Punching Shear Strength of Reinforced Concrete Flat Plate Slabs Containing Carbon Fibers

Zrar Sedeeq Othman   Sanaa Ismael Khaleel   Bayan Anwer Ali
University of Salahaddin-Erbil
Department of Civil Engineering

Abstract

This paper presents the results of an experimental research investigating the punching shear strength of flat slabs containing carbon fibers and reinforced with flexural steel bars. Tests were carried out on 12 800×800×60 mm slabs subjected to pure shear. The experimental study considered the influence of the type of concrete grade (normal-and moderately high strength concretes), of the carbon fiber percentage and of the percentage of the steel bars on the punching shear strength of the slabs. Within the scope of the test program, an increase in the volume fraction of carbon fibers, steel reinforcement ratio, compressive strength of concrete slabs was found to lead to an increase the punching shear strength of the slabs. The results show a significant increase in the punching shear capacity and improved integrity of the CFRC slab-column connections in the post-cracking stage in comparison with conventional reinforced concrete slabs. Carbon fibers may be considered as practical way to increase the punching capacity and the strain capacity of the flat plate building system.

Keywords: Reinforced concrete, Punching-shear, Flat slab, Carbon fiber reinforced concrete.

1. Introduction

Reinforced concrete flat plates are widely used for structural systems. The absence of beams makes these systems attractive due to advantages such as easier formwork, shorter construction time, less total building height with more clear space, and architectural flexibility. Design of RC flat slabs is often compromised by their ability to resist shear stresses at the punching-shear surface area. The connections between slabs and supporting columns could be susceptible to high shear stresses and might cause brittle and sudden punching-shear failure. These connections may become the starting points leading to catastrophic punching-shear failure of a flat slab system (Gardner et al. 2002). Extensive research work has been conducted on the punching-shear behavior of steel-reinforced flat slabs. Many investigations

(Swamy and Ali 1982; Shaaban and Gesund 1994; Tan and Paramasivam 1994; Harajli et al. 1995; McHarg et al. 2000; Hanai and Holanda 2008; Muttoni 2008;Ellouze et al. 2010; Moraeset al. 2014) demonstrated that to increase the strength and improve the ductility of slabs, it is necessary to integrate or partially substitute the secondary shear steel reinforcements by using fiber reinforced concrete. These studies also stress the use of fibers in producing significant increases in the tensile properties and ductility of slabs.

However numerous studies have been conducted to determine the behavior of fiber reinforced concrete slabs. The punching-shear strength of RC flat slabs reinforced with chopped carbon fibers is yet to be fully investigated and understood. This is due to the limited research work on the subject and to the numerous parameters affecting punching-shear behavior. Thus, this study aims at investigating the punching-shear behavior of concrete two-way slabs containing chopped carbon fiber. The investigation included test specimens without shear reinforcement and others with carbon fibers to evaluate the performance of specimens without shear reinforcement and the effect of carbon fiber reinforcement on the punching-capacity and performance.

2. Experimental Investigation

2.1.Test Specimen

All the slabs were geometrically similar having dimensions of 800 × 800 × 60 mm loaded through a central steel plate of dimensions 100 × 100 mm. All slabs were reinforced with 6.0 mm diameter deformed longitudinal steel bars (primary internal reinforcement), and they were designed to fail in punching according to ACI Building Code (ACI Committee 318 2008). The slabs were simply supported along four edges with a span of 700mm in each direction. A clear cover of 8.0 mm was provided below the mesh.

2.2.Test Matrix

The test matrix is given in Table 1. A total of 12 specimens were constructed and tested. The test specimens were constructed to obtain a cylinder compressive strength of approximately 30 MPa and 50 MPa at 28 days. The specimens were divided into two main groups based on their flexural reinforcement ratio. In each group, one specimen did not include carbon fiber to act as a control for each concrete compressive strength. The remaining specimens were reinforced with chopped carbon fibers and presence of steel bars. Within each group, the volume fraction of the carbon fibers and concrete compressive strength were varied.

Table 1.Details of Test Specimen

Group No.	Specimen No.	ρ_w %	f'_c MPa	V_f of carbon fiber %	Detail of main reinforcement
A	A_1	0.6	30	0.0	8 - Ø6 mm @100 mm c/c
	A_2			0.2	
	A_3			0.4	
	A_4		50	0.0	
	A_5			0.2	
	A_6			0.4	
B	B_1	1.0	30	0.0	13 - Ø6 mm @ 60 mm c/c
	B_2			0.2	
	B_3			0.4	
	B_4		50	0.0	
	B_5			0.2	
	B_6			0.4	

2.3.Materials

All slabs were provided with two-way flexural reinforcement consisting of deformed bars 6.0 mm diameter placed in the tension face of the slab with average yield strength of 500 N/mm^2. Chopped carbon fiber brought form Qidong Carbon Material factory in China as filaments was used in this investigation. The fibers had an average length of 20 mm, a diameter of 7-8 μm, a tensile strength of 2840 MPa, a Young's modulus of 235 GPa, and a density of 1.78 gm/cm^3. A high range water reducing admixture (PC175) was used to produce the concrete mix. Chemically it is high performance polycarboxylic based super-plasticizer, and it is known commercially as Hyperplast PC175. It was used in its liquid state as a percentage of cement content (by weight). Densified silica fume (imported from Dubai, United Arab Emirates) was used as pozzolanic admixture as recommended by ACI committee 544 instructions (2002).The cement used in this investigation was Iraqi Portland cement type I (P. C. type I). The fine and coarse aggregate obtained from Aski Kalak which is commonly used in Erbil Governorate, there grading satisfies ASTM C33 specification. The maximum size of coarse aggregate was 9.52 mm.

A normal and moderately high strength concrete were used. Matrix I designated with mix proportions of (1:1.19:1.8) by weight, w/c of 0.45, admixture of 0.5% by weight of cement, and silica fume 10% as replacement by weight of cement. This can produce a cylinder compressive strength of approximately 30 MPa at 28 day. For Matrix II, several trial mixes were carried out to determine silica fume content and dosage of super-plasticizer in order to obtain a mix with the required compressive strength. thus same proportions as Matrix I were used, but with w/c of 0.35, admixture of 1%, and silica fume of 15% as replacement by weight of cement which produce a cylinder compressive strength of approximately 50 MPa at 28 day. Finally chopped carbon fiber with volume fractions of 0.2% and 0.4% were added to the selected concrete mixes.

2.4.Mixing Method, Casting and Curing

Mixing was performed by using tilting mixer with capacity of 0.1 m^3. The mechanical mixing procedure for fibrous and nonfibrous concrete was different in sequence of mixing process and mixing time. The procedure of mixing non-fibrous concrete conforms to ASTM C192 (2007). Coarse aggregate, some of the mixing water, and the solution of admixture were placed in the mixer and mixed for about 1 min, after that, fine aggregate, cement, silica fume and the remaining water were loaded to the mixer and mixed for about 3 min followed by 3 min rest to check any unmixed materials, followed by 2 min final mixing. Mixing of carbon fiber concrete raised a number of problems because of the small diameter and short length of the fiber filaments. After the water, aggregate and cement have been fully mixed, fibers were slowly added to the concrete by hand spraying, while the mix was rotating. Mixing was continued for 3 min to encourage a uniform distribution of fibers throughout the concrete.

Before placing concrete in the slab mold, the reinforcement was positioned in the mold, and plastic spacers were used to ensure that cover to main bars in slabs was maintained at 8.0mm for all slabs. The compaction was done using the vibrating table. The specimens were moist-cured for 28 days. Companion 100mm cubes were cast and cured along with the slab specimens. These cubes were tested along with the slabs to obtain the compressive strength of the concrete.

2.5.Test Setup and Instrumentation

A testing machine with a bearing capacity of 2500 kN was used to perform the slabs tests at age of 56 days. The load was applied incrementally by means of a hydraulic actuator. The deflection under the column segment was measured by using a dialgauge with an accuracy of 0.01 mm and a search was made for the appearance of any cracks. Before testing the specimens, positions of supports, applied load and dial gauge position were marked. Tensile strains that occurred at the main reinforcing bars were measured using precision pre-wired strain gauges of type FLA-6-11-3L. The positions of steel strain gauges are shown in Figure 1.

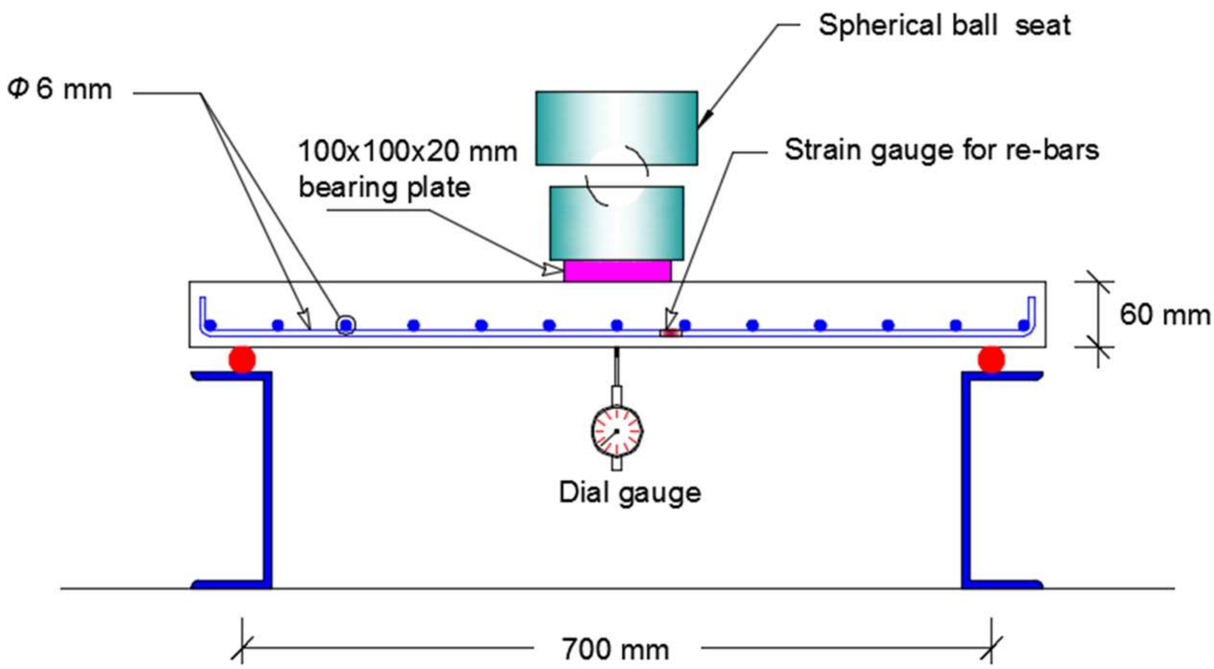

Figure 1: Test setup and specimen details

3. Results and Discussion

In this section, the test results on slabs containing carbon fibers are presented. The results discussed through crack patterns; load deflection curves, steel strains, and punching shear resistances. The test results including the first cracking and ultimate loads for different slabs are shown in Table 2.

Table 2.Cracking and ultimate load of the tested slabs

Group No.	Specimen No.	ρ_w %	* f'_c MPa	V_f of carbon fiber %	Cracking load kN	Ultimate load kN
A	A_1	0.6	30.1	0.0	11.9	66.5
	A_2		30.5	0.2	13.1	71.0
	A_3		31.2	0.4	14.4	77.5
	A_4		49.6	0.0	16.5	79.9
	A_5		51.0	0.2	18.0	87.0
	A_6		52.7	0.4	20.1	95.9
B	B_1	1.0	30.5	0.0	13.7	83.9
	B_2		30.9	0.2	15.0	91.0
	B_3		31.4	0.4	17.0	100.3
	B_4		51.3	0.0	18.8	105.3
	B_5		51.6	0.2	19.8	110.5
	B_6		52.3	0.4	23	121.7

*f'_c taken as 0.8 f_{cu}

3.1.Failure of Specimens

The punching-shear-crack patterns for typical slabs are illustrated in Figure 2. Shear failure of slabs without fibers was sudden and brittle, accompanied by falling apart the bottom concrete cover. In slabs containing fibers however cracks of only smaller widths were created and their distribution was more uniform. The punching failures in the carbon fiber reinforced slabs were gradual and usually with no damage of the concrete cover as well as the structural continuity. The number of cracks in specimen with carbon fiber was much more than the number of cracks in specimens without carbon fiber. The crack width and the crack spacing in specimen with carbon fiber were smaller as compared to the control specimens without fiber. The cracking in fibrous specimens was mostly confined to a region close to the column periphery. The result of all slabs also declared that only a small region of the slab specimen near the slab-column intersection is highly stressed in tension before rupture, namely punching shear failure occurs in a progressive manner. The compression side of the slabs remained uncracked and uncrushed until the failure. The test was terminated at the moment of appearance of the punching cone simultaneously with rapid decreasing of the loading.

3.2 Load-Displacement Responses

In general, the behavior of the slabs can be divided in two stages. Whereas in the first (pre-cracking) stage all slabs behaved similarly and approximately linearly, in the second (post-cracking) stage, the slab stiffness decreased. At the same loading level, the displacements of CFRC slabs were lower in comparison with slabs without fibers as shown in Figure 3. The typical measured values of strain of the longitudinal bars at slab failure of group B are summarized in Figure 4. As shown in the figure the behavior of all the specimens was similar up to the crack stage. The curves were steepest and terminated at the occurrence of the first crack. After the formation of first cracks, an abrupt change in the steel strain was recorded. At the same applied load level strain decreased with the increase in volume fraction of fibers. The maximum tensile steel strain was greater than 0.25% which proves that slabs failed in punching shear with yielding of the tensile reinforcement.

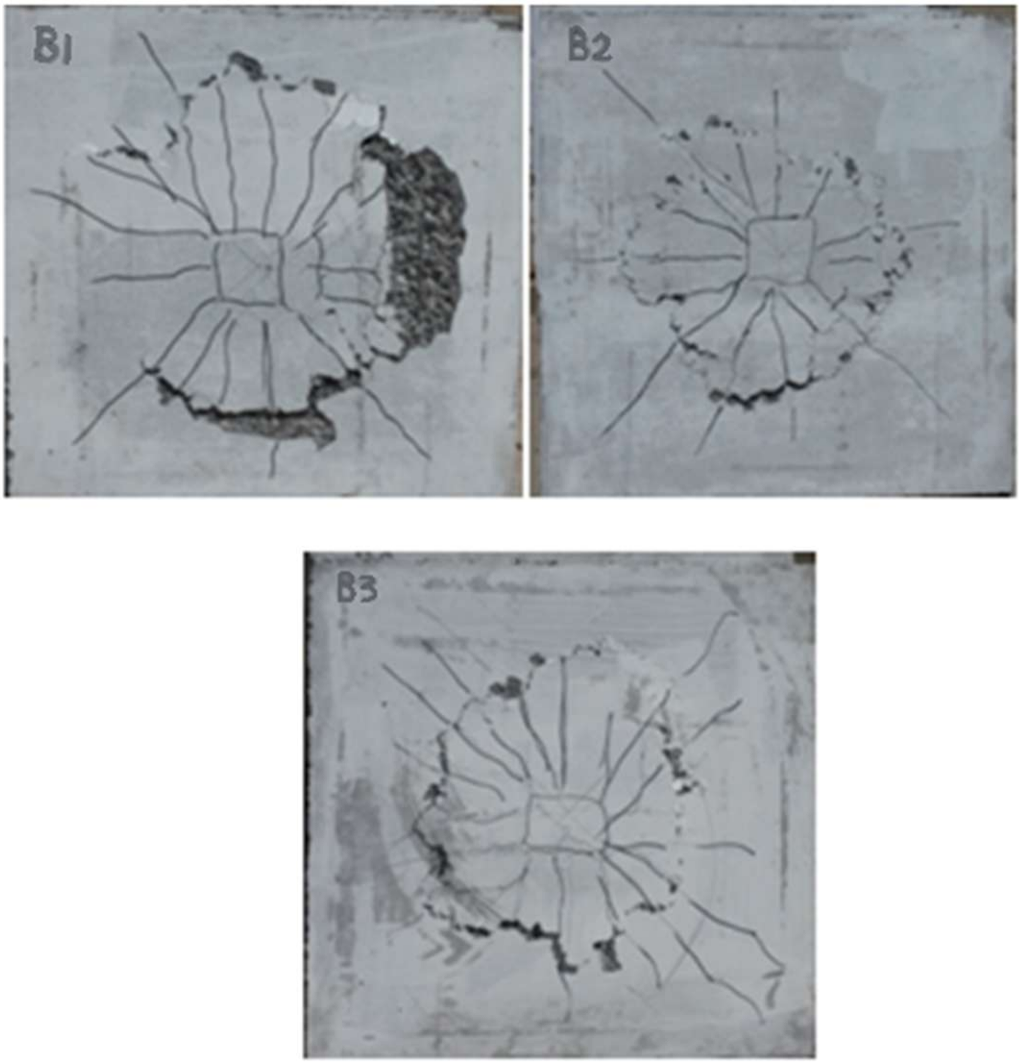

Figure 2: Typical crack pattern in tested slabs of 1% reinforcement ratio - bottom face: B1- without fiber; B2- with fiber 0.2%; B3- with fiber 0.4%

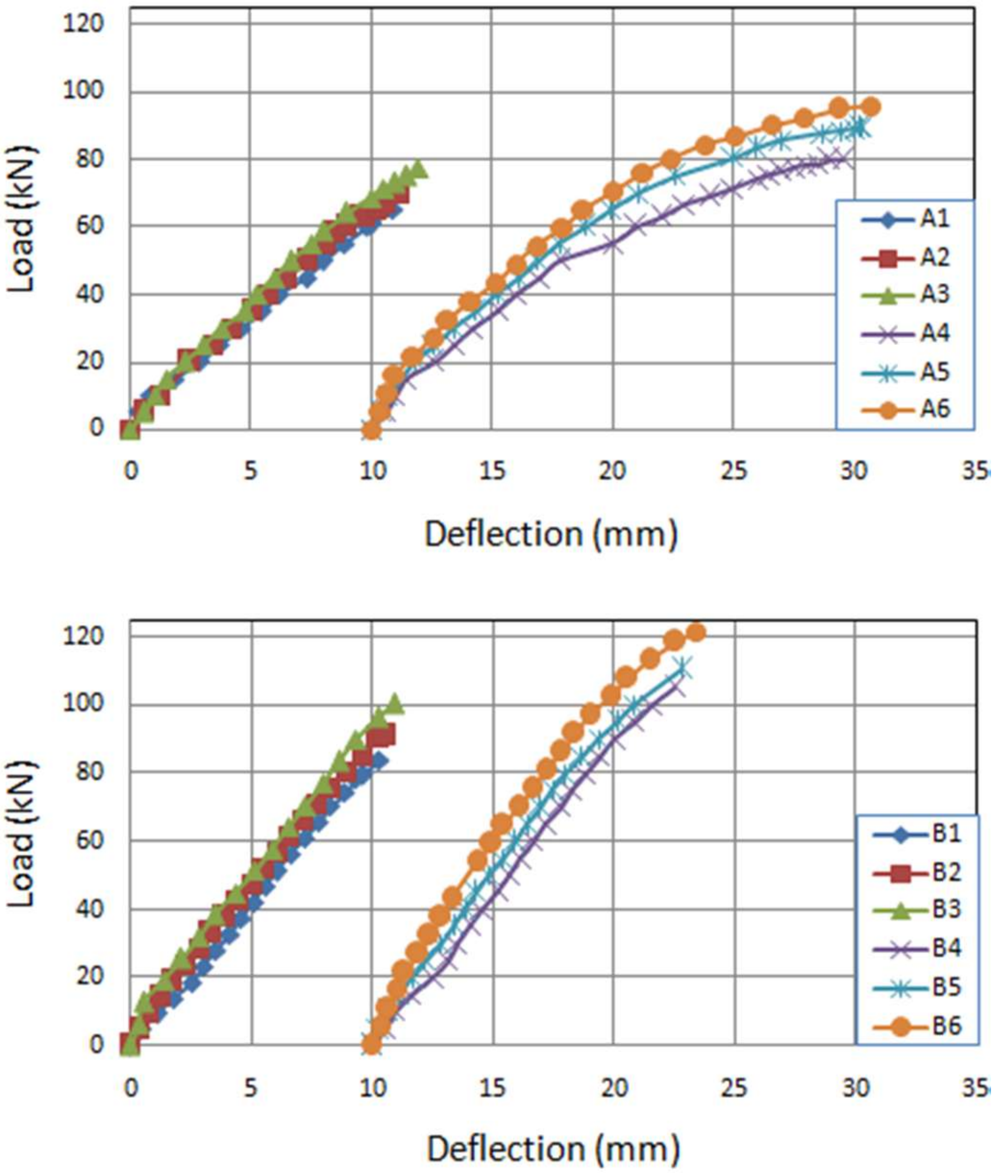

Figure 3: Load versus deflection curves of tested slabs under punching shear load

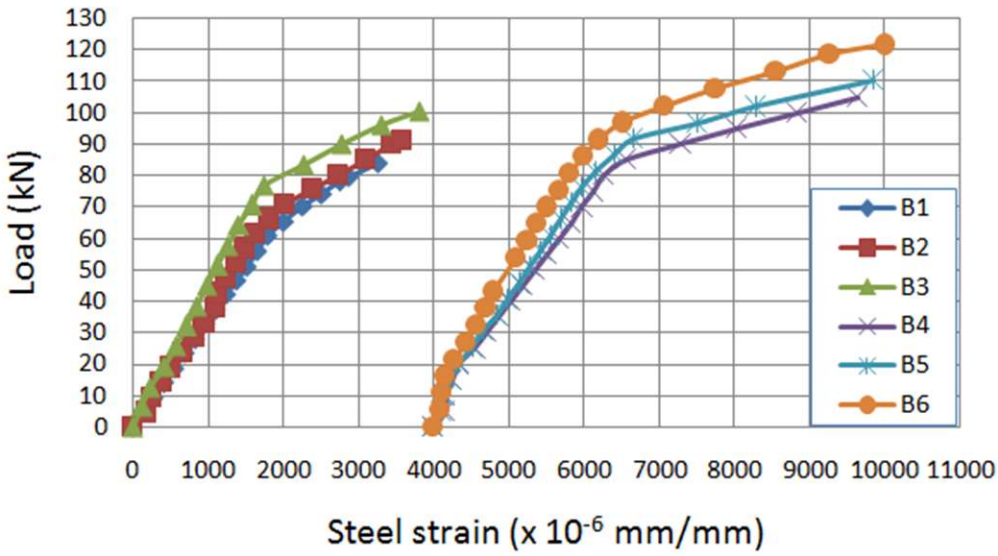

Figure 4:Typical load versus steel strain curves of the tested slabs under punching shear load

3.3.Punching Shear Resistances

The result presented in Table 2 and Figure 5 indicate that the addition of carbon fibers for all slabs resulted in higher resistance against formation of the first crack. The first crack loads for non fibrous concrete specimen with ρ_w 0.6% were 11.9 kN and 16.5 kN for slabs with normal and moderately high strength concrete respectively. The values approximately increased up to 10% due to presence of 0.2% carbon fibers. While the percentage increases in the first cracking loads were about 22% due to the presence of carbon fibers at 0.4%.

While, the first crack loads for non fibrous concrete specimen with ρ_w 1% were 13.7 kN and 18.8 kN for slabs with normal and moderately high strength concrete respectively. The values increased 9% and 5% due to presence of 0.2% carbon fibers respectively. While the percentage increases in the first cracking loads were 24% and 22% due to the presence of carbon fibers at 0.4%. The results indicated that the slab first shear cracking load can be enhanced upon the addition of carbon fibers up to 24%.

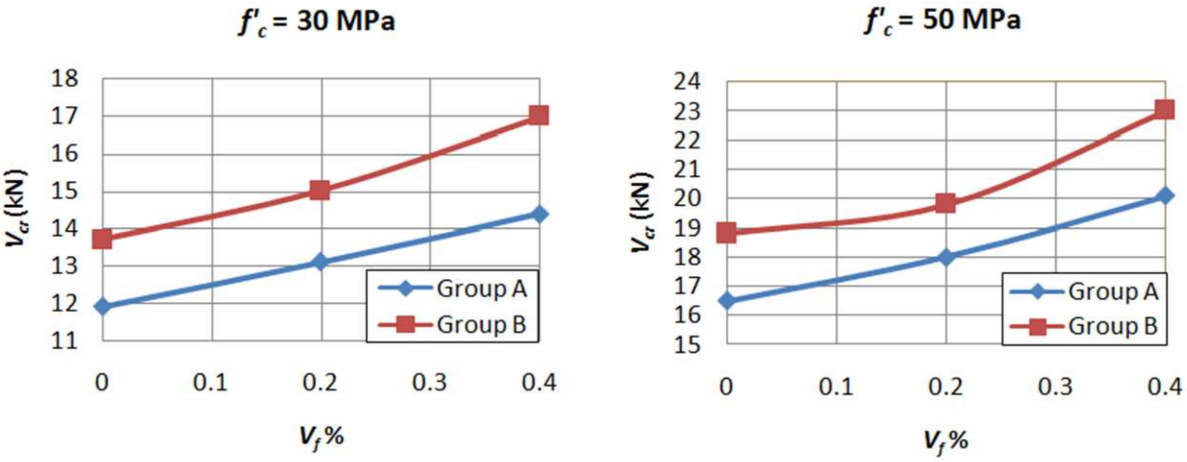

Figure 5: Effect of different carbon fibers content on first crack loads

Finally, it can be indicated that the presence of carbon fibers has also effect on ultimate load capacity of tested slabs. The ultimate load for non fibrous concrete specimens with ρ_w 0.6% were 66.5 kN and 79.9 kN for normal and moderately high strength concrete respectively. The percentage increases in ultimate loads were 7% and 9% due to the presence of 0.2% carbon fibers respectively. The percentage increase in the ultimate shear cracking loads were 17% and 20% due to the presence of carbon fibers at 0.4%.

The ultimate load for non fibrous concrete specimens with ρ_w 1% were 83.9 kN and 105.3 kN for normal and moderately high strength concrete respectively. The percentage increases in ultimate loads were 8% and 5% due to the presence of 0.2% carbon fibers respectively. Finally, the percentage increase in the ultimate loads were 20% and 16% due to the presence of carbon fibers at 0.4%.

Effect of volume fraction of fibers on the ultimate load for slabs with various concrete grades is shown in Figure 6. Adding adequate amount of carbon fibers (0.4%) to concrete increased the punching shear resistance up to 20%. From the results summarized in Table 2 follows that carbon fibers considerably increase the punching shear capacity of slabs attributable to their beneficial effect to bridge cracks within the entire concrete matrix. Even in the stage of initiation and propagation of cracks, the tensile zone of CFRC slabs is still able to participate in carrying loads. This results in increasing of the punching shear resistance of slabs. The test results presented in Table 2 also indicated that the increase in compressive strength and steel reinforcement ratio generally leads to an increase in the shear strength of the tested slabs.

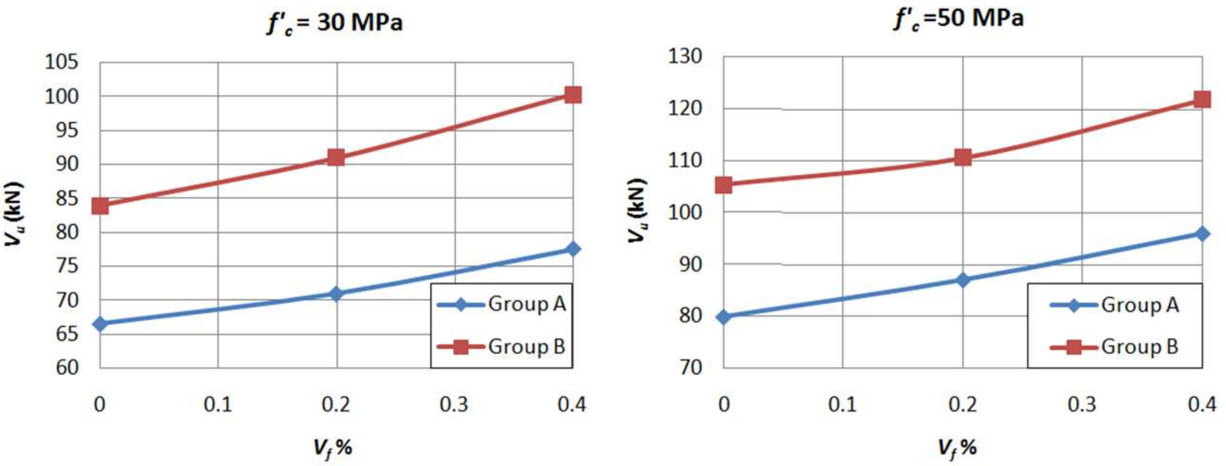

Figure 6. Effect of carbon fiber content on ultimate loads

4. Conclusions

Within the scope of the study, the following conclusions may be drawn.

- Carbon fibers improve slab integrity in the vicinity of the slab-column connections. The crack resistance was enhanced when carbon fibers were added, hence the first crack was delayed, the crack width reduced and the crack propagation was formed and fine.
- An increase in the volume fraction of carbon fibers, steel reinforcement ratio, compressive strength of concrete slabs, generally leads to an increase in the cracking load, ultimate load of reinforced concrete slabs.
- Tests showed that the use of carbon fibers in slabs subjected to punching shear loads have many benefits. It increases in the punching shear resistance (up to 20%) and increases the ductility.

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Notations

The following symbols are used in this paper:

CFRC : Carbon Fiber Reinforced Concrete;
ACI : American Concrete Institute;
ρ_w : Web reinforcement ratio;
f'_c : Cylinder compressive strength of concrete, N/mm^2;
f_{cu} : Cube compressive strength of concrete, N/mm^2;
V_f : Volume fraction of carbon fibers;
V_{cr} : Cracking load, kN; and
V_u : Ultimate load, kN.

مقاومة القص الثاقب للبلاطات الخرسانية المسلحة المحتوية على الكاربون فايبر

الخلاصة

هذا البحث يفحص عمليا مقاومة القص الثاقب للبلاطات الخرسانية المسلحة المحتوية على الكاربون فايبر والمسلحة بالفولاذالرئيسياالمضاد للانحناء. واجريت الدراسة على 12 بلاطة ذات ابعاد 800*800*60 ملم ذات اسناد بسيط على حوافها الاربعة وحملت خلال عمود فى وسطها. المتغيرات الاساسية التى درست هى تاثير مقاومة الانضغاط ونسبة الكاربون فايبر ونسبة التسليح الرئيسي على مقاومة القص الثاقب للبلاطات. لقد وجد بان زيادة استعمال الكاربون فايبر ونسبة التسليحومقاومة الانضغاط للبلاطات الخرسانية تزيد من مقاومة القص الثاقب لها. وتبين ايضا ان مقاومة القص الثاقب للبلاطات المحتوية على الكاربون فايبر اظهرت سلوكا افضل ضد التشققات. ختاما ان استعمالالكاربون فايبر هى طريقة عملية لزيادةمقاومة القص وتعزيز الاستطالةللبلاطات الخرسانية.

بەرگری بڕینی کونکەر بۆ بنمیچە کۆنکریتی یەکان بە بوونی ریشاڵی کاربۆنی تیایدا

پوختە

ئەم تۆژینەوەیە بریتیی یە لە تاقیکردنەوەی کرداری بۆ زانینی بەرگری بڕینی کونکردن بۆ بنمیچی کۆنکریتی شیشدار کە ڕیشاڵی کاربۆنی تیایدا بە کار هاتووە. تاقیکردنەوە لە سەر 12 بنمیچی کۆنکریتی کە دووری یەکانی 800 * 800 * 60 ملم بوو ئەنجام دراوە کە لە هەر چوار لاوە بە شیوەیەکی ئاسایی ڕاگیراوە. ئەو گۆڕاوە سەرەکی یانەی کە لێکۆڵینەوەی لەسەر کراوە بریتی بوون لە کاریگەری بەرگری پەستانی کۆنکریت و ڕێژەی ڕیشاڵی کاربۆنی و هەروەها ڕێژەی شیشی بەکارهاتوو لە سەر بەرگری بڕینی کونکردن بۆ بنمیچەکان. لە ئەنجامی تاقیکردنەوەکان دەرکەوت کە زیادکردنی ڕێژەی ڕیشاڵی کاربۆنی و ڕێژەی شیش و بەرگری پەستانی کۆنکریت دەبێتە هۆی زیادبوونی بەرگری بنمیچەکان بۆ فشاری بڕینی کونکردن. هەروەها دەرکەوت کە ئەو بنمیچانەی ریشاڵی کاربۆنی تیایدا بە کارهاتووە بە شێوەیەکی باشتر هەڵسوکەوت دەکەن لە بەرگری بڕینی کونکردن و بەرهەڵستی دژی درووستبون و فراوان بوونی درزەکان. دەتوانین بەکارهێنانی ڕیشاڵی کاربۆنی لە ناو کۆنکریت بە ڕیگایەکی کرداری دابنێین بۆ زیادکردنی بەرگری بڕینی کونکردن و لە خۆگرتنی جێفشارەکان بۆ بنمیچی کۆنکریتی شیشدار.