also, additional cracks were found near notches positions which are manually located during the experimental tests [10], these cracks are various in both location and magnitude of load from the internal micro cracks detected by using ANSYS 16.1. In which, ANSYS result refers to a location of the concrete first crack above the main steel bar as shown in Figure11, and the load value of this numerically detected crack is lower in comparing with the visible external one that manually detected. Generally, the internal cracks appeared before the external cracks, for beam B1-S0-R the first visible external crack occurred at load of 159.424 kN while the first micro internal crack load was 99.895 kN.

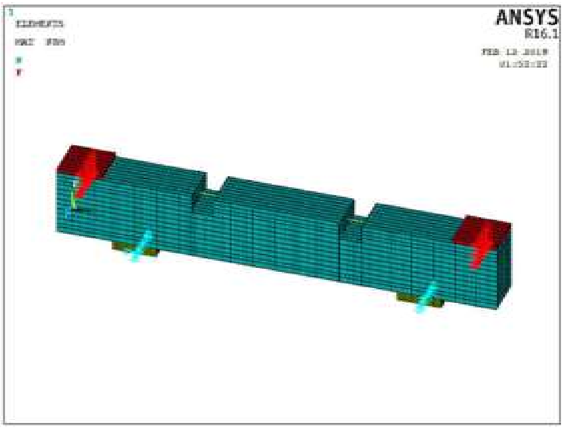

Figure 3: Numerical model for beam B1-S0-R

Table 4: Experimental and numerical results

Beam	Ultimate load (Pu) (kN)			Upward mid span deflection (Δu) (mm)			Bond strength (μ) (MPa)			Maximum slip at notch (mm)			Maximum concrete compressive strain		
	Experimental	Numerical	Agreement %	Experimental	Numerical	Agreement %	Experimental	Numerical	Agreement %	Experimental	Numerical	Agreement %	Experimental × 10^{-5}	Numerical × 10^{-5}	Agreement %
B1-S0-R	558.23	587.68	94.99	9.100	8.041	88.36	6.875	7.576	90.75	2.480	2.240	90.32	442	412.3	93.28
B2-S1-80	603.81	647.26	93.29	9.475	8.590	90.66	7.100	7.835	90.62	1.687	1.489	88.26	395	320.6	81.16
B3-S1-90	629.89	697.11	90.36	11.36	10.556	92.92	7.746	9.065	85.45	0.808	0.723	89.48	343	290.5	84.69
B4-S2-0	489.52	537.95	91.00	8.328	6.905	82.91	5.219	6.205	84.11	2.776	2.354	84.80	282	238.1	84.43
B5-S2-1.5	647.31	697.22	92.84	10.44	9.312	89.20	7.527	8.403	89.58	2.205	1.909	86.58	477	429.5	90.04
B6-S2-2	688.66	745.06	92.43	11.18	9.452	84.54	8.051	9.100	88.47	1.954	1.644	84.14	523	436.9	83.54
B7-S3-16	426.46	478.16	89.19	6.383	5.248	82.22	8.009	9.170	87.34	1.809	1.548	85.57	345	281.1	81.48
B8-S3-25	847.99	898.5	94.38	13.68	11.330	82.82	5.706	6.642	85.91	2.934	2.562	87.32	492	426.9	86.77
B9-S4-200	587.09	618.00	95.00	9.272	8.432	90.94	6.235	6.684	93.28	3.231	2.732	84.56	455	422.3	92.81
B10-S4-300	506.45	541.68	93.50	9.001	8.080	89.77	7.280	7.917	91.95	2.338	2.226	95.21	413	385.3	93.29
B11-S5-25	600.85	647.37	92.81	7.815	6.909	88.41	6.329	7.226	87.59	2.775	2.321	83.64	427	387.5	90.75
B12-S5-50	545.07	578.32	94.25	10.30	9.217	89.49	7.439	8.232	90.37	2.212	2.042	92.32	457	416.9	91.23

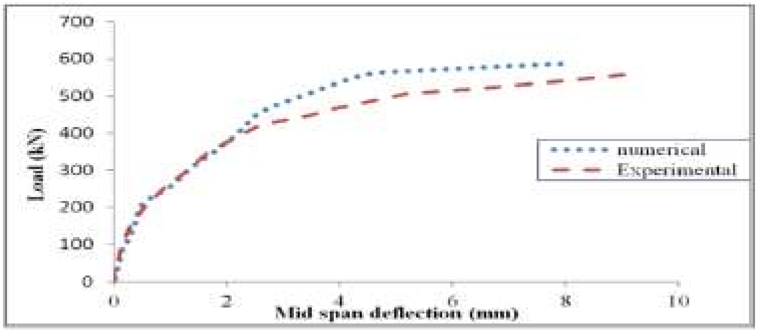

Figure 4: Relationship of load- upward mid span deflection beam B1-S0-R

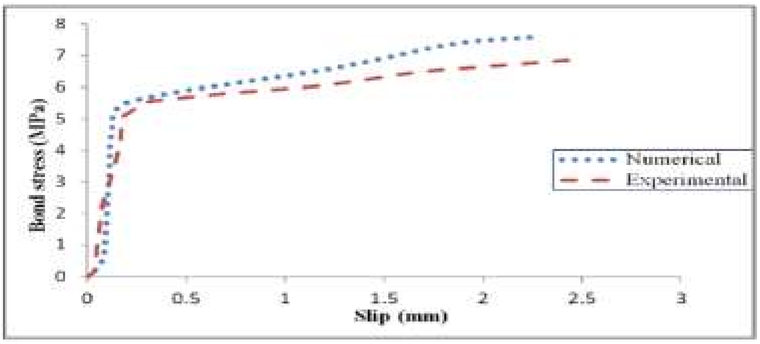

Figure 5: Relationship of bond stress–slip beam B1-S0-R

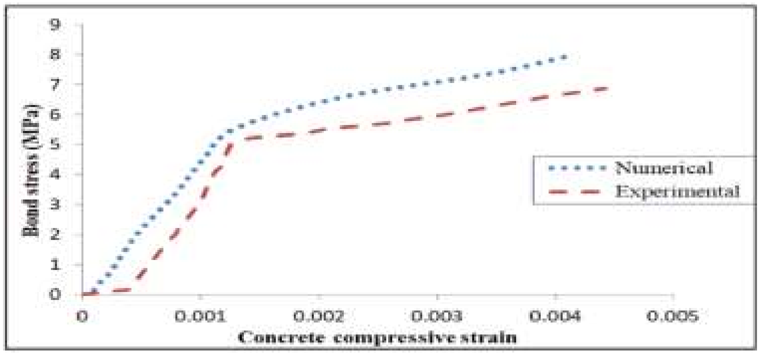

Figure 6: Relationship of bond stress–concrete compressive strain beam B1-S0-R

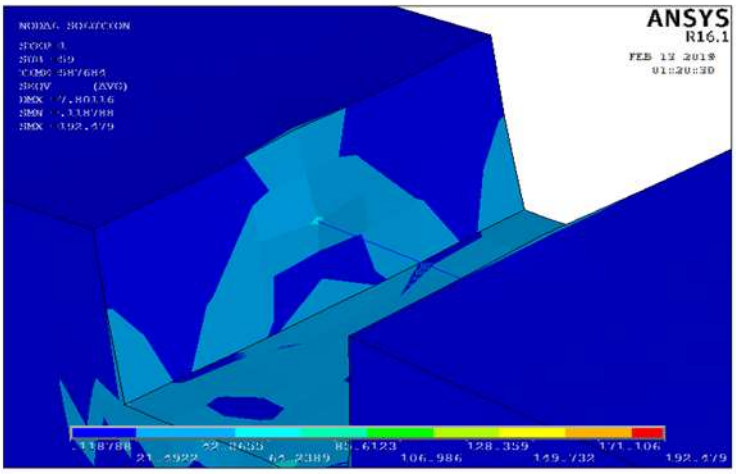

Figure 7: Maximum loading stresses contour at notch model (B1-S0-R)

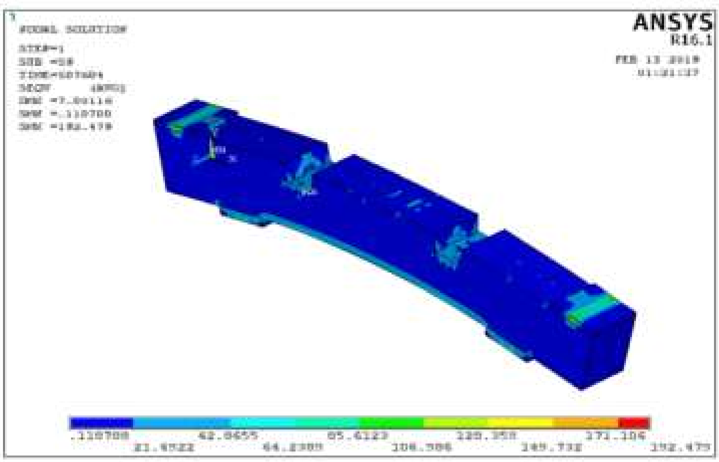

Figure 8: Maximum loading stresses contour model (B1-S0-R

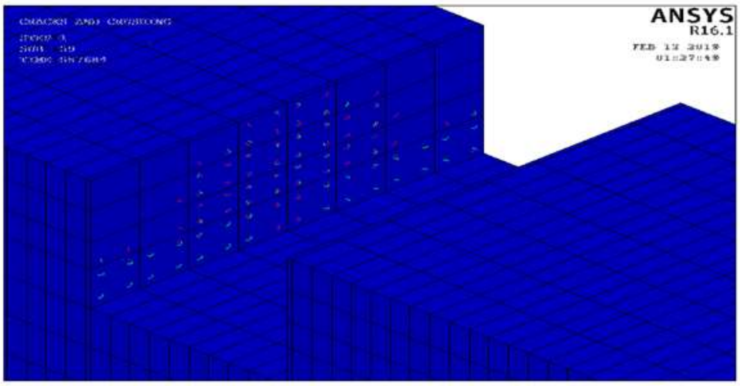

Figure 9: Cracks distribution above and around the main steel bar at notch model (B1-S0-R)

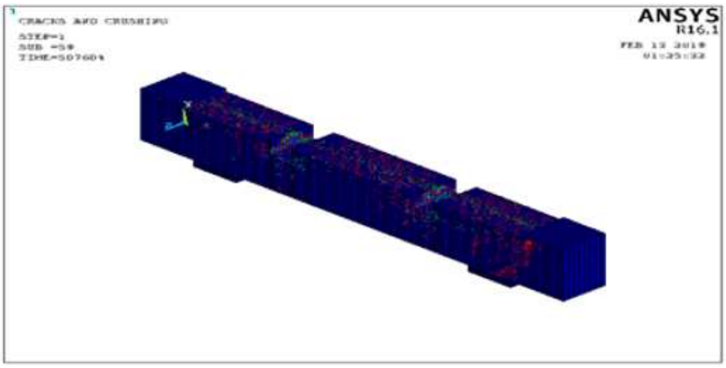

Figure 10: Cracks distribution for model (B1-S0-R)

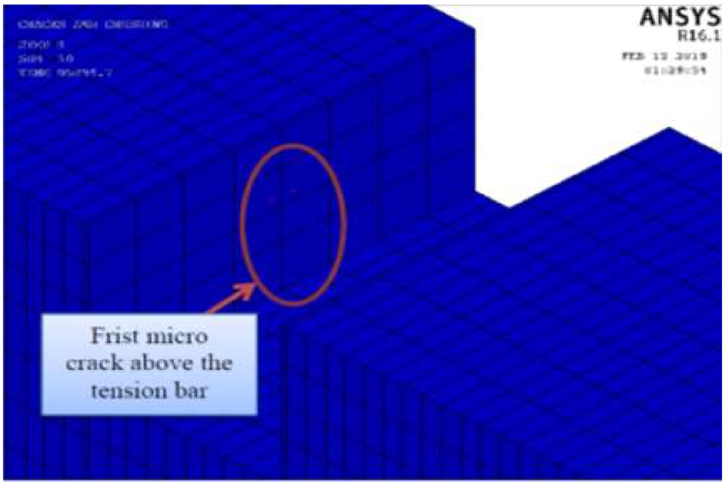

Figure 11: First micro crack determined by using ANSYS16.1 model (B1-S0-R)

7. Extended Parametric Study Results and Discussion

Additional parameters are numerically examined in addition to the experimental one, in which four models have been simulated and investigated by ANSYS16.1 up to failure.

a. Transvers reinforcement effects

Two models were numerically modeled to investigate the effects of transvers reinforcement, where the spacing are varied, from 80 mm to 120 mm, the analysis results are studied and compare with the 100 mm spacing available by the experimental beams[10]. In order to simulate the behavior of these theoretical models, modeling process based on element types, real constants as well as material properties as same as used in the tested beams analysis. The additional models (B13-S6-80 and B14-S6-120) were used to investigate the influence of stirrups spacing with 80 and 120 mm respectively.

Table 5 shows the numerical results for these models. Figure 12, Figure 13 and Figure 14 illustrate relationships of load versus upward mid span deflection, slip versus bond stress and concrete strain versus bond stress for models B13-S6-80, B14-S6-120 and the reference beam respectively.

The numerical results of these models show a noticeable influencing appeared in bond of RPC with the steel bars. The decreasing in the spacing of stirrups as in model B13-S6-80 enhancing bond strength by ratio of 16.24% while slip decreased by 10.491% in compare with ANSYS results of B1-S0-R. On the other hand, for model B14-S6-120 the higher values of stirrups spacing shows a negative impact on bond strength as decreased by 11.206%. However, slip increased by 7.143%. While, no effects were found on the other measurements for these models.

Table 5: Transvers reinforcement spacing effects

Beam designation	Max. Load (Pu) (kN)	Upward deflection (Δu) (mm)	Bond strength (μ) (MPa)	Notch Max. slip (mm)	Max. Compressive of concrete
B1-S0-R	587.68	8.041	7.576	2.240	0.004123
B13-S6-80	607.53	7.781	8.790	2.005	0.004033
B14-S6-120	577.68	8.254	6.727	2.400	0.004110

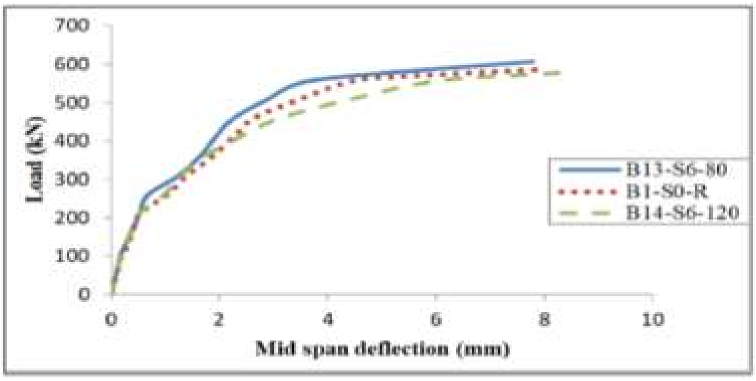

Figure 12: Relationship of numerical load-upward deflection models B13-S6-80, B14-S6-120 and B1-S0-R

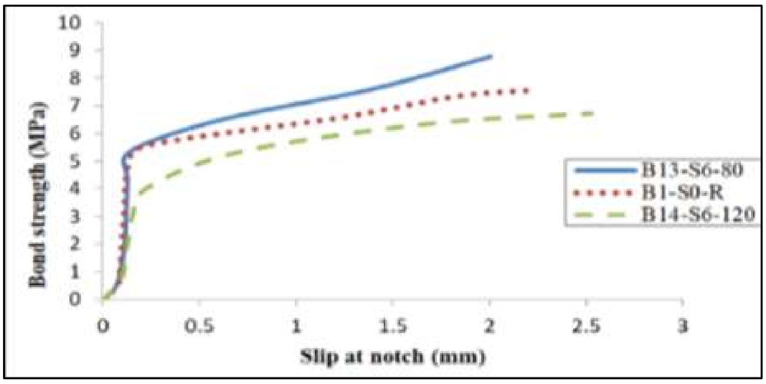

Figure 13: Relationship of numerical slip load stress models B13-S6-80, B14-S6-120, and B1-S0-R

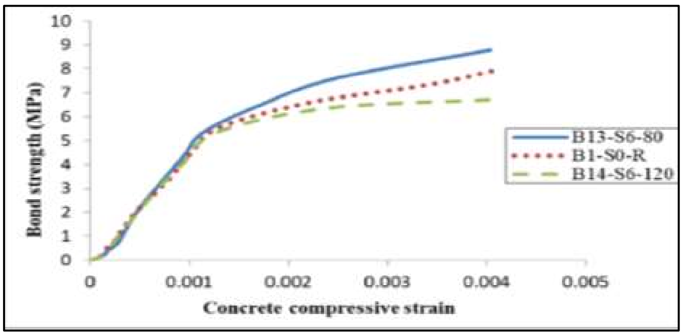

Figure 14: Relationship of numerical concert compressive strain bond stress models B13-S6-80, B14-S6-120, and B1-S0-R

Table 6: Ultra-high strength effects

Beam designation	Max. Load (Pu) (kN)	Upward deflection (Δu) (mm)	Bond strength (μ) (MPa)	Notch Max. slip (mm)	Max. Compressive of concrete
B1-S0-R	587.68	8.041	7.576	2.240	0.004123
B15-S7-130	760.02	10.855	10.3156	0.6226	0.0023995
B16-S7-140	794.32	10.896	10.8518	0.6092	0.0023097

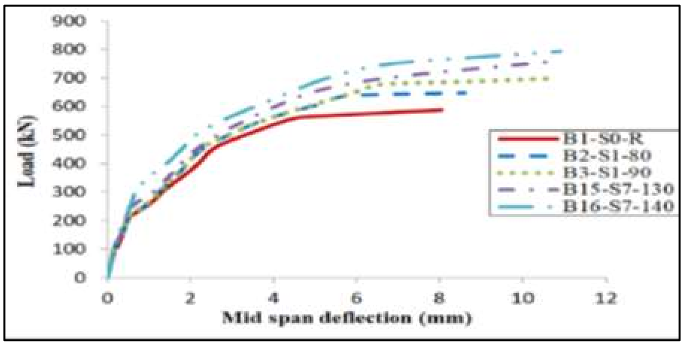

Figure 15: Relationship of numerical load-upward deflection models B15-S7-130, B16-S7-140 and B1-S0-R1

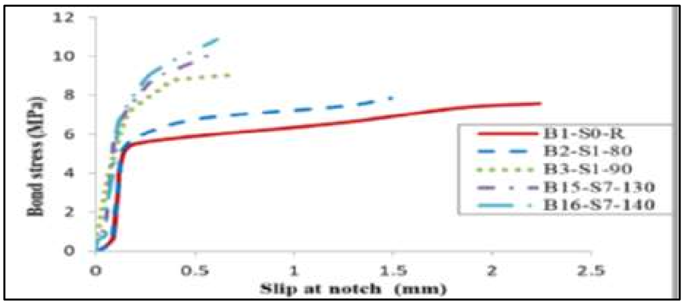

Figure 16: Relationship of numerical slip-bond stress models B15-S7-130, B16-S7-140 and B1-S0-R

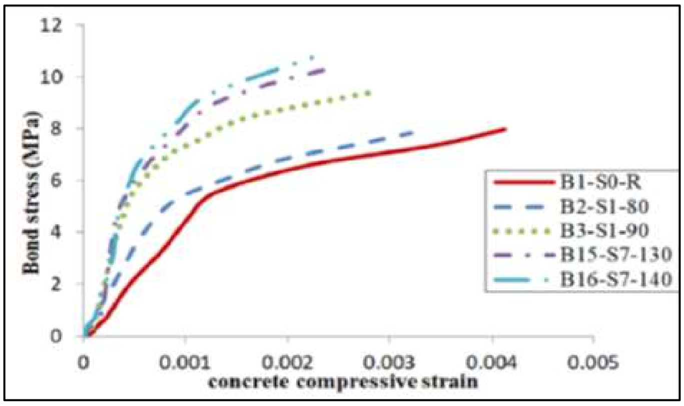

Figure 17: Relationship of numerical concrete compressive–strain bond stress models B15-S7-130, B16-S7-140 and B1-S0-R

b. Ultra-high strength effects

Two models B15-S7-130 and B16-S7-140, having compressive strength of 130 and 140 MPa respectively were modeled in this study in order to examine the influence of ultra-high strength RPC on the bond strength, slip and other parameters. Table 6 shows the results numerically obtained by ANSYS 16.1, the relationships of load versus upward deflection, slip versus bond stress and concrete strain versus bond stress were illustrated in Figure 15, Figure 16 and Figure 17 respectively. The numerical results of these two models were compared with the results of B1–S0-R, B2-S1-80 as well as B3-S1-90 found by ANSYS 16.1. The steel reinforcement for models B15-S7-130 and B16-S7-140 were used as in simulation process for B1-S0-R, while for RPC additional values of compressive strength were investigated, the RPC modulus of elasticity in addition to the splitting tensile strength that required to be used in modeling process in ANSYS 16.1 were used as found by Eyad Kadhem et al.[11]. After the end of simulation of models B15-S7-130 and B16-S7-140, the results refer to an increasing in maximum load by 35.162% as compressive strength changed from 73.214 to 140 MPa. Additional influences were found such as the increasing in bond of RPC and steel reinforcement by 35.505%, and the decreasing ratio in measured slip of 72.804%. Finally, no significant effects on concrete strain were detected.

8. Conclusions

Depending on the numerical results found by the finite element program ANSYS 16.1 of the tested beams [10] and the comparisons that made with the experimental results, and the analysis of the additional studied parameters, the following conclusions can be drawn.

1. The results of numerical analysis provide good agreements for maximum load, upward deflection, bond, measured notch slip and RPC compressive strain.
2. The numerically detected load capacity as well as the bond strength for all beams that simulated by ANSYS 16.1 show higher values than the experimental results.
3. The magnitude of the first cracking load determined by ANSYS 16.1 is lower in compare with the visible first external crack manually detected, in which the internal micro cracks usually occurred before the visible one appeared.
4. The increasing in stirrups spacing, lead to an obvious reduction in bond strength as found by the numerical analysis. In which, the increasing in spacing between stirrups from 80 mm to 120 mm increased the slip by 19.701%, on the other hand the bond strength reduced by 23.47%.
5. The investigation of ultra-high strength concrete that numerically studied, refer to highly increasing in bond strength and a remarkable reduction in the measured slip. Where, the increasing in RPC compressive strength from 73.214 MPa to 140 MPa provide a slip reduction by 72.812%, contrary the bond strength increased by 43.218%.

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