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Research Paper

Experimental Strengthening of Damaged and Un-Damaged RC Frames with Ultra-FRC Composite Layers

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ABSTRACT: FRC concretes with high strength are practical material for strengthening existing particularly damaged concrete structures and able to dissipate seismic energy. The main purpose of this paper was to using high strength-FRC concrete for strengthening the damaged and undamaged frames. The five experimental specimens were loaded laterally and vertical gravity loads, simultaneously. The first specimen was a reference without strengthening, but the second same specimen was strengthened. The other three specimens were initially were loaded up to 55, 75, and 100% of the maximum capacity of the reference specimen and prepared as damaged specimens. The damaged specimens were laterally and vertically loaded. The test results showed that ductility of the undamaged strengthened frame was 2.2 times that of the reference specimen, while these amounts for three strengthened specimens (55, 75, and 100%) were up to 110, 60, 15 increase compared to the reference. The maximum lateral capacity of second undamaged, third fourth, and fifth damaged specimens were 38 and 35, 16, 9% more than that of reference; while the significant increase of energy absorption from 1.28 to 2.37 times reference was observed.

Keywords: Composite, Compressive Strength, Detection of Cracks, Fiber, Flexural Strength.

INTRODUCTION

Recently High-Performance Concrete (HPC) and High-Performance Fiber Reinforced Cementitious Composite (HPFRCC) were used widely for special Infrastructure construction concrete projects. Naaman et al. (2003) and Cao et al. (2018) proposed the same material with high strain hardening beside other mechanical properties higher than conventional concrete. Krenchel et al. (1989) and Poh-Yap et al. (2017) also conducted several tests on FRC and HPFRCC and showed higher toughness and ductility for these concretes and composites reinforced with Steel fibers. Moreover, Ductal, ECC, and HPFRCC materials were recommended for new and existing concrete buildings and other infrastructures (Chanvillard and Rigaud, 2003; Fischer et al., 2003; Li and Fischer, 2002a,b). Since there were no coarse aggregates in those materials, higher tensile strength and ductility but and lower elasticity modulus were mechanical properties. Many micro-cracks happened during loading in those materials and inducing higher strain hardening as special characteristics (Curbach and Jesse, 1999; Reinhardt et al., 2003). Short

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fibers had a main rule to extend micro and preventing opening cracks (Choi et al., 2014).

The experimental tests conducted by Hemmati et al. (2015, 2016) showed that the ductility of full HPFRCC beam and frames were significantly increased compared to those of the conventional concert beam. Load- displacement curves for dog-bone tensile tests for HPFRCC materials were improved (Fischer and Li, 2002a,b). Parra-Montesinos (2005) showed that plastic hinge zones of beam-column connection made with HPFRCC were improved. Canbolat (2005) investigated coupled shear walls with HPFRCC composites and showed that the performance of specimens was improved. Many existing weak concrete building can be strengthened with metal jacket (Sharbatdar et al., 2012), even other the new material such as TRC also are applicable for new structure, and also strengthening existing concrete buildings (Choi and et al., 2014; Verbruggen et al., 2014).

The amount of elastic modulus of Steel Fiber Reinforced Concrete (SFRC) and resistance Factors for reinforced concrete members are important parameters for analytical calculation particularly for damaged specimens (Akbari and Jafari, 2018; Shadafza and Saleh Jalali, 2016).

Akbar et al. (2019) have conducted several experimental tests for the seismic strengthening of deficient reinforced concrete frames using reinforced concrete haunch and their results showed that the proposed strengthening technique reduced the joint damageability and enhanced the structural stiffness, strength and ductility (Akbar et al., 2019). Also Akin and Sezer (2016) studied an experimental strengthening of several reinforced concrete frames using precast concrete panels in different geometric shapes and experimental and analytical results demonstrated that the reinforcement method significantly improved properties, such as resistance to lateral loads, energy dissipation capacity, of brick infill, reinforced concrete frames. Hu et al. (2019) conducted an experimental and analytical study on the seismic behavior of the strengthened existing single frame structures with exterior cantilevers, including 1 reference specimen and 2 specimens strengthened with shear walls. Test results indicate that the stiffness and load-bearing capacities of strengthened frames increased considerably in comparison with the reference frame.

The most recent experimental strengthening researches were concentrated on un-damaged existing RC frames, but the novelty of this paper research is on strengthening of frames damaged partially after each earthquake, so the effectiveness of the proposed methods is dependent on the number of damaged parts.

RESEARCH HIGHLIGHTS

Many existing concrete buildings are servicing but are deficient according to the design codes under seismic loading. Also some concrete structures were damaged with several percentages after severing earthquakes. The deficient undamaged or seismic damaged existing RC building should be strengthened with several economic and practical and efficient methods. The using HPFRCC or high-strength FRC material is applicable material for this purpose, so an experimental program was conducted in this paper to show the effectiveness of strengthening methods for different concrete buildings, prior to or after each earthquake. The RC frames were strengthened with ultra-FRCC HPFRCC material.

EXPERIMENTAL DETAILS

The sand (smaller than 4.75 mm) and gravel (4.75 to 12.5 mm) were used as aggregates. The used cement was type 2. PPS fibers were mixed with mortar for strengthening of the frames. The properties and shape of these fibers was shown in Table 1 and Figure 1.

Table 1. PPS fiber characteristics (Peypolsazan Factory, 2015)

Length (mm)	Diameter (micron)	Tensile Strength (MPa)
40-70	18	800
Module of Elasticity (MPa)	**Density** (kg/m^3)	**Max elongation (mm)**
3500	0.9	10

Fig. 1. PPS fibres

The longitudinal (10 and 12 mm) and stirrups (8 mm) steel bar were used for frames. Table 2 gives the detail of the tensile strengths of steel rebars.

Table 2. Tensile strengths of steel bars

Nominal diameter (mm)	Yielding stress (MPa)	Yielding strain
6	251.4	0.0012
8	410	0.00195
12	423	0.002

Table 3 showed the weights of concrete components for one cubic meter for normal concrete and also HPFRCC composite. The cylinder compressive strengths of conventional concrete and HPFRCC composite specimens were given in Table 4, and the strengths during testing of specimens were 38 and 36.3 MPa, respectively. By purpose, both concretes were design to have almost the same compressive strength.

The frame reinforcement details was shown in Figure 2. The beam and columns were reinforced with four 10 and 12 mm diameter bars as longitudinal and 6 mm diameter were used as stirrup for both beam and columns. The total lengths of the beam and column were 1.6 and 1 meter.

The name and detail of the five tested specimens are given in Table 5. RCF was initially tested to obtain the maximum load capacity (P_{max}) and then three specimens were initially tested up to 55,75 and 100% of the P_{max} of reference specimen to have damaged specimens. RCJFND (undamaged) and three specimens RCJF55, RCJF75, RCJF100 (damaged) were then strengthened with HPFRCC composite and loaded and tested.

Table 3. Concrete design (kg/m^3)

Concrete	Gravel	Sand	Cement	Initial water	w/c	Final water	PPS fibre	Silica fume
Mass concrete	834	1111	295	149	0.5	180	-	-
HPFRCC with PPS fibers	–	1730	470	155	0.33	180	9	23.5

Table 4. Concrete compressive strength (MPa)

Specimens (cylinder)	Normal concrete (casted frames) 28-day	Normal concrete (casted frames) During frame testing	Ultra-FRC During frame testing
1	28.3	44.8	37.5
2	26.7	41.9	36.0
3	26.8	38.7	35.6
4	--	36.4	--
5	--	32.3	--
Average		38.82	37.45

Table 5. Details of experimental frames

No.	Name	Description
1	RCF	Reference
2	RCJFND	Undamaged strengthened
3	RCJF55	Damaged strengthened frame (55% damage)
4	RCJF75	Damaged strengthened frame (75% damage)
5	RCJF100	Damaged strengthened frame (100% damage)

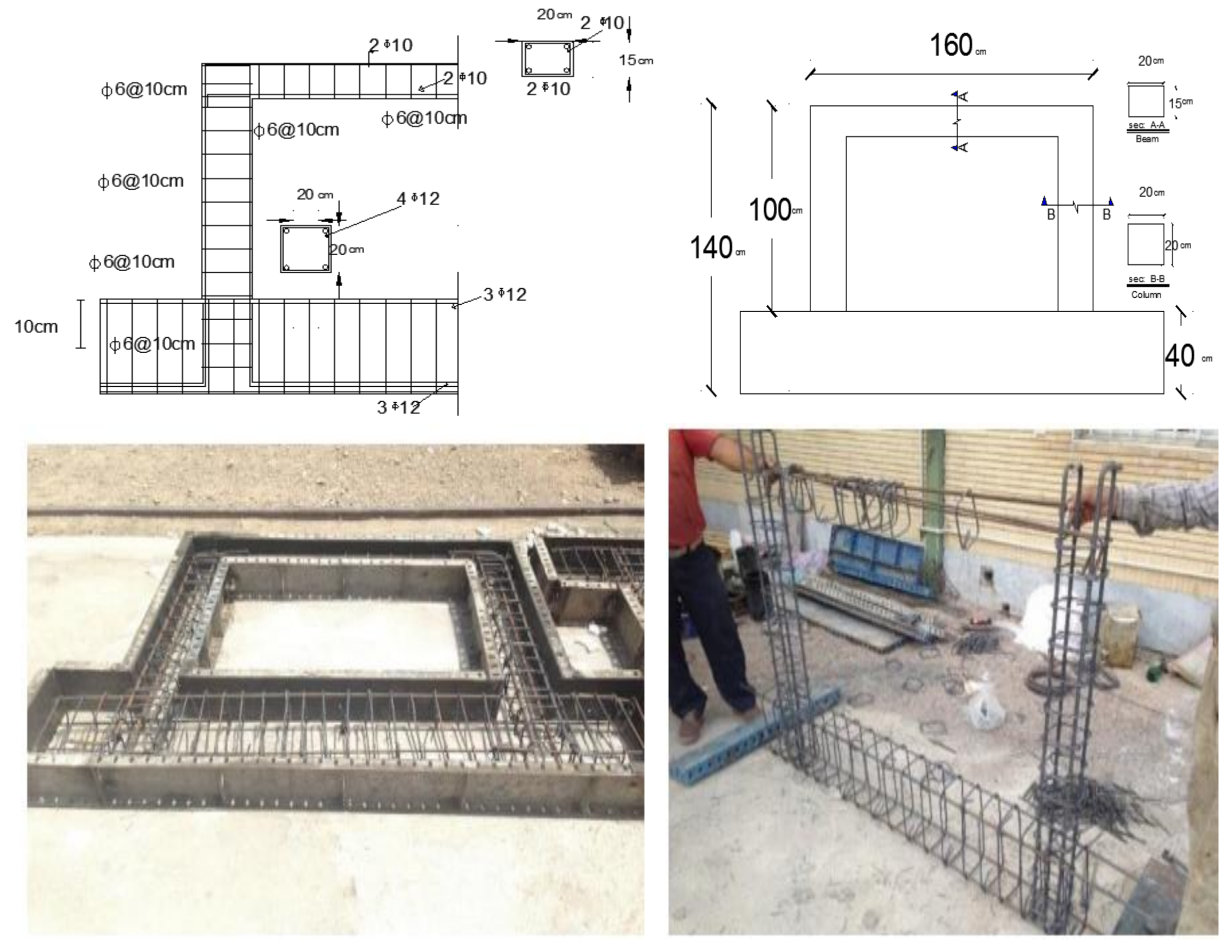
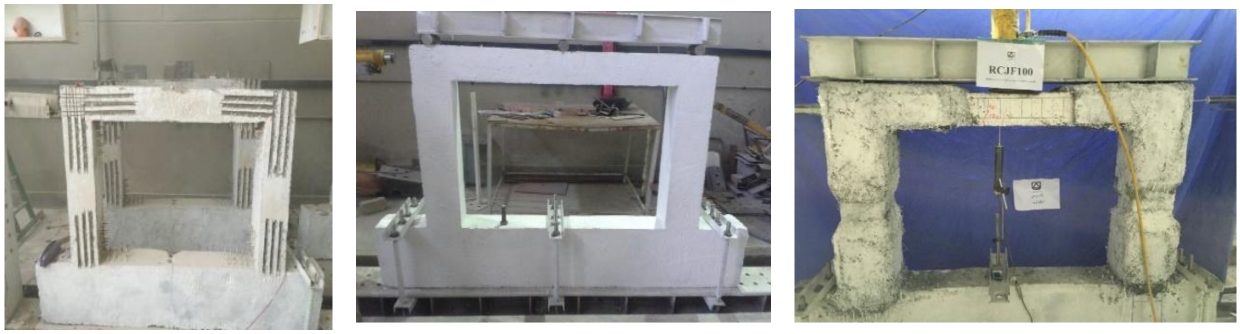


Fig. 2. Geometry and bar arrangement of specimens

To prevent probable de-bonding between the HPFRCC layer and hardened concrete, the grooves parallel the beam and column axial direction were considered on members covers. The general view of undamaged reference and strengthened undamaged and damaged frames with initial grooves before testing are shown in Figure 3.

The vertical displacement of beam and lateral displacement of the frame of all specimens was measured via three LVDT, and also the vertical and lateral load were measure by 300 kN load cells. Apart from bearing increasing lateral force by frame, a constant vertical loads was applied that was equivalent to around 10% nominal capacity (excluding rebar's strength) around 15 tons, shown in Figure 4. The loading system is displacement control and it was continued up to the collapse stage.



(a) **(b)** **(c)**

Fig. 3. Specimens before testing: a) Grooves on concrete beam and column cover; b) RCF; c) strengthened

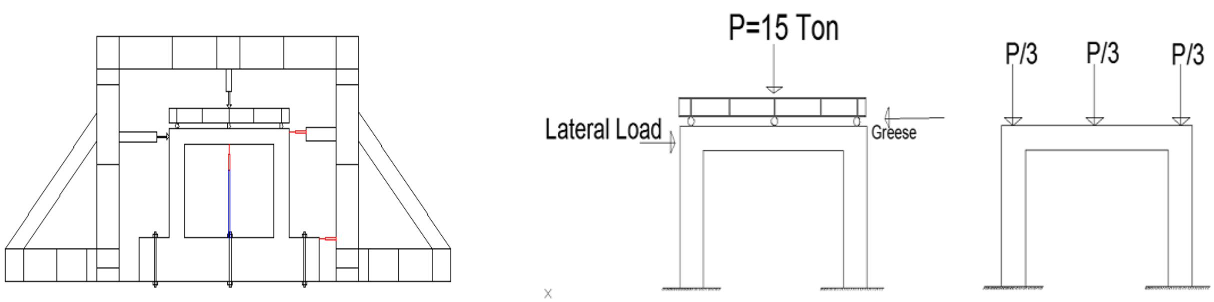


Fig. 4. Loading set-up

DISCUSSION

The load-displacement curves of five tested specimens are illustrated in Figure 5 with given details in Table 5. Also Figure 6 gives the comparison of all tested specimens curves. Tables 6 and 7 present the details of experimental results at four different steps.

The results given in Tables 6 and 7 indicate that the ratio of displacement and loads of four strengthened specimens to those of Reference specimen is increased at different four different loading steps.

Table 6. Comparison of frames displacements

Specimen	Δ_{cr} (mm)	Δ_y (mm)	$\Delta_{\max}$ (mm)	Δ_u (mm) $(at\ 0.85P_{\max})$	$\frac{\Delta_{cr}}{\Delta_{cr\ RCF}}$	$\frac{\Delta_y}{\Delta_{y\ RCF}}$	$\frac{\Delta_u}{\Delta_{u\ RCF}}$
RCF	1.10	5.5	18.89	52.79	1	1	1
RCJFND	1.60	5.8	27.09	76.76	1.41	1.02	1.42
RCJF55	1.65	5.4	44.1	110.48	1.44	0.96	2.03
RCJF75	3.2	6.9	25.4	64.9	2.76	1.21	1.21
RCJF100	2.6	7.9	21.6	60.5	2.26	1.35	1.15

Table 7. Loads of specimens

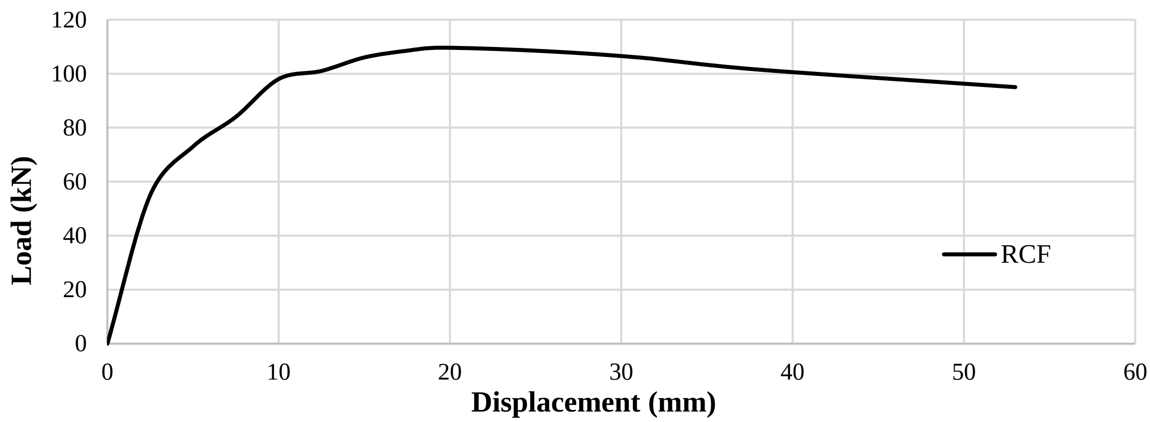
Frame	P_{cr} (kN)	P_y (kN)	$P_{\max}$ (kN)	$\frac{P_{\max}}{P_y}$	$\frac{P_{cr}}{P_{cr\ RCF}}$	$\frac{P_y}{P_{y\ RCF}}$	$\frac{P_{\max}}{P_{\max\ RCF}}$
RCF	37.3	77.1	109.1	1.39	1	1	1
RCJFND	59.1	115.1	141.9	1.21	1.53	1.46	1.28
RCJF55	47.5	99.8	138.8	1.37	1.24	1.25	1.24
RCJF75	50.8	99.8	119.9	1.18	1.32	1.26	1.08
RCJF100	50	97.7	112	1.15	1.33	1.26	1.02

The displacements of the undamaged strengthened specimen at three cracking, yielding, and ultimate stages were 1.43, 1.05, and 1.45 times of that of reference. These ratios for damaged strengthened specimens varied from 1.15 to 2.26. The reason for this increase was using HPFRCC composite with higher tensile strength around the panel zone and increasing flexibility and ductility of specimens even for those specimens with initial cracks.

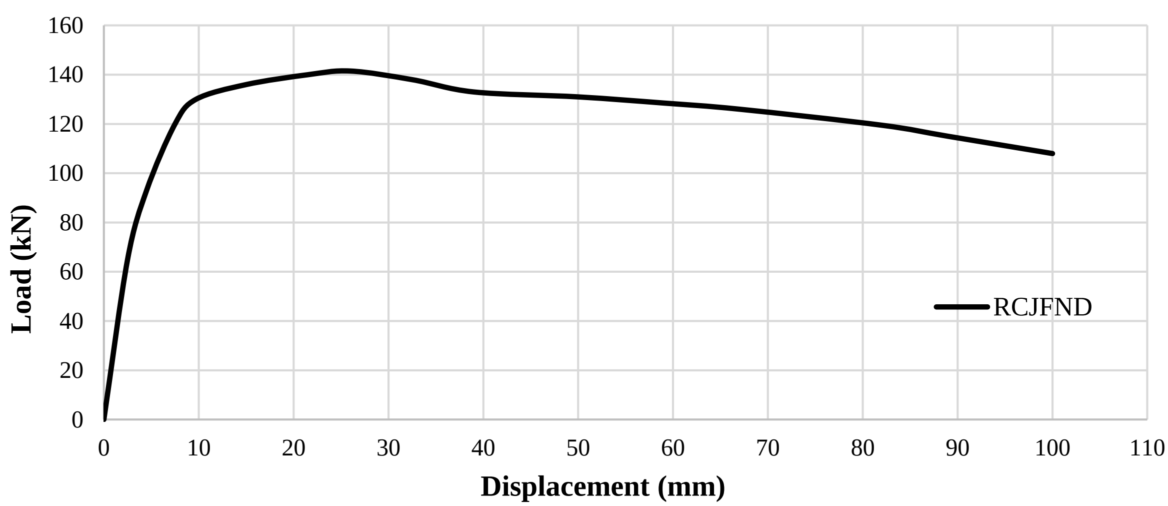
Loads of undamaged strengthened specimen at three cracking, yielding, and ultimate stages were 1.57, 1.49 and 1.30 times of that of reference. These ratios for damaged strengthened specimens varied from 1.02 to 1.33.

By increasing the initial cracks and damages from 55, 75 and 100%, the increase in amounts of maximum loads of damaged strengthened frames was reduced from 1.3 in undamaged specimens to 1.27, 1.1 and 1.02 in three damaged strengthened specimens compared to the reference frame.

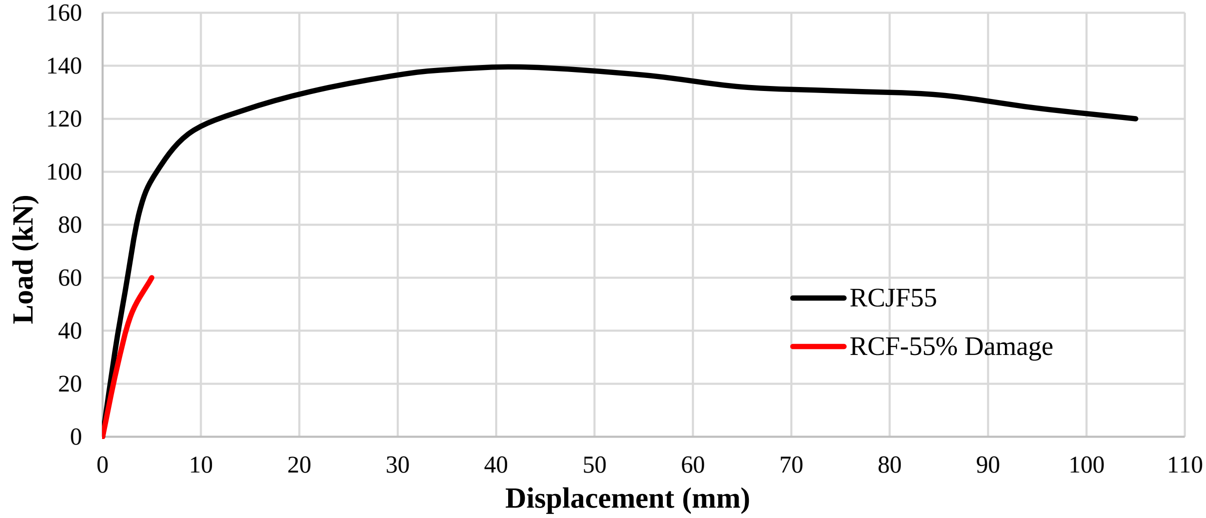
The results showed that the cracking and yielding strengths of all three damaged strengthened frames were almost the same as that of reference specimen, but the higher decreasing was observed in ultimate loads. The strengthened specimen with 100% initial dame had the same ultimate load with Ref specimen, indicating the effectiveness of the proposed method for the strengthening of seismic induced damaged buildings after severe earthquakes.



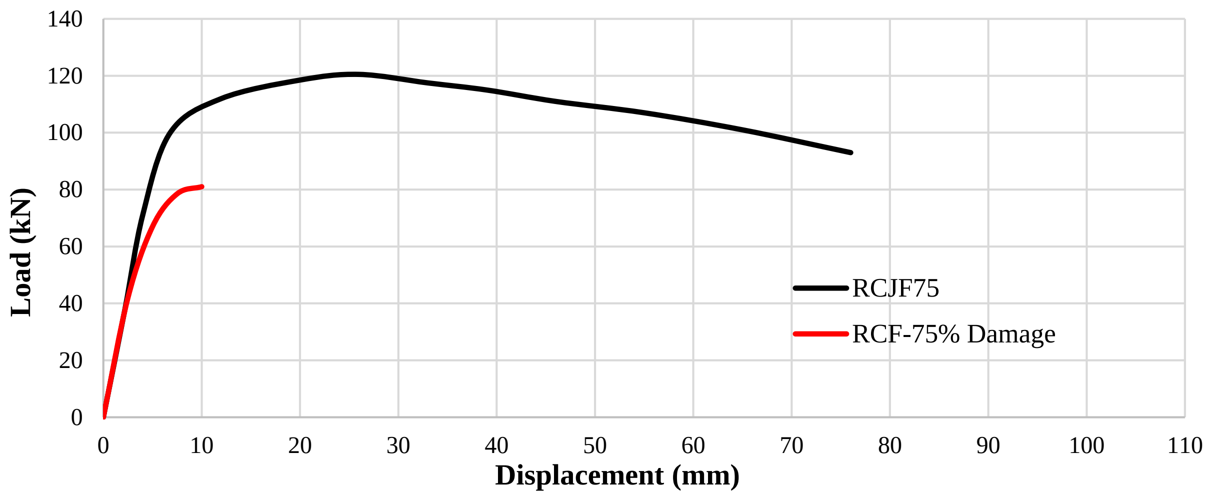
(a) RCF



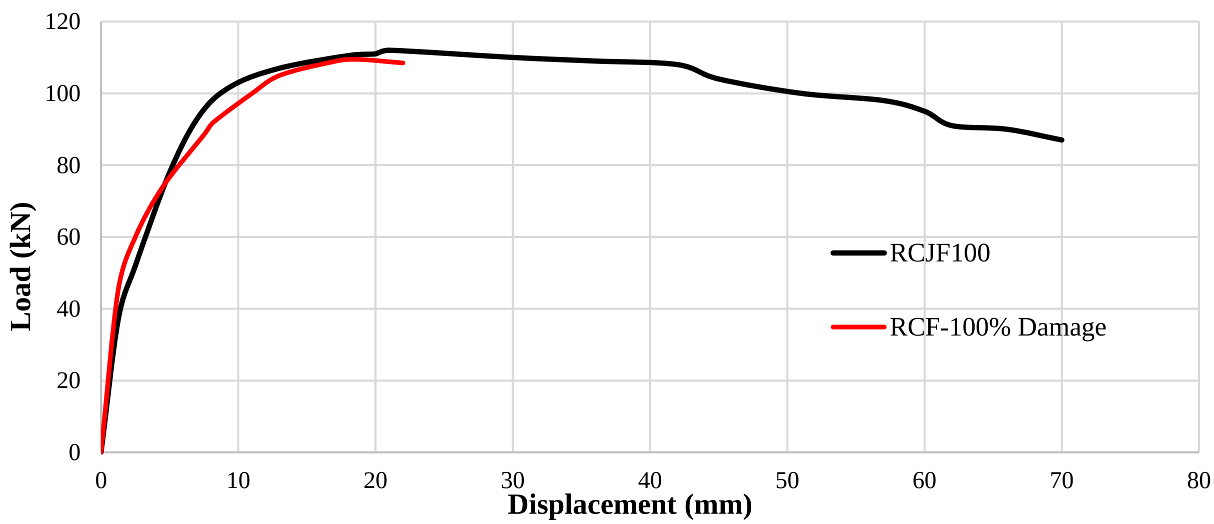
(b) RCJFND



(c) RCJF55



(d) Damaged at 75% P_{max} -RCJF75



(e) Damaged at 100% P_{max} -RCJF100

Fig. 5. Load-displacement curves of specimens

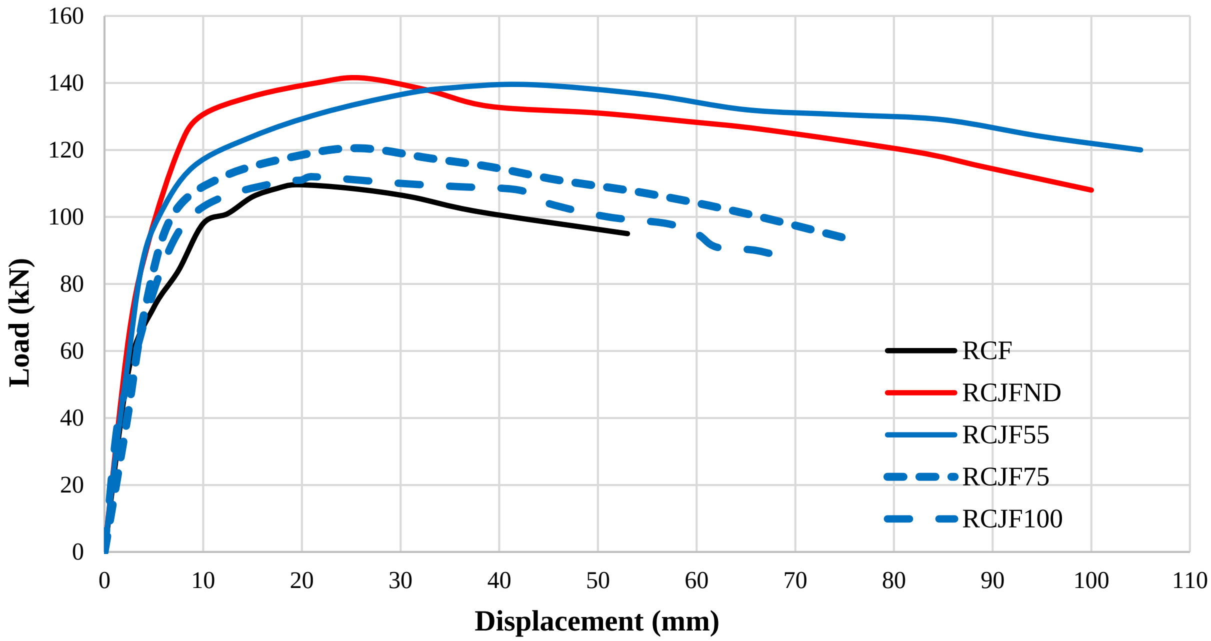


Fig. 6. Comparison of load-displacement curves

Beside of the strength loads at a different stages of each specimen, the general performance particularly due to seismic loads is very important. The seismic performance of RC buildings can be achieved through different indexes are given following.

The ductility index is defined as the ratio of the ultimate to yielding displacements and shown as $\mu = \frac{\Delta_u}{\Delta_y}$. The ultimate displacements was calculated after 15% degradation. The drift is the percentage ratio of displacement to column high at each loading case.

Table 8 gives the amounts of ductility and drift for five frames and also the increasing rate compares to the Ref frame. The drift of undamaged strengthened specimen increased 45%, while this increasing for two severe damaged specimens (75 and 100%) were 23 and 15%. The whole damaged specimen had a max drift more than that of the Reference specimen. The proposed method caused the bigger dimensions for beam and columns of each specimen and expected to have more stiffness inducing lower ductility, but the ductility of the undamaged strengthened frame was increased up to 40% due to using HPFRCC composite with higher tensile strength. The more initial cracks decreased the more initial stiffness in damaged specimens, the strengthening method improved the more reduction, and results showed that the ductility of the high damaged specimen was increased.

Comparison of strengthened frames behavior with reference frame shows that an increase up to 108 and 113% at ultimate drift and ductility was observed due to this strengthening technique, this increasing at the undamaged frame was 45% and significant 113% at frame with minor 55% damage (caused prior yielding) while decreasing was decreased at major damaged frames 75 and 100%.

Energy absorption is defined as the ratio of area under the load-displacement curve up to ultimate displacement. Table 9 gives the energy absorption of specimens. Absorbed energy by undamaged strengthened specimen increased up to 90% compared to that of the Ref specimen. This increasing proportion was decreased to 57 and 18% for strengthened frames with initial 75 and 100% damages.

Table 8. The drift and ductility of specimen

Specimen	Δ_y (mm)	$Drift_y$ **(%)**	Δ_u (mm)	$Drift_u$ **(%)**	$\frac{Drift_i}{Drift_{RCF}}$	$\mu = \frac{\Delta_u}{\Delta_y}$	$\frac{\mu_i}{\mu_{RCF}}$
RCF	5.5	0.58	52.79	5.55	1	9.35	1
RCJFND	5.8	0.60	76.76	8.06	1.43	13.05	1.38
RCJF55	5.4	0.56	110.48	11.5	2.06	19.7	2.09
RCJF75	6.9	0.72	64.9	6.81	1.21	9.15	0.97
RCJF100	7.9	0.83	60.5	6.37	1.15	7.65	0.81

Table 9. The absorption in tested frames

Schemes	W $(kN.mm)$	$\frac{W_i}{W_{RCF}}$
RCF	5075	1
RCJFND	9665	1.88
RCJF55	13318	2.59
RCJF75	7985	1.57
RCJF100	6026	1.18

The general deformability of RC frames can be shown with stiffness index what is defined as the ratio of load to displacement at the yielding stage. This index was calculated as a bilinear load-displacement curve. Table 10 gives the amounts of stiffness for five frames. The stiffness index by undamaged strengthened frame was increased up to 42% compared to that of the Ref specimen. By increasing the amount of damage from 55, 75, 100%, the stiffness index of damaged strengthened frames was decreased even less than that of the Ref specimen.

The initial crack effect on different specimens (undamaged and damaged) is calculated and shown in Table 11. The general performance of specimens is investigated by comparison of their loads (at three stages), ductility, energy absorption, and stiffness with those of undamaged frame, RCJFND.

The cracking loads of three damaged frames (55, 75 and 100%) decreased up to 29, 21 and 22% compared to undamaged specimen, while these decreasing amounts for yielding loads were 21, 20 and 20%, respectively. More decreases were observed at maximum load capacity from 4 to 26% by increasing the number of initial cracks. The significant decreasing happened for stiffness amounts of damaged frames from; 12, 38 and 51% for specimens with of initial damages of 55, 75 and 100%.

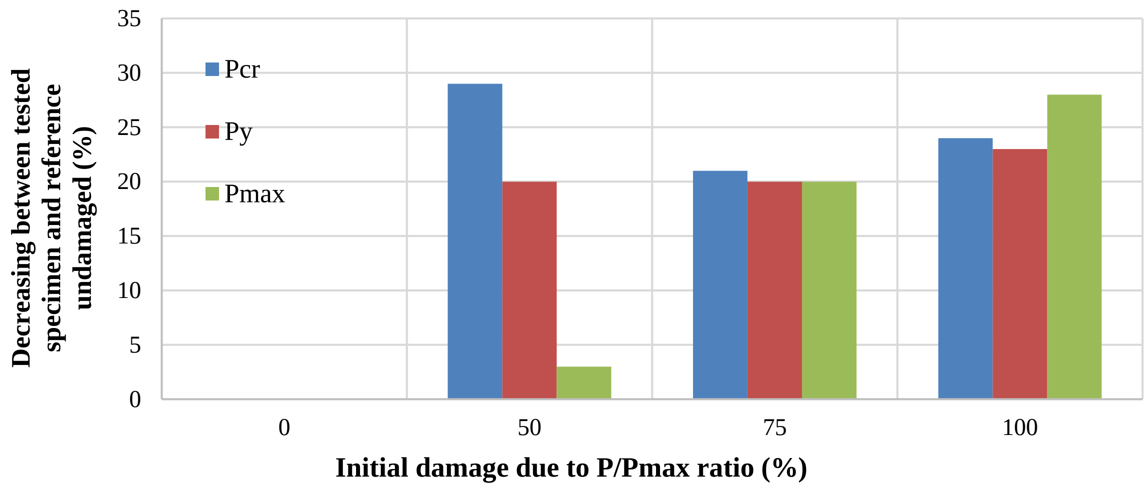
The minor damage 55% (less than yielding stage) had a positive effect on ductility and energy absorption of the frame and these amounts were increased up to 73%. The ductility and energy absorption of frames with 75% (almost at the yielding point) and 100% (maximum damage) were averagely decreased up to 37 and 67%. The differences in loads and performance parameters of all five frames versus the percentage of damage of frames and the effects of the proposed strengthening method are shown in Figure 7.

Table 10. The stiffness of specimens

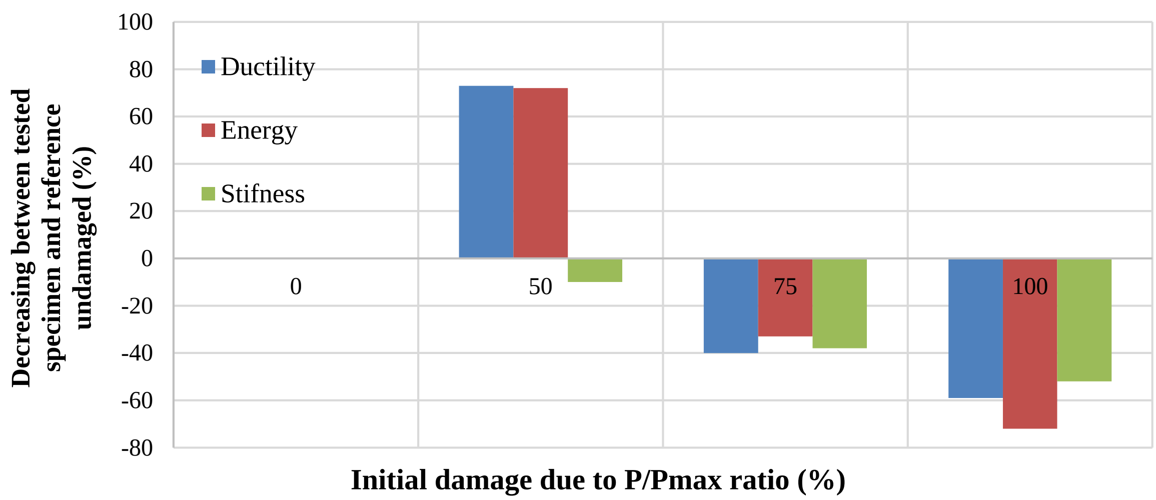
Specimen	Δ_y (mm)	P_y (kN)	$k = \frac{P_y}{\Delta_y}$ (kN/ mm)	$\frac{k_i}{k_{RCF}}$
RCF	5.5	77.1	13.6	1
RCJFND	5.8	115.1	19.3	1.41
RCJF55	5.4	99.8	18.08	1.29
RCJF75	6.9	99.8	14.21	1.03
RCJF100	7.9	98	12.4	0.9

Table 11. The effects initial cracks on specimens

Frame	$\frac{P_{cr}}{P_{cr\ RCF}}$	$\frac{P_y}{P_{y\ RCF}}$	$\frac{P_{max}}{P_{max\ RCF}}$	$\frac{\mu_i}{\mu_{RCF}}$	$\frac{W_i}{W_{RCF}}$	$\frac{k_i}{k_{RCF}}$
RCJFND	1.53	1.46	1.28	1.38	1.88	1.41
RCJF55	1.24	1.25	1.24	2.09	2.59	1.29
RCJF75	1.32	1.26	1.08	0.97	1.57	1.03
RCJF100	1.31	1.26	1.02	0.81	1.18	0.9
Changing on 55% damaged frame (%)	-29	-21	-4	+71	+69	-12
Changing on 75% damaged frame (%)	-21	-20	-20	-41	-31	-38
Changing on 100% damaged frame (%)	-22	-20	-26	-57	-70	-51



(a) Comparison of loads



(b) Comparison of performance parameters

Fig. 7. Loads and performance parameter difference versus the percentage of damage of frames

The comparison of all test results showed that the application of the suggested method helped to increase of load capacity, ductility, energy absorption and stiffness of un-damaged specimen up to 30, 40, 90 and 42%. The specimen with minor damage before the yielding of tensile bars had the same capacity and stiffness but higher ductility and energy absorption. Also the suggested method helped the major damaged specimen to back to its initial capacity, stiffness and energy but the strengthened specimen had lower ductility. Generally, this method and idea can be used for many concrete structures such as beams or columns damaged after extra loading.

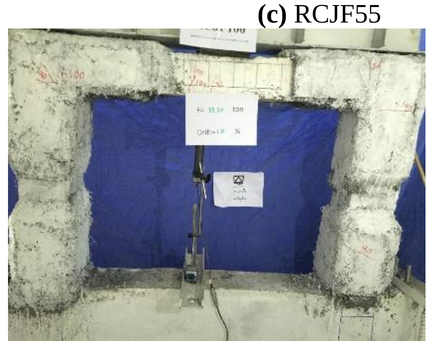
The crack patterns of five frames for two different load stages, the yielding and maximum, are and shown in Figures 8 and 9. Up to yielding stage, all cracks for all specimens were flexural cracks at two ends of the beam and after that, the crack widths were extended at the beam and new cracks happened at two ends of the columns.

(a) RCF

(b) RCJFND

(c) RCJF55

(d) RCJF75



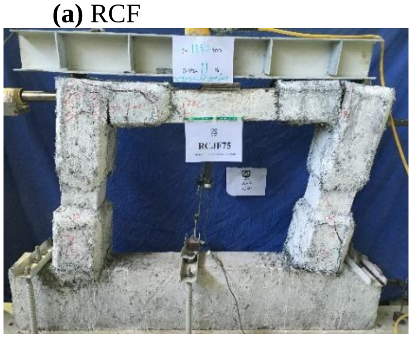
(e) RCJF100

Fig. 8. Crack patterns yielding displacement

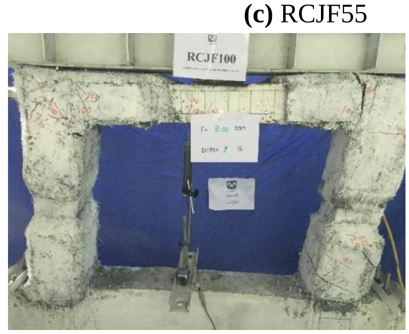
(a) RCF

(b) RCJFND

(c) RCJF55



(d) RCJF75



(e) RCJF100

Fig. 9. Crack patterns ultimate displacement

CONCLUSIONS

Five companion reinforced concrete frames were cast and one of them as weak reference specimen was tested and the other four specimens were strengthened with HPFRCC composite and tested with two different cases, un-damaged and initial damaged cases. The obtained results were given as follows:

- The ductility of initial damaged frames was increased up to 68% via strengthening with HPFRCC composite, indicating the positive effect of this proposed method.
- In frame with steel fiber concrete (0.25% fiber), ductility and energy absorption are 86% and 237% of reference frame, respectively. This is due to the favorable performance of steel fibers and bridging and energy depreciation.
- Undamaged strengthened specimen had the highest load capacity, stiffness and energy absorption.
- The amounts of yielding loads and energy absorption of the undamaged frame with strengthened with HPFRCC were 157 and 42% more than those of the reference frame due to micro-cracks observed in the strengthened frame.
- The ultimate loads of strengthened specimens were decreased compared with the reference frame depending on their initial crack damages.

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