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Compression Splices of Reinforcing Bars in Reactive Powder Concrete

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Abstract

Compression splices are widely used in compression members such as columns in multi- story buildings. There are efficient design equations for compression splice of reinforcement embedded in conventional concrete proposed by design codes of practice. However, there is no design equation for compression splice in compression members made of reactive powder concrete (RPC). So, it is required to introduce a design equation to calculate the steel bars lap splice length of RPC compression members. In this study, an experimental work was conducted to investigate the effect of different variables on compression splices strength. These variables were compressive strength of concrete, transverse reinforcement amount, splice length, yield stress of reinforcement and spliced rebar diameter. The experimental results showed that; Increase in the yield stress of reinforcing bars, length of spliced bars and compressive strength of concrete result in increasing in splice strength. Meanwhile, increase in diameter of reinforcing bars result in decreasing in compression splice strength. The increase in the amount of transverse reinforcement has insignificant effect on compression spliced strength of rebar. Finite element analysis was used to analyze the tested specimens and compared between numerical and experimental result was carried out. The numerical and experimental ultimate load and load-deflection behavior is very close to each other. Finite element method was used to investigate a wide range of experimental variables values through a parametric analysis. A new proposing equation for compression splicing of rebar in RPC column is presented in this research.

Keywords: RPC; Column; Compression Splice Bars.

1. Introduction

Recent studies have been concerned with improving the properties of concrete mixtures at hardened state. RPC is proposed as a new type of concrete mixture to improve the mechanical properties of concrete for cast-in-place and precast applications [1]. Reinforcing bars are stocked by the suppliers in a length of 18 m for bars from No.16 to No.57 and in 6 or 12 m lengths for smaller sizes. In site work, it is frequently required to splice bars especially in compression members as columns in multi-story buildings. Splice mechanism represented by transfer the stresses between the lap splice steel bars through sufficient length of splice. The lapped bars are usually bonded using welding or by steel wired [2].

Over the past decade, most research and code of practice has established the minimum compression spliced length of normal strength concrete (NSC). The minimum compression spliced length in NSC is set to be according to ACI Code 318- 14 [3] as:

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For bars with $f_y \leq 420$ Mpa $\quad 0.071 f_y . d_b$ (1)

For bars with $f_y > 420$ Mpa $\quad (0.13 f_y\ 24)\ d_b$ (2)

But not less than 300 mm.

The CEB-FIB [4] proposed an equations for compression spliced length.

$$L_{sc} = \frac{(f_y . d_b)}{(1.45\ f_c{}^{0.66})} \qquad f_c \leq 50\ \text{MPa} \tag{3}$$

$$L_{sc} = \frac{(f_y . d_b)}{(5.15\ f_c{}^{0.33})} \qquad f_c > 50\ \text{MPa} \tag{4}$$

According to the test results, Carins [5] proposed an equation to calculate the length of compression splice.

$$f_{sc} = \left\{1.4\ \left(\frac{L_{sc}}{d_b}\right) + 29.4 + 0.32\left(\frac{A_{st}\ .\ f_{ys} . L_{sc}}{S_{tr.} d_b{}^2 . n}\right)\right\} . \sqrt{f_c} \tag{5}$$

For concrete compressive strength between 40 to 60 MPa, Chun et al. [6] proposed design equation for compression splice based on a regression analysis of experimentally tests conducted on 21 columns.

$$f_{sc} = \left\{\left[11.1 + 1.5\ \left(\frac{K_{tr}}{d_b}\right)\right]\sqrt{\frac{L_{sc}}{d_b}} + 16.4 + 1.8\ \delta\right\} . \sqrt{f_c} \tag{6}$$

For specimens with concrete compressive strength between 80–100 MPa, Askar (2016) [7] proposed the empirical equation.

$$\frac{L_{sc}}{d_b} = 0.008\left(\frac{f_y}{\psi_{sc.} \sqrt{f_c}}\right) - 2.17 \tag{7}$$

Where $\psi_{sc} = 1 + \left\{0.11\left(\frac{K_{tr}}{d_b}\right)\right\}$ and $K_{tr} = (\frac{40 * A_{tr}}{S_{tr.} * n})$, δ=1 in the case of presence lateral reinforcing bars at the end of the splice bars and δ=0 in the case of no lateral reinforcing bars at the end of the splice bars.

Askar [7], investigated the influence of splice length, volume of transverse reinforcement and end bearing condition on the behavior of compression lap splice. The experimental program was conducted on nine circular columns under uniaxial compression loads. Based on the experimental investigation, a design equation for splice length in compression has been developed. Also, the formulas adapted by different codes for predicting the compression lap splice length have been checked with the proposed equation. Giamundo et al. [8], studied retrofit technique for wrapping the square and rectangular cross section columns. They proposed analytical model for calculating the reinforcing bars stresses and anchorage length of spliced bars. The model was verified with the experimental results and a good agreement was found.

Tabatabaei et al. [9], demonstrated the effect of splice length of GFRP reinforcing bars on the compression splice strength. Eleven specimens were tested in the experimental program. The variables considered were splice length and reinforcing bars type. The results show that the compression splice strength of steel bars is more than that of GFRP bars. Further, $8d_b$ can be considered as the required splice length for No. 5 GFRP bars in compression splice. Chen et al. [10] studied the behavior of non-contact splices of rectangular column-circular drilled shaft interface through experimental and numerical analysis. The effect of spliced length, lap spacing, transvers reinforcement ratio and concrete compressive strength were the variables considered. The work results provided provisions in design of non-contact lap splices compression members. Najafgholipour et al. [11] tested nine RC beams under cyclic loading. Different splice length and reinforcement configuration were considered in experimental program. Pure bending of four point loads was considered in test setup. Test results showed that the spliced bars specimen designed according to ACI 318-14 could not withstand the failure loading.

Naqvi et al. [12] tested six rectangular column spliced with GFRP bars under quasi-static cyclic loads. The effect of steel fiber and the level of axial load were considered in the experimental program. The results showed that the spliced length of 60 times the bar diameter was adequate to provide a full bond along the spliced bars. Rave-Arango et al. [13] studied the behavior of reinforcement splicing at the column-column connection under cyclic loading. The results showed that there are slight differences between cast-in-place column-column connection with and without splices in cracking and damage distribution. Anagnostou et al. [14], investigated the behavior of retrofitted RC column under seismic load. Focus on the lap-spliced bars with and without previous damages externally confined with FRP. They proposed a model for calculating the shear strength and chord rotation capacity to improve the accuracy of predictions. Chun [15], studied the resistance of high strength concrete compression members under the conditions of: normal splice; splice with bond only; splice with bearing only. The results showed that the splice strength can be improved by increasing both bearing and bond splice strength. Pam and Ho [16] Investigated lap splice locations of reinforcing bars in high strength column. All columns had spliced bars within and outside the critical region and subjected to compression load and reversed cyclic displacement. It was found that the columns with lap splice within the critical zone had poor ductility and largest strength compared with the columns that had lap splices outside the critical zone.

In summary, it has been noted that, there are relatively a few experimental work in the area of compression splice strength of RPC compression member. Further, to date, as the author's knowledge, no attempts have been made to predict a new equation for compression splicing strength in RPC. So, the objective of the present study is:

- Study the compression splices strength of reinforcing bars in RPC compression members.
- Investigate the effects of several variables such as compressive strength of concrete, transverse rebar amount, yield stress of reinforcing bar, splice length and splicing rebar diameter on the compression strength of spliced rebar in RPC compression member.

Proposed a new equation to determine the compression strength of spliced rebar in RPC compression member.

2. Specimens Description

A specimen with dimensions shown in Figure 1 was used to study the compression strength of spliced rebar in RPC columns. A 12 mm diameter steel bars were chosen as longitudinal reinforcement. A 10 mm diameter rectangular ties of grade 420 MPa were used as transverse reinforcement.

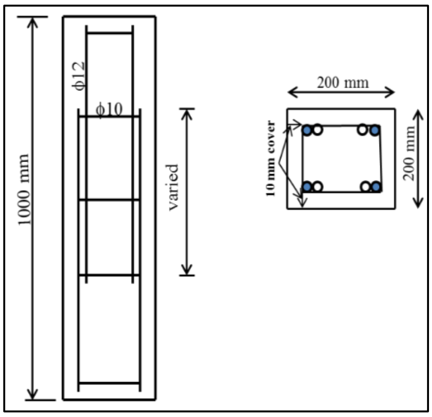

Figure1. Tested specimens details

3. Materials and Mix Proportions

Table 1 lists the composition of RPC mixture used to fabricate the tested specimens. The mean values of compressive strength of three 100× 200 mm concrete cylinders used in this investigation were 150, 170, 190 and 210 MPa. Steel fibers that has a diameter of 0.2 mm, length of 15 mm and were used in constructing all specimens.

Table1. Mix proportion of RPC

Material	Weight (kg/m^3)			
	f_c=150 MPa	f_c=170 MPa	f_c=190 MPa	f_c=210 MPa
Cement	810	910	1010	1110
Silica fume	186.3	209.3	232.3	255.3
Quartz sand	631.8	709.8	787.8	865.8
Superplasticizer	36.4	40.95	45.45	49.88
Steel fiber (0.5%)	39.25	39.25	39.25	39.25
Water	178.2	182	181.8	177.6
Water/Cement	0.22	0.20	0.18	0.16

4. Experimental Program

The experimental work was carried out in the Structural Laboratory – Civil Engineering Department at the University of Technology-Iraq. The experimental program included testing of sixteen RPC columns under compression load. Specimen designated C1-f_c150 was used as reference column.

The rest of columns properties were changed compare with reference column to investigate the effect of various variables on compression strength of spliced bars. In first group, the variable was compressive strength of concrete ranged from 150 to 210 MPa. In second group, the yield stress of spliced bars was the second variable ranged from 250 to 700 MPa. In the third group, the lateral reinforcement amount in the region of splicing rebar was the variable ranged from 2-ϕ10 to 8-ϕ10. In the fourth group, the diameter of spliced bars was the variable ranged from 12 to 25 mm. Finally, in the fifth group, splicing rebar length was the variable ranged from 120 to 350 mm. The descriptions of the tested columns were listed in Table 2.

Table2. Characteristics of tested specimens

Group	Specimens	f_c (MPa)	Lateral reinforcement in spliced zone	Yield stress of reinforcing bar (MPa)	Splice length (mm)	Diameter of bars (mm)
1	C1-fc150	150	2-ϕ10	420	120	12
	C2-fc170	170	2- ϕ 10	420	120	12
	C3-fc190	190	2- ϕ 10	420	120	12
	C4-fc210	210	2- ϕ 10	420	120	12
2	C5-fy250	150	2- ϕ 10	250	120	12
	C6-fy550	150	2- ϕ 10	550	120	12
	C7-fy700	150	2- ϕ 10	700	120	12
3	C8-T4	150	4- ϕ 10	420	120	12
	C9-T6	150	6- ϕ 10	420	120	12
	C10-T8	150	8- ϕ 10	420	120	12
4	C11-dia16	150	2- ϕ 10	420	120	16
	C12-dia22	150	2- ϕ 10	420	120	22
	C13-dia25	150	2- ϕ 10	420	120	25
5	C14-S180	150	2- ϕ 10	420	180	12
	C15-S250	150	2- ϕ 10	420	250	12
	C16-S350	150	2- ϕ 10	420	350	12

In the experimental test, all casted columns were tested under uniaxial compression load using 125 ton compression testing machine illustrated in Figure 2. The vertical displacement was measured at the end of the each column using linear variable displacement transducers (LVDT). The strains in the middle of spliced bars were measured using strain gauges attached to the bars to calculate the splice strength.

Before testing, the steel rings were placed at the ends of the tested columns to avoid the bearing failure. The applied load and LVTD were adjusted and calibrated before testing. The vertical load was applied on the top of columns using a load control method at rate of 1 kN/Sec. All specimens were tested up to failure. The failure mode were indicated and recorded using photographs.

Figure 2. Compression test machine and test setup

5. Results and Discussions

The effect of different parameters was investigated in the experimental work; compressive strength of concrete, yield stress of spliced bars, transverse reinforcement ratio in the region of spliced bars, diameter of splicing rebar and length of reinforcing splicing rebar.The following sections discuss the variables effect on spliced strength and load deflection curves of RPC columns.

5.1. Bars Splice Strength and Ultimate Compression Strength of Columns

Table 3 summarizes the bars splice strength and the ultimate axial strength of columns at failure. As expectedly, increasing the compressive strength of concrete, amount of transverse reinforcement, yield stress of reinforcing bars, bars spliced length and spliced bar diameter result in increasing the compression strength of column. Further, it can be noted the following:

- Increase the compressive strength of concrete from 150 to 210 MPa in columns (C1-f_c150, C2-f_c170, C3-f_c190 and C4-f_c210), increase the compression splice strength of reinforcing bras by 20.8%. This is due to; stresses transfer between the spliced bars is increased when the compressive strength of concrete increased.
- Increasing of transverse reinforcement amount in the zone of spliced bars from 2-ϕ10 to 8-ϕ10 in columns (C1-f_c150, C8-T4, C9-T6 and C10-T8) results in decreasing in splice strength but with a small amount. The compression splices strength of reinforcing bars increased by percentage of 3.6% compare with reference column. This, merely reflect the small effect of confinement produce by transverse reinforcement on the splice strength of reinforcing bars.
- Increase the spliced length from 120 to 350 mm in columns (C1fc150, C14-S180, C15-S250, C16-S350) increases the compression splice strength of bars. The percentage of increasing in compression splice strength was 55.9%. This confirms the dominant role of spliced length in bond splice strength. When the splice length increases, more stresses can be transfers between steel bars due to increasing the bonding between them.
- Increase the diameter of spliced bars from 12 to 25 mm in columns (C1f_c150, C11- dia16, C12-dia22 and C13-dia25) result in decreasing in spliced bar strength in columns by 26.8%. Using a big bars size increases the circumference bond area which decrease the spliced bar strength.
- Increase the yield stress of reinforcing spliced bars from 250 to 700 MPa in columns (C1-f_c150, C5-f_y250, C6-f_y550 and C7-f_y700) increase the spliced strength by 36.1%. This, due to increase in stresses transferred between the spliced bars when the yield stress of bars increased.

Table 3.Spliced bar strength and compressive strength of tested specimen

Group	Specimens	Splice strength (MPa)	Compression strength of RPC column (kN)
1	C1-fc150	280.2	5137.3
	C2-fc170	300.2	5399.2
	C3-fc190	319.1	5643.2
	C4-fc210	338.6	5872.3
2	C5-fy250	225.2	2797.7
	C6-fy550	285.2	6801.6
	C7-fy700	306.5	8789.8
3	C8-T4	324.9	5529.6
	C9-T6	318.5	5648.9
	C10-T8	312.1	5741.6
4	C11-dia16	256.7	5205.2
	C12-dia22	216.7	5341.1
	C13-dia25	205.1	5410.4
5	C14-S180	371.8	6331.6
	C15-S250	412.1	7031.3
	C16-S350	469.8	8004.2

5.2. Load-Deformation Behavior

The experimental load-deflection curves of group 1, 2, 3, 4 and 5 are shown in Figures 3a, 3b, 3c, 3d and 3e. In these figures, all specimens failed mainly by brittle cracked and the specimens behave linear elastic behavior till about 93% of the maximum load, then, due to cracks formulation and yielding of steel bars, the tested columns shows nonlinear behavior until failure. The stiffness of the splice specimen especially after the first crack increased by increasing the bar diameter, transverse reinforcement percentage, yield stress of steel bars, compressive strength of concrete and spliced length.

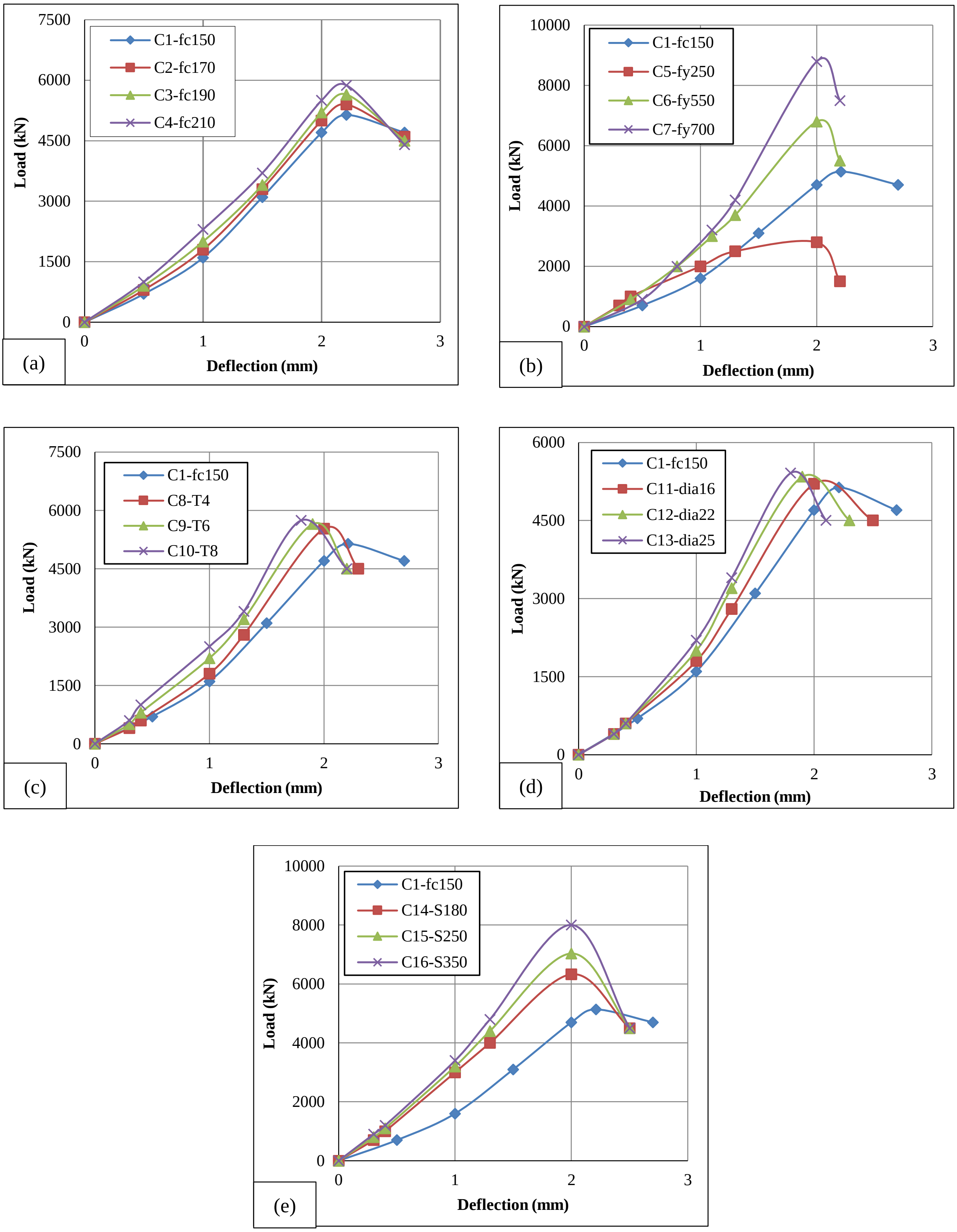

Figure 3. Load-deflection curve of tested specimens

5.3. Modes of Failure

During experimental tests, all specimens showed a brittle failure. The columns failed suddenly without any warning and they did not show any crack propagation before failure. The concrete specimens spalled horizontally at the end of spliced bars due to concentration of stresses. Splitting occurred after yielding of steel bars and a maximum stress exceeds the concrete compressive strength. Figure 4 shows the failure modes for each tested specimens.

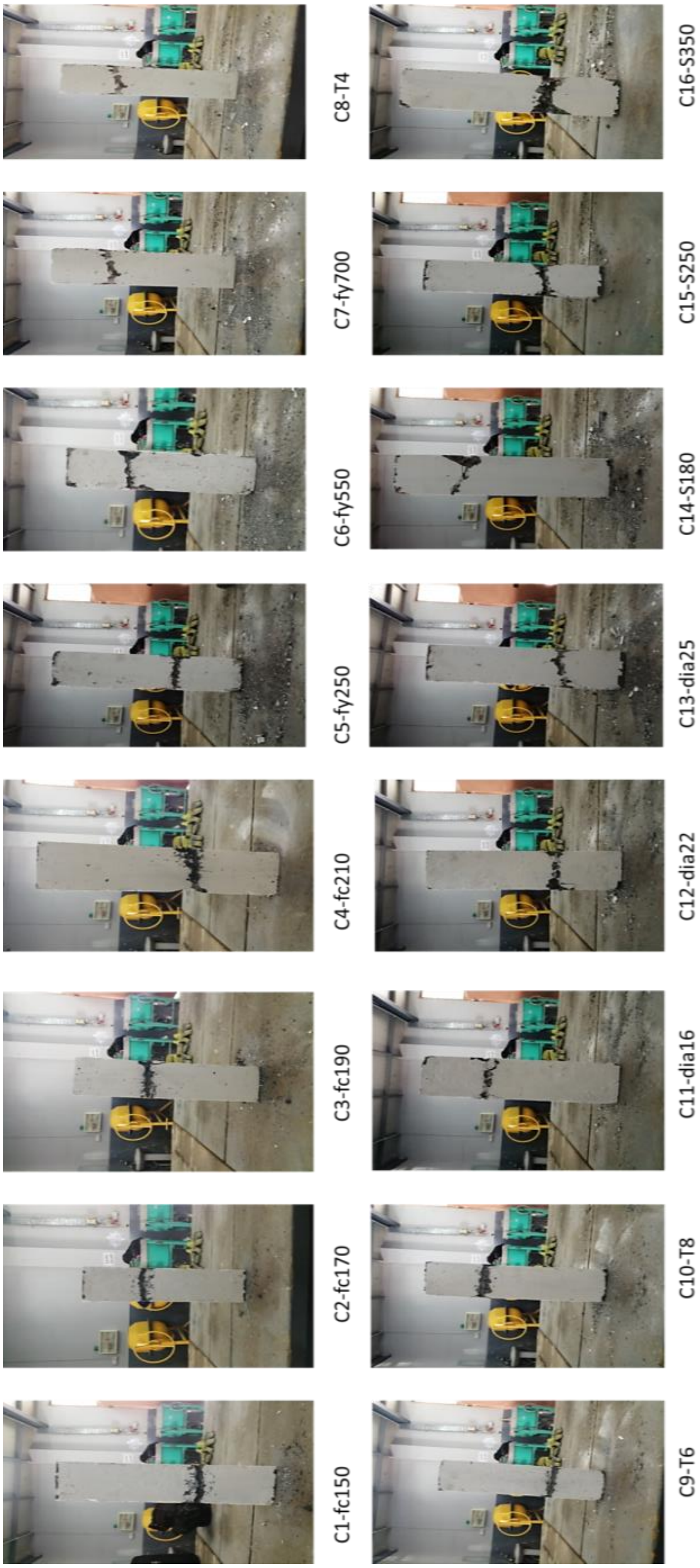

Figure 4. Modes of failure of tested specimens

6. Finite Elements Analysis

To propose equation for splicing rebar strength, more data are needed. As experimental tests are costly and time consuming, FEM was utilized in this investigated to analysis RPC column samples with different properties. LUSAS software [17] was used to conduct the numerical analysis.

6.1. Material Modeling

Multi crack concrete was chosen to simulate the reactive powder concrete. This modeling takes into consideration the non-linear behavior in compression, loss of tensile strength with compressive crushing, softening in tension leading to the formation of fully formed stress- free cracks, and crack opening and closing with both shear and normal crack surface movements [17].

The model is thermodynamically consistent, i.e. non-negative energy is produced on any loading increments. The reinforcement bond-slip relationship according to CEB-FIB model code 1990 [4] was considered in this investigation.

The bilinear law (elastic-perfect plastic) is used to model the steel reinforcing bars. The uniaxial experimental test results of concrete prisms in tension and concrete cylinders in compression were used In the FEA. Newton-Raphson method was used in nonlinear iterative solver with load steps 0.01 kN.

6.2 Geometric Modeling

The tested specimens were simply supported along the edges and subjected to axial compression load. A 3D nonlinear isotropic brick element with 16 nodes was used to represent the concrete columns. The specimens were discretized into a fine mesh of 0.01×0.01×0.01m. The load was applied on the columns by a deformation control through a steel plate with deformation step of 0.001 m. The bars reinforcement were modeled using 3-D bar element with two nodes at ends. Figure 5 illustrates the general FE geometry of the analyzed samples.

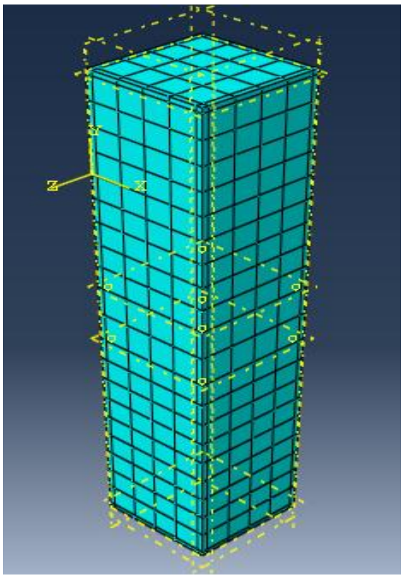

Figure 5. Geometrical modeling of RPC column

7. Validation of Numerical Results

Geometrical and material model were verified through comparing the numerical results with the experimental results as shown in Figures 6a, 6b, 6c, 6d and 6e as the compressive strength of concrete, yield stress of reinforcing bars, amount of transverse reinforcement, diameter of rebar, and length of spliced rebar was the variables selected respectively. The comparison results showed that the numerical load- deflection curves are very close to the experimentally load deflection curve. The ultimate numerical compression loads are larger than experimentally compression ultimate loads by about 9%. As a result, FE model has a good predicted to the experimental results. The verified FE model was used then to conduct a parametric study as discussed in the following section.

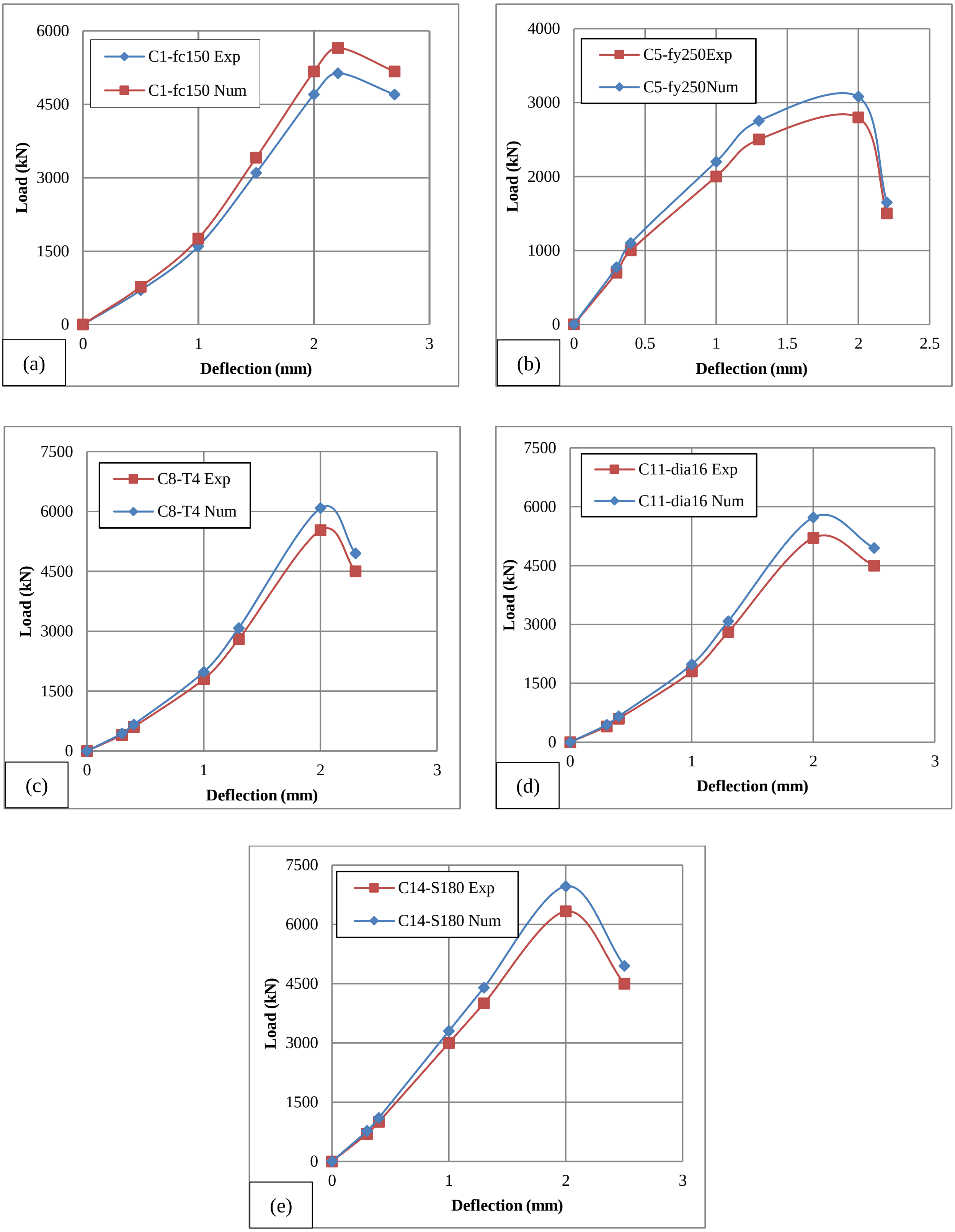

Figure 6. Experimental and numerical load-deflection curve

8. Parametric Analysis

The parametric study conducted in this study included a wide range of values for most effective variables that effect on the compression splicing of rebar in RPC. These parametric analyses investigated the following:

a. Twelve spliced bar diameters numerically analyzed ranged from 12 to 42 mm were utilized to investigate the bar diameter effect on the splicing strength (see Figure 7a). A decreasing with 0.47 power function between the compression splice strength and bar diameter was observed.

b. Fifteen yield stresses of reinforcing bar were used in the numerical analysis ranged from 250 to 1000 MPa to investigate the yield stress effect on the splicing strength. Figure 7b shows that the compression spliced strength increases when the yield stress of reinforcement was increased by a power function of 0.3.

Eleven compressive strength of concrete values ranged from 150 to 250 MPa were utilized to investigate the compressive strength effect on the splice strength. A 0.56 power function is describe the increasing in compressive strength of concrete with the splice strength of reinforcing rebar (see Figure 7c).

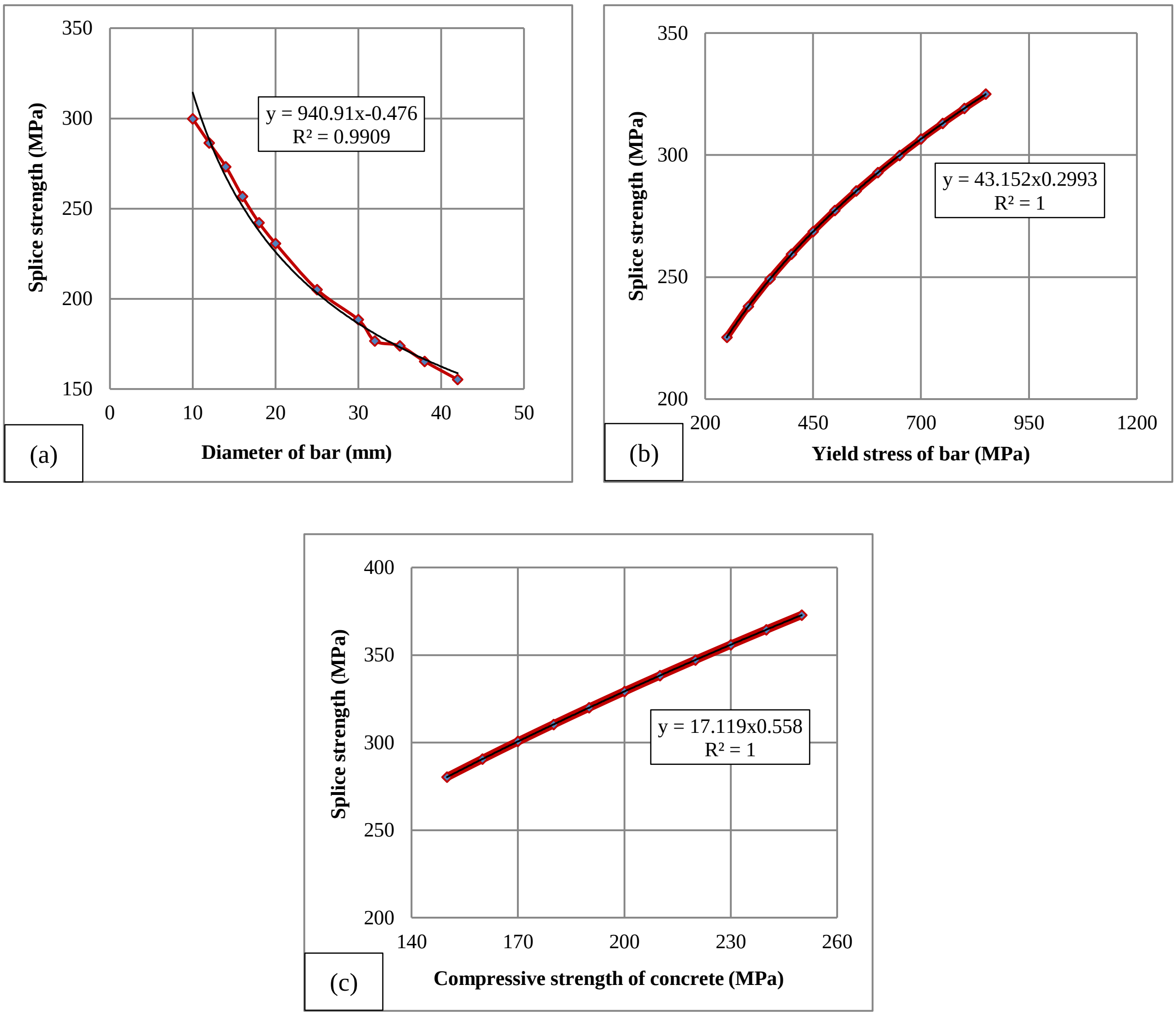

Figure 7. Variables effect on compression spliced strength

9. Proposed Design Equation

The wide range bank data provided by the numerical analysis was utilized to propose a new design equation to calculate the compression splicing strength of reinforcing rebar in RPC. The parametric analysis shows the dominate role of each variables on the compression splice strength. A regression analysis was used to analyze the data and produce the required equation. The formula of the compression splice strength in general has the following form:

$$f_{sp} = C \times \frac{(f_y^{K1} \times f_c^{K2})}{d_b^{K3}} \tag{8}$$

Where f_{sp} is the compression splice strength; C is statistics analysis constant taken to make the average propose to numerical splicing strength ratio equal to 1.0; d_b is the diameter of spliced bar; f_y is the yielding stress of rebar; constant K1, K2 and K3 were taken from the power function of the variables consideration in a parametric analysis.

After conducting the regression analysis using the parametric study results, the equation of the compression splicing strength has the following form:

$$f_{sp} = 8.6 \times \frac{(f_y^{0.3} \times f_c^{0.56})}{d_b^{0.47}} \quad (9)$$

From Figure 8 which shows the comparisons between the numerically splicing strength (from section 9) and proposed splicing strength (from Equation 9), it is clear that the two sets of values are in satisfactory agreement with the mean value of 1.02 and R^2=0.98.

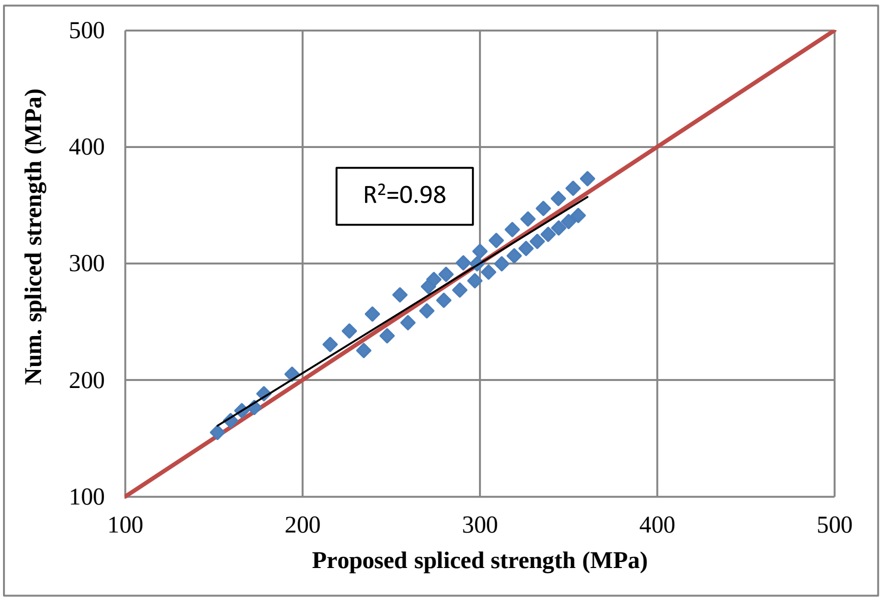

Figure 8. Relations between numerically and proposing splicing strength

10. Conclusions

In this research, the steel bars splice strength in RPC column was investigated experimentally and numerically. The influence of different variables on bars splicing strength was studied using parametric analysis. The following conclusions can be drawn from this study:

- Increase in the yield stress of reinforcing bars, splicing rebar length and compressive strength of concrete result in increasing in splice strength. Meanwhile, increase in diameter of reinforcing bars result in decreasing in compression splice strength. The increase in the amount of transverse reinforcement has insignificant effect on compression splice strength of reinforcing bars.
- The splitting at the end of spliced length is the major type of failure that happened in the RPC column with splicing bars.
- New design equation to calculate the compression splicing strength of rebar in RPC column was presented and examined with the 16 experimental results and 39 numerical results presented herein. This equation shows a good agreement with numerical result presented in this investigation with the R^2=0.98 and mean value of 1.01.

11. Notation

A_{st}	Area of transverse reinforcement	K_{tr}	Transverse reinforcement index(40A_{st}/n.s)
C	Constant of statistical analysis	L_{sc}	Length of compression splice
d_b	Diameter of reinforcing bars	n	Number of stirrups
f_y	Yield stress of reinforcement	S_{tr}	Spacing of transverse reinforcement
f_c	Concrete compressive strength	f_{sc}	Splice strength of reinforcing bars

12. Conflicts of Interest

The authors declare no conflict of interest.

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