Experimental evaluation of advanced techniques for repair and strengthening of reinforced concrete slabs

Magdy A. Tayel [a], Nageh N. Meleka [a] and Ahmed M. Ramadan [b]
[a] *Civil Eng. Dept., Faculty of Eng., Menoufiya University, Menoufiya, Egypt*
[a] *Civil Eng. Dept., Faculty of Eng., Alexandria University, Alexandria, Egypt*

This research concerns with experimental study of repair and strengthening of reinforced concrete slabs using advanced techniques. These techniques include Carbon Fiber Reinforced Polymer (CFRP), ferrocement mix with expanded wire mesh, and steel strips. Twelve reinforced concrete slabs having dimensions of 140×50×6 cm with effective span of 120 cm are used to apply the evaluated repair and strengthening techniques. 6mm diameter bars are used to reinforce the slabs. The spacing between bars were 6.25 cm in the main direction and 15.5 cm in the other direction. The tested slabs are divided into four groups. First group was not subjected to any loads at first and then strengthened by three different techniques. The fourth group was loaded till failure, then repaired and tested again after repairing. The second and the third groups were loaded up to 60% and 80% of the failure load, then repaired by the three mentioned methods of repair and then tested to evaluate the efficiency of the repairing methods. The slabs strengthened and repaired by carbon fiber reinforced polymer showed best results. The slabs repaired by ferrocement with expanded wire mesh showed less results but they were better than those repaired using steel strips. Comparisons for different techniques of repair and strengthening regarding load-deflection curves are presented along with crack pattern and deflection of slabs at load increments. This investigation proves and compares the efficiency of strengthening and repair techniques for reinforced concrete slabs greatly needed for repair and strengthening of reinforced concrete structures.

يهدف هذا البحث إلى دراسة طرق تقوية وإصلاح البلاطات الخرسانية المسلحة باستخدام أساليب متقدمة تتضمن المعالجة بألياف الكربون ، الشبك الممدد، وشرائح الصلب. تم تجهيز و اختبار اثنى عشر بلاطة بأبعاد ١٤٠×٥٠×٦ سم لتقييم طرق الإصلاح والتقوية المختلفة. وقد تم تسليح هذه البلاطات باستخدام حديد تسليح أملس بقطر ٦مم كل ٦,٢٥ سم فى الاتجاه الرئيسى وكل ١٥,٥ سم فى الاتجاه الثانوى. وقد تم تحميل إحدى المجموعات حتى الانهيار وأخذ متوسط النتائج بإعتبارها النتائج المرجعية. وقد تم تسيم البلاطات المختبرة إلى أربع مجموعات بكل مجموعة ثلاثة بلاطات تم تحميلها قبل الإصلاح بنسبة ٠,٠، ٦٠%، ٨٠%، ١٠٠% من الحمل المرجعى. وقد تم تقوية وإصلاح بلاط من كل مجموعة بألياف لكربون CFRP والبلاطة الثانية تم تقويتها باستخدام طبقة واحدة من الفيروسيمنت، أما البلاطة الثالثة فقد تم تقويتها باستخدام شرائح الصلب (صلب ٣٧). و قد تم دراسة سلوك هذه البلاطات التى تم إصلاحها وتقويتها بالطرق المختلفة للإصلاح وذلك بإعادة تحميلها حتى الانهيار تحت نفس ظروف التحميل الأولى قبل الإصلاح والتقوية. وتم تسجيل حمل التشريخ الابتدائي وحمل الانهيار وقيم الترخيم عند مراحل التحميل المختلفة. وقد ظهرت نتائج الاختبارات أن علاج البلاطات السابق تحميلها بحمل أكثر فاعلية من البلاطات السابق تحميلها بحمل قريب من حمل الانهيار. وقد أتضح أن علاج البلاطات الخرسانية السابق تحميلها بحمل قريب من حمل الانهيار باستخدام الفيروسيمنت يكون أفضل من الطرق الأخرى، أما ألياف الكربون فتفضل عند الرغبة فى زيادة كفاءة التحميل للبلاطات أو البلاطات السابق تحميلها بحمل صغير. أما فى حالة استخدام شرائح الصلب فإن كفاءة الإصلاح أو التقوية تعتمد أساساً على كفاءة تثبيت شرائح الصلب فى البلاطات الخرسانية المسلحة.

Keywords: Repair and strengthening, Carbon fiber, Steel strips, Ferrocement

1. Scheme of experimental work

The experimental program was planned to repair and to strengthen twelve reinforced concrete slabs. Three of these slabs were tested under concentrated loads up to failure (P_{max}). Three slabs were tested under 0.8 of the failure load ($0.8P_{max}$). Three slabs were subjected to an applied load equal to 0.6 the failure load ($0.6P_{max}$). The final three slabs were not subjected to any preloading (Applied load =0.0). Fig. 1 shows the used methods for repair and strengthening.

The repaired and strengthened slabs were tested by reloading them at the same primary

Alexandria Engineering Journal, Vol. 43 (2004), No. 3, 355-373

loading conditions to study the behavior and the efficiency of repairing techniques.

2. Properties of used materials

The materials used in making up and repairing the tested slabs were clean sand, graded gravel, silica fume, cement, water, steel reinforcement, ferrocement composite, epoxy, carbon fibers (Carbon Fiber Reinforced Polymers (CFRB)), and steel strips. The properties of these materials are as follows.

2.1. Sand

Natural siliceous sand was used as fine aggregates in the cement mix. It is clean and almost free from impurities. It has a fineness modulus of 2.72 and apparent specific gravity 2.58 t / m^3.

2.2. Gravel

Coarse aggregates used in concrete mix were all composed of siliceous gravel and having a general particle shape of a combination of round and subangular, and the surface texture was more or less smooth and uniform. Two different types of the coarse aggregates according to their grading were used in this work as follows.

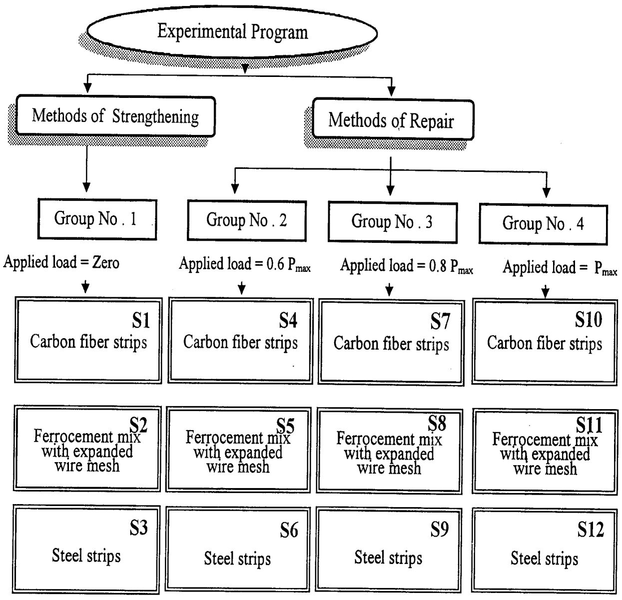

Fig. 1. Details of repaired and strengthened slabs.

2.2.1. Gravel G$_1$

The nominal maximum size of this gravel was of 19 mm. It was used in preparing the concrete mix for casting the original slabs.

2.2.2. Gravel G$_2$

The nominal maximum size of this gravel was of 4-8 mm. It was used in casting the concrete used for repair.

2.3. Silica fume

Silica fume is a bi-product material resulting from the reduction of high purity quartz with coal in electric arc furnaces in the manufacture of ferrosilicon and silicon metal. Silica fume which was used in ferrocement mix has the ability to increase early age strength of the mix, reduction of permeability, reduction of chloride associated corrosion, improving durability phenomena, and reducing bleeding phenomena. Silica fume used has a specific surface area of 20.00 m^2/kg.

2.4. Cement

Ordinary Portland cement used in all experimental work was provided from Suez-factory. The usual chemical and physical properties are in compliance with the Egyptian Standard Specification (E.S.S) 373/1991.

2.5. Water

Clean drinking fresh water free from impurities was used for mixing and curing the tasted slabs.

2.6. Steel reinforcement

Mild steel 37 used in this work provided from the national companies, Bars were round plain and 6 mm diameter, yield strength is 2400 kg/cm^2.

2.7. Expanded wire mesh

Expanded wire mesh was obtained from METAL-X Company. The wire mesh is known commercially by (X-8), the opening size of the hole is 31× 9.5 mm. The expanded wire mesh was delivered with dimensions 2 × 3 m and 3.54 kg/m^2 weight.

2.8. Carbon fiber reinforced polymer

CFRP was obtained from Sika Company, it is known commercially by Sika CarboDur, and it consists of Sikadur-30 adhesive for bonding reinforcement and Sika CarboDur-Laminates. The CFRP which used in this investigation was Sika CarboDur S612 with dimension 50×1.2 mm. The mechanical properties of CarboDur are given in table 1.

2.9. Steel strips

Mild steel 37 strips used in this work was obtained from the national companies. Sikadur-30 adhesive was used for bonding the steel strips with the reinforced concrete slabs. The strips dimensions were 3 mm thickness and 70 mm wide. The mechanical properties are given in table 2.

Table 1
Mechanical properties of CarboDur

Tensile strength	2400 N / mm^2
Elongation	1.40 %
E-modulus	150000 N/mm^2

Table 2
Mechanical properties of steel strips (St. 37)

Yield strength	235 N/mm^2
Elongation at break	25 %
Young's Modulus	210000 N/mm^2

3. Contents of concrete mixes

3.1. Concrete mix

The absolute method was used to design the required concrete mix. The concrete mix proportions, slump, and compressive strength at 7 and 28 day are presented in table 3.

3.2. Ferrocement mix

The ferrocement mortar mix used in this investigation contains a high ratio of cement content, sand, silica fume, and workability agent. The proportion of the material used is represented in table 4.

4. Dimension and reinforcement of slabs

All tested slabs have same dimensions of 140×50×6 cm with effective span of 120 cm. 6mm diameter bars are used to reinforce the slabs. They are used each 6.25 cm in the main direction and 15.5 cm in the perpendicular direction. Fig. 2 shows the dimensions and reinforcement details for the tested slabs.

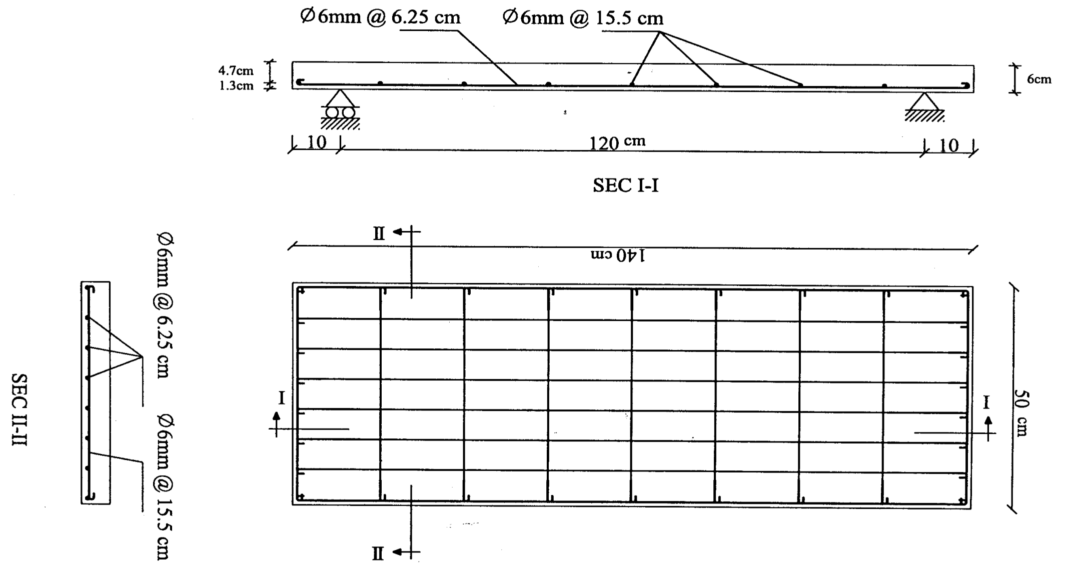

Fig. 2. The reinforcement details for tested slabs.

Table 3
Concrete mix proportions and compressive strength

Mix No.	Mix Proportions Kg/m^3				Unit weight	C.A. / F.A.	W/C %	Slump (mm)	Compressive strength kg/cm^2	
	C	W	F.A.	C.A.					7 days kg/cm^2	28ays kg/cm^2
1	350	175	602	1204	2331	2	50	55	195	250
2	350	185.5	593	1186	2315	2	53	55	165	225
3	350	157.5	616	1232	2356	2	45	30	230	290
4	350	150.5	600	1200	2360	2	43	40	242	303

C = Cement F.A. = Fine Aggregate W = Water C.A. = Coarse Aggregate

Table 4
Compressive strength for ferrocement mortar mix at 3, 7 and 28 days.

Mix No.	Mix proportions (by weight)					Compressive strength kg/cm^2		
	C	W	F.A.	S	A	3 days	7 days	28 days
1	1	0.35	2	0.0	0.015	200	250	340
2	1	0.35	2	0.05	0.015	240	300	365
3	1	0.35	2	0.10	0.015	250	320	420
4	1	0.35	2	0.15	0.015	230	305	335
5	1	0.35	2	0.20	0.015	210	290	370
6	1	0.35	2	0.30	0.015	200	275	350

C = Cement W = Water F.A.= Fine Aggregate
S = Silica Fume A = Admixture C.A.= Coarse Aggregate

5. Repairing techniques

5.1. Strengthening by using carbon fibers (CFRP)

The strengthening procedures were executed as follows:

1. The tension side of concrete slab was roughen and prepared by removing loose materials and dust from cracks by using of compressed air.
2. CFRP strips were cleaned and Sikadur-30 was prepared.
3. CFRP strips were bonded to the tension surface of slabs by Sikadur-30 adhesive and compressed with a hard rubber roller.
4. The excess of Sikadur-30 was removed, voids were checked and then CFRP strips were covered with mortar.

5.2. Strengthening by ferrocement mix with expanded wire mesh

The strengthening procedures were executed as follows.

1. The tension surface of slabs was roughened.
2. Loose materials and dust were removed by using compressed air.
3. The expanded wire mesh was fixed by using hooks and covered with the epoxy resin.
4. The surface was coated with ferrocement mix as a one layer of 2 cm thick to reach that total thickness of the strengthened slab equal 8cm.

The slabs were cured with water for 28 days and then tested.

5.3. Strengthening by using steel strips

The strengthening procedures were executed as follows:

1. The tension concrete surface was roughened and prepared by removing loose materials and dust from cracks by using of compressed air.
2. The position of steel bolts at the tension side was marked and then drilled to grip the steel strips to the slab and prevent voids formation between the steel strips and the adhesive material (Sikadur -30).

3. Steel strips were cleaned and painted with anti corrosion paint by using Sikadur-31.
4. Steel strips were fixed to the tension surface of slabs by using Sikadur-30. The steel strips were fixed also by steel bolts to assure complete contact between the steel strips and Sikadur-30.
5. The excess of Sikadur-30 was removed.

6. Experimental test results

6.1. Deflection

The load deflection curves for slabs strengthened or repaired by the three different methods in different groups are shown in figs. 3 to fig. 5. Figs. 6 to 9 show deflection comparisons between slabs of each group regarding the repair technique and the pre-loading level. From these Figures the following results were obtained:

1. Deflections of slabs in the same repairing or strengthening method at the same loading stage were increased with increasing pre-loading level. This increase attributed to the developing of cracks in pre-loading process which reduces the effective moment of inertia of the slab cross section. Stresses in reinforcing steel exceeded the yield stress in heavy pre-loading stages.
2. Slabs repaired and strengthened using the CFRB or ferrocement showed smaller deflections compared to the control slab.
3. Slabs repaired and strengthened using ferrocement showed deflection values nearly equal to the deflection of slabs repaired and strengthened using CFRP because of increasing the slab thickness with ferrocement layer, but in higher loads the carbon fiber showed smaller deflections.
4. Slabs repaired and strengthened using ferrocement subjected to high per-loading levels (80% and 100%) showed deflection values less than steel strips and less than carbon fibers CFRP so it seems to be a suitable solution.

6.2. Cracking behavior

The cracking behavior of tested slabs can be represented through the following.

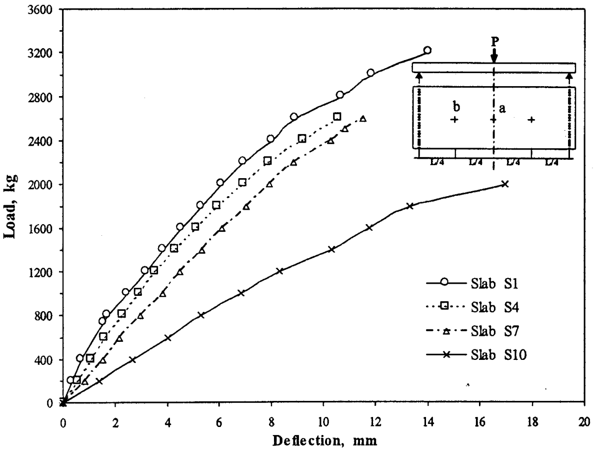

Fig. 3. Deflection comparison for the slabs repaired and strengthened with carbon fibers (point a).

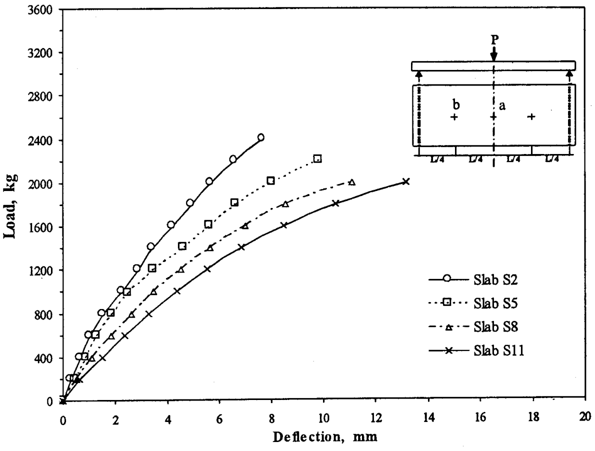

Fig. 4. Deflection comparison for the slabs strengthened with ferrocement (point a).

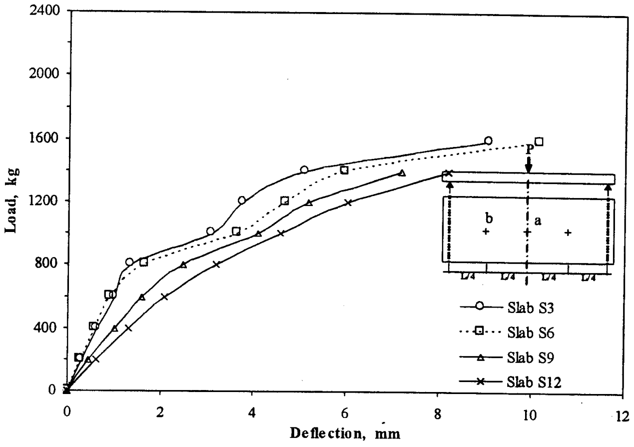

Fig. 5. Deflection of the slabs repaired and strengthened with steel strips (point a).

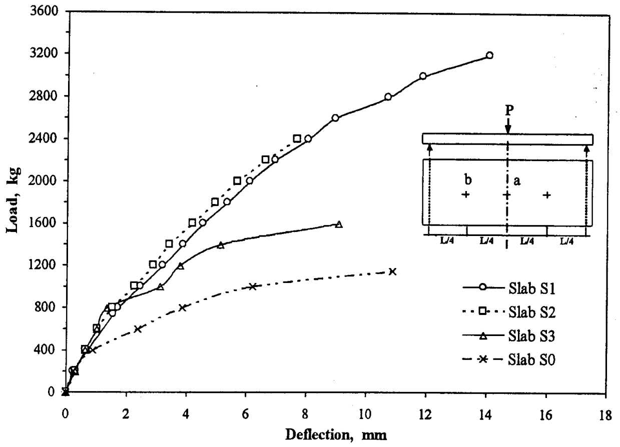

Fig. 6. Deflection comparison between tested slabs of group 1 at point a (applied load P=zero).

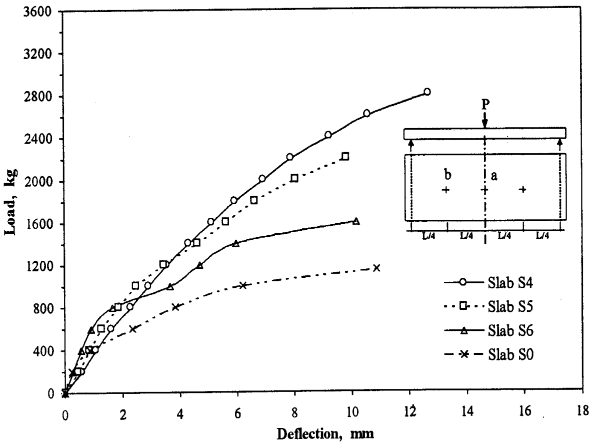

Fig. 7. Deflection compartison between tested slabs of group 2 at point a (applied load P=0.6 pmax).

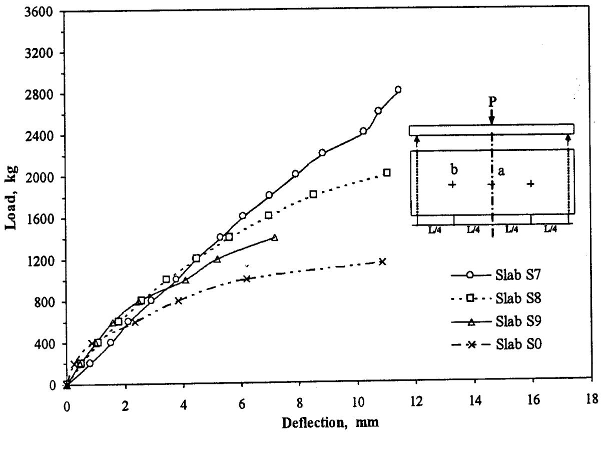

Fig. 8. Deflection comparison between tested slabs of group 3 at point a (applied load P=0.8 pmax.).

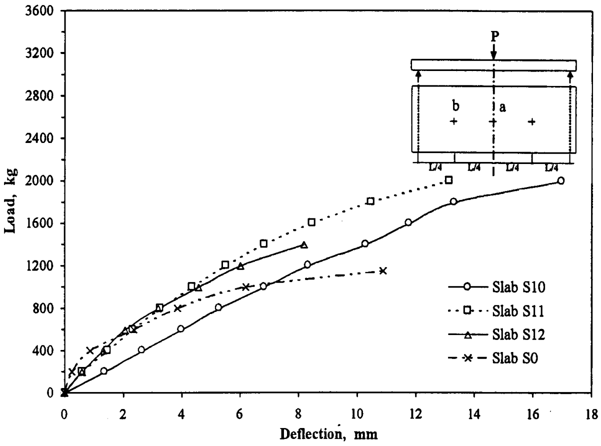

Fig. 9. Deflection comparison between tested slabs of group 4 at point a (applied load P=Pmax.).

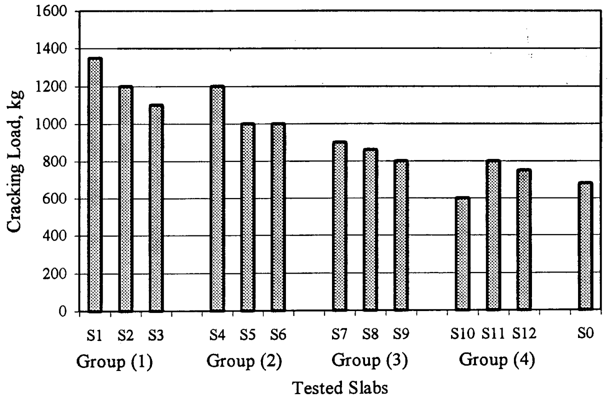

Fig.10. Initial cracking loads for the tested slabs.

6.2.1. First cracking load

Fig. 10 show the first cracking load for all slabs and the control slabs. A comparative study based on the test results showed that:

1. Group (1) showed the highest initial cracking loads compared to group (2), group (3), group (4) and the control slab S0.
2. The initial cracking loads increased compared to the control slab So by the following percentages:

a. For group (1) were 99% for slab S1, 76% for S2, and 62% for slab S3.

b. For group (2) were 76% for slab S4, and 47% for slabs S5 and S6.

c. For group (3) were 33% for slab S7, 26% for S8 and 18% for S8.

d. For group (4) were 16% for slab S11, 10% for S12 where the slab S10 showed 12%

decrease in initial cracking load compared to S0.

3. The pre-loading level affects greatly the cracking load.

6.2.2. Crack patterns

Figs. 11 to 23 show the crack patterns for all tested slabs. The cracks occurred during pre-loading were marked, and after repairing the newer cracks were also marked.

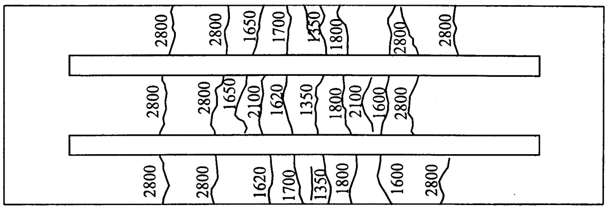

Fig.11. Crack pattern for slab S_1.

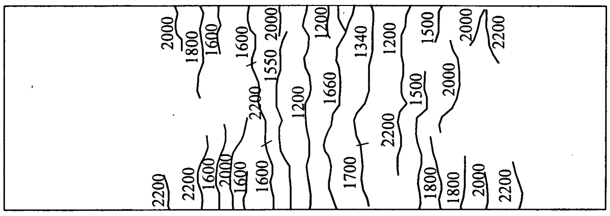

Fig. 12. Crack pattern for slab S_2.

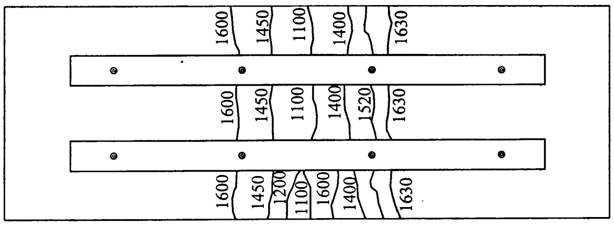

Fig. 13. Crack pattern for slab S_3.

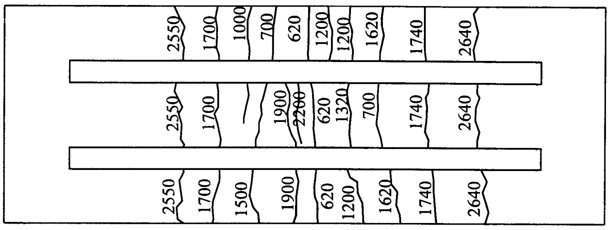

Fig. 14. Crack pattern for slab S_4.

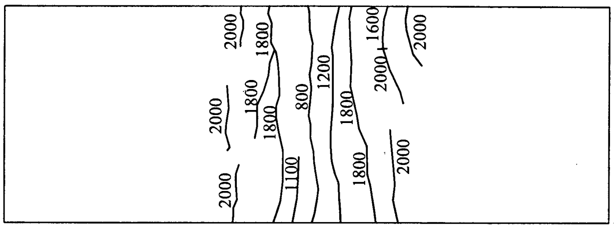

Fig. 15. Crack pattern for slab S_5.

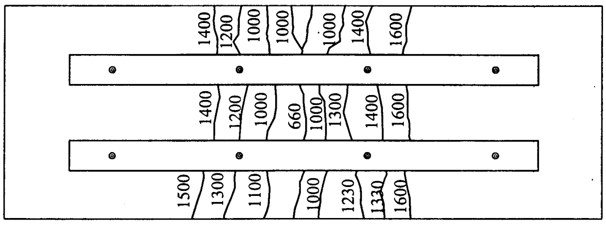

Fig. 16. Crack pattern for slab S_6.

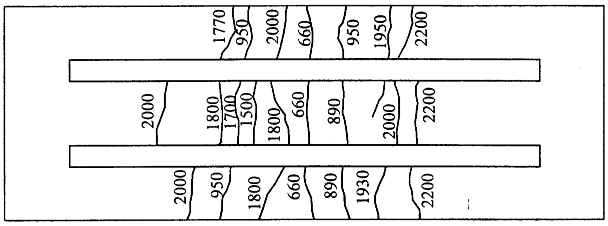

Fig. 17. Crack pattern for slab S_7.

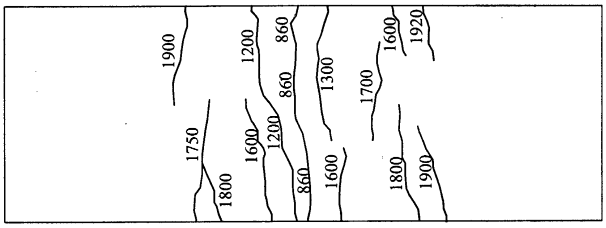

Fig. 18. Crack pattern for slab S_8.

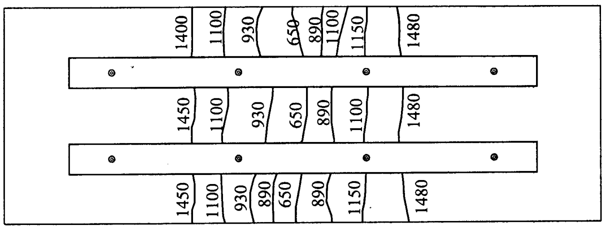

Fig. 19. Crack pattern for slab S_9.

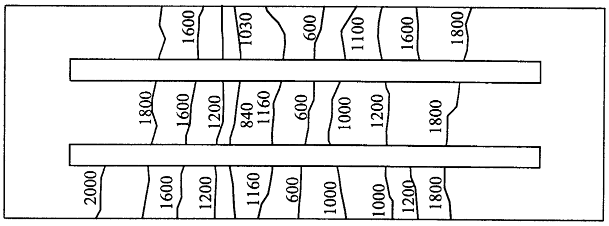

Fig. 20. Crack pattern for slab S_{10}.

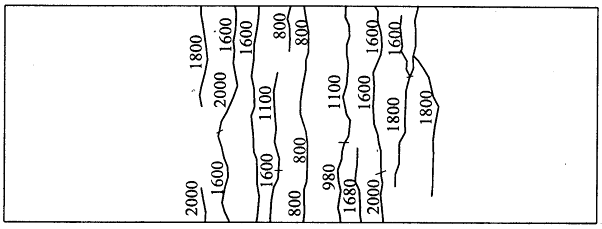

Fig. 21. Crack pattern for slab S_{11}.

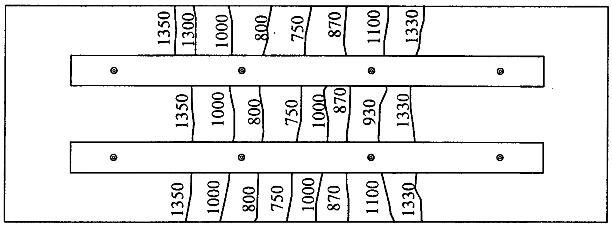

Fig. 22. Crack pattern for slab S_{12}.

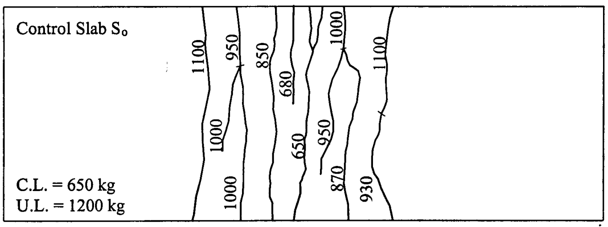

Fig. 23. Crack pattern for slab S_o.

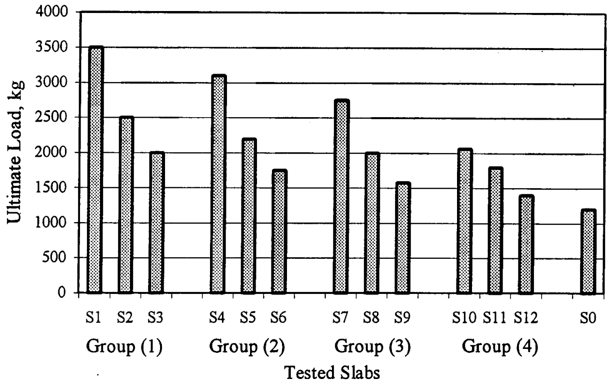

Fig. 24. Crack pattern for slab.

7. Ultimate loads

The ultimate loads for all repaired and strengthened slabs are shown in fig. 24. The slabs repaired and strengthened using carbon fiber reinforced polymers showed the higher ultimate loads than all other slabs. A comparative study based on these test results showed that:

1. Group (1) showed the highest ultimate loads compared to group (2), group (3), group (4) and the control slab S0.
2. The ultimate loads were increased compared to the control slab S0 by the following percentages:
   a. For group (1) were 192% for slab S1, 108% for S2, and 67% for slab S3.
   b. For group (2) were 158% for slab S4, and 83 % for slabs S5 and 49% for S6.
   c. For group (3) were 129% for slab S7, 67% for S8 and 32% for S8.
   d. For group (4) were 72% for slab S10, 50% for S11, and 17% for S12.
3. The higher the pre-loading level the lower the ultimate load regardless of the repairing or strengthening technique.

8. Conclusions

The previous investigations which carried out in this study led to the following conclusions:

1. Repair or strengthening at lower pre-loading levels is more efficient than the higher ones because higher pre-loading causes defects in R.C. slabs as cracks and excessive deflections.
2. Strengthening by CFRP improves the behavior of R.C. slabs as follows:
   a. Increasing the first cracking loads than the control slab by 99%, 78%, 33%, and 16% for pre-loading levels 0.0%, 60%, 80% and 100% respectively.
   b. Increasing the ultimate loads than the control slab by 192%, 158%, 129%, and 72% for pre-loading levels 0.0%, 60%, 80% and 100% respectively.
   c. Improving the deflection at different loading stages compared to the control slab.
3. Strengthening by ferrocement improves the behavior of R.C. slabs as follows:
   a. Increasing the first cracking loads more than the control slab by 76%, 47%, 26%, and 10% for pre-loaded slabs by 0.0%, 60%, 80% and 100% of the ultimate load.
   b. Increasing the ultimate loads more than the control slab by 108%, 83%, 67%, and 50% for pre-loaded slabs by 0.0%, 60%, 80% and 100% of the ultimate load.
   c. Improving the deflection of the previously loaded slabs compared to the control slab.
4. Strengthening by steel strips improves the behavior of R.C. slabs as follows:
   a. Increasing the first cracking loads more than the control slab by 62%, 47%, 18% for pre-loaded slabs by 0.0%, 60%, 80% of the ultimate load respectively whereas there was a reduction of 12% for the slab previously pre-loaded by 100% of the ultimate load.
   b. Increasing the ultimate loads more than the control slab by 67%, 49%, 32%, and 17% for

pre-loaded slab by 0.0%, 60%, 80% and 100% of the ultimate load.

c. Improving the deflection at different loading stages compared to the control slab except for the slab previously pre-loaded by 100% of the ultimate load where the deflection values were greater than the control slab at initial loading stages.

5. Strengthening by ferrocement gives deflection values nearly equal the deflection of slab repaired or strengthened by CFRP due to the thickness increase.
6. Strengthening by ferrocement gives high reduction in deflection values because of high rigidity of slab due to increase percentage of reinforcement in limited area.
7. The efficiency of epoxy injection repair depends on many factors and special precautions represented in validity of the material used high quality of execution procedures, and curing time.
8. Strengthening and repair using CFRP at high pre-loading levels (80% or 100%) is not recommended and more expensive than other methods.
9. Strengthening by CFRP is considered good solution when increasing loading capacity is required (192 % increasing percentage for 0.0% pre-loading level compared to the control slab).
10. Repair by ferrocement or additional R.C. layer is more suitable in case of excessive defects in R.C. slabs and gives results nearly equal the results of expensive methods.
11. In case of repair and strengthening by steel strips, it is better to use suitable number of bolts to fix the steel strips to the concrete in addition to cohesive material.

References

[1] ACI Committee 318, (1983)., Building Code Requirements for Reinforced Concrete (ACI 318-83), American Concrete Institute, Detroit (1983).

[2] ACI Committee 318, (1989)., Building Code Requirements for Reinforced Concrete (ACI 318-89) and Commentary (ACI 318R-89), American Concrete Institute, Detroit (1989).

[3] Egyptian code of practice., U.A.R. Code of practice for the use of reinforced concrete in buildings, Building research centre, ministry of scientific research (1973).

[4] Egyptian code of practice., "Design and Construction for Reinforced Concrete Structures, Research Centre for Housing, Building and Physical Planning (1989).

[5] M.H. Soliman N.M. and Meleka "Nonlinear Analysis of Flat Plate", Eng. Research Bull., Faculty of Eng. Menoufiya University, Vol. XII, Part 1 (1991).

[6] M.H. Soliman "Study of Behavior and Cracks Propagation of Reinforced Concrete Flat Slabs", Eng. Research Bull., Faculty of Eng. Menoufiya University, Vol. XII, Part 2 (1991).

[7] M.H. Soliman "Nonlinear Analysis of Beamless Reinforced Concrete Slabs with Central Openings", Eng. Research Bull., Faculty of Eng. Menoufiya University, Vol. XV, Part 1 (1992).

Received May 27, 2003
Accepted February 16, 2004