Original Research Article

REPAIR AND STRENGTHENING OF R.C FLAT SLAB CONNECTION WITH EDGE COLUMNS AGAINST PUNCHING SHEAR

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ABSTRACT

Aims: Study the strengthening and repair of the flat slab-edge column connections against punching shear.
Study design: Parametric study is carried out by varying the number of strengthening and repair stirrups rows and the stirrups materials.
Methodology: This paper presents the efficiency of using Fiber Reinforced Polymers (FRP) systems to strengthen and repair the flat slab-edge column connections subjected to punching shear. These systems consisted of external FRP stirrups made from glass and carbon fibers. Also, steel links were used as a conventional system for strengthen and repair for comparison. Test results of Thirteen half-scale specimens reinforced concrete flat slab-edge column connections were prepared and tested under vertical punching shear load. The research included - one specimen not strengthened nor repaired - which considered as control specimen. Three specimens strengthened with one external row of stirrups made from Glass Fiber Reinforced Polymer (GFRP), Carbon Fiber Reinforced Polymer (CFRP), steel links, respectively. Three specimens strengthened with two external rows of stirrups made from (GFRP), (CFRP), steel links, respectively. Three specimens repaired with one external row of stirrups made from (GFRP), (CFRP), steel links, respectively. Three specimens repaired with two external rows of stirrups made from Glass (GFRP), (CFRP), steel links, respectively. Also, the experimental ultimate loads were compared with the calculated values according to ACI 440.
Results: The experimental results included ultimate load, load-deflection relationships, punching shear resistance, relative ductility, flexural stiffness & punching shear angle**.**
Conclusion: The experimental results showed an increase in punching shear resistance and flexural stiffness for the strengthened and the repaired specimens compared to control specimen. Also, the strengthened and the repaired tested specimens showed a relative ductility enhancement and increase in punching shear angle. The calculated ultimate loads based on ACI 440 procedures were higher than the experimental results by 36 to 66%.

Keywords: Edge column-flat slab connections, Punching shear Failure, strengthening and repair , Fiber Reinforced Polymer.

1. INTRODUCTION

Now flat slab is one of the most common systems in reinforced concrete structures. A flat slab floor system is often the choice when there is a need for more clear head such as multi-storey car parks, libraries and multi-storey buildings where larger spans are also required. It provides architectural flexibility, more clear space, less building height, easier formwork and, consequently shorter construction time. Failures of flat slab structures were reported during construction [1], flat slab can be supported by a column capital or a drop panel in order to provide a good resistance to punching shear around the column. However, in some cases, column capitals and drop panels cannot be used for architectural reasons or to save space between the floors. In this case, flat slabs have a major weakness, namely vulnerability to punching shear failure at the column-slab junction column. A serious problem that can arise in flat slab is the brittle punching failure due to transfer of shearing forces. When the slab-column connection is subjected to heavy vertical loading, cracks will occur inside the slab in the vicinity of the column [2]. Then shear stresses due to heavy vertical loading in the region of the slab around the column become too high, a punching failure will occur. In case of edge connections the distribution of stresses around the column is uneven, therefore the behaviour is non-symmetric [3]. There are mainly two ways to increase the punching shear strength of concrete slabs: 1- Increasing the slab thickness in the vicinity of the column by providing a drop panel or a column head. 2- The strengthening of slab-column connection against punching shear stress by using traditional methods (steel plates, steel stirrups, steel studs, or increasing concrete dimensions) [4].

2. Experimental Investigation

A test program was carried out to study the potential of using different materials in the repair and strengthening of reinforced concrete flat slab-edge column connections subjected to punching shear. The tested specimens were half-scale models of a typical prototype flat-plate structure. The dimensions of the tested slabs were chosen to cover the area of the negative moment region around the edge column and inside the line of contra-flexure.

2.1 Details of test specimens

Thirteen half-scale specimens were prepared, All the specimens have the same dimensions, as shown in Fig.1, the plane dimensions are 900*900 mm, the thickness is 130 mm with average effective depth 115 mm. Column cross section dimensions are 150*150 mm and its height is 150 mm. Column was casted monolithically at the edge of the slab, with extension upper and lower the slab faces. The tested specimens were designed to be simply supported at the column (point support) and on the opposite side of the slab (line support) with clear spans 750 mm. High tensile steel bars of 12 mm diameters were used as top and bottom reinforcement, the top rft. is 9 Φ 12 mm in the transversal direction (parallel to the edge) and 5 Φ 12 mm in the longitudinal direction, and the bottom rft. is 12 Φ 12 mm in the longitudinal direction and 5 Φ 12 mm in the transversal direction. The columns were reinforced with 4 Φ 12 vertical high tensile steel bars and 8 mm normal mild steel stirrups every 100 mm. The reinforcement details of the specimen are shown in Fig. 2. The specimens are divided into five groups, as shown in Table 1.

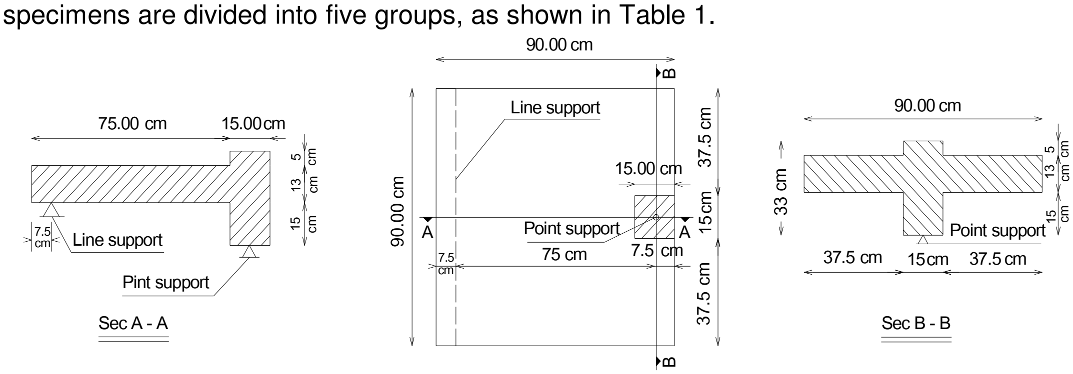


Fig. 1. The specimen dimensions and supports.

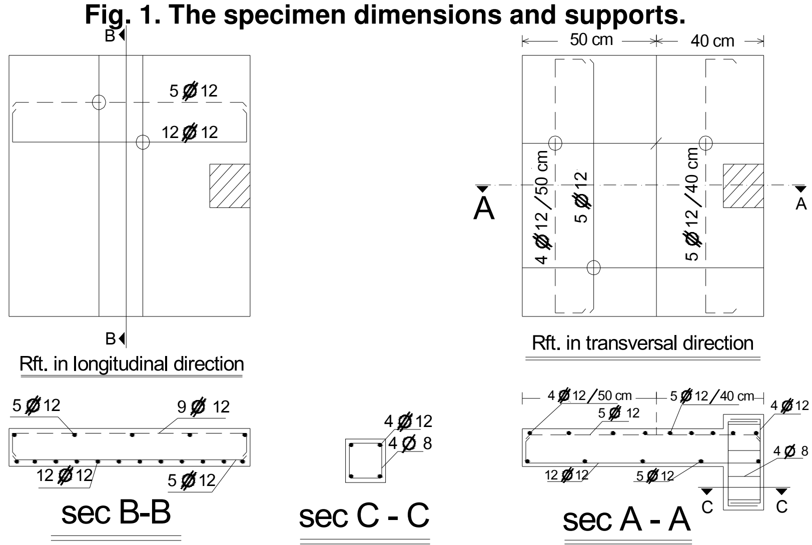


Fig. 2. Full details of the specimen reinforcement.

Table 1. The experimental test program.

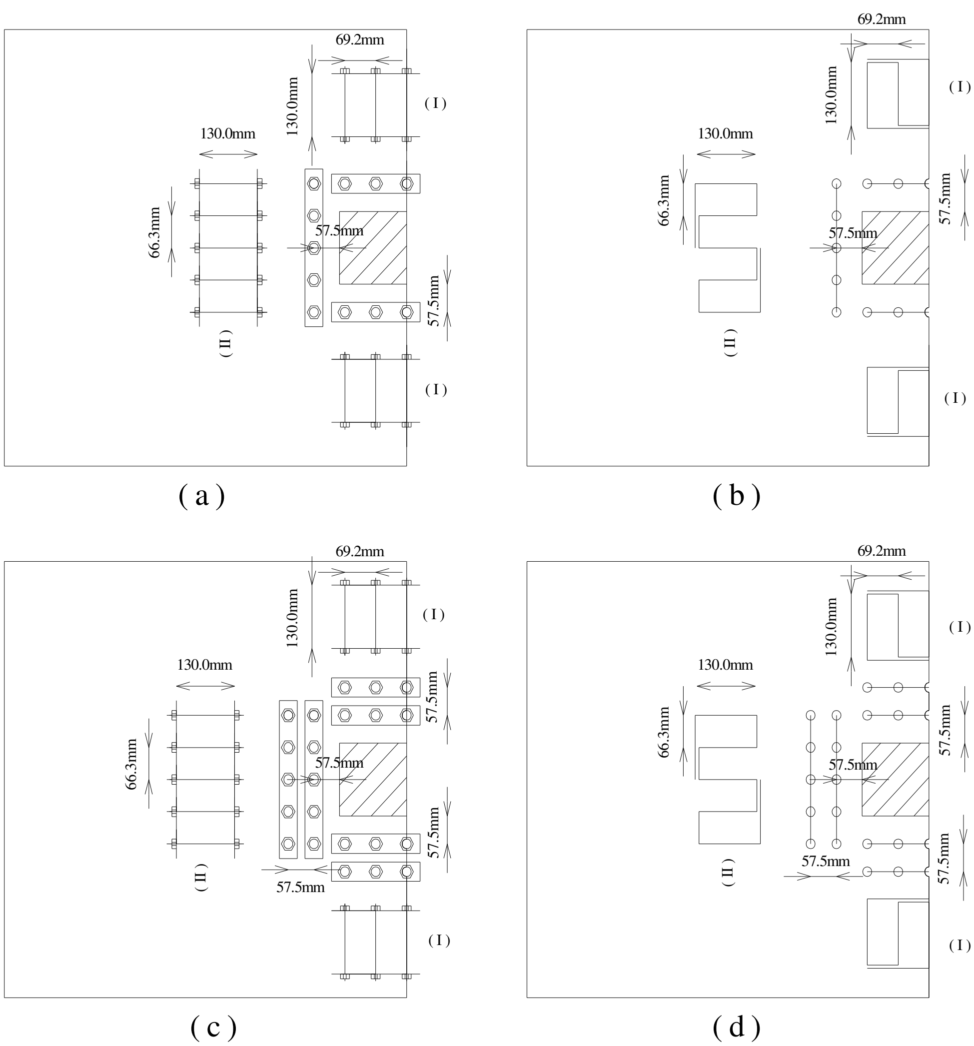
Group	Specimen code	Specimens Description			Pre-loading level
		Specimen state	Number of rows	Strengthening/ Repair elements	
No. 1	C	control	---	----------	0
No. 2	SG1	Strengthening	1	GFRP stirrups	0
	SC1	Strengthening	1	CFRP stirrups	0
	SS1	Strengthening	1	Steel Links	0
No. 3	SG2	Strengthening	2	GFRP stirrups	0
	SC2	Strengthening	2	CFRP stirrups	0
	SS2	Strengthening	2	Steel Links	0
No. 4	RG1	Repair	1	GFRP stirrups	0.75Pmax.
	RC1	Repair	1	CFRP stirrups	0.75Pmax.
	RS1	Repair	1	Steel Links	0.75Pmax.
No. 5	RG2	Repair	2	GFRP stirrups	0.75Pmax
	RC2	Repair	2	CFRP stirrups	0.75Pmax

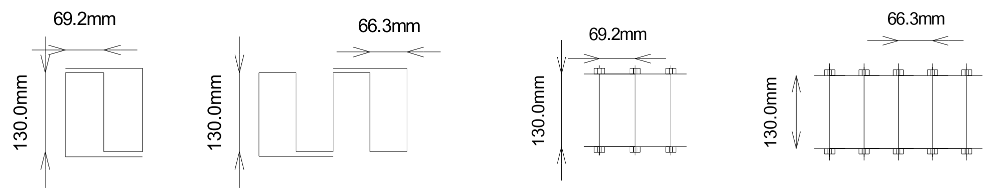
RS2	Repair	2	Steel Links	0.75Pmax.

*Pmax. : The ultimate load of the control specimens

2.2 Preparation of test specimens

A wooden moulds were made from plywood sheets achieving the required dimensions. The forms were painted with thin layer of oil before concrete placing. After the steel reinforcement were installed concrete mix was placed after mixing, then the concrete was vibrated mechanically and the concrete surface was finished. After curing period the specimens were left in the lab atmosphere until test date. After that, the thirteen specimens were divided to five groups as shown in Table 1. All the specimens, except the control one, were drilled to make full penetrated holes of 10 mm diameter at the positions of vertical legs of FRP stirrups or steel links. For strengthening or repair of the column-slab connection of the tested specimens; GFRP, CFRP and steel stirrups of one row and two rows were used as shown in Fig. 3. The interwined FRP closed stirrups were manually manufactured using fiber cross sectional area equivalent to circular cross-section of 8 mm diameter. The FRP wraps were saturated by polyester in case of glass fiber and by epoxy resin (sikadur-330) in case of carbon fiber, and the interwined strands were formed and stitched through holes along the slab thickness. 24 hours later, the clearance between GFRP or CFRP stirrups and holes was filled by polyester and epoxy resin, respectively, to ensure good bond between FRP stirrups and concrete. The steel stirrups were locally fabricated using normal tensile steel bars of 8 mm diameter fixed at upper and lower surface by steel nuts supported on steel plates of 5 mm thickness and 40 mm width.





[FRP stirrup type I] [FRP stirrup type II] [Steel stirrup type II] [Steel stirrup type II]

(e)

Fig. 3. Details of strengthening and repair systems; one row of steel stirrups (a), one row of FRP stirrups (b), two rows of steel stirrups (c), two rows of FRP stirrups (b) and details of stirrups types (e).

3. Material properties.

3.1 Concrete

A trial mixes were prepared and a suitable mix was selected to get target cubic compressive strength of 250 kg/cm2 after 28 days, A concrete admixture, commercially called Addicrete BVF was used to improve the workability of fresh concrete. The constituents of concrete mix and its proportions are presented in Table 2.

Table 2. The constituents of concrete mix and its proportions.

Compressive target strength kg/cm2	Cement (Kg)/m3	Crushed dolomite (Kg) /m3	Sand (Kg) /m3	Water (Liter)/m3	Super Plasticizer (Kg) /m3
250	350	1260	630	175	3.5

3.2 FRP

The E-glass fibers used to produce the GFRP stirrups were sika wrap Hex-430G, which is a product of sika company, and the used polymer was polyester. High strength carbon fibers manufactured by Sika Company under trade name Sika Wrap Hex-230C and epoxy Sikadur-330 are used to produce the CFRP stirrups. The Mechanical properties of the used fibers are given - according to the manufacturer- in Table 3.

3.3 steel links

8 mm diameter normal mild steel (24/35) bars are used to fabricate the steel stirrups for strengthening and repair.

Table 3. Mechanical properties of FRP [5].

Property	GFRP	CFRP

Fabric design thickness	0.17 mm	0.14 mm
Weight / Area	0.43 kg/m^2	0.225 kg/m^2
Tensile strength	22500 kg/cm^2	35000 kg/cm^2
Modulus of elasticity	700000 kg/cm^2	2300000 kg/cm^2
Strain at failure	3.10%	1.5%

4. Test Procedure

The tests were carried out in the Reinforced Concrete Laboratory at the Faculty of Engineering in Benha. The loading system consisted of rigid system of reaction frame, 100 ton maximum capacity, and hydraulic jack, 100 ton maximum capacity, connected to electrical pump which provides oil pressure. The specimens were tested under vertical concentrated load which is distributed to uniform line load acting on the slab upper surface, as shown in Fig. 4. A rigid steel frame is used to distribute the concentrated load to uniform distributed line load, as shown in Fig. 5. As already mentioned, the specimen was supported at the column -as a point support- and at line support on the opposite side of the column. A load cell of 100 ton maximum capacity was installed between the column and its support to record the force which causes the punching shear. Vertical deflection, first cracking load and ultimate failure load, were recorded. Five linear variable differential transformers (LVDT) were used to record the deflection at 5 detected points, as shown in Fig. 6. Propagation of cracks was marked after each load increment up to failure. Fig.7. illustrates the test set-up.

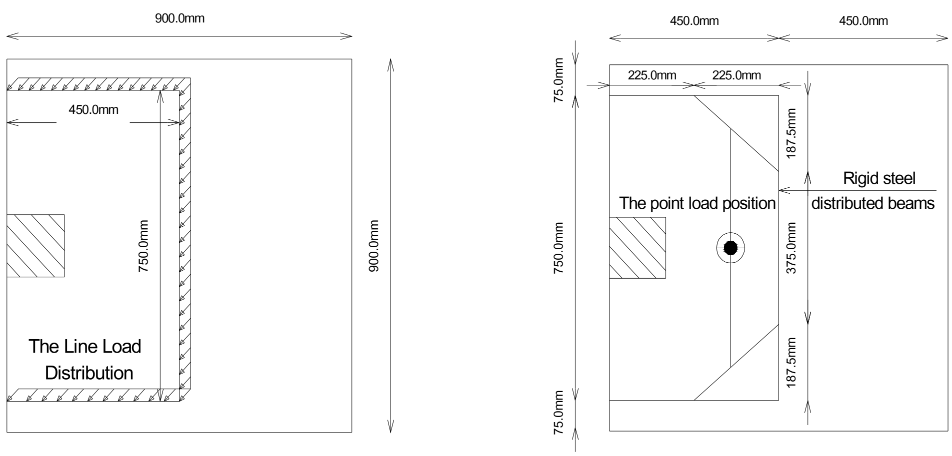


Fig. 4. The line load distribution.

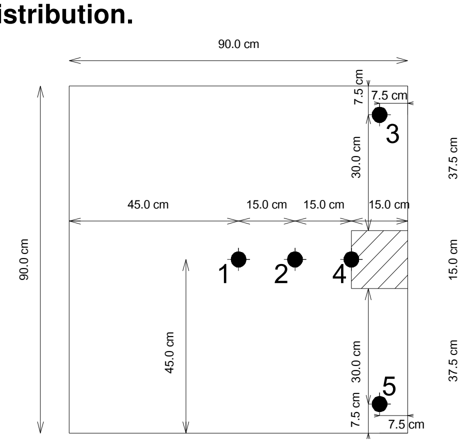


Fig. 5. The rigid steel system used to distribute the concentrated load.

Fig. 6. LVDT locations (bottom side).

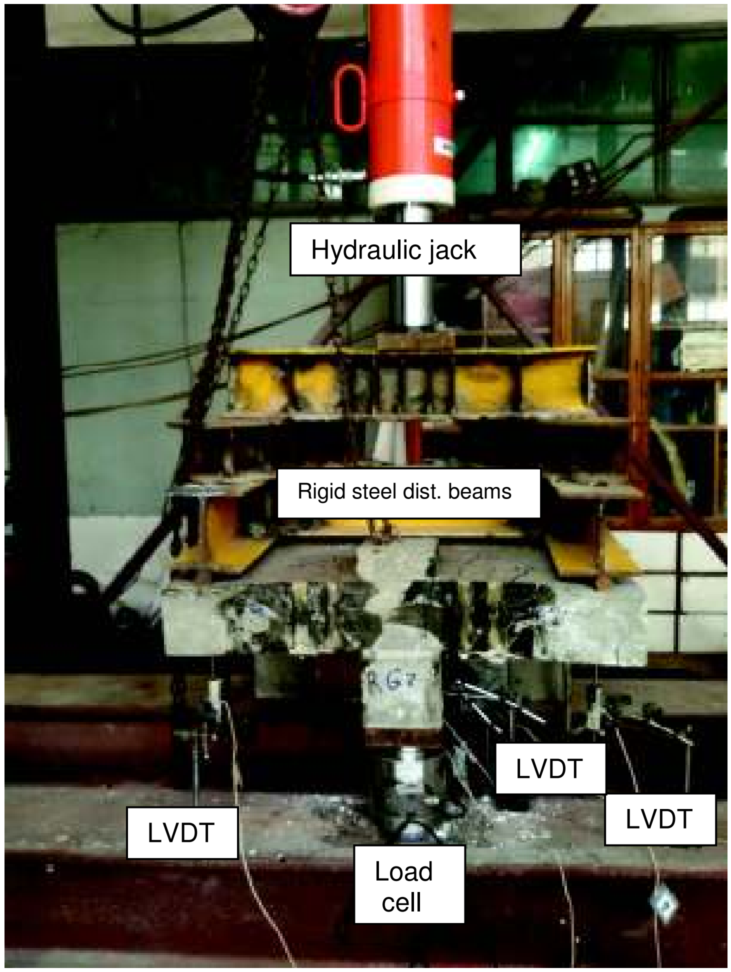


Fig. 7. Test set up.

5. Results and Discussion

For the all tested specimens, the load deflection curve was plotted and the crack propagation was monitored and recorded. Comparisons between the results of different specimens were carried out to reveal the effect of the parameters considered in this study.

5.1 Load-deflection relationships

For all the thirteen tested specimens, the vertical deflections were measured at specified locations, as shown in Fig. 6. Vertical deflections were recorded against each load increment up-till slab failure. For each tested specimen the relationship between the central deflection at point (1) versus the applied load was plotted. In this sub-section the load deflection relationships were compared to reveal the effect of the study parameters. The strengthened and repaired specimens had similar load-deflection relationships. All the strengthening and repair systems used in this study led to a significant increase of the strength and the rigidity of the tested specimens against the shear punching. At the same loading level, lower deflection values were recorded for strengthened and repaired specimens, either with steel links, GFRP or CFRP stirrups, in comparison with the control specimen, as shown in Figs. (8, 9, 13 & 14).

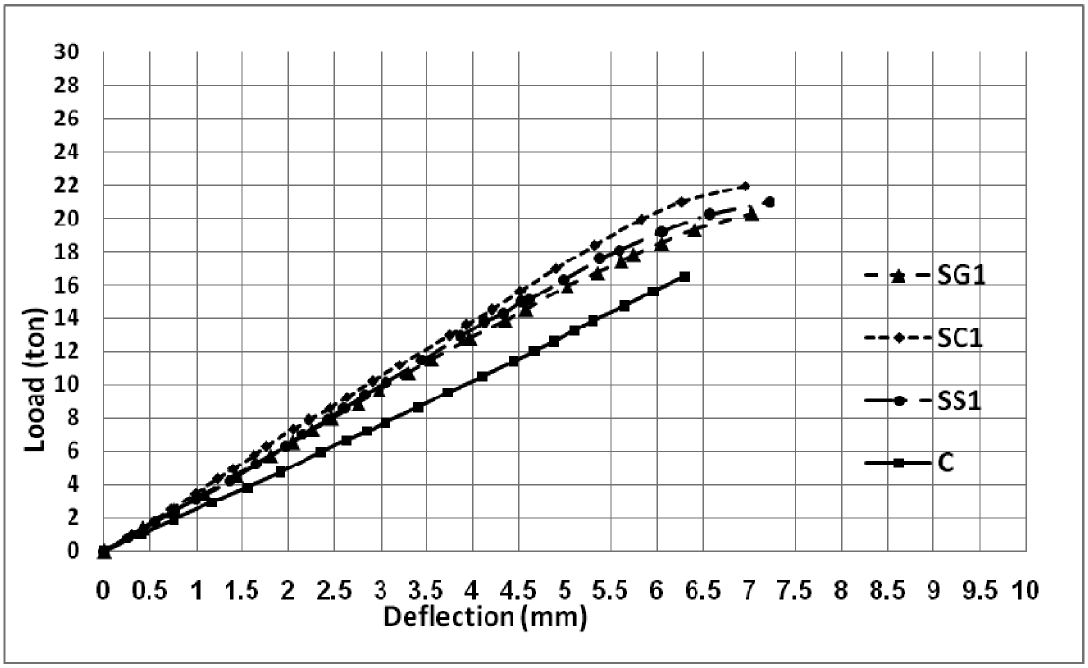


Fig. 8. Comparison between Load-Central deflection relationships of the specimens (SG1), (SC1), (SS1), and (C).

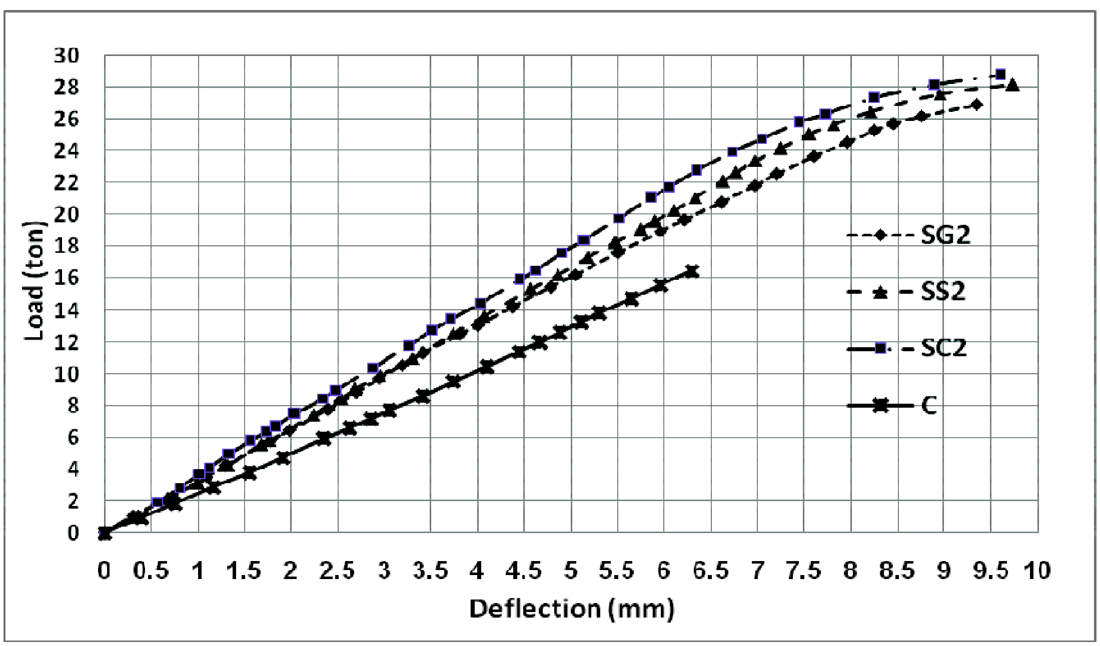


Fig. 9. Comparison between Load-Central deflection relationships of the specimens (SG2), (SC2), (SS2), and (C).

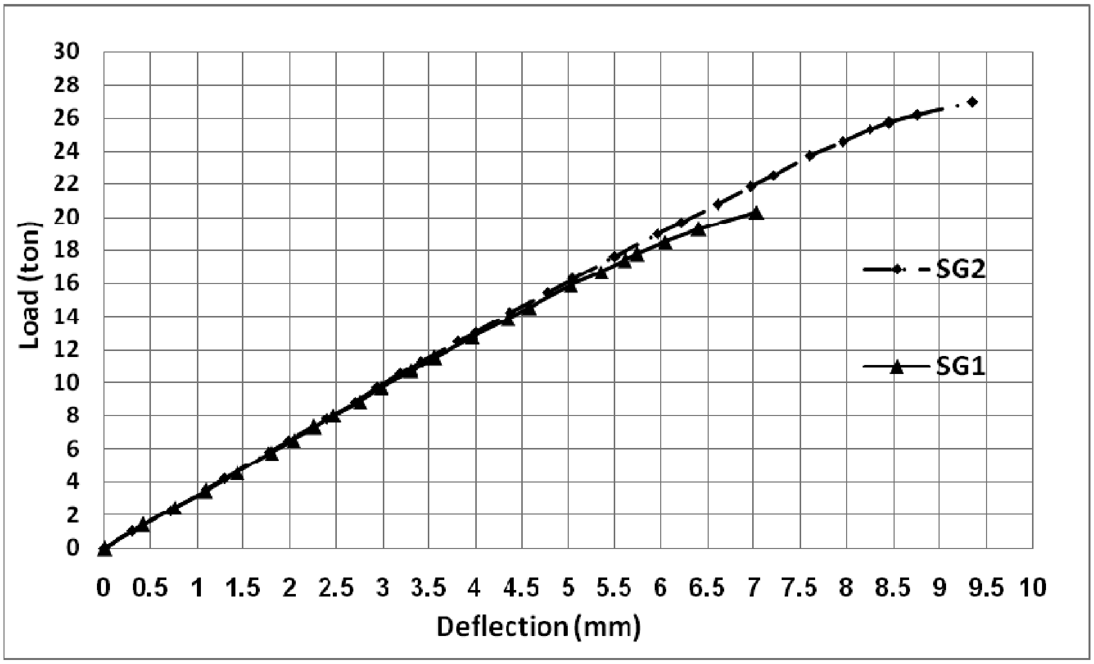


Fig. 10. Comparison between Load-Central deflection relationships of the specimens (SG1) and (SG2).

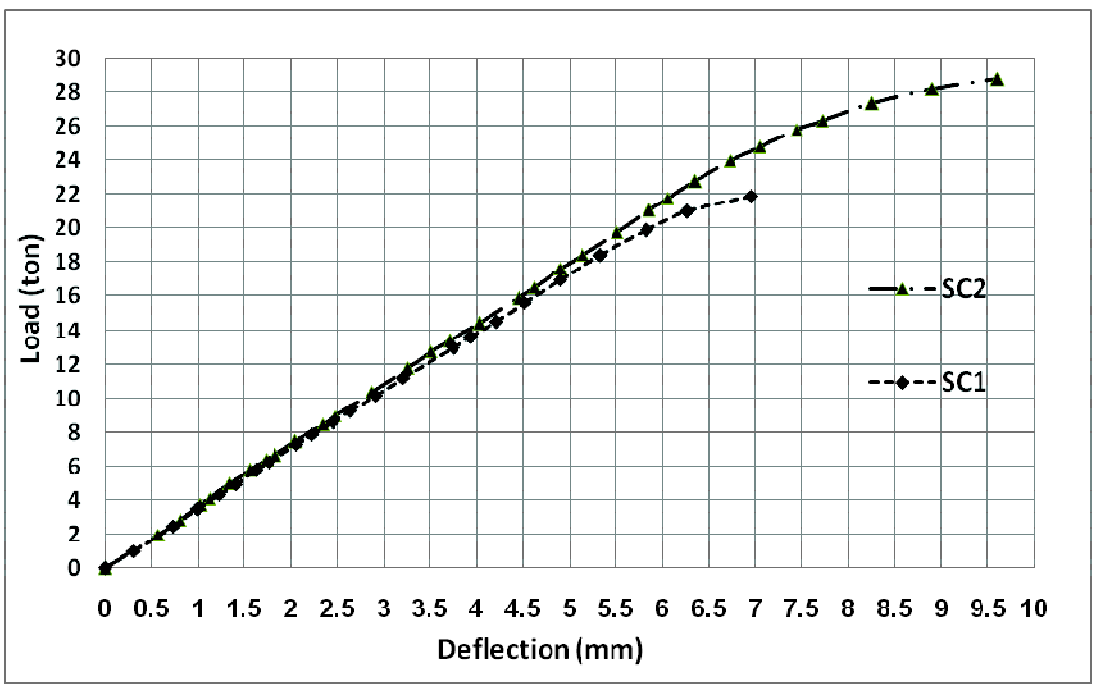


Fig. 11.Comparison between Load-Central deflection relationships of the specimens (SC1) and (SC2).

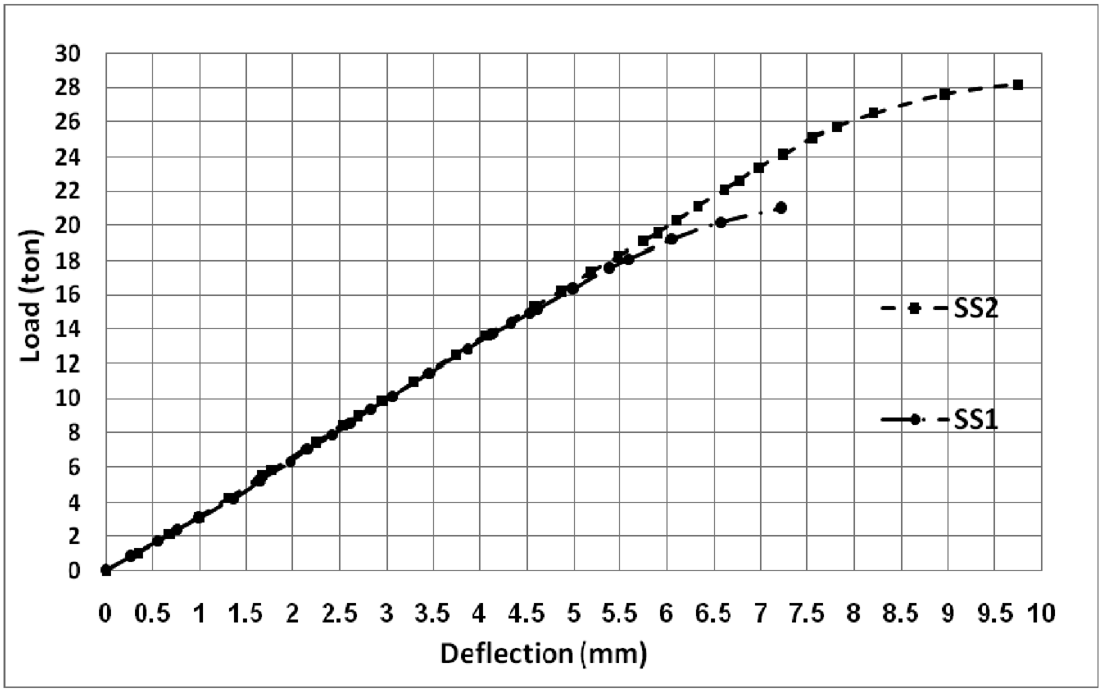


Fig. 12. Comparison between Load-Central deflection relationships of the specimens (SS1) and (SS2).

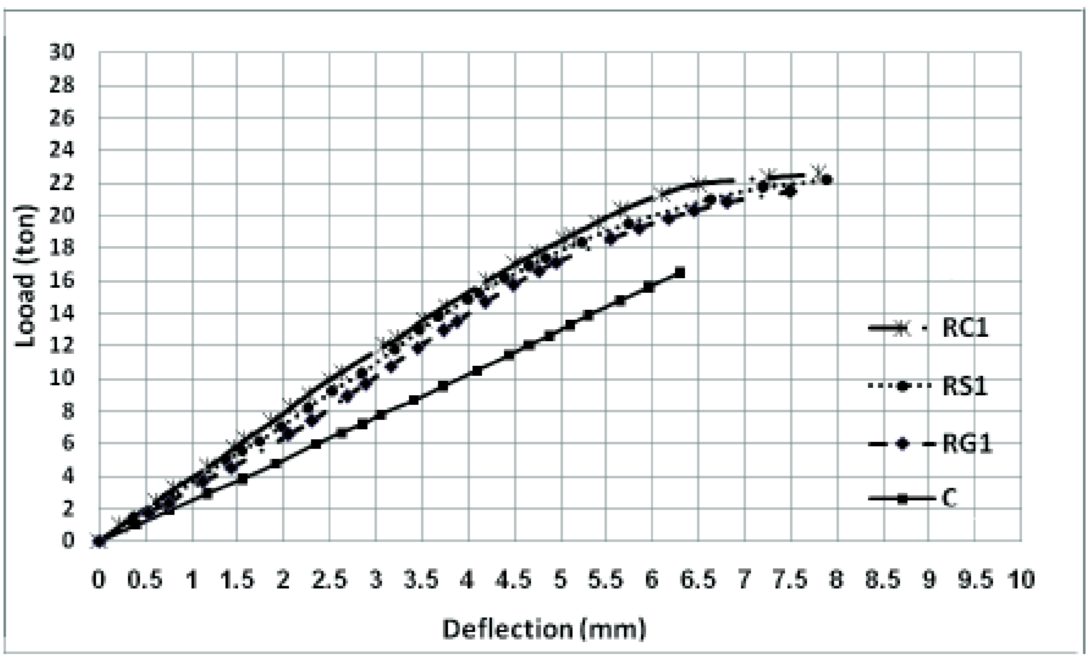


Fig. 13. Comparison between Load-Central deflection relationships of the specimens (RG1), (RC1), (RS1), and (C).

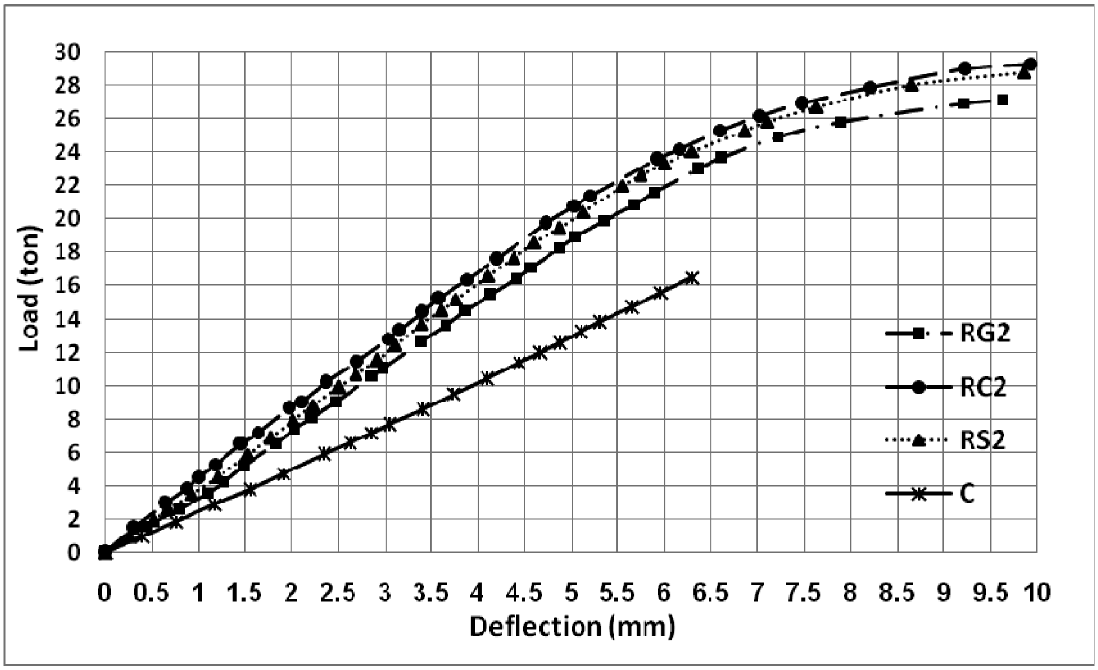


Fig. 14. Comparison between Load-Central deflection relationships of the specimens (RG2), (RC2), (RS2) and (C).

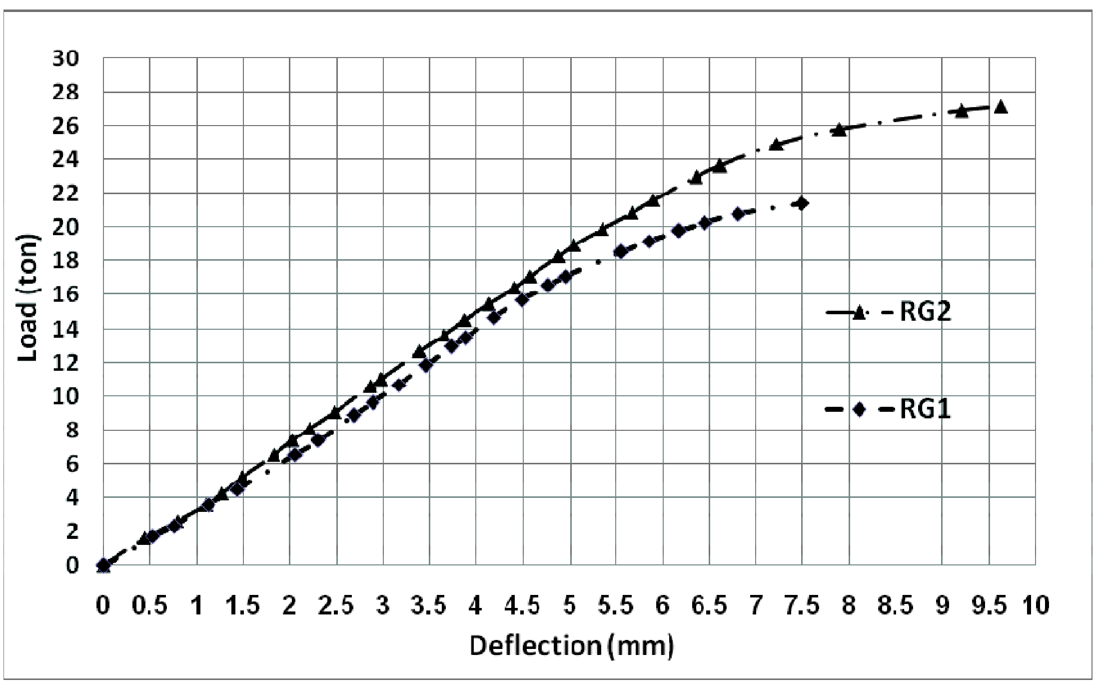


Fig. 15. Comparison between Load-Central deflection relationships of the specimens (RG1) and (RG2).

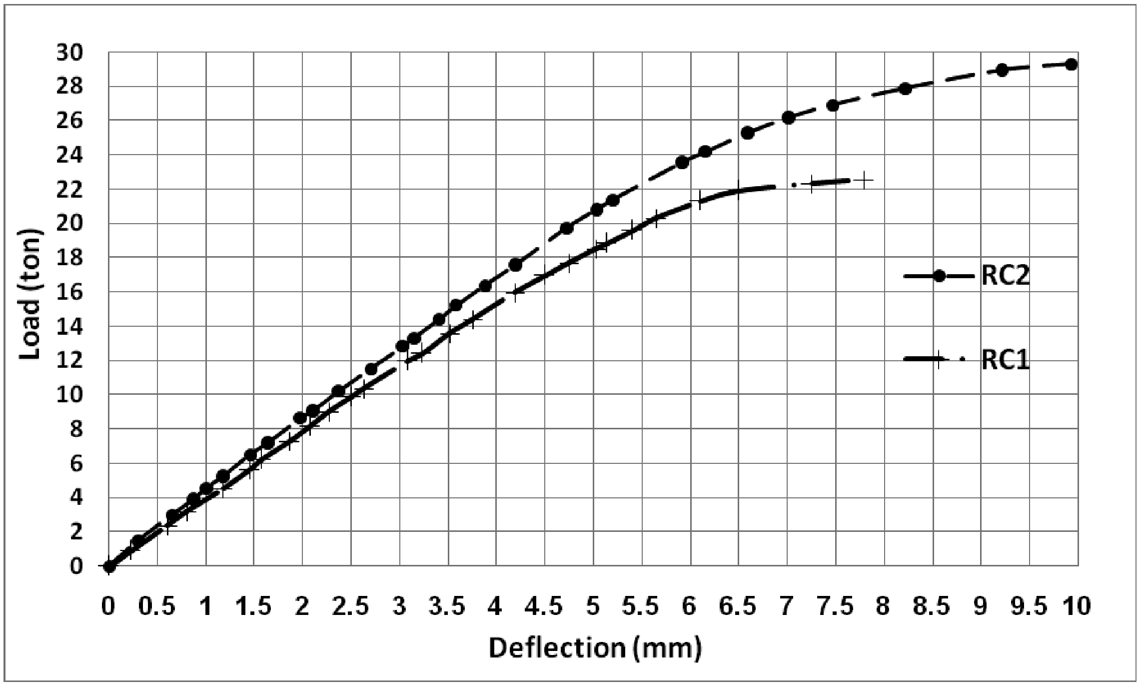


Fig. 16. Comparison between Load-Central deflection relationships of the specimens (RC1) and (RC2).

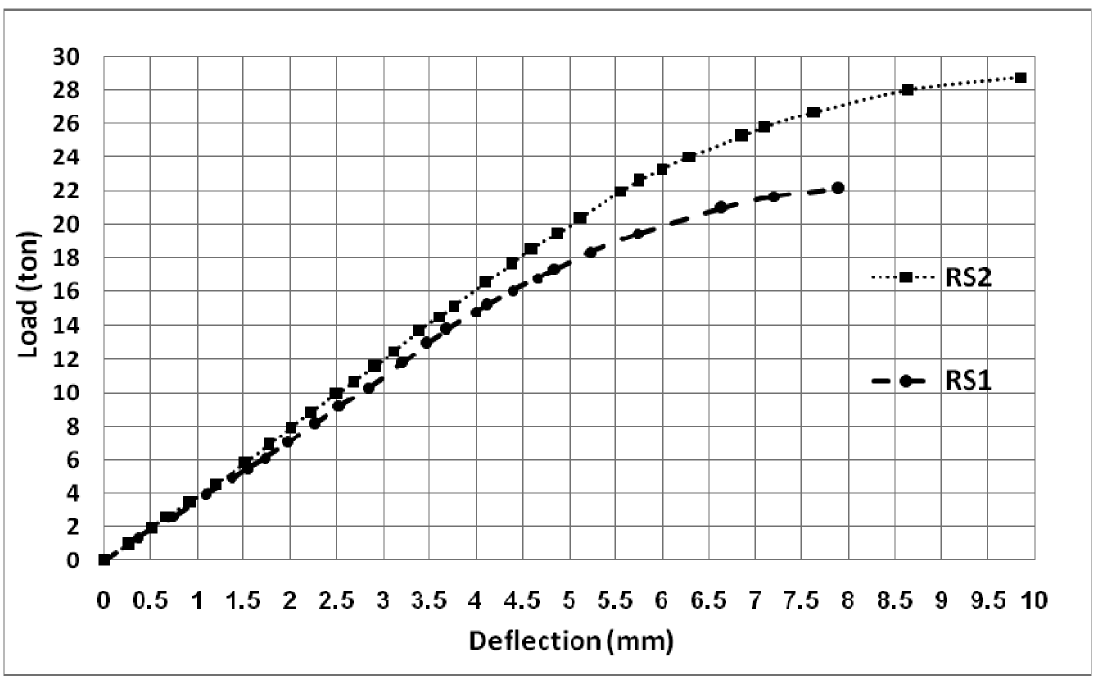


Fig. 17. Comparison between Load-Central deflection relationships of the specimens (RS1) and (RS2).

5.2 Ultimate punching shear resistance.

Table. 4. Presents the deflection and load value at first cracking and at failure, and also the ductility and the stiffness indices, for the thirteen tested specimens. For strengthened or repaired specimens, using CFRP stirrups was the more effective system where the ultimate load had the highest values compared to the other. Its observed that the repaired specimens gave higher ultimate load than the strengthened specimens, the reloading may improves the ultimate strength. Figs.(18 & 19). show the material type and number of stirrups rows effect on the ultimate punching shear resistance. Table. 4. Also, observes the effect of using strengthening and repair systems on the ultimate punching shear load when using one or two rows of stirrups compared with the control specimen which was not strengthened nor repaired.

Table. 4. Main results of the tested specimens.

Specimen code	1st Crack		Ultimate		Ultimate load (specimen) / ultimate load (control)	Ductility	Ki=Vcr /Δcr	Ku= (Vul-Vcr) / (Δul-Δcr)	stiffness degradation
	Load (ton)	Δ cr Deflection (mm)	Load (ton)	Δ ul Deflection (mm)		Δ ul / Δ cr	(t/mm)	(t/mm)	(Ki-Ku)*100 / Ki
C	8.00	3.25	16.50	6.29	1.00	1.94	2.46	2.80	13.59
RG1	9.50	2.85	21.45	7.49	1.30	2.63	3.33	2.58	22.74
RC1	9.50	2.40	22.89	7.79	1.39	3.25	3.96	2.42	38.83
RS1	10.00	2.75	22.17	7.89	1.34	2.87	3.64	2.37	34.89
RG2	11.00	2.95	27.15	9.63	1.65	3.26	3.73	2.42	35.16
RC2	11.20	2.65	29.31	9.93	1.78	3.75	4.23	2.49	41.14
RS2	10.50	2.65	28.79	9.85	1.74	3.72	3.96	2.54	35.89
SG1	8.70	2.70	20.31	7.02	1.23	2.60	3.22	2.69	16.59
SC1	9.00	2.60	21.93	6.94	1.33	2.67	3.46	2.98	13.93
SS1	9.80	2.95	20.98	7.21	1.27	2.44	3.32	2.62	21.00
SG2	11.00	3.30	26.96	9.34	1.63	2.83	3.33	2.64	20.73
SC2	11.00	3.00	28.75	9.65	1.74	3.22	3.67	2.67	27.20
SS2	10.50	3.15	28.16	9.73	1.71	3.09	3.33	2.68	19.48

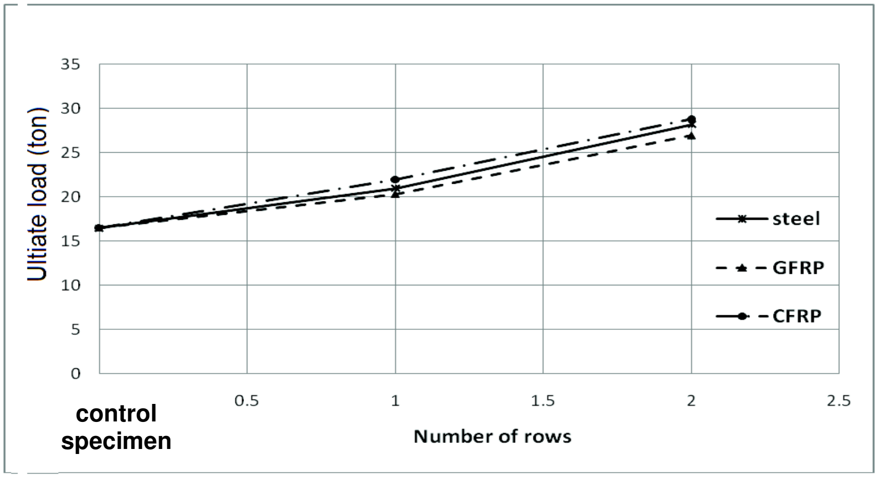


Fig. 18. Effect of the number of strengthening rows on the ultimate punching shear resistance.

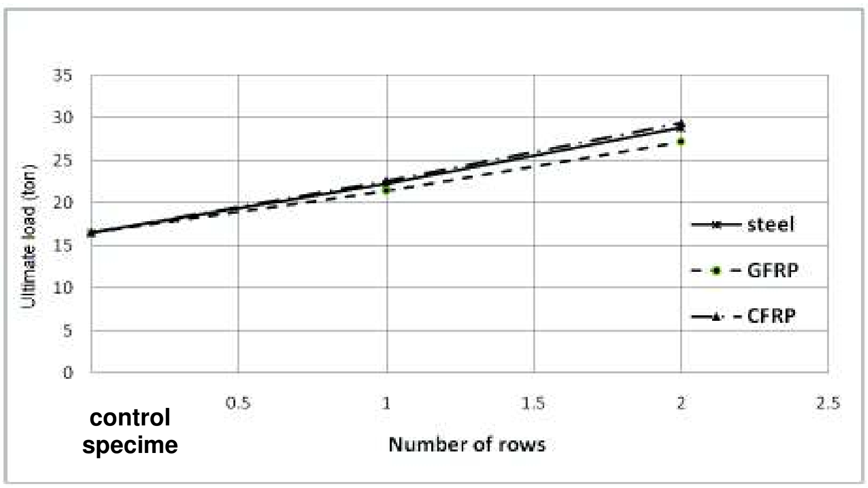


Fig. 19. Effect of the number of repair rows on the ultimate punching shear resistance.

5.3 Ductility

The ductility was determined from the load-deflection relationships of the tested specimens as the ratio of the deflection at ultimate load to the deflection at first crack load, as shown in Table.4. As can be seen in Table. 4. The use of different strengthening and repair materials such as steel links, GFRP stirrups and CFRP stirrups led to ductile failure rather than brittle one of the control specimen. As mentioned by Hawkins [6], displacement ductility greater than 2.0 must be achieved for the specimen to be called a ductile specimen. The ductility measurement was greater than 2.0 in all strengthened and repair specimens. However, the control specimen revealed brittle behavior where the ductile measurement was less than 2.0.

5.4 Stiffness

The un-cracked stiffness Ki and the ultimate stiffness Ku were obtained from the load-deflection values of the tested specimens, as presented in Table. 4. It shows that the un-cracked stiffness (Ki) is increased significantly when punching shear strengthening or repair systems were used. Using steel links, GFRP stirrups, and CFRP stirrups led to increase Ki by 31% to 49% for strengthened specimens and by 35% to 61% for repaired specimens. It's observed that strengthening and repair systems increase the first cracking load which causes cracks appearance at a higher loading level which reduces the slope of the load deflection relationship after cracking load, this led to decrease the ultimate stiffness (Ku) for all strengthened or repaired specimens except specimen SC1. Therefore, as the ultimate stiffness (Ku) decreased, a considerable increase in the stiffness degradation was observed for all strengthened and repaired specimens.

5.5 Cracking behavior and mode of failure.

All the tested specimens were loaded until failed due to punching shear. For all specimens, the first crack was recorded, cracks propagation were monitored, and the mode of failure was determined. Table. 4. shows the load value corresponding to cracking initiation (Vcr). Strengthening and repair systems led to an increase of the first crack load. Cracks began firstly at the slab compression side near to the column edges. As the applied load increases the number and width of the cracks increase and new cracks develop and began to propagate in radial directions towards the slab edges. Also, fine cracks were observed running from column edges at tension side towards the slab edges in the three directions. For all the tested specimens, it was observed that the column penetrated the slab at failure and the upper perimeter crack had a semi - rectangular shape at the slab tension face.

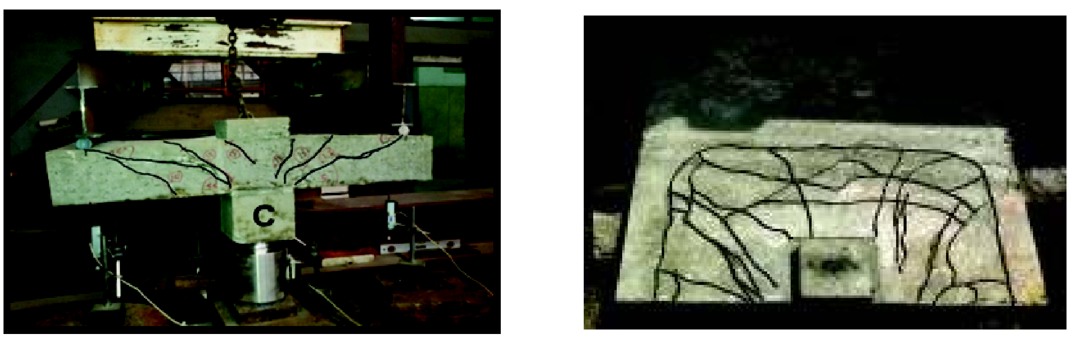


Fig. 20. Cracking pattern of specimen (C).

Fig. 21. Cracking pattern of specimen (SG1).

Fig. 22. Cracking pattern of specimen (SC1).

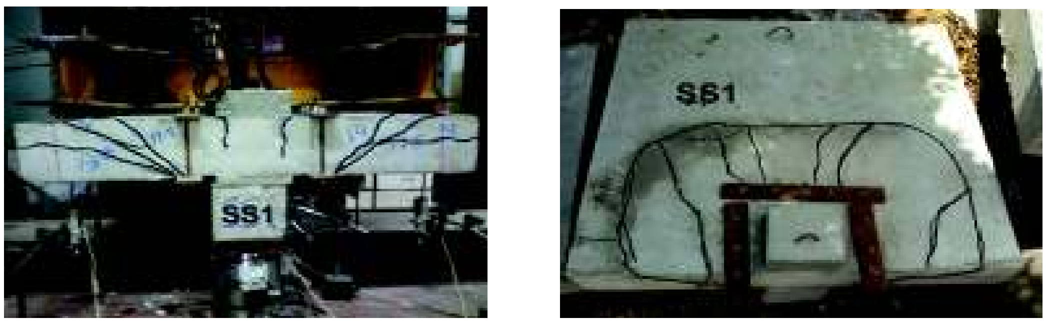


Fig. 23. Cracking pattern of specimen (SS1).

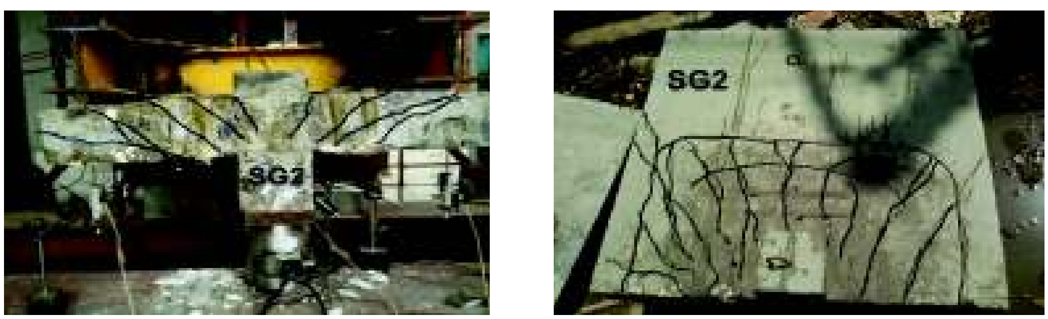


Fig. 24. Cracking pattern of specimen (SG2).

Fig. 25. Cracking pattern of specimen (SC2).

Fig. 26. Cracking pattern of specimen (SS2).

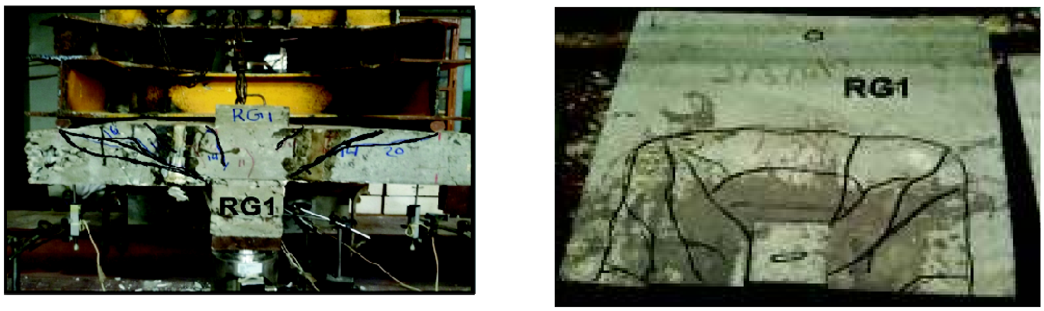


Fig. 27. Cracking pattern of specimen (RG1).

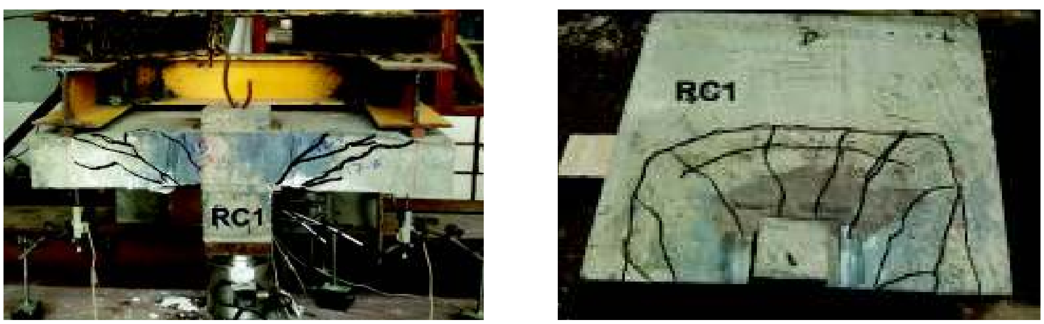


Fig. 28. Cracking pattern of specimen (RC1).

Fig. 29. Cracking pattern of specimen (RS1).

Fig. 30. Cracking pattern of specimen (RG2).

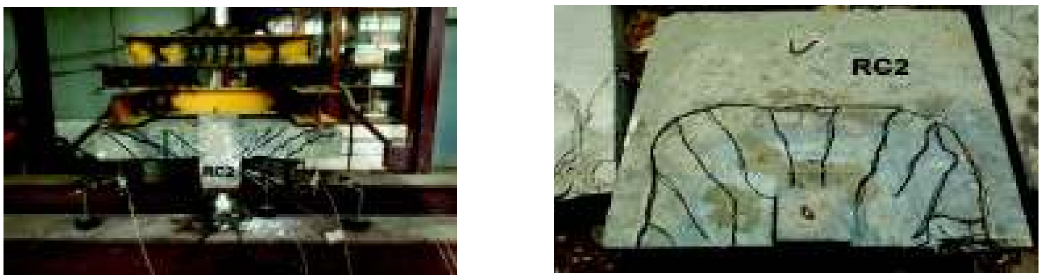


Fig. 31. Cracking pattern of specimen (RC2).

Fig. 32. Cracking pattern of specimen (RS2).

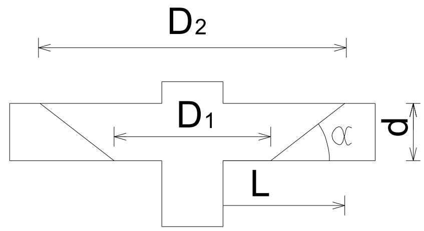
5.6. Punching shear failure angle (α)

For all the tested specimens similar shapes of punching failure surface were observed, where the failure surfaces ended approximately at the same section - at the loading line - from column face but started from different sections from the column face - at the outermost row of punching shear reinforcement strengthening or repair - producing different angles with horizontal as presented in Table. 5. The punching shear failure angle (α) increased for all strengthened or repaired specimens compared to the control specimen.

Table. 5. Characteristics of the observed failure mode.

Notation	Punching propagation distance (cm)		L/d	Punching failure angle α
	D1	D2		
C	15	75	2.73	23.5

RG1	25	75	2.73	27.5
RC1	31	75	2.73	30.5
RS1	37	75	2.73	34.5
RG2	33	75	2.73	31.5
RC2	39	75	2.73	36
RS2	43	75	2.73	39
SG1	33	75	2.73	31.5
SC1	35	75	2.73	28.5
SS1	37	75	2.73	34.5
SG2	31	75	2.73	30.5
SC2	41	75	2.73	37.5
SS2	43	75	2.73	39



6. Analytical Model

All the tested specimens failed as a result of concrete exhaustion under punching shear stress at the critical section located at a distance d/2 from the outermost row of punching shear reinforcement. For the prediction of the ultimate test load, based on ACI 440 procedures, the following equation can be used to calculate the values of concrete nominal punching shear strength (v_c) [7];

$$v_c = 0.33 \left(1 - \frac{\alpha - 1}{6}\right) \sqrt{f_{c'}} \quad \text{(MPa)} \qquad (1)$$

Where; α: ratio of the critical section distance from the column face to the slab effective depth $4 \geq \alpha \geq 1$;

$f c'$: concrete cylinder compressive strength;

For the specimens reinforced, strengthened or repaired with steel links the nominal punching shear strength may be expressed as:

$$v_n = (v_c + v_s) \qquad (2)$$

Where; v_c : shear resisted by the concrete;

v_s : shear resisted by steel links;

$$V_s = (A_v . f_{yv} . d)/s \qquad (3)$$

Where; A_v : area of the vertical legs forming the punching shear reinforcement strengthening or repair units in one row;

f_{yv} : yield stress of the used steel for punching shear reinforcement strengthening or repair units;

S : spacing between rows;

The punching shear force resisted by concrete only at any critical section can be calculated from the following equation;

$$V_c = (v_c . b . d) \qquad (4)$$

Where; v_c : given by equation (5.6);

b : perimeter of the critical section (at a distance d/2 from the outermost row of punching shear reinforcement strengthening or repair);

In specimens strengthened with FRP, the nominal punching shear strength may be expressed as:

$$v_n = (v_c + \psi v_f) \leq \text{Vmax}. \qquad (5)$$

$$\text{Vmax} = 0.60 \sqrt{fc'}$$

where V_f is the shear resisted by glass or carbon fiber;

ψ = 0.95 (completely wrapped elements), this definition agree with strengthening stirrups types A;

ψ = 0.85 (3-sides "U-wraps"), this definition agree with strengthening stirrups types B;

Where; V_f : is the shear resisted by fiber reinforcement;

The shear strength provided by the fiber reinforcement (V_f) can be determined by calculating the force resulting from the effective tensile stress in the fiber (f_{fe}) which depnds on its effective strain (ϵ_{fe}).

$$v_f = (A_{fv}.f_{fe}.d_f)/s_f \qquad (6)$$

$$A_{fv} = n_s.n_v.t_f.w_f \qquad (7)$$

$$f_{fe} = \epsilon_{fe}.E_f \qquad (8)$$

Where; ϵ_{fe} = 0.004 (for completely wrapping arround all 4 sides) [8];

s_f : spacing between fiber rows;

t_f : fiber thickness;

w_f : width of the fiber strip;

n_v : number of side row links;

n_s : number of vertical legs in one side of row;

A_{fv} : area of fiber in one row;

d_f : depth of fiber stirrups;

The above equations were applied to predict the ultimate punching shear load of the tested specimens. Table. 6. shows a comparison between the calculated values of the ultimate load ($V_{u,\ cal.}$) and the corresponding experimental values ($V_{u,\ exp.}$). The equations used to predict the ultimate loads are moderately conservative, where the experimental values are higher than the calculated ones.

Table. 6. Comparison of experimental and predicted results.

Notation	$V_{u,\ exp.}$	$V_{u,\ cal.}$	$\frac{V_{u,\ exp.}}{V_{u,\ cal.}}$
C	16.50	11.5	1.43
RG1	21.45	15.4	1.39
RC1	22.89	15.4	1.49
RS1	22.17	15.4	1.44
RG2	27.15	17.7	1.53
RC2	29.31	17.7	1.66
RS2	28.79	17.7	1.63
SG1	20.31	15.4	1.32
SC1	21.93	15.4	1.42
SS1	20.98	15.4	1.36
SG2	26.96	17.7	1.52
SC2	28.75	17.7	1.62
SS2	28.16	17.7	1.59

7. Conclusions

Flat slabs column connections have a major weakness, namely vulnerability to punching shear failure even if they are shear-reinforced.

Strengthening and repair systems were effective and improved significantly these connections punching shear behavior.

All the used materials in this research for strengthening or repair led to increase the flexural rigidity, initial cracking increased load by 9% to 38% for strengthened specimens and by 19% to 40% for repaired specimens and the ultimate punching shear capacity also increased by 23% to 74% for strengthened specimens and by 30% to 78% for repaired specimens.

All specimens failed in punching shear with approximately semi-rectangular shape.

The CFRP intertwined stirrups was the best strengthening and repair material, which led to the highest improvement in the rigidity and the ultimate punching shear capacity.

The strengthening and repair systems enhancement the ductility of these slabs by 26% to 66% for strengthened specimens and by 36% to 92% for repaired specimens. These systems led to increase the number of radial cracks, and, also, increased the distance between the punching shear surface and the column face.

The prediction of ultimate shear strength based on ACI 440 gave underestimated strength for all the tested specimens, so, it is a conservative method, where the experimental values are higher than the calculated ones.

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