Behavior and punching shear strength of reinforced high strength concrete slabs with and without short randomly distributed fibers

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This paper presents results from an experimental program on the behavior and punching shear strength of reinforced normal and high-strength concrete slabs subjected to single concentrated load applied at the center of each slab. The experimental program included the fabrication, instrumentation, and testing of sixteen reinforced concrete slabs. The effect of many important parameters were studied. In order to assess the behavior of tested slabs deflections and steel strains were measured and recorded for all tested slabs. Cracking loads and failure loads were determined for all tested slabs. Cracking patterns and failure modes were observed for all tested slabs. Test results revealed the significant effect of the following parameters on the behavior and punching shear strength of reinforced concrete slabs: concrete strength; reinforcement percent; size of loaded area; and the presence and type of short randomly distributed fibers. It was found that the inclusion of short randomly distributed fibers significantly enhanced the behavior and punching shear load of both normal and high-strength concrete slabs. The experimental results for punching shear load were compared to the theoretical predictions from four major codes of practice. Such codes were: the ACI Code; the BS8110 code, the Japanese code JSCE; and the European code. It was found that the equations presented by both the BS 8110 code and the Japanese code JSCE reasonably predict the punching shear load for tested normal strength and high-strength concrete slabs. However, the equations presented by the ACI code and the European code are extremely conservative in predicting the punching shear load of tested normal strength and high-strength concrete slabs.

يقدم هذا البحث نتائج من دراسة معملية أجريت على سلوك و إجهاد القص الثاقب للبلاطات الخرسانية المسلحه ذات الخرسانه عادية المقاومة أو عالية المقاومة المعرضة لحمل واحد مركز عند مركز كل بلاطة. تضمن البرنامج العملى صب وتجهيز وإختبار ستة عشر بلاطة خرسانية مسلحة وتم دراسة تأثير عدة عوامل. من أجل التعرف على سلوك البلاطات المختبرة تم قياس وتسجيل سهم الإنحناء والإنفعال فى حديد التسليح. تم كذلك ملاحظة حمل التشريخ و حمل الانهيار وشكل التشريخ وشكل الإنهيار لجميع البلاطات المختبرة. أوضحت النتائج المعملية التأثير الكبير للعوامل الآتية على سلوك وإجهاد القص الثاقب للبلاطات الخرسانية المسلحة: إجهاد الخرسانة، نسبة حديد التسليح، مقاس لوح التحميل، ووجود ونوعية الألياف القصيرة الموزعة عشوائياً. كما أوضحت النتائج أن وجود تلك الألياف القصيرة الموزعة عشوائياً يؤدى الي تحسن كبير فى سلوك وحمل القص الثاقب الأقصى للبلاطات الخرسانية المسلحة ذات الخرسانة عادية المقاومة أو الخرسانة عالية المقاومة. تم مقارنة النتائج المعملية لحمل القص الثاقب الأقصى إلى النتائج النظرية للمعادلات الموجودة فى أربعة من الأكواد الكبرى وهى: كود معهد الخرسانة الأمريكى، الكود البريطانى، الكود اليابانى، والكود الأوروبى، وقد وجد أن المعادلات الموجودة بكل من الكود البريطانى والكود اليابانى تعطى نتائج مقبولة بالنسبة لحمل القص الثاقب الأقصى للبلاطات الخرسانية المسلحة ذات الخرسانية عادية المقاومة أو الخرسانة عاليه المقاومة. على الرغم من ذلك فإن المعادلات الموجودة بكل من كود معهد الخرسانة الأمريكى والكود الأوروبى تعطى نتائج أقل بكثير من النتائج المعملية بالنسبة لحمل القص الثاقب الأقصى للبلاطات الخرسانية المسلحة ذات الخرسانة عادية المقاومة أو الخرسانة عالية المقاومة .

Keywords: Codes of practice, Fibers, High strength, Punching shear, Reinforced concrete, Slabs

1. Introduction

The use of high – strength concrete in reinforced concrete slabs is becoming popular in many countries. High strength concrete is defined by the ACI 318 [1] as concrete having cylinder compressive strength greater than 40 MPa. The use of high strength concrete is due to the increasing requirement for higher strengths and improved long–term properties. Also, the introduction of randomly distributed short fibers leads to significant reductions of the thickness of reinforced concrete slabs. The concept of using fibers to improve the characteristics of construction materials is very old [2]. The mechanical behavior of fiber reinforced concrete differs considerably from that of conventional reinforced concrete. The use of randomly distributed fibers in reinforced concrete slabs leads to a significant increase in their failure loads and ductility. This is because such fibers are uniformly distributed and randomly oriented such that some of them effectively bridge the diagonal tension cracks, thereby increasing the slab's shear strength.

Several experimental investigations were found in the literature regarding the behavior of normal strength concrete slabs [3 to 12]. Also, several theoretical investigations were found in the literature regarding the punching shear strength of normal strength concrete slabs. An empirical approach was suggested for the determination of the punching shear capacity of normal strength concrete slabs [13]. The upper-bound theory of plasticity was employed to predict the punching shear failure loads of normal strength concrete slabs [14]. A new empirical model has been developed to predict the punching shear capacity of double layer grids having either restrained or simply supported edges and including an overlapping splice [15]. The model was shown to give reasonably good predictions for both simply supported and restrained slabs. A new model for the prediction of punching shear capacity of normal strength concrete two-way slabs was developed [16]. The accuracy of the model was evaluated against the existing test data. The proposed model had a very good agreement with test results with better predictions for both FRP and steel reinforced normal strength concrete two-way slabs. Furthermore, several researchers examined the equations presented by different codes of practice for the calculation of punching shear capacity of normal strength concrete slabs [17 – 24].

1.1. Punching strength of high-strength concrete slabs

The use of high-strength concrete improves the punching shear resistance of reinforced concrete slabs. In spite of its wide use, only a few research projects have been conducted on the punching shear resistance of high-strength concrete slabs. One of the reasons why some structural engineers are reluctant to use high-strength concrete is due to the lack of information regarding the behavior of this type of concrete. Furthermore, the empirical expressions given in design codes are based on the experimental results from slabs with concrete strength between 15–35 MPa [25]. Hence it is necessary to examine the applicability of the present punching shear design methods for high-strength concrete slabs and to generate experimental data for this purpose. Very limited number of investigations were found in the literature considering the punching strength of high-strength concrete slabs [26 to 28].

1.2. Punching strength of fiber-reinforced concrete slabs

A concrete slab cracks when the diagonal tension or combined action of shear and direct stress exceeds the tensile strength of the concrete [29]. In this case, the flexural reinforcement is less effective than short randomly distributed fibers, because it is placed in areas of maximum flexural stress, not maximum diagonal tension. Short fibers, on the other hand, are uniformly distributed and randomly oriented such that some of them effectively bridge the diagonal tension cracks, thereby increasing the slab's shear strength. However, little research efforts were directed towards the study of the punching strength of fiber-reinforced concrete slabs. Little number of investigations were found in the literature considering the punching strength of fiber-reinforced concrete slabs [30]. Furthermore, a design method was developed for the determination of the punching capacity of steel-fiber-reinforced concrete slabs [31]. The method takes into account a wide range of fiber variables, concrete type and strength, tension steel ratio, size of slab and loaded area.

1.3. The required research

From the above presented available previous investigations, it is clear that there is a need for more detailed experimental investigations in order to cover all the important aspects of the problem of punching strength of reinforced concrete slabs. It was found that previous researchers have concentrated on studying punching strength of reinforced normal strength concrete slabs. Although, high-strength concrete is being widely used in the construction industry in order to increase the strength to dead weight ratio of reinforced concrete structures, however, little research efforts were found in the literature regarding punching strength of reinforced high-strength concrete slabs. Furthermore, although the use of short randomly distributed fibers is known to enhance the punching strength of reinforced concrete slabs, however little research efforts were found in the literature regarding the punching strength of fiber-reinforced concrete slabs. Also, the equations presented in different codes of practice for the calculation of punching strength of reinforced concrete slabs were based on experimental data from testing normal strength concrete slabs with concrete strengths between 15-35 MPa. For this reason, some structural engineers are reluctant to use high-strength concrete. The validity of the equations presented by different codes of practice for the calculation of punching strength of reinforced concrete slabs are questionable in the case of using high-strength concrete.

1.4. The current research

In this paper, an extensive experimental program was conducted in order to study the behavior and punching strength of reinforced normal and high-strength concrete slabs with and without short randomly distributed fibers. The experimental program included casting, instrumentation, and testing 16 RC slabs up to failure. Many variables were studied through the experimental program such as: (i) concrete strength; (ii) flexural reinforcement ratio; (iii) size of loaded area; (iv) presence of short randomly distributed fibers; and finally (v) type of short randomly distributed fibers. For all tested slabs the initiation and propagation of cracks were observed and cracking loads were recorded. Vertical deflections and flexural steel strains were measured and recorded. Also, failure loads and modes of failure were observed and recorded. Finally, the experimental results for the punching failure loads of some of the tested slabs were used to check the validity of the equations presented by codes of practice.

2. Experimental program

The effect of many important variables on the behavior and punching strength of reinforced concrete slabs were studied through an extensive experimental program. The experimental program included casting, instrumentation, and testing of 16 reinforced concrete slabs.

2.1. Details of tested slabs

All tested slabs were square in plan with a total side length of 600 mm and a span length of 500 mm and were simply supported from the four sides. The slab thickness was 50 mm for all tested slabs. Tested slabs were divided into two main groups. The first group “N” included 8 reinforced normal strength concrete slabs whereas the second group “H” included 8 reinforced high-strength concrete slabs. Comparing the results of testing slabs in group “N” to those in group “H” shall yield the effect of concrete strength on punching shear resistance. The first four slabs in each group were made without adding short randomly distributed fibers whereas the second four slabs in each group were made with short fibers. Steel fibers were used for two slabs in each group with a volume content percent of 1.8%. The steel fibers used had a length of 30 mm. polypropylene fibers were used for another two slabs in each group with a content of 3 kg/m^3. The polypropylene fibers used had a length of 15 mm. It should be noted that special care was given during casting of slabs containing fibers. The concrete mix was well vibrated in order to uniformly distribute the fibers and also to prevent balling of fibers.

Two different reinforcement schemes were used for the four slabs without fibers in each group. Two of these slabs in each group were provided with bottom flexural reinforcement consisting of seven mild steel bars diameter 8 mm whereas the other two slabs in each group were provided with bottom flexural reinforcement consisting of seven high tensile steel bars diameter 10 mm. Two different loading plates were used for testing the slabs. Four slabs in each group were tested using loading plate having dimensions of 50 mm x 50 mm whereas the other four slabs were tested using loading plate having dimensions of 75 mm x 75 mm. Details of tested slabs are shown in fig. 1 and are listed in table 1.

2.2. Materials

The concrete mix used for normal strength concrete slabs consisted of ordinary Portland cement, natural sand, and broken stones with 20 mm maximum size, and the mix proportions were 1.0 : 1.6 : 2.55, respectively by weight. The water cement ratio w/c was 0.4. For high-strength concrete slabs pink limestone with maximum aggregate size of 13mm was used as coarse aggregate and the water cement ratio was reduced to 0.26. Silica fume was added to replace 10% of the cement weight in order to increase concrete strength. A commercially available super-plastisizer (water reducing agent) was used to increase workability. In order to determine concrete strength standard cubes 150x150x150 mm were cast from each concrete batch. These cubes were tested in the same day of testing the corresponding slabs. The average concrete cube compressive strength f_{cu} was 27 MPa for normal strength concrete and was 69 MPa for high strength concrete.

The 8 mm diameter mild steel bars used for four slabs had a yield and ultimate strength of 250 and 400 MPa, respectively. The 10 mm diameter high tensile steel bars used for twelve slabs had a yield and ultimate strength of 390 and 580MPa, respectively.

2.3. Instrumentation and test procedure

Deflection at the center of each tested slab was measured by means of mechanical dial gauge. An electrical strain gauge of 10 mm gauge length was used to measure the strain in the bottom flexural reinforcement at the center of each tested slab. All slabs considered in the experimental program were tested to failure under the effect of one central concentrated load as shown in fig. 2. The load was applied using a hydraulic jack of 500 kN capacity. The load was monitored using an electrical load cell. The load was applied in increments of 2.5 kN up to the failure of each slab. For all tested slabs the initiation and propagation of cracks were observed and the cracking loads were recorded. Also, failure loads and modes of failure were observed and recorded.

3. Test results and discussions

The experimental test results are presented in table 2. for all tested slabs. The results include: (i) deflections in the elastic range δ_e at a load = 5.0 kN; (ii) deflections at cracking loads, δ_{cr}; (iii) deflections at failure loads δ_f; (iv) cracking loads; and (v) finally failure loads. Fig. 3 shows load-deflection relationships for all tested slabs whereas fig. 4 shows the effect of concrete strength on such load-deflection relationships. Fig. 5 shows load-steel strain relationships for all tested slabs whereas fig. 6 shows the effect of concrete strength on such load-steel strain relationships. Figs. 7 and 8 present the effect of test parameters on cracking loads and failure loads of tested slabs, respectively. Fig. 9 shows a top view for one of the tested slabs after failure. Figs. 10 and 11 show cracking patterns for tested normal strength concrete slabs without fibers and with fibers, respectively. Figs. 12 and 13 show cracking patterns for tested high strength concrete slabs without fibers and with fibers, respectively. The main objective of the current experimental program was to investigate the effect of a number of important parameters on the behavior and punching strength of reinforced concrete slabs. Such parameters are: (i) concrete strength; (ii) presence of short

Fig. 1. Dimensions and loading setup for tested slabs.

Table 1
Details of tested reinforced concrete slabs

Group	Slab identification	Type of concrete	Reinforcement	Fibers	Size of loading plate
Group "N"	N-5-F0-R8	Normal strength	Seven bars diameter 8 mm	No fibers	5.0 cm x 5.0 cm
	N-7.5-F0-R8	Normal strength	Seven bars diameter 8 mm	No fibers	7.5 cm x 7.5 cm
	N-5-F0-R10	Normal strength	Seven bars diameter 10 mm	No fibers	5.0 cm x 5.0 cm
	N-7.5-F0-R10	Normal strength	Seven bars diameter 10 mm	No fibers	7.5 cm x 7.5 cm
	N-5-FS-R10	Normal strength	Seven bars diameter 10 mm	Steel fibers	5.0 cm x 5.0 cm
	N-7.5-FS-R10	Normal strength	Seven bars diameter 10 mm	Steel fibers	7.5 cm x 7.5 cm
	N-5-FP-R10	Normal strength	Seven bars diameter 10 mm	Polypropylene Fibers	5.0 cm x 5.0 cm
	N-7.5-FP-R10	Normal strength	seven bars diameter 10 mm	Polypropylene fibers	7.5 cm x 7.5 cm
Group "H"	H-5-F0-R8	High strength	Seven bars diameter 8 mm	No fibers	5.0 cm x 5.0 cm
	H-7.5-F0-R8	High strength	Seven bars diameter 8 mm	No fibers	7.5 cm x 7.5 cm
	H-5-F0-R10	High strength	Seven bars diameter 10 mm	No fibers	5.0 cm x 5.0 cm
	H-7.5-F0-R10	High strength	Seven bars diameter 10 mm	No Fibers	7.5 cm x 7.5 cm
	H-5-FS-R10	High Strength	Seven bars diameter 10 mm	Steel fibers	5.0 cm x 5.0 cm
	H-7.5-FS-R10	High strength	Seven bars diameter 10 mm	Steel fibers	7.5 cm x 7.5 cm
	H-5-FP-R10	High strength	Seven bars diameter 10 mm	Polypropylene fibers	5.0 cm x 5.0 cm
	H-7.5-FP-R10	High strength	seven bars diameter 10 mm	Polypropylene fibers	7.5 cm x 7.5 cm

Table 2
Test results

Slab Identification	Elastic deflection*, δ_e (mm)	Deflection at cracking load, δ_c (mm)	Deflection at failure load, δ_f (mm)	Cracking load (kN)	Failure load (kN)
N-5-F0-R8	1.13	2.28	5.84	10.0	32.5
N-7.5-F0-R8	0.94	2.35	6.71	15.0	42.5
N-5-F0-R10	0.80	1.73	4.93	15.0	40.0
N-7.5-F0-R10	0.61	2.17	5.84	20.0	50.0
N-5-FS-R10	0.57	1.77	5.19	17.5	47.5
N-7.5-FS-R10	0.54	2.34	6.55	25.0	62.5
N-5-FP-R10	0.55	1.80	5.15	15.0	42.5
N-7.5-FP-R10	0.51	2.17	6.04	25.0	57.5
H-5-F0-R8	0.64	1.79	6.80	15.0	45.0
H-7.5-F0-R8	0.40	2.02	6.97	20.0	55.0
H-5-F0-R10	0.56	1.63	6.14	22.5	60.0
H-7.5-F0-R10	0.51	2.14	6.23	25.0	65.0
H-5-FS-R10	0.43	2.03	6.64	25.0	67.5
H-7.5-FS-R10	0.40	2.59	7.56	35.0	80.0
H-5-FP-R10	0.37	2.72	7.02	35.0	70.0
H-7.5-FP-R10	0.36	2.19	7.75	35.0	95.0

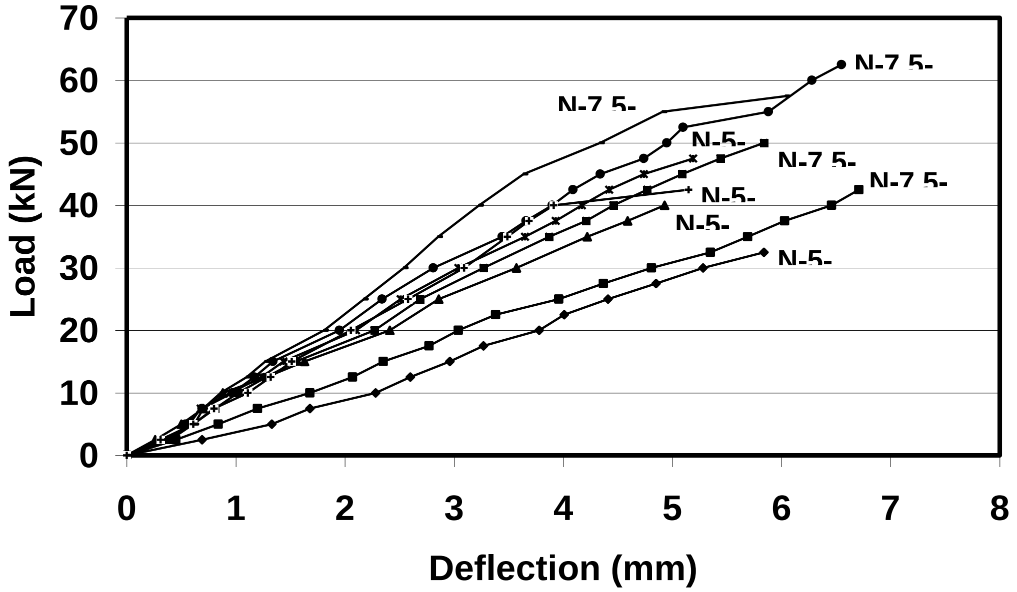
* δ_e = Deflection in the elastic range at a load = 5.0 kN.

Fig. 2. One of the tested reinforced concrete slabs under load.

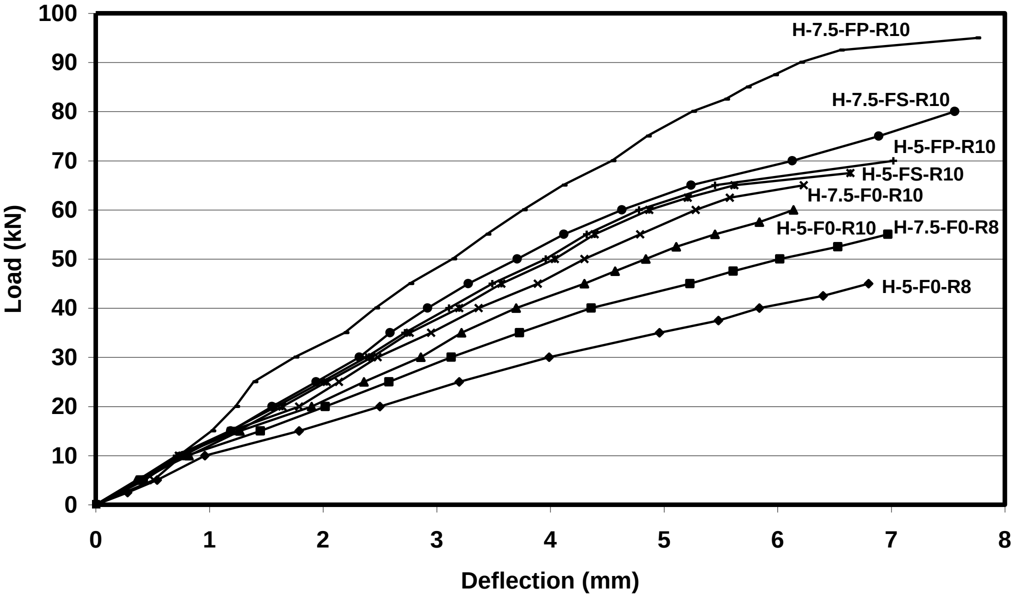
randomly distributed fibers and its type; (iii) flexural reinforcement percent; and (iv) size of loaded area. In the following sections the effect of these parameters on the behavior and punching strength of reinforced concrete slabs shall be presented.

3.1. Effect of concrete strength

The effect of concrete strength on the behavior and punching strength of reinforced concrete slabs can be determined from a comparison of the results of testing the eight reinforced normal strength concrete slabs in group “N” (f_{cu} = 27 MPa) to those from testing the eight reinforced high-strength concrete slabs in group “H” (f_{cu} = 69 MPa). Vertical deflections were significantly affected by a change in the concrete strength. For example, the deflection in the elastic range decreased from 1.13 mm for normal strength concrete slab without fibers (N-5-F0-R8) to 0.64mm for the corresponding high-strength concrete slab without fibers (H-5-F0-R8), representing a 43% decrease. Also, the deflection in the elastic range decreased from o.55 mm for normal strength concrete slab with fibers (N-5-FP-R10) to 0.37 mm for the corresponding high-strength concrete slab with fibers (H-5-FP-R10), representing a 33% decrease. Similar observations are found for the effect of concrete strength on the elastic deflection for all other cases of tested slabs. The deflection at cracking load was also affected by the concrete strength. For example, the deflection at cracking load decreased from 2.35 mm for normal strength concrete slab without fibers (N-7.5-F0-R8) to 2.02 mm for the corresponding high-strength concrete slab without fibers (H-7.5-F0-R8), representing a 14% decrease. However, different observations were found for the effect of concrete strength on the deflection at cracking load for slabs with short randomly distributed fibers. For example, the deflection at cracking load increased from 1.8 mm for normal strength concrete slab with fibers (N-5-FP-R10) to 2.72 mm for the

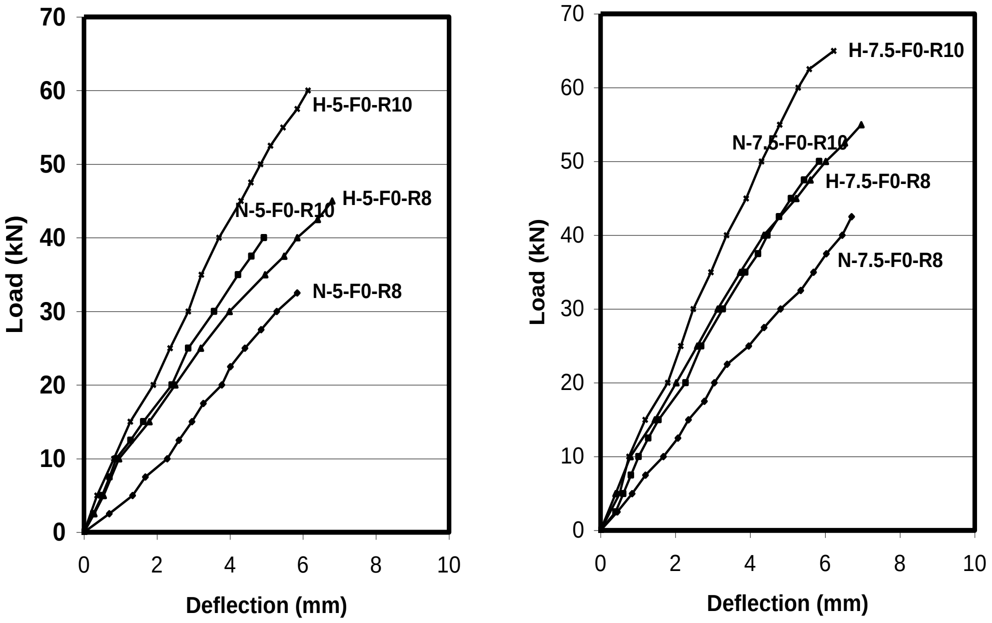


(a) Normal Strength Concrete Slabs



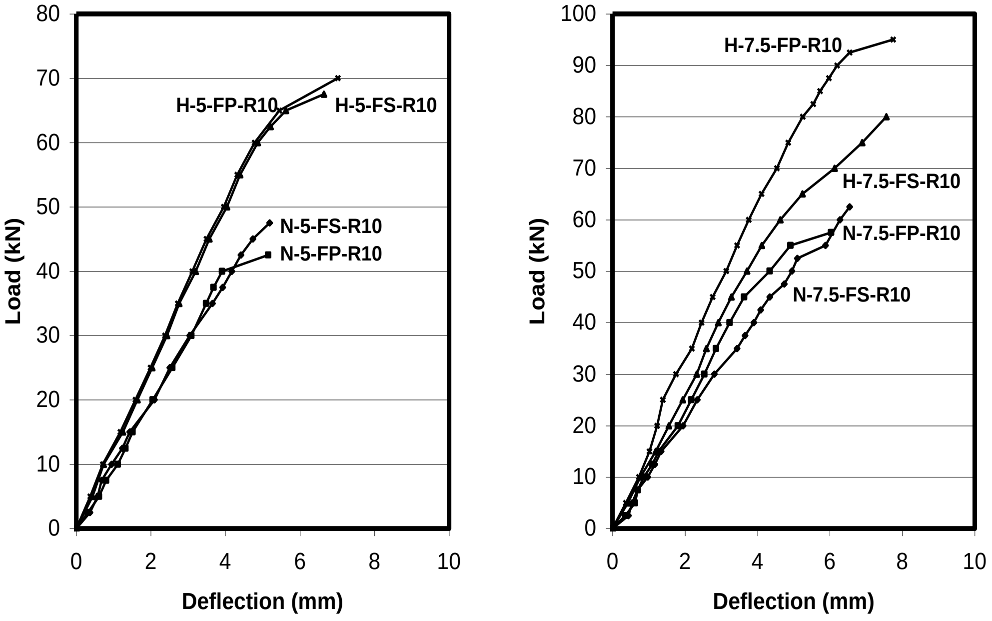
(b) High Strength Concrete Slabs

Fig. 3. Load-deflection relationships for all tested slabs.



(a) Plate 50 mm, no fibers

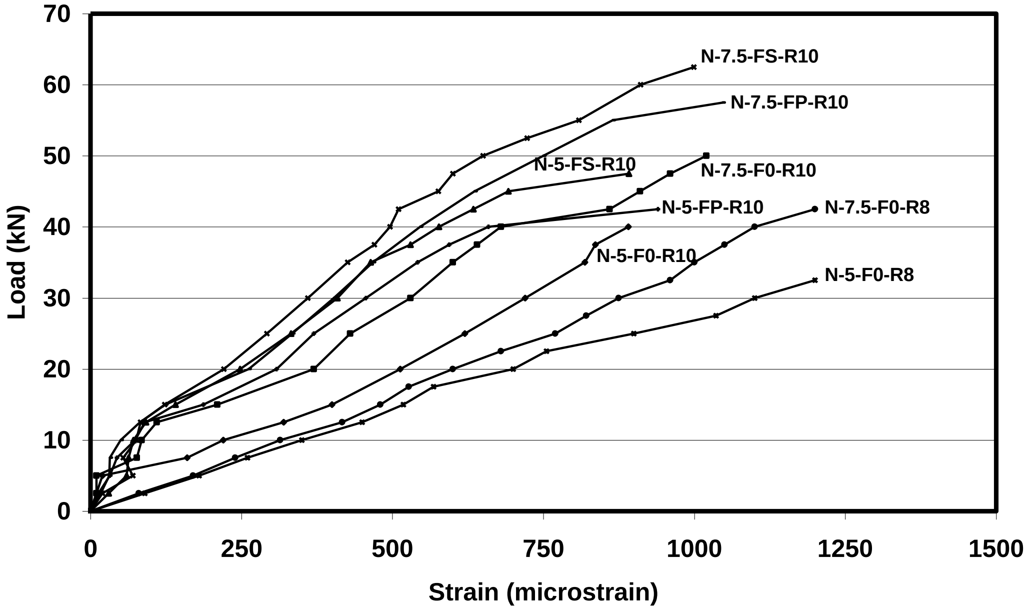
(b) Plate 75 mm, no fibers



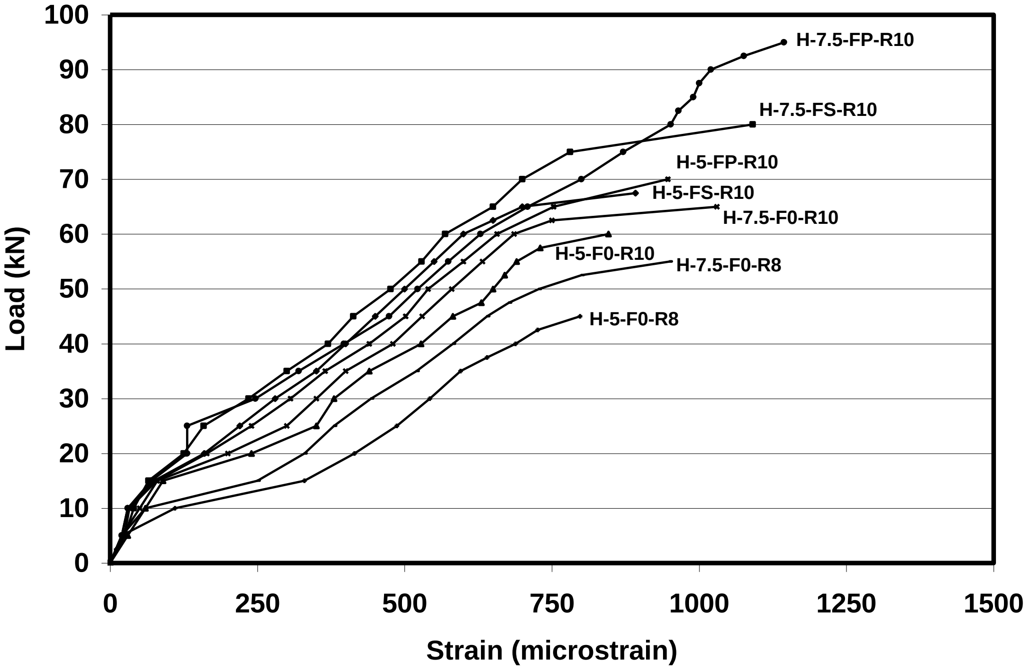
(c) Plate 50 mm, with fibers

(d) Plate 75 mm, with fibers

Fig. 4. Effect of concrete strength on load-deflection relationships.

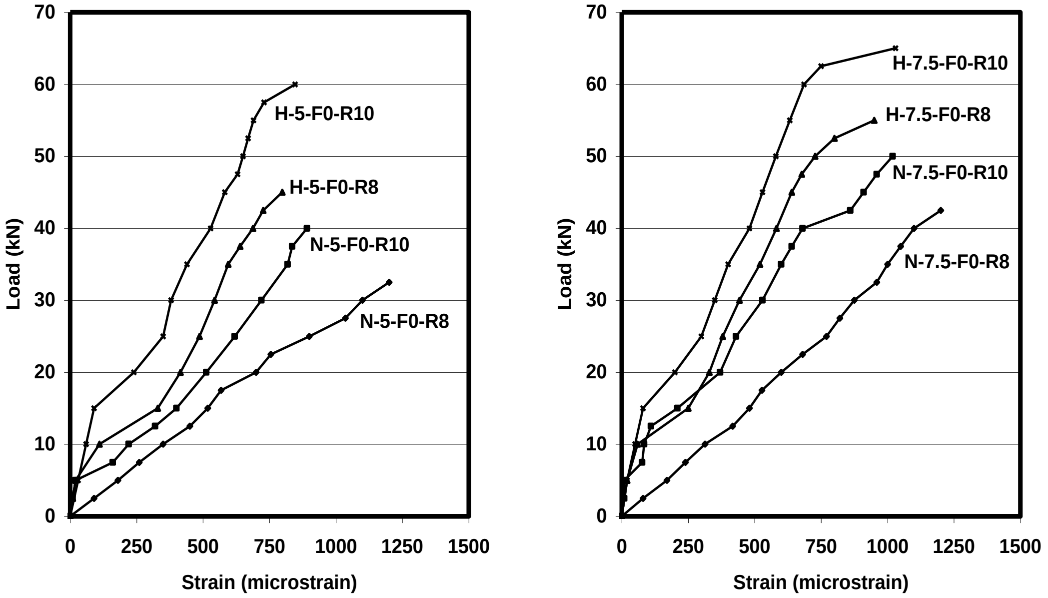


(a) Normal Strength Concrete Slabs



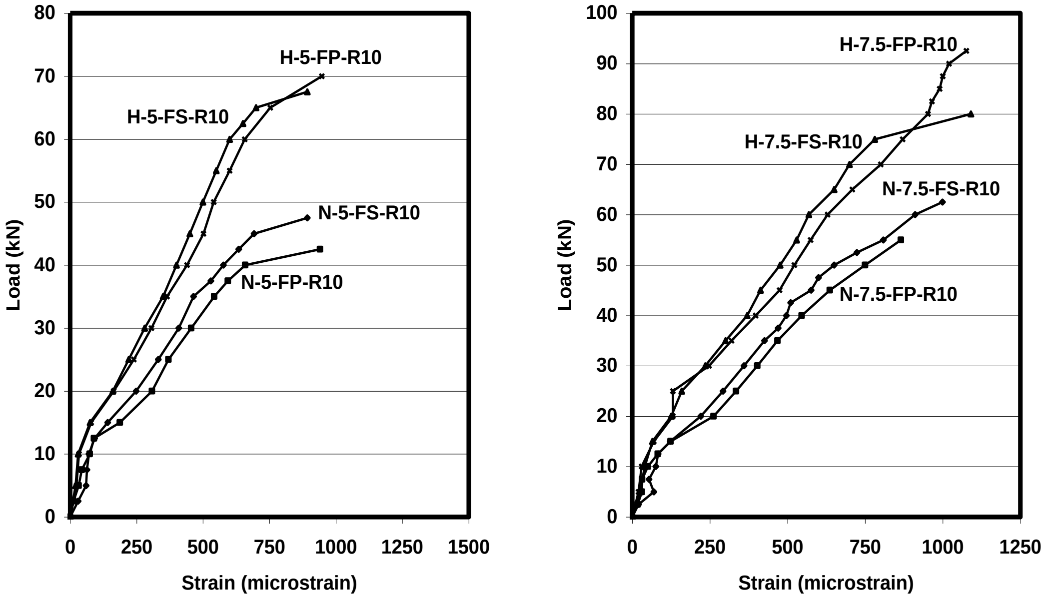
(b) High Strength Concrete Slabs

Fig. 5. Load-strain relationships for all tested slabs.



(a) Plate 50 mm, no fibers

(b) Plate 75 mm, no fibers



(c) Plate 50 mm, with fibers

(d) Plate 75 mm, with fibers

Fig. 6. Effect of concrete strength on load-strain relationships.

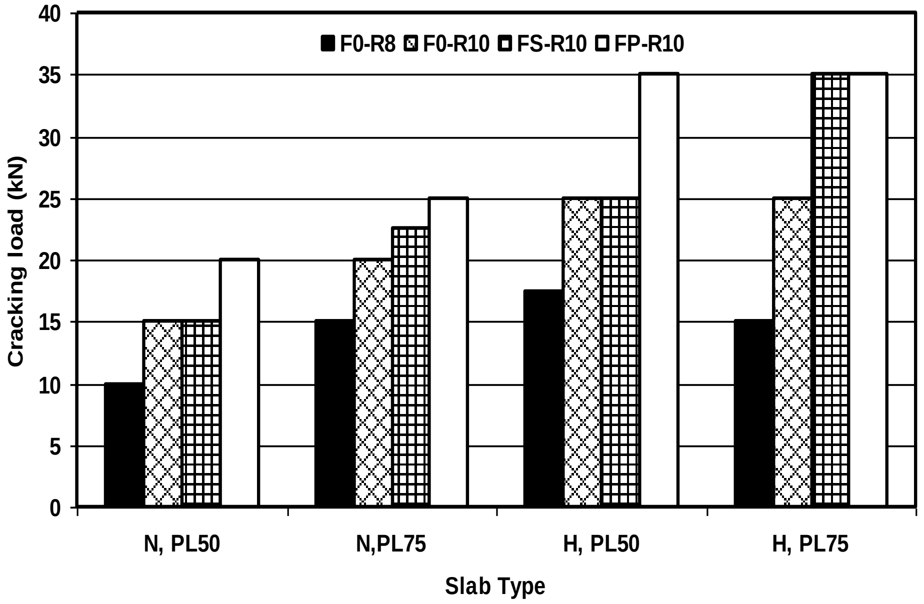


Fig. 7. Effect of test parameters on cracking loads of tested slabs.

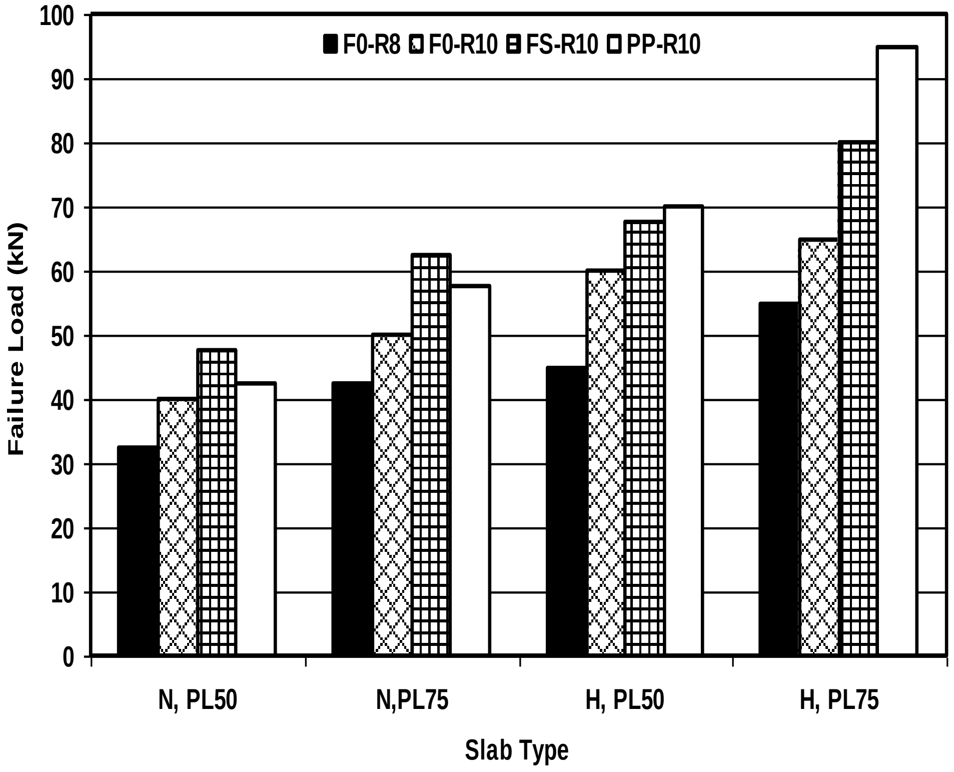


Fig. 8. Effect of test parameters on failure loads of tested slabs.

Fig. 9. Top view for one of the tested slabs after failure.

corresponding high-strength concrete slab with fibers (H-5-FP-R10), representing a 51% increase.

The deflection at failure load significantly increased in the case of high-strength concrete slabs than that in the case of normal strength concrete slabs. For example, the deflection at failure load increased from 6.55 mm for normal strength concrete slab with fibers (N-7.5-FS-R10) to 7.56 mm for the corresponding high strength concrete slab with fibers (H-7.5-FS-R10), representing a 15% increase.

Therefore, it can be concluded herein that the use of high-strength concrete resulted in: (i) significant decrease in the deflection in the elastic range for slabs with or without fibers having any reinforcement ratio, and any size of loading plate; (ii) significant decrease in the deflection at cracking load for slabs without fibers; (iii) significant increase in the deflection at cracking load for slabs with fibers; and (iv) significant increase in the deflection at failure load for slabs with or without fibers having any reinforcement ratio and size of loading plate.

Concrete strength also affected the bottom flexural steel strain as shown in fig. 6. In the case of tested slabs without fibers, the steel strain decreased significantly in the case of high-strength concrete slabs than that in the case of normal strength concrete slabs over the complete range of loading up to failure. The effect of concrete strength on the steel strain was less significant in the case of slabs with short randomly distributed fibers, especially in the elastic range of loading.

The results presented in table 2 and fig. 7 reveals a significant effect of the concrete strength on the tested slabs cracking loads. The cracking loads increased significantly in the case of high-strength concrete slabs than those in the case of normal-strength concrete slabs. The following can be observed: (i) the enhancement in the cracking loads ranged between 25% and 50% in the case of slabs without fibers; (ii) such enhancement in the cracking loads ranged between 40% and 133% in the case of slabs with fibers; (iii) the effect of concrete strength in enhancing the cracking loads always decreases with increasing the

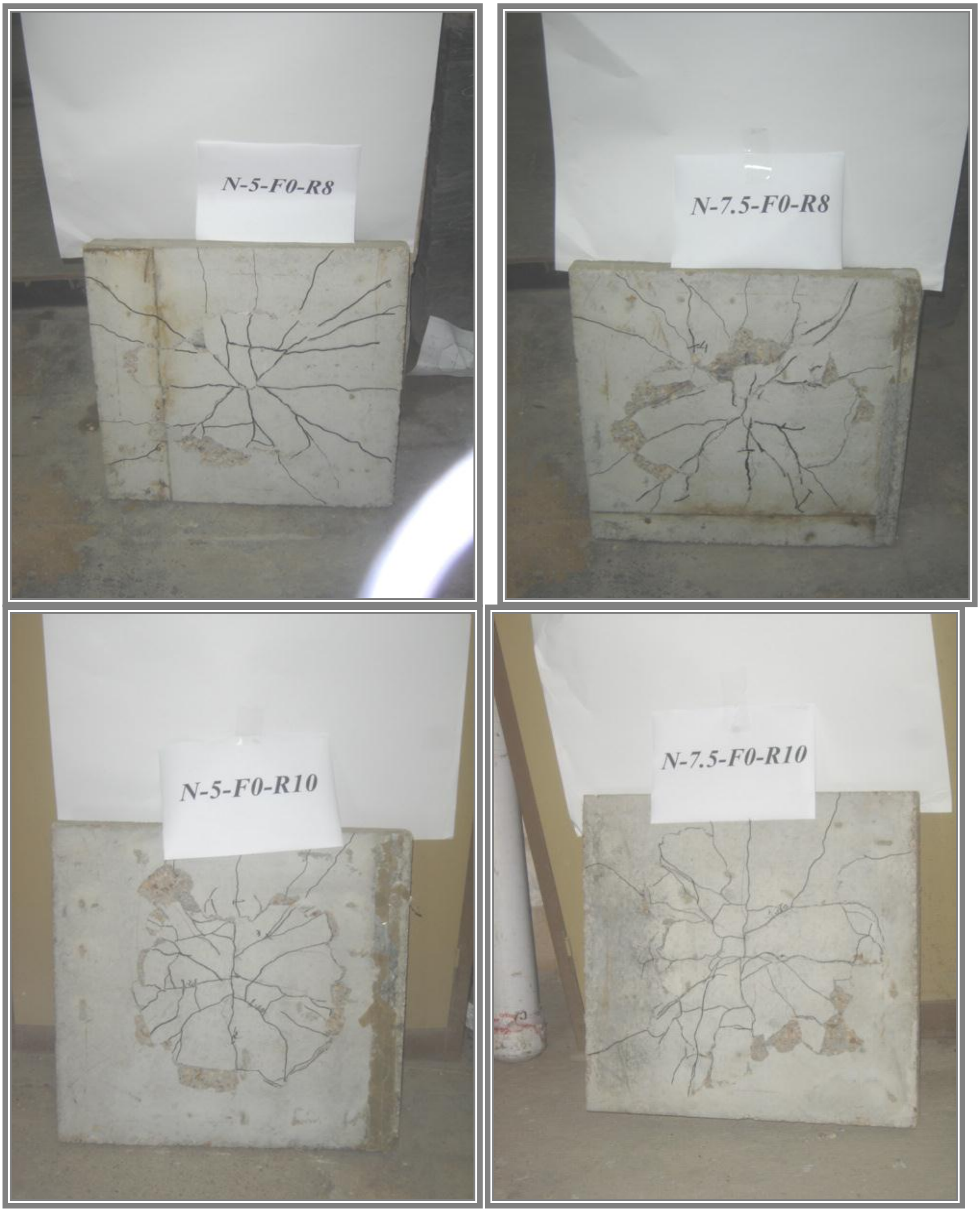


Fig. 10. Cracking patterns for tested normal strength concrete slabs without fibers.

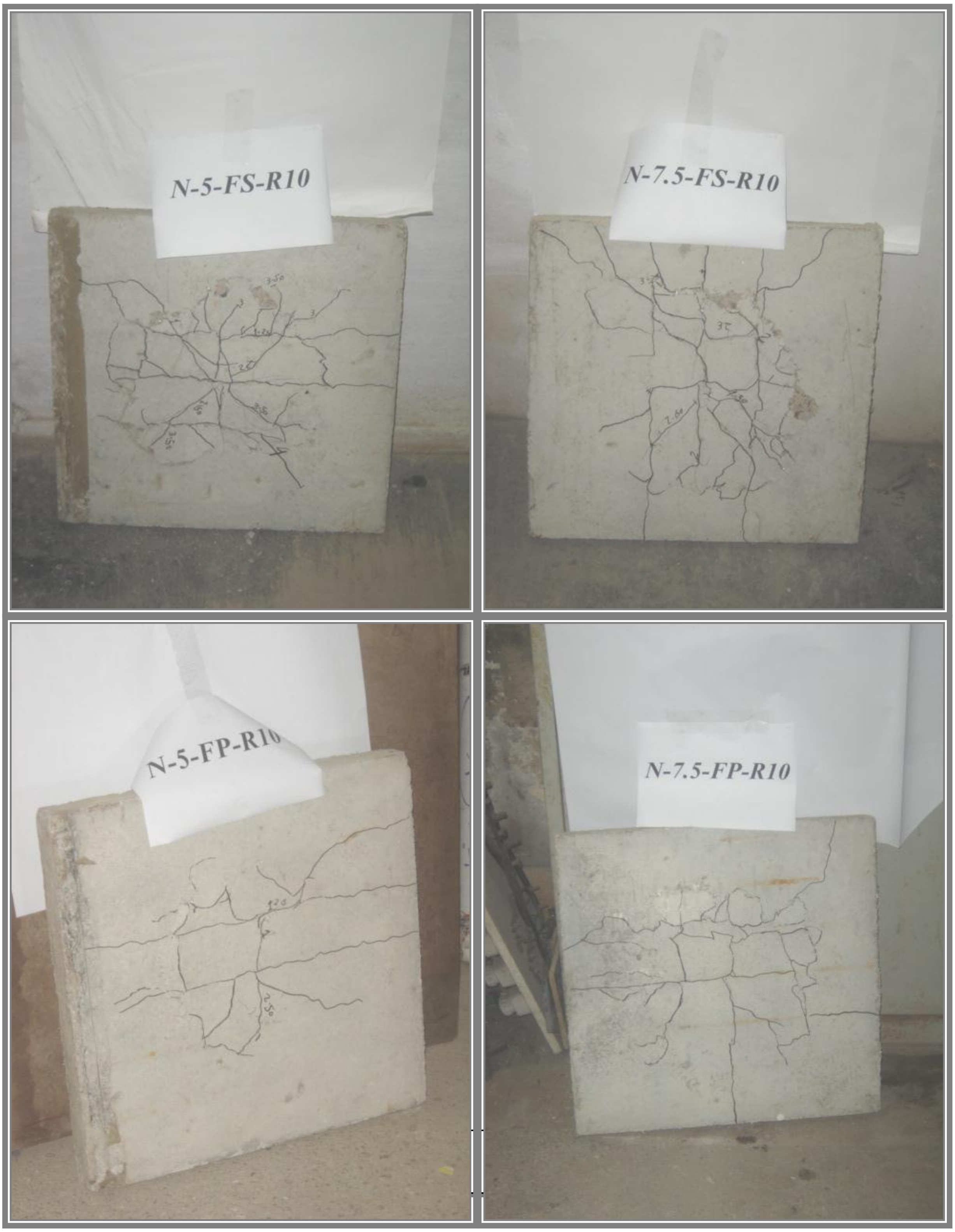


Fig. 11. Cracking patterns for tested normal strength concrete slabs with fibers.

Fig. 12. Cracking patterns for tested high strength concrete slabs without fibers.

Fig. 13. Cracking patterns for tested high strength concrete slabs with fibers.

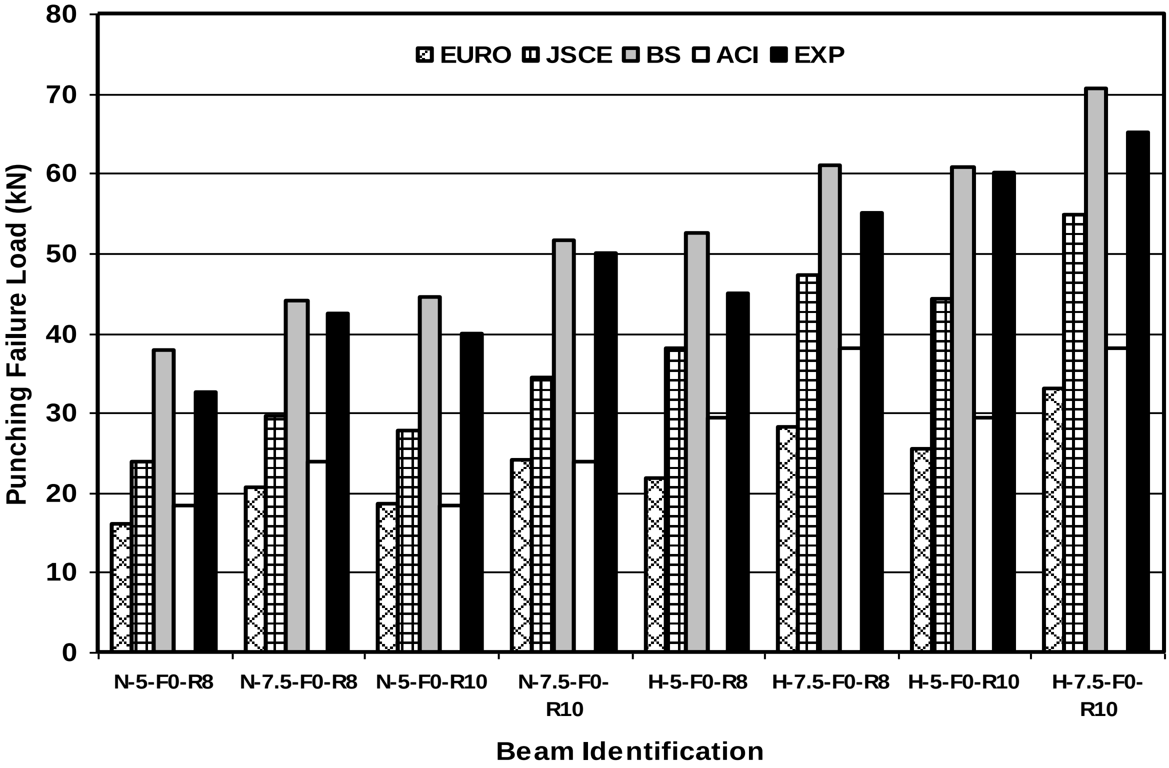


Fig. 14. Experimental punching failure loads versus codes predictions.

size of loading plate; and (iv) the effect of concrete strength in enhancing the cracking loads increases in the case of slabs with short randomly distributed fibers. This may be attributed to the fact that the presence of such fibers provides a crack arresting mechanism. The failure loads also increased significantly in the case of high-strength concrete slabs than that in the case of normal-strength concrete slabs as shown in table 2. and fig. 8. The following can be observed: (i) the increase in the failure loads ranged between 29% and 50% in the case of slabs without fibers; (ii) such increase in the failure loads ranged between 28% and 65% in the case of slabs with fibers; (iii) the effect of concrete strength in increasing the failure loads decreases with increasing the size of loading plate; and (iv) the effect of concrete strength in increasing the failure loads increases in the case of slabs having short randomly distributed fibers.

It should be noted that the mode of failure was not affected by the concrete strength. All tested slabs failed in a punching shear mode of failure. In all cases, the failure was sudden and explosive. The failure consists of a cone of concrete being completely pushed out of the slab, leaving a square hole at the top of the slab which was slightly larger than the square loading plate, as shown in fig. 9. However, some observations regarding the effect of concrete strength on the failure modes and cracking patterns may be summarized as follows: (i) although the failure mode of tested slabs was not affected by concrete strength, however in the case of high strength concrete slabs the failure was much more catastrophic and explosive and was associated with louder noise; and (ii) the punching failure surface area on the tension face of the slabs was much smaller in the case of high strength concrete slabs than that in the case of normal strength concrete slabs.

3.2. Effect of the presence and type of short randomly distributed fibers

The effect of the presence and type of short randomly distributed fibers on the behavior and punching strength of reinforced concrete slabs can be determined for normal strength concrete slabs when comparing the results of testing slabs (N-5-FS-R10) and (N-7.5-FS-R10) having steel fibers and results of testing slabs (N-5-FP-R10) and (N-7.5-FP-R10) having polypropylene fibers to those of testing slabs (N-5-F0-R10) and (N-7.5-F0-R10), without fibers. Also the effect of the presence and type of short randomly distributed fibers on the behavior and punching strength of high strength concrete slabs can be determined when comparing the results of testing slabs (H-5-FS-R10) and (H-7.5-FS-R10) having steel fibers and the results of testing slabs (H-5-FP-R10) and (H-7.5-FP-R10) having polypropylene fibers to those of testing slabs (H-5-F0-R10) and (H-7.5-F0-R10), without fibers.

Generally, deflections of tested slabs were significantly affected by the presence of short randomly distributed fibers. For example, the deflection in the elastic range decreased significantly as a result of the presence of fibers. The following can be observed from table 2: (i) the decrease in the deflection in the elastic range as a result of the presence of fibers ranged between 11% and 31% in the case of normal strength concrete slabs; (ii) Such decrease ranged between 22% and 34% in the case of high strength concrete slabs; (iii) The presence of fibers results in a much more significant decrease in the deflection in the elastic range in the case of high strength concrete slabs than that in the case of normal strength concrete slabs; (iv) the effect of the presence of fibers in decreasing the deflection in the elastic range decreases with an increase in the size of loading plate; and (v) polypropylene fibers were more effective in reducing the deflection in the elastic range than steel fibers.

Different observations were found for the effect of the presence of short randomly distributed fibers on the deflection at cracking load and failure load. The following can be observed from table 2: (i) the presence of fibers leads to an increase in the deflection at cracking load raged between 0% and 8% in the case of normal strength concrete slabs and ranged between 2% and 67% in the case of high strength concrete slabs; and (ii) the presence of fibers leads to an increase in the deflection at failure load ranged between 3% and 12% for normal strength concrete slabs and ranged between 8% and 24% for high strength concrete slabs. Therefore, it can be concluded that the presence of short randomly distributed fibers resulted in a more significant increase in the deflection at cracking load and failure load in the case of high strength concrete slabs than that in the case of normal strength concrete slabs.

The presence of short randomly distributed fibers also affected the bottom flexural steel strain as shown in fig. 5. It was found that the steel strain slightly decreased in the elastic range of loading as a result of the presence of fibers. However, such decrease became significant in the post-elastic range of loading. This is because of the fact that a part of the applied land in transferred to the fibers and is resisted by debonding and stretching. It should be noted that the presence of fibers results in a significant increase in the steel strain at failure load especially in the case of high strength concrete slabs. Furthermore, there is a definite increase in the area under load-strain curves as a result of the presence of short randomly distributed fibers which reflects an enhancement in the slab ductility, especially in the case of high strength concrete slabs.

The results presented in table 2. and fig. 7 indicate a significant enhancement in the cracking loads of tested slabs as a result of the presence of short randomly distributed fibers which can be explained by the crack arresting mechanism provided by the fibers. The following can be observed: (i) the enhancement in the cracking loads as a result of the presence of fibers ranged between 0% and 25% in the case of normal strength concrete slabs; (ii) such enhancement in the cracking loads ranged between 11% and 56% on the case of high strength concrete slabs; (iii) the presence of fibers is much more effective in enhancing the cracking loads in the case of high strength concrete slabs than that in the case of normal strength concrete slabs; (iv) steel fibers are much more effective in enhancing the cracking loads of normal-strength concrete slabs than polypropylene fibers; and (v) polypropylene fibers are more effective in enhancing the cracking loads of high strength concrete slabs than steel fibers.

Failure loads of tested slabs were also significantly enhanced as a result of the presence of short randomly distributed fibers. From table 2. and figure 8, the following can be observed: (i) the increase in the failure loads as a result of the presence of fibers ranged between 6% and 25% in the case of normal-strength concrete slabs; (ii) such increase in the failure loads ranged between 13% and 46% in the case of high-strength concrete slabs; (iii) the inclusion of short randomly distributed fibers is much more effective in enhancing the failure loads of high strength concrete slabs than that in the case of normal-strength concrete slabs; (iv) steel fibers are more effective in enhancing the failure loads of normal-strength concrete slabs than polypropylene fibers; and (v) polypropylene fibers are much more effective in increasing the failure loads of high strength concrete slabs than steel fibers.

The presence of short randomly distributed fibers did not affect the mode of failure of normal or high strength concrete slabs which was in all cases punching shear mode. However, some observations were found in the case of slabs having fibers which can be summarized as follows: (i) the presence of short randomly distributed fibers resulted in a less catastrophic and explosive failure and was associated with much less noise; (ii) such effect of the presence of fibers was much more clear in the case of high-strength concrete slabs than that in the case of normal strength concrete slabs: (iii) the punching failure surface area on the tension face of the slabs became much smaller as a result of the inclusion of short randomly distributed fibers; and (iv) the cracking pattern on the tension face of the slabs was significantly affected by the presence of fibers as shown in figs. 10 to 13. In the case of slabs containing fibers much less number of cracks were observed after failure. Also, crack widths were much less in the case of slabs containing fibers.

3.3. Effect of flexural reinforcement percent

The effect of flexural reinforcement percent on the behavior and punching strength of reinforced concrete slabs can be determined for normal strength concrete slabs when comparing the results of testing slabs (N-5-F0-R8) and (N-7.5-F0-R8) provided with seven bars diameter 8 mm mild steel to the results of testing slabs (N-5-F0-R10) and (N-7.5-F0-R10) provided with seven bars diameter 10 mm high tensile steel. Also, the effect of flexural reinforcement percent on the behavior and punching strength of high strength concrete slabs can be detected when comparing the results of testing slabs (H-5-F0-R8) and (H-7.5-F0-R8) provided with seven bars diameter 8 mm mild steel to the results of testing slabs (H-5-F0-R10) and (H-7.5-F0-R10) provided with seven bars diameter 10 mm high tensile steel.

As expected, the increase of the flexural reinforcement percent resulted in a significant reductions in the deflection in the elastic range, the deflection at cracking load, and the deflection at failure load. From the results presented in table 2. and fig. 3, the following can be observed: (i) for normal strength concrete slabs the deflection in the elastic range decreased by about 29% and 35% as a result of increasing the reinforcement percent for size of loading plate 50 mm and 75 mm, respectively; (ii) for high strength concrete slabs the deflection in the elastic range decreased by about 12% and 35% as a result of increasing the reinforcement percent for size of loading plate 50 mm and 75 mm, respectively; (iii) for normal strength concrete slabs the deflection at cracking load decreased by about 24% and 8% as a result of increasing the reinforcement percent for size of loading plate 50 mm and 75 mm, respectively; (iv) for high strength concrete slabs the deflection at cracking load decreased by about 9% as a result of increasing the reinforcement percent for size of loading plate 50 mm; (v) however, in the case of loading plate 75 mm such deflection at cracking load increased by about 6% as a result of increasing the reinforcement percent; (vi) for normal strength concrete slabs the deflection at failure load decreased by about 16% and 13% as a result of increasing the reinforcement percent for size of loading plate 50 mm and 75 mm, respectively; and (vii) for high strength concrete slabs the deflection at failure load decreased by about

10% and 11% as a result of increasing the reinforcement percent for size of loading plate 50mm and 75mm, respectively.

Based on these observations it can be concluded that the percent of flexural reinforcement plays an important role in controlling the slab deflections not only within the elastic range of loading but also in the post-elastic range of loading up to the failure of the slabs. Furthermore, it can be concluded that such effect of increasing the flexural reinforcement percent in controlling the slab deflections in less significant in the case of high strength concrete slabs than that in the case of normal strength concrete slabs.

The bottom flexural steel strain was also affected by an increase in the reinforcement percent as shown in fig. 5. It can be observed that the steel strain at any given load decreases significantly as a result of increasing the reinforcement percent of normal and high strength concrete slabs and for any size of loading plate. However, the following can also be observed: (i) the effect of increasing the reinforcement percent in decreasing the steel strain is marginal within the elastic range of loading; (ii) such effect becomes much more significant in the post elastic range of loading; (iii) such effect is much more significant in the case of normal strength concrete slabs than that in the case of high strength concrete slabs; (iv) an increase in the reinforcement percent results in a decrease in the steel strain at failure load in the case of normal strength concrete slabs; (v) however, an increase in the reinforcement percent results in an increase in the steel strain at failure load in the case of high strength concrete slabs; and (vi) the area under load-strain curves increases as a result of increasing the reinforcement percent which indicates an enhancement in the slab ductility.

The increase in the reinforcement percent not only affected the deflections and steel strains of tested slabs, but also affected the cracking loads and failure loads of the slabs as shown in table 2. and figs. 7 and 8. With respect to cracking loads, the following can be observed: (i) for normal strength concrete slabs the cracking load increased by about 50% and 33% as a result of increasing the reinforcement percent for size of loading plate 50 mm, and 75 mm, respectively; (ii) for high strength concrete slabs the cracking load increased by about 50% and 25% as a result of increasing the reinforcement percent for size of loading plate 50 mm and 75 mm, respectively; (iii) for normal strength concrete slabs the failure load increased by about 23% and 18% as a result of increasing the reinforcement percent for size of loading plate 50 mm and 75 mm, respectively; and (iv) for high strength concrete slabs the failure load increased by about 33% and 19% as a result of increasing the reinforcement percent for size of loading plate 50 mm and 75mm, respectively. Based on these observations it can be concluded that the reinforcement percent is an important factor that enhances both cracking loads and failure loads of reinforced concrete slabs. However, the effect of the reinforcement percent is much more significant in enhancing the cracking loads of normal strength concrete slabs than that for high strength concrete slabs. Also, the effect of the reinforcement percent is much more significant in enhancing the failure loads of high strength concrete slabs than that for normal strength concrete slabs. It should be noted that a change in the percent of the bottom flexural reinforcement did not affect the failure modes of the slabs which was a punching shear mode in all cases. Also, the cracking patterns after failure were similar for slabs having different reinforcement percents.

3.4. Effect of size of loaded area

In order to determine the effect of the size of loaded area on the behavior and punching shear strength of reinforced concrete slabs, two identical slabs were made for all cases of concrete strength, reinforcement percent, and for all cases of short randomly distributed fibers. One of the two identical slabs in each case was tested using a loading plate having dimensions 50 mm x 50 mm whereas the other slab was tested using a loading plate having dimensions 75 mm x 75 mm. Therefore, a comparison between the results of the two slabs in each case shall reveal the effect of the size of loading plate.

The results presented in table 2 and fig. 3 indicate a significant effect of the size of loaded area on the deflection of the slabs in the elastic range of loading. The following can be observed: (i) an increase in the size of loaded area from 50 mm x 50 mm to 75 mm x 75 mm resulted in a significant decrease in the deflection in the elastic range of loading for all cases of concrete strength, reinforcement ratio, and for all cases of slabs with and without short randomly distributed fibers; (ii) the effect of increasing the size of loaded area on decreasing the deflection in the elastic range was much more significant in the case of normal strength concrete slabs than that in the case of high strength concrete slabs; and (iii) such effect of the size of loaded area was much less significant in the case of slabs having short randomly distributed fibers.

Different observations were found for the effect of the size of loaded area on the deflection at cracking loads and failure loads. In this case the value of the deflection increases as a result of increasing the size of loaded area. The following can be observed: (i) an increase in the size of loaded area from 50 mm x 50 mm to 75 mm x 75 mm resulted in an increase in the deflection at cracking load ranged between 3% and 32% for normal strength concrete slabs; (ii) such increase in the deflection at cracking load ranged between 13% and 31% for high strength concrete slabs; (iii) an increase in the size of loaded area from 50 mm x 50 mm to 75 mm x 75 mm resulted in an increase in the deflection at failure load ranged between 15% and 26% for normal strength concrete slabs; and (iv) such increase in the deflection at failure load ranged between 1 % and 14% for high strength concrete slabs.

It should be noted that the effect of increasing the size of loaded area on increasing the deflection at failure load was much more significant in the case of normal strength concrete slabs than that for high strength concrete slabs. Furthermore, the effect of increasing the size of loaded area on increasing the deflection at failure load was much more significant in the case of slabs having short randomly distributed fibers than that in the case of slabs without fibers.

Another effect of increasing the size of loaded area was a significant decrease in the bottom flexural steel strain at any given load. However, the following can be observed from fig. 5: (i) no effect of the size of loaded area was found within the elastic range of loading; (ii) within the post-elastic range of loading at any given load the increase in the size of loaded area from 50 mm x 50 mm to 75 mm x 75 mm resulted in a significant decrease in the bottom flexural steel strain; (iii) at failure load the increase in the size of loaded area resulted in a significant increase in the bottom flexural steel strain for all cases of concrete strength, reinforcement percent, and for all cases of slabs provided or not provided with short randomly distributed fibers; (iv) the effect of increasing the size of loaded area on decreasing the steel strain within the post-elastic range of loading was found more significant in the case of normal strength concrete slabs than that in the case of high strength concrete slabs; and (v) such effect of the size of loaded area on the steel strain was much more significant in the case of slabs without short randomly distributed fibers than that in the case of slabs provided with fibers.

The increase in the size of loaded area from 50 mm x 50 mm to 75 mm x 75 mm resulted in a significant increase in both the cracking loads and failure loads of tested slabs as shown in table 2. and figs. 7 and 8. The following can be observed: (i) an increase in the size of loaded area resulted in an increase in the cracking loads of tested normal strength concrete slabs ranged between 33% and 66%; (ii) such increase in the cracking loads ranged between 0% and 40% for high strength concrete slabs; (iii) an increase in the size of loaded area resulted in an increase in the failure loads of tested normal strength concrete slabs ranged between 25% and 35%; and (iv) such increase in the failure loads ranged between 8% and 35% for high strength concrete slabs.

It can be concluded herein that the effect of increasing the size of loaded area on increasing the cracking loads and failure loads was much more significant in the case of normal strength concrete slabs than that in the case of high strength concrete slabs. Also, cracking loads of tested slabs were much more sensitive to a change in the size of loaded area than failure loads. It should be noted that the increase in the size of loaded area from 50 mm x 50 mm to 75 mm x 75 mm did not change the failure modes of the slabs which were punching shear mode in all cases. However, a change was observed in the cracking patterns after failure as a result of increasing the size of loaded area. As was expected, the punching failure surface area on the tension face of the slab increased significantly with an increase in the size of loaded area.

4. Validity of codes of practice predictions

The validity of the design equations for the calculation of punching shear failure loads of reinforced concrete slabs, presented in some international codes of practice shall be assessed in this section using the experimental test results from testing the eight reinforced concrete slabs which were not provided with short randomly distributed fibers. The equations given by the following codes of practice were examined: (i) The ACI Building code (ACI 318-05) [1]; (ii) The British Standards Institution (BS 8110) [32]; (iii) The Japanese Society of Civil Engineers (JSCE) [33]; and (iv) The European code (CEB-FIP) [34].

4.1. The ACI Building code (ACI 318-05) [1]

The ultimate punching shear load is taken as the smallest of:

$$V_u = 0.083\,(2 + \frac{4}{\beta_c})\sqrt{f'_c}\; b_o\; d\,. \tag{1}$$

$$V_u = 0.083\,(2 + \frac{a_s\, d}{b_o})\sqrt{f'_c}\; b_o\; d\,. \tag{2}$$

$$V_u = 0.083 \times 4\sqrt{f'_c}\; b_o\; d\,, \tag{3}$$

where: b_o is the critical perimeter = $4(c+d)$; β_c=ratio of the long-to-short sides of loaded area; c = side length of loaded area; a_s = 40, 30, or 20 for interior columns, edge columns, and corner columns, respectively; f_c = concrete cylinder compressive strength; and d= effective depth.

4.2. The British Standards Institution (BS 8110) [32]

The ultimate punching shear load is taken as:

$$V_u = 0.79\,\sqrt[3]{100\,\rho}\;\sqrt[3]{\frac{f_{cu}}{25}}\;\sqrt[4]{\frac{400}{d}}\;U\,d\,, \tag{4}$$

where: U is the critical perimeter = $4(c+3d)$; f_{cu}= concrete cube compressive strength; ρ = reinforcement ratio < 0.03; d = effective depth; and c = side length of loaded area.

4.3. The Japanese Society of Civil Engineers (JSCE) [33]

The ultimate punching shear load is taken as:

$$V_u = 0.188\;\beta_d\;\beta_p\;\beta_r\;\sqrt{f'_c}\,U\,d\,. \tag{5}$$

$$\beta_p = (1000/d)^{\frac{1}{4}} \quad < 1.5. \tag{6}$$

$$\beta_p = (100\,\rho)^{\frac{1}{3}} \quad < 1.5. \tag{7}$$

$$\beta_r = 1 + \frac{1}{1 + c/d}\,, \tag{8}$$

where: U is the critical perimeter = $4c + \pi d$; f_c' = concrete cylinder compressive strength; ρ = reinforcement percent; c = side length of loaded area; and d = effective depth.

4.4. The European Code (CEB-FIP) [34]

The ultimate punching shear load is taken as:

$$V_u = 0.12\,[1+\sqrt{\frac{200}{d}}\,]\;(100\,\rho\, f_{ck})^{\frac{1}{3}}\;U\,d\,, \tag{9}$$

where: *U* is the critical perimeter = 4(*c* + *d*); *d* = effective depth; *c* = side length of loaded area; ρ = reinforcement ratio; and f_{ck} = concrete cylinder compressive strength.

4.5. Comparison of the experimental results to codes predictions

The equations presented above for the calculation of the ultimate punching shear load of reinforced concrete slabs which are proposed by four major codes of practice throughout the world are based on empirical relationships which were originally developed from experimental data of testing normal-strength concrete with compressive strength between 15 and 30 MPa. Moreover, in the four codes the punching shear load is taken as the product of a nominal shear strength and the area of a chosen control surface. Through the four equations presented, the critical section for punching shear is situated between 0.5 and 2 times the effective depth [25]. The equations presented by codes of practice take into account the beneficial effect of the flexural reinforcement on enhancing the punching shear load of the slabs, except the equations presented by the ACI Building code (ACI 318-05) [1] which neglect the beneficial effects of the flexural reinforcement. Another factors taken by the four codes are slab effective depth and the concrete compressive strength. However, the variation of the concrete compressive strength with the punching shear load differs considerably from a code to another. For example, in the ACI Building code (ACI 318-05) [1] and the Japanese code (JSCE) [33] the punching shear load is expressed as proportional to the square root of (f_c'). However, in both the British Standards Institution (BS 8110) [32] and the European code (CEB-FIP) [34] the punching shear load is expressed as proportional to the cubic root of (f_c'). Many modification factors are applied to the code equations. However, the methods adopted by the codes do not reflect the physical reality of the punching phenomenon [25].

The equations presented above by four major codes of practice were used to calculate the ultimate punching shear load for the eight slabs tested in the current experimental program which were not provided with short randomly distributed fibers. Experimental test results were compared to code predictions as shown in table 3. and fig. 14. The following can be observed: (i) among the equations examined for four different codes of practice, the equation presented by the British Standards Institution (BS 8110) [32] performs the best in predicting the ultimate punching shear failure loads of normal-strength and high-strength concrete slabs. Also, the equation overestimates the ultimate punching shear load of some slabs by a maximum of 16% and underestimates the ultimate punching shear load of other slabs by a maximum of 3%; (ii) the equation presented by the Japanese code (JSCE) [33] reasonably predicts the ultimate punching shear load of tested slabs and is considered conservative. The equation underestimates the ultimate punching shear load of all tested slabs with a maximum of 31%; (iii) the equations presented by the ACI Building code (ACI 318-05) [1] neglects the beneficial effect of the flexural reinforcement on enhancing the ultimate punching shear load of reinforced concrete slabs and are considered extremely conservative. The equations underestimate the ultimate punching shear load of all slabs with a maximum of 54%; and (iv) the equation presented by the European code (CEB-FIP) [34] is also extremely conservative. The equation underestimates the ultimate punching shear load of all tested slabs with a maximum of 58%.

Therefore, it is concluded herein that the equations presented by both the British Standards Institution (BS 8110) [32] and the Japanese code (JSCE) [33] may be used for estimating the ultimate punching shear failure loads of both reinforced normal-strength concrete slabs and also for reinforced high-strength concrete slabs having concrete cube compressive strength up to 70 MPa.

5. Summary and conclusions

Detailed literature review was conducted including all available previous experimental and theoretical investigations on the behavior and punching shear strength of reinforced concrete slabs. It was found that previous researchers have concentrated on studying the behavior and punching strength of reinforced normal strength concrete slabs. Although, high strength concrete is being widely used in the construction industry in order to increase the strength to dead weight ratio of reinforced concrete structures, however, very little research efforts were found in the literature regarding punching strength of reinforced high strength concrete slabs. Furthermore, although the use of short randomly distributed fibers is known to enhance the punching strength of reinforced concrete slabs, however very little research efforts were found in the literature regarding the punching strength of fiber-reinforced concrete slabs. Also, the equations presented in some international codes of practice for the calculation of punching strength of reinforced concrete slabs were based on experimental data from testing normal strength concrete slabs with concrete compressive strengths between 15-35 MPa. For this reason, some structural engineers are reluctant to use high-strength concrete. The validity of these equations for the calculation of punching strength of reinforced concrete slabs are questionable in the case of high-strength concrete. An extensive experimental program was conducted in this paper to study the behavior and punching shear strength of reinforced normal and high-strength concrete slabs subjected to single concentrated load applied at the center of each slab. The experimental program included the fabrication, instrumentation, and testing of sixteen reinforced concrete slabs. The effect of many important parameters were studied in order to assess the behavior of tested slabs deflections, steel strains, cracking loads and failure loads. Cracking patterns and failure modes were observed for all tested slabs. Furthermore, the experimental results for punching shear load were compared to the theoretical predictions from four major codes of practice. Such codes were: the ACI Code; the BS8110 code, the Japanese code JSCE; and the European code. Based on this study the following conclusions were drawn:

The use of high-strength concrete resulted in: (i) significant decrease in the deflection in the elastic range for slabs with or without fibers having any reinforcement ratio, and any size of loading plate; (ii) significant decrease in the deflection at cracking load for slabs without fibers; (iii) significant increase in the deflection at cracking load for slabs with fibers; and (iv) significant increase in the deflection at failure load for slabs with or without fibers having any reinforcement ratio and size of loading plate.

1. The cracking loads of tested RC slabs increased significantly in the case of high-strength concrete slabs than those in the case of normal-strength concrete slabs. The effect of concrete strength in enhancing the cracking loads increases in the case of slabs with short randomly distributed fibers. This may be attributed to the fact that the presence of such fibers provides a crack arresting mechanism. The failure loads also increased significantly in the case of high-strength concrete slabs than that in the case of normal-strength concrete slabs. The effect of concrete strength in increasing the failure loads increases in the case of slabs having short randomly distributed fibers.
2. Although the failure mode of tested RC slabs was not affected by concrete strength, however in the case of high-strength concrete slabs the failure was much more catastrophic and explosive and was associated with louder noise The punching failure surface area on the tension face of the slabs was much smaller in the case of high-strength concrete slabs than that in the case of normal-strength concrete slabs.
3. The presence of short randomly distributed fibers results in a much more significant decrease in the deflection in the elastic range in the case of high strength concrete slabs than that in the case of normal strength concrete slabs. The effect of the presence of fibers in decreasing the deflection in the elastic range decreases with an increase in the size of loading plate. Polypropylene fibers were more effective in reducing the deflection in the elastic range than steel fibers

Table 3
Comparison of experimental results to codes predictions

Slab identification	Experimental punching failure loads, V_{exp} (kN)	Punching failure loads calculated from codes equations, V_{code} (kN)				V_{code}/V_{exp}			
		ACI	BS	JSCE	Euro code	ACI	BS	JSCE	Euro code
N-5-F0-R8	32.5	18.4	37.8	23.9	16.0	0.56	1.16	0.74	0.49
N-7.5-F0-R8	42.5	23.8	43.9	29.6	20.7	0.56	0.97	0.69	0.49
N-5-F0-R10	40.0	18.4	44.5	27.7	18.6	0.46	1.11	0.69	0.47
N-7.5-F0-R10	50.0	23.8	51.6	34.3	24.1	0.48	1.03	0.68	0.48
H-5-F0-R8	45.0	29.4	52.4	38.1	21.8	0.65	1.16	0.85	0.49
H-7.5-F0-R8	55.0	38.0	60.9	47.2	28.3	0.69	1.11	0.85	0.52
H-5-F0-R10	60.0	29.4	60.8	44.2	25.4	0.49	1.01	0.74	0.42
H-7.5-F0-R10	65.0	38.0	70.6	54.8	32.9	0.58	1.09	0.84	0.51

4. The presence of short randomly distributed fibers is much more effective in enhancing the cracking loads and failure loads in the case of high strength concrete slabs than that in the case of normal strength concrete slabs. Also, steel fibers are much more effective in enhancing the cracking loads and failure loads of normal strength concrete slabs than polypropylene fibers. However, polypropylene fibers are more effective in enhancing the cracking loads and failure loads of high strength concrete slabs than steel fibers.

5. The presence of short randomly distributed fibers did not affect the mode of failure of normal or high strength concrete slabs which was in all cases punching shear mode. However, the presence of short randomly distributed fibers resulted in a less catastrophic and explosive failure and was associated with much less noise. Such effect of the presence of fibers was much more clear in the case of high strength concrete slabs than that in the case of normal strength concrete slabs.

6. The punching failure surface area on the tension face of the slabs became much smaller as a result of the inclusion of short randomly distributed fibers. The cracking pattern on the tension face of the slabs was significantly affected by the presence of fibers. In the case of slabs containing fibers much less number of cracks were observed after failure. Also, crack widths were much less in the case of slabs containing fibers.

7. An increase in the size of loaded area resulted in a significant decrease in the deflection in the elastic range of loading for all cases of concrete strength, reinforcement ratio, and for all cases of slabs with and without short randomly distributed fibers. Also, the effect of increasing the size of loaded

area on decreasing the deflection in the elastic range was much more significant in the case of normal strength concrete slabs than that in the case of high strength concrete slabs. Furthermore, such effect of the size of loaded area was much less significant in the case of slabs having short randomly distributed fibers.

8. The effect of increasing the size of loaded area on increasing the cracking loads and failure loads was much more significant in the case of normal strength concrete slabs than that in the case of high strength concrete slabs. Also, cracking loads of tested slabs were much more sensitive to a change in the size of loaded area than failure loads. The increase in the size of loaded area did not change the failure modes of the slabs. However, a change was observed in the cracking patterns after failure as a result of increasing the size of loaded area. As was expected, the punching failure surface area on the tension face of the slab increased significantly with an increase in the size of loaded area.

9. Among the equations examined for four different codes of practice, the equation presented by the British Standards Institution (BS 8110) performs the best in predicting the ultimate punching shear failure loads of normal strength and high strength concrete slabs. The equation overestimates the ultimate punching shear load of some slabs by a maximum of 16% and underestimates the ultimate punching shear load of other slabs by a maximum of 3%. Also, the equation presented by the Japanese code (JSCE) reasonably predicts the ultimate punching shear load of tested slabs. The equation is generally conservative. The equation underestimates the ultimate punching shear load of all slabs with a maximum of 31%.

10. The equations presented by the ACI Building code (ACI 318-05) neglects the beneficial effect of the flexural reinforcement on enhancing the ultimate punching shear load of reinforced concrete slabs. The equations are extremely conservative. The equations underestimate the ultimate punching shear load of all slabs with a maximum of 54%. Also, the equation presented by the European code (CEB-FIP) is also extremely conservative. The equation underestimates the ultimate punching shear load of all tested slabs with a maximum of 58%.

11. The equations presented by both the British Standards Institution (BS 8110) and the Japanese code (JSCE) may be used for estimating the ultimate punching shear failure loads of both reinforced normal strength concrete slabs and also for reinforced high strength concrete slabs having concrete cube compressive strength up to 70 MPa.

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