Shear behavior of steel fiber high-strength reinforced concrete continuous beams

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In this paper the shear behavior of steel fiber high strength reinforced concrete continuous beams was studied. A series of ten continuous beams were fabricated and tested to failure under two concentrated loads in order to investigate the effect of several important parameters on the shear behavior of such type of beams. These parameters included: the steel fiber volume content and the shear span to depth ratio. For all tested beams the initiation of cracks and its propagation was observed and recorded. Deflections and steel strains were measured thus load-deflection and load-strain relationships were detected. Also, failure loads and failure modes were observed for all tested beams. Test results have revealed the beneficial effects of the inclusion of steel fibers in the enhancement of shear behavior of high strength concrete continuous beams. The presence of steel fibers significantly enhanced the post cracking tensile strength of concrete and therefore the shear strength of continuous beams was improved. Also, it was found that the brittle nature of failure in the case of high strength concrete continuous beams was transformed into a more ductile one for beams containing steel fibers. Finally, the experimental results for shear strength of tested continuous beams were compared to theoretical predictions from empirical equations found in the literature for the estimation of shear strength of simply supported steel fiber high strength concrete beams.

فى هذا البحث تم دراسة سلوك القص للكمرات المستمرة المسلحة ذات الخرسانة عاليه المقاومة المحتوية على ألياف حديدية. وقد تم صب وإختبار مجموعة مكونة من عشرة كمرات مستمرة حتى الإنهيار تحت تأثير حملين مركزين وذلك لدراسة تأثير العديد من العوامل الهامة على سلوك القص لمثل هذا النوع من الكمرات. هذه العوامل شملت: النسبة الحجمية لمحتوى الألياف الحديدية وكذلك النسبة بين بحر القص إلى العمق. وقد تم ملاحظة بداية ظهور الشروخ وتتبع تطورها لجميع الكمرات المختبرة. وتم قياس سهم الإنحناء والإنفعال فى الحديد ومن ثم إيجاد العلاقة بين الحمل وكل من سهم الإنحناء والإنفعال. كذلك تم ملاحظة أحمال الإنهيار وشكل الإنهيار لجميع الكمرات المختبرة. وقد أظهرت النتائج المعملية التأثير الفعال لإضافة ألياف حديدية فى تحسن سلوك القص للكمرات المستمرة المسلحة ذات الخرسانة عالية المقاومة. وقد أدى وجود الألياف الحديدية إلى تحسن مقاومة الشد للخرسانة فى مرحلة مابعد التشريخ وبالتالى تحسن مقاومة القص للكمرات المستمرة. أيضاً وجد أن طبيعة الإنهيار المفاجىء بالنسبة للكمرات المستمرة ذات الخرسانة عالية المقاومة قد تحولت لتكون أكثر ممطوليه وذلك بالنسبة للكمرات المحتواة على ألياف حديدية. أخيراً تم مقارنة النتائج المعملية لمقاومة القص للكمرات المستمرة المختبرة ذات الالياف الحديديه مع النتائج النظرية لبعض المعادلات التجريبية التى وجدت فى بعض المراجع لحساب مقاومة القص للكمرات بسيطة الإرتكاز ذات الخرسانة عالية المقاومة و المحتويه علي الياف حديديه.

Keywords: Continuous beams, High strength concrete, Reinforced concrete, Shear strength, Steel fibers

1. Introduction

Recently, the use of high strength concrete, defined by the ACI 318 [1] as concrete having cylinder compressive strength greater than 40 Mpa, has increased rapidly in the construction industry. High strength concrete may be used to reduce structure's dead load, especially in the case of long spans or tall buildings. However, a drawback of using high strength concrete is found for beams which are subjected to shear. This is because the rate of increase in the tensile strength of high strength concrete is much lesser than that for the compressive strength of concrete. Also, high strength concrete is considered to be a brittle material since the post-peak portion of its stress-strain curve descends deeply as compressive strength increases [2]. These disadvantages of high strength concrete can be overcame by the inclusion of small discrete steel fibers in the concrete mix [2]. The concept of using fibers to improve the characteristics of construction materials is very old [3].

Furthermore, steel fibers may also totally replace conventional regularly spaced stirrups and are more effective in arresting crack propagation and maintaining the integrity of the surrounding concrete [4]. The effectiveness of using steel fibers as shear reinforcement was confirmed in many reports [5-11]. Some of the benefits of using steel fibers can be summarized as follows [12]: (i) it relieves reinforcement congestion at critical sections such as beam-column junctions; (ii) fiber reinforcement may also significantly reduce construction time and costs, especially at locations of high labor costs and possibly even labor shortages, since conventional stirrups require relatively high labor input to bend and fix in place; and, (iii) fiber concrete can be easily placed in thin or irregularly shaped sections such as architectural panels, where it may be very difficult to place stirrups.

1.1. Effect of fibers on the flexural behavior of simply supported high strength reinforced concrete beams

The effect of addition of steel fibers on the flexural behavior and load-deformation behavior of simply supported normal strength concrete beams has been studied extensively in the last twenty years [13-15]. Many research studies carried out to date have concentrated in studying the effect of the inclusion of fibers on the flexural behavior of simply supported high strength concrete beams. Hsu et al. [16] studied experimentally the stress-strain behavior of steel fiber high strength concrete. They concluded that the addition of steel fibers to high strength concrete changes the basic characteristics of its stress-strain behavior especially the descending portion of the stress-strain curve. The slope of the descending part increases with increasing the fiber content. Also, with addition of reasonable amount of fibers to the concrete, higher ductility and toughness can be achieved.

Ashour and Wafa [17] studied the flexural behavior of simply supported high strength fiber reinforced concrete beams. They pointed out that the presence of fibers reduced the crack width, increased the number of cracks, increased the ductility and delayed the final crushing of concrete. Ashour et al. [18] concluded that the addition of fibers improves the modulus of rupture and the splitting strength of high strength concrete. Also, the addition of fibers has significant effect on the post-cracking beam stiffness, yield moment, ultimate moment and post-yield behavior of beams. Padmarajaiah and Ramaswamy [19] showed that the addition of fibers enhanced both the cracking and ultimate flexural strength of beams. They pointed out that at a given load, the steel strain decreased with an increase in the fiber content. Also, the tensile strength of concrete increased substantially with the increase in fiber content.

1.2. Effect of fibers on the shear behavior of simply supported high strength reinforced concrete beams

The effect of addition of steel fibers on the shear behavior of simply supported normal strength concrete beams has been investigated by many researchers [5-11] and [20]. Comparatively, little research efforts were directed towards the effect of fibers on the shear behavior of simply supported high strength reinforced concrete beams.

Ashour et al. [2] tested 18 simply supported high strength reinforced concrete beams without shear reinforcement but containing fibers. They concluded that the disadvantages of high strength concrete can be overcame by the addition of steel fibers in the concrete mix as follows: (i) the inclusion of steel fibers makes the concrete homogeneous and isotropic material and converts its brittle characteristics to a more ductile one; (ii) when concrete cracks the randomly oriented fibers arrest microcracking thus improve strength and ductility; and, (iii) adding fibers influences the ascending portion of the stress-strain curve only slightly but leads to a noticeable increase in the peak strain and a significant increase in ductility.

Khunita et al. [12] pointed out the improvement in the post-cracking tensile strength of concrete and the significant enhancement in the shear strength of reinforced high strength concrete beams as a result of adding steel fibers to the concrete mix. Similar observations was found by Imam et al. [21]. Furthermore, Padmarajaiah and Ramaswamy [22] concluded that the use of fibers in the shear span only of simply supported high strength concrete beams could be economical and leads to considerable cost savings in the design without sacrificing on the desired performance.

1.3. The required research

From the above presented available previous investigations, it is clear that the majority of research efforts was directed towards the study of the effect of addition of fibers on the flexural and shear behavior of normal strength reinforced concrete beams. Little researches and applications carried out to date have been aimed at the study of the effect of addition of fibers on the flexural and shear behavior of high strength reinforced concrete beams, although high strength concrete has been widely used in the construction industry. Furthermore, no research efforts has been directed towards the study of the shear behavior of continuous normal strength reinforced concrete beams. Also, the effect of the addition of fibers on the shear behavior of high strength concrete continuous beams was not studied by any researcher. In continuous beams, the position of maximum bending moment and maximum shear force coincide.

Therefore, there is a need for a study on high strength concrete continuous beams, considering all-important aspects affecting the shear behavior of such beams. The study should also include the effect of addition of fibers on the shear behavior of high strength concrete continuous beams.

1.4. The current research

In this paper the shear behavior of high strength steel fiber reinforced concrete continuous beams is studied. An experimental program was conducted including the fabrication and testing of ten continuous beams under two concentrated loads. The parameters studied included: the steel fiber volume content and the shear span to depth ratio. Also, the experimental results for shear strength of tested continuous beams were compared to theoretical predictions from empirical equations found in the literature for the estimation of shear strength of simply supported steel fiber high strength concrete beams.

2. Experimental program

Ten steel fiber high strength reinforced concrete continuous beams were tested in the current experimental program. Table 1 presents the details of the tested continuous beams. All tested beams had a rectangular cross section of 100 mm width and 200 mm height. All tested beams were continuous beams having two spans of 1625 mm each. All tested continuous beams had a bottom reinforcement of 2-12 mm diameter high tensile steel, and a similar reinforcement was used as an upper reinforcement. The percentage of steel reinforcement μ was 0.0133. The yield stress and the ultimate stress of the steel reinforcement were 419 and 663 N/mm^2, respectively.

The tested continuous beams were divided into two groups, each group containing five beams. The difference between continuous beams in group BI and group BII is the length of the shear span, a. Therefore, the effect of shear span to depth ratio (a/d) can be detected comparing beams in groups BI and BII.

In each of the two groups, beam number "1" was made without shear reinforcement and also without steel fibers. Therefore, beam number "1" in each group will serve as a control one. Beam number "2" in each group was provided with vertical stirrups of diameter 6 mm @ 120 mm mild steel having yield and ultimate stress of 254 and 465 N/mm^2, respectively.

Steel fibers were added to the mix of the high strength concrete for beams number "3", "4", and "5" in each of the two groups, with a volume content percent (V_f) of 0.6, 1.2, and 1.8%, respectively. No vertical stirrups were provided for these beams. The steel fibers used had a length of 30 mm. It should be

Table 1
Details of tested continuous beams

Group	Beam	Shear span, a (mm)	Shear span to depth ratio (a/d)	Steel fiber volume content V_f (%)	Vertical stirrups
BI	BI-1	400	2.35	----	-----
	BI-2	400	2.35	-----	Diameter 6 mm @ 120 mm
	BI-3	400	2.35	0.6	-----
	BI-4	400	2.35	1.2	-----
	BI-5	400	2.35	1.8	-----
BII	BII-1	550	3.24	----	-----
	BII-2	550	3.24	-----	Diameter 6 mm @ 120 mm
	BII-3	550	3.24	0.6	-----
	BII-4	550	3.24	1.2	-----
	BII-5	550	3.24	1.8	-----

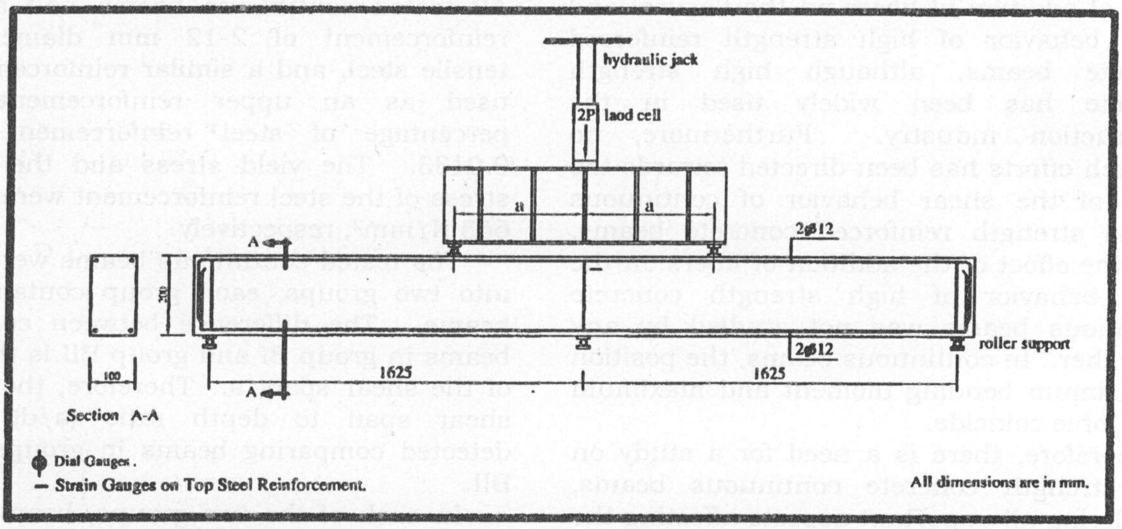


Fig. 1. Dimensions, reinforcement details, and loading setup for tested continuous beams.

noted that special care was given during casting of beams having steel fibers. The concrete was well vibrated in order to uniformly distribute the steel fibers and also to prevent balling of steel fibers.

High strength concrete was used for all continuous beams tested. The cement used was locally produced commercially available ordinary Portland cement, type I. Locally available natural desert sand was used as fine aggregate. The water cement ratio, w/c was kept in the range of 0.28, pink limestone with maximum aggregate size of 13 mm was used as coarse aggregate. Silica fume was added to replace 10% of cement weight in order to increase concrete strength. A commercially available super-plastisizer (water-reducing agent) was used to increase workability. The 28-day concrete cube compressive strength f_{cu} ranged between 71.0 N/mm² and 78.3 N/mm².

All continuous beams were tested to failure under the effect of two concentrated loads, one on each span, as shown in fig. 1. The loads were applied to the beams by using hydraulic jack of 200 kN capacity with a load cell to monitor the load. Deflections under the load points were measured by means of dial gauges. Longitudinal strains in flexural upper reinforcement at the central support were measured by means of electrical strain gauges with 10 mm gauge length.

3. Experimental results and discussions

The experimental results from testing ten steel fiber high strength reinforced concrete continuous beams are summarized in table 2. The experimental results presented in the table included the values of deflection at a given load within the elastic range of loading before cracking. The results also included both flexural cracking loads and shear cracking loads. Table 2 also lists the ultimate shear failure loads and the ultimate shear strength for the ten tested continuous beams. Figs. 2-a and 2-b show load-deflection relationships for tested continuous beams in groups (BI) and (BII), respectively. Figs. 3-a and 3-b show load-strain relationships for tested continuous beams in groups (BI) and (BII), respectively. Figs. 4 and 5 present the effect of steel fiber volume content on shear cracking load and ultimate shear failure load, respectively. Fig. 6 shows cracking patterns for tested continuous beams (BI-1) without steel fibers and (BI-3) having steel fibers of a volume content of 0.6%.

3.1. Deflections

The values of deflections within the elastic range of loading at a load P = 10 kN are listed in table 2, for all continuous beams tested. Examining these values of deflection for beams in group (BI), with shear span to depth ratio (a/d) of 2.35, revealed the following: (i) the value of elastic deflection δ_e was 0.96 mm for the control beam (BI-1) which was made without vertical stirrups or steel fibers; (ii) using vertical stirrups diameter 6 mm @ 120 mm (BI-2) resulted in a reduction in the elastic deflection from 0.96 mm to 0.85 mm, which represents about 11.5%; (iii) adding steel fibers with volume content (V_f) of 0.6%, 1.2%, and 1.8% for beams BI-3, BI-4, and BI-5 resulted in a significant reduction in the value of elastic deflection δ_e. The elastic deflection decreased from 0.96 mm for the control beam (BI-1) to 0.83 mm, 0.52 mm, and 0.42 mm for beams BI-3, BI-4, and BI-5, respectively. This decrease in the value of elastic deflection represents 13.5%, 45.8%, and 56% for beams BI-3, BI-4, and BI-5, respectively.

Table 2
Test results

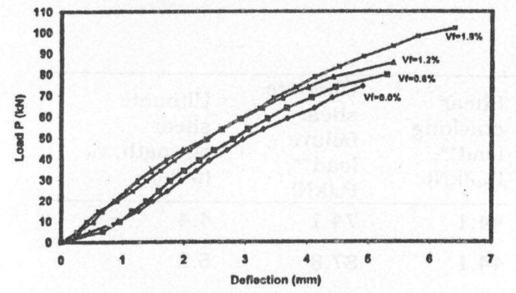
Group	Beam	Deflection* δ_e (mm)	Top flexural cracking load**, P_{tcr} (kN)	Bottom flexural cracking load**, P_{bcr} (kN)	Shear cracking load**, P_{scr}(kN)	Ultimate shear failure load**, P_u(kN)	Ultimate shear strength, v_u (MPa)
BI	BI-1	0.96	24.5	34.3	44.1	74.1	4.4
	BI-2	0.85	19.6	31.9	44.1	87.8	5.2
	BI-3	0.83	26.9	39.2	53.5	79.5	4.7
	BI-4	0.52	29.4	44.1	54.9	85.3	5.0
	BI-5	0.42	34.3	44.1	56.9	102.0	6.0
BII	BII-1	1.42	14.7	19.6	34.3	61.3	3.6
	BII-2	1.12	19.6	24.5	39.2	70.1	4.1
	BII-3	0.92	17.2	29.4	39.2	63.8	3.8
	BII-4	0.60	14.7	44.1	49.1	66.2	3.9
	BII-5	0.57	24.5	39.2	56.4	76.0	4.5

*δ_e : Deflection in the elastic range at a load P = 10 kN.
** Total load applied on beam = 2P.

These significant reductions in the values of deflection were expected since the addition of steel fibers significantly increases the beam stiffness and therefore reduces the deflection at a given load. This finding for the deflection of high strength concrete continuous beams is in accordance with previous investigations on the effect of steel fibers on the deflection of simply supported high strength concrete beams [2, 21] and also for simply supported normal strength concrete beams [14, 20].

Similar observations were found for beams in group (BII) with shear span to depth ratio (a/d) of 3.24. However, the percentage of reduction in the elastic deflection, as a result of the inclusion of steel fibers increased for beams in group (BII) as a/d ratio increased to 3.24 compared to 2.35 for beams in group (BI). Such reductions in the elastic deflection were 35.2%, 57.7%, and 59.9% for beams BII-3, BII-4, and BII-5, having steel fibers with volume content of 0.6%, 1.2%, and 1.8%, in comparison to beam BII-1 without steel fibers. Therefore, it is concluded herein that the effect of steel fibers on the deflection of continuous high strength concrete beams becomes more significant as a/d ratio increases.

(a) Tested beams group (BI), a/d = 2.35



(b) Tested beams group (BII), a/d = 3.24

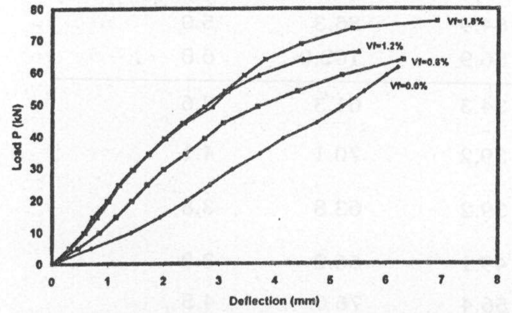
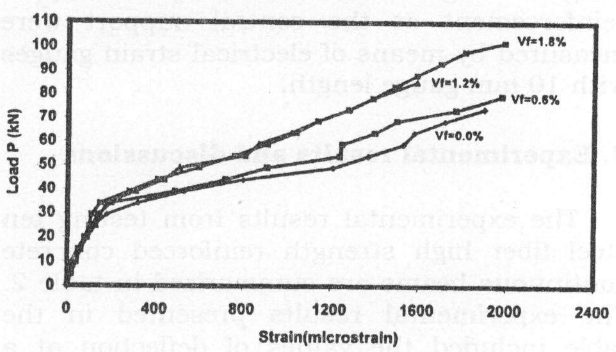


Fig. 2. Load-deflection relationships for tested continuous beams.

(a) Tested beams group (BI), a/d = 2.35



(b) Tested beams group (BII), a/d = 3.24

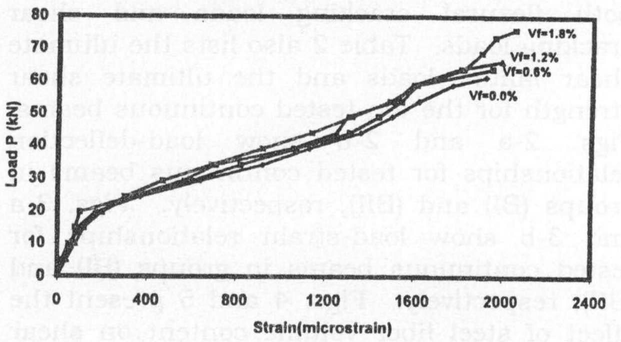


Fig. 3. Load-strain relationships for tested continuous beams.

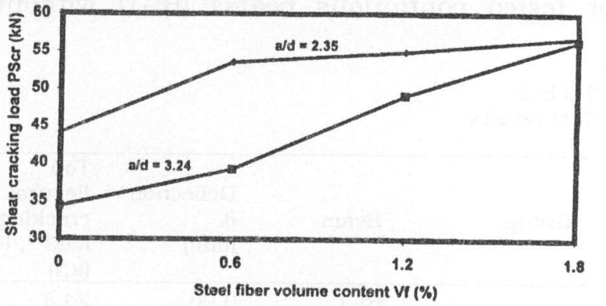


Fig. 4. Effect of steel fiber volume content on shear cracking load PScr for tested continuous beams.

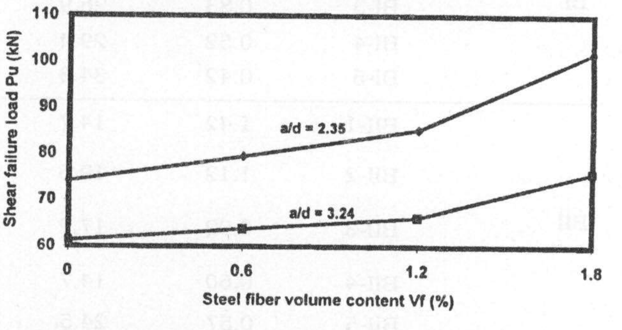
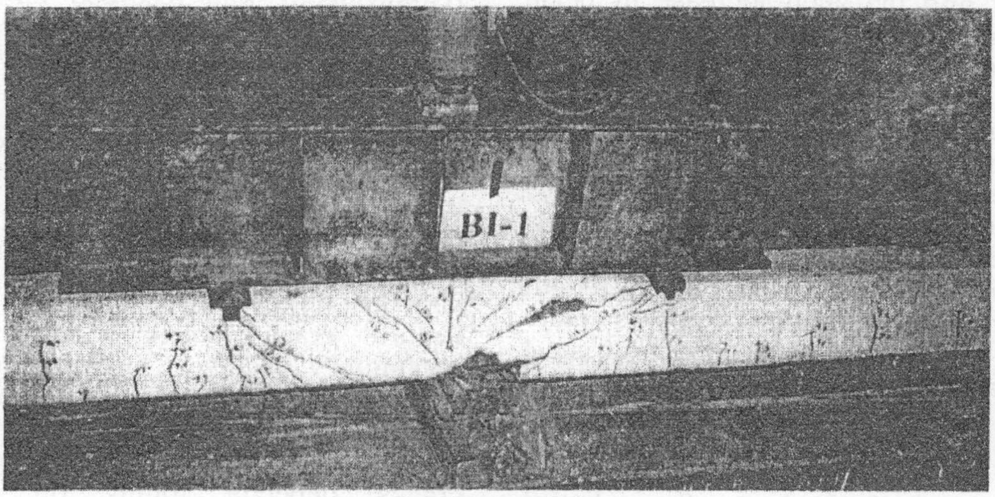
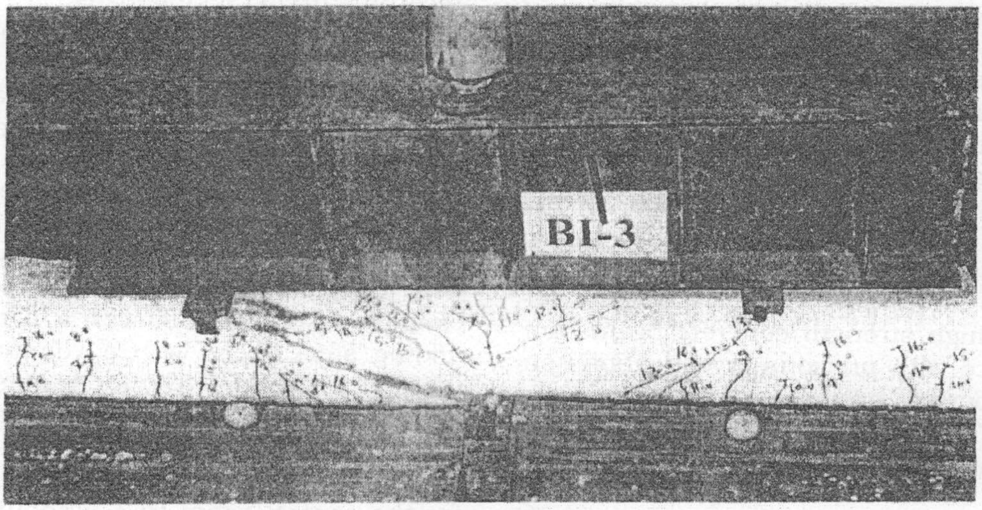


Fig. 5. Effect of steel fiber volume content on shear failure load Pu for tested continuous beams.



(a) Beam BI-1



(b) Beam BI-3

Fig. 6. Cracking patterns for tested continuous beams BI-1 and BI-3.

The effect of a/d ratio on the elastic deflection of continuous high strength concrete beams can be observed comparing the deflection of corresponding beams in groups (BI) and (BII), listed in table 2. It is seen that the value of elastic deflection increased significantly as a/d ratio increased from 2.35 (group BI) to 3.24 (group BII). Such increase in the elastic deflection was about 48% for beams without steel fibers, and between 11% and 36% for beams having steel fibers.

Fig. 2 presents load deflection relationships for tested continuous beams. Examining such relationships revealed the following: (i) the effect of the inclusion of steel fibers on deflection is not only significant in the elastic range of loading but over the complete range of loading up to the ultimate failure load; (ii) it is observed from the relationships that at any load increment, the increase in deflection is lesser for beams with steel fibers of larger volume content; (iii) the value of beam deflection at ultimate failure load is greater for beams having steel fibers in comparison to that of a control beam without steel fibers; and (iv) such increase in beam deflection at ultimate load becomes more significant as the steel fiber volume content increases. These observations for the beam deflection at ultimate failure load indicates that the ductility of continuous high strength concrete beams is significantly enhanced by the inclusion of steel fibers giving ample warning of impending failure. Such enhancement in ductility of high strength concrete continuous beams becomes more significant as the volume content of steel fibers increases.

3.2. Strains

Fig. 3 presents the load – top flexural steel strain relationships for tested continuous beams. It can be observed that the steel strain is marginally affected by the addition of steel fibers in the elastic range of loading before cracking. However, within the post-cracking range of loading and up to the ultimate failure load, a significant reduction in the steel strain can be observed as a result of adding steel fibers. Such reduction in the steel strain becomes more significant as the steel fiber volume content increases. These observations for the steel strain for continuous high strength concrete beams are in accordance with previous investigations on simply supported normal strength concrete beams [4]. This reduction in the steel strain can be explained by the fact that a part of the load applied on the beam is transferred to the steel fibers and is resisted by debonding and stretching. Such part of load transferred to the steel fibers increases as the steel fiber volume content (V_f) increases.

Furthermore, since the toughness can be defined as the area under load strain curves [4]. Examining load strain curves for tested continuous beams, fig 3, revealed an increase in the area under such curves with the increase in the steel fiber volume content. Therefore, it is concluded that the toughness of steel fiber high strength concrete continuous beams increases with an increase in the steel fiber volume content.

It should be noted that no yielding of steel reinforcement was recorded for any of the tested continuous beams.

3.3 Cracking loads

Table 2 lists the cracking loads for all tested continuous beams. The cracking loads include: (i) the load at which the first top flexural crack formed at the position of maximum negative moment (at middle support); (ii) the load at which the first bottom flexural crack formed at the position of maximum positive moment (under the concentrated load); and (iii) the load at which the first diagonal shear crack formed. It should be noted that the detection of first cracks depends totally on the visual inspection and is affected by the observer's judgment which may leads to inaccuracy in recording first cracking loads.

Examining the results presented in table 2, it can be observed that there is a significant increase in the flexural top and bottom cracking loads as a result of adding steel fibers. Such enhancement in the flexural cracking loads increases with the increase in the steel fiber volume content. Furthermore, a similar enhancement was observed also for the diagonal shear-cracking load. For example for group (BI), with a/d ratio of 2.35, adding steel fibers with a volume content of 0.6%, 1.2%, and 1.8%, for beams BI-3, BI-4, and BI-5, resulted in an increase in the diagonal shear cracking load of 21.3%, 24.5%, and 29% respectively, in comparison to that for the control beam BI-1 without steel fibers or vertical stirrups. Such enhancement in the diagonal shear cracking loads can also be detected from fig. 4 for the two groups (BI) and (BII). The enhancement in the diagonal shear-cracking load can be explained by the crack arresting mechanism provided by the steel fibers. It should be noted that the diagonal shear-cracking load was not affected by the presence of vertical stirrups in the case of beam BI-2 in comparison to the control beam BI-1 without vertical stirrups.

3.4. Ultimate shear failure loads

The results for the ultimate shear failure loads are presented in table 2 for all continuous beams tested. Examining these results for continuous beams in group (BI), having a shear span to depth ratio (a/d) of 2.35, the following can be observed: (i) the ultimate shear failure load for the control beam BI-1, without steel fibers or vertical stirrups is 74.1 kN; (ii) the addition of steel fibers with volume content of 0.6% for beam BI-3 increases the ultimate shear failure load to 79.5 kN which represents an increase of 7.3%; and (iii) on increasing the fiber volume content to 1.2% and 1.8% for beams BI-4 and BI-5 the ultimate shear failure load increased to 85.3 kN and 102 kN, which represents an increase of 15.1% and 37.7%, respectively. The enhancement in the ultimate shear failure load with the increase in the steel fiber volume content is shown in fig. 5.

Such enhancement in the ultimate shear failure loads of continuous high strength concrete beams as a result of adding steel fibers is in accordance with results from previous investigations on simply supported high strength concrete beams [2, 12, 21]. This may be attributed to the improvement in the post cracking tensile strength of concrete that enhances the shear strength of beams. Much energy is absorbed in debonding and pullout of steel fibers from the concrete before complete separation and failure of concrete occurs. Steel fibers also increase the shear-friction strength of concrete [4].

Similar observations are found for the effect of adding steel fibers on the ultimate shear failure loads for tested continuous beams in group (BII), having a shear span to depth ratio (a/d) of 3.24. However, the percentage of increase in the ultimate shear failure load in this case was 4.1%, 8.0%, and 24.0%, for beams BII-3, BII-4, and BII-5 with fiber volume content 0.6%, 1.2%, and 1.8%, respectively. Therefore, it is concluded herein that the beneficial effect of steel fibers on enhancing the ultimate shear failure load of continuous high strength concrete beams becomes more significant as the shear span to depth ratio (a/d) decreases.

Comparing the results for the ultimate shear failure loads for groups (BI) and (BII) shown in table 2, it can be also concluded that the ultimate shear failure loads decrease significantly with an increase in the shear span to depth ratio (a/d) for both continuous beams without steel fibers and those having steel fibers. Such decrease in the ultimate shear failure load was up to 25.5% as a/d ratio increased from 2.35 (group BI) to 3.24 (group BII).

3.5. Failure modes and cracking patterns

The application of high strength concrete for beams is hindered by its relative brittleness and lack of ductility [12]. Shear failure of beams usually occurs without any warning due to the brittle nature of plain concrete behavior in tension. This drawback of using high strength concrete can be overcome by the addition of steel fibers in the high strength concrete mix.

Tested high strength concrete continuous beams BI-1 and BII-1 without steel fibers failed in shear. The failure was catastrophic, sudden, and explosive, associated with a loud noise. Tested high strength concrete continuous beams BI-3 and BII-3 with steel fiber of low volume content (0.6%) failed also in shear. Although the failure in this case was also sudden, however it was less catastrophic in comparison to beams without steel fibers. The failure in this case was not accompanied by a loud noise. Tested high strength concrete continuous beams BI-4 and BII-4 with steel fibers of moderate volume content (1.2%), and BI-5 and BII-5 with steel fibers of high volume content (1.8%) failed also in shear. However, the failure in this case was much more ductile, especially for beams BII-4 and BII-5 with larger values of shear span to depth ratio (a/d).

An examination of the cracking patterns for tested continuous high strength concrete beams after failure revealed that in the case of beams having steel fibers several diagonal cracks were formed which are more closer than that in the case of beams without steel fibers. This observation for the cracking patterns of continuous high strength concrete beams is in accordance to previous investigations on simply supported high strength concrete beams [2, 21].

The increase in the number of diagonal cracks indicates a redistribution of stresses beyond cracking. The effect of steel fibers becomes more significant after the formation of shear cracks. The steel fibers continued to resist the principal tensile stresses until a complete pullout of all fibers occurred at one critical crack. Fig. 6 shows cracking patterns for tested continuous high strength concrete beams BI-1 and BI-3.

4. Validity of existing models in predicting shear strength of steel fiber high strength concrete continuous beams

Existing models found in the literature for estimating the ultimate shear strength of steel fiber high strength concrete beams were originally developed using experimental results from testing simply supported beams. The validity of such models in the case of steel fiber high strength concrete continuous beams is questionable and will be examined herein using test results from current experimental program.

Khunita et al. [12] presented an equation for the estimation of ultimate shear strength of simply supported steel fiber high strength concrete beams in the form of:

$$V_u = (0.167\,\alpha + 0.25\,F)\sqrt{f_c'}\quad \text{MPa}\,. \qquad (1)$$

The equation is in terms of the arch action factor α which depends on the shear span to depth ratio (a/d), the fiber factor F which depends on the steel fiber content and properties, and the fiber concrete cylinder compressive strength f_c'. The equation suggests explicit relationship between the concrete strength and the post-cracking tensile strength of concrete. The equation ignores the effect of both the aggregate size and the percentage of tensile steel reinforcement. Both factors are taken into account in the equation presented by Imam et al. [21] which is in the form of;

$$v_u = 0.7\,\xi\,\sqrt[3]{\rho}\,[f_c^{0.44}\,(1 + F^{0.33}) + 870\sqrt{\frac{\rho}{(\frac{a}{d})^5}} \quad \text{MPa}\,, \qquad (2)$$

where ξ = aggregate size effect factor; and ρ = tension reinforcement ratio.

The equation is based on regression analysis using experimental results and the influence of steel fibers was accounted for by incorporating the splitting tensile strength of fiber concrete obtained from test results.

The ultimate shear strength of steel fiber high strength concrete continuous beams tested in the current experimental program was estimated using eqs. (1, 2). The theoretical results were compared to the experimental ones and the ratio $V_{(theoretical)}/V_{(experimental)}$ is presented in table 3.

Table 3
Comparison of theoretical to experimental ultimate shear strength for tested steel fiber high strength reinforced concrete continuous beams

Group	Beam	$V_{u\,(theoretical)}/V_{u\,(experimental)}$				
		Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (5)
	BI-3	0.55	0.71	0.87	-----	0.51
BI	BI-4	0.72	0.71	1.05	-----	0.62
	BI-5	0.77	0.62	1.13	-----	0.64
	BII-3	0.66	0.64	0.79	0.51	-----
BII	BII-4	0.90	0.67	1.02	0.63	-----
	BII-5	1.00	0.62	1.10	0.66	-----

Examining such ratios revealed that the equations are extremely conservative, in most of the cases, in predicting the ultimate shear strength of steel fiber high strength concrete continuous beams.

Ashour et al. [2] presented a modification for the ACI equation for the estimation of the ultimate shear strength of steel fiber high strength concrete simply supported beams in the form of;

$$V_u = (2.11\sqrt[3]{f_c'} + 7F)(\rho\frac{d}{a})^{0.333} \quad \text{MPa} . \qquad (3)$$

Furthermore, Ashour et al. [2] presented another two equations based on a modification to Zsutty's equations, the first equation is applicable for simply supported beams having a/d > 2.5, whereas the second equation is applicable for simply supported beams having a/d < 2.5. The equations are in the form of;

For a/d > 2.5;

$$V_u = (2.11\sqrt[3]{f_c'} + 7F)(\rho\frac{d}{a})^{0.333} \quad \text{MPa} . \qquad (4)$$

For a/d < 2.5;

$$v_u = (2.11\sqrt[3]{f_c'} + 7F)(\rho\frac{d}{a})^{0.333}(\frac{2.5}{a/d}) + v_b(2.5 - \frac{a}{d}) \quad \text{MPa} . \qquad (5)$$

Examining the results presented in table 3 for the ratio between the theoretical ultimate shear strength, estimated using eqs. (3-5), and the experimental ultimate shear strength for tested continuous beams it can be observed that: (i) eqs. (4, 5) are extremely conservative in estimating the ultimate shear strength of steel fiber high strength concrete continuous beams; (ii) among all equations presented, eq. (3) which is a modified ACI equation is the most reliable one in estimating the ultimate shear strength of high strength concrete continuous beams having steel fibers with low and moderate volume content; and (iii) however, eq. (3) tends to be unsafe for continuous high strength concrete beams having steel fibers with high volume content (beams BI-5 and BII-5 with V_f = 1.8%).

Therefore, it can be concluded herein that generally the models found in the literature which were originally developed for simply supported steel fiber high strength concrete beams are not applicable in the case of continuous beams. More experimental data is needed to enable the development of a reliable empirical equation for estimating the ultimate shear strength of steel fiber high strength concrete continuous beams.

5. Summary and conclusions

Detailed literature review was conducted including the previous experimental and theoretical investigations on simply supported steel fiber high strength concrete beams. It was observed that none of the previous investigations has considered continuous steel fiber normal strength or high strength concrete beams. Therefore, an experimental study was conducted in this paper including fabrication, instrumentation, and testing ten continuous high strength concrete beams. The behavior of continuous beams made without vertical stirrups or steel fibers was compared to that for continuous beams having vertical stirrups or steel fibers. The main parameters studied were the shear span to depth ratio and the steel fiber volume content. Finally, the experimental results for the ultimate shear strength of tested continuous beams were compared to theoretical predictions from empirical equations found in the literature for the estimation of shear strength of simply supported steel fiber high strength concrete beams. Based on this study the following conclusions can be drawn:

1- The inclusion of steel fibers in continuous high strength concrete beams resulted in significant reduction in the elastic deflection. This is because the addition of steel fibers increases the beam stiffness and therefore reduces the deflection. Such reduction in the elastic deflection increases with an increase in the steel fiber volume content.

2- The presence of steel fibers resulted in an increase in the beam deflection at the ultimate failure load. This indicates that the ductility of continuous high strength concrete beams is significantly enhanced by the inclusion of steel fibers giving ample warning of impending failure.

3- The inclusion of steel fibers significantly reduced the strain in the top flexural steel reinforcement starting from the post elastic range of loading and up to the ultimate failure load. This is because of the fact that a part of the load applied on the beam is transferred to the steel fibers and is resisted by debonding and stretching.

4- The area under load strain curves for tested continuous high strength concrete beams increased with an increase in the steel fiber volume content which indicates an enhancement in the toughness of beams.

5- There is a definite increase in the diagonal shear cracking load of continuous high strength concrete beams as a result of the presence of steel fibers. Such enhancement in the diagonal shear-cracking load is explained by the crack arresting mechanism provided by the steel fibers.

6- There is an increase in the ultimate shear failure load as a result of adding steel fibers. This is due to the significant improvement in the post cracking tensile strength of concrete that enhances the shear strength of beams. Much energy is absorbed in debonding and pullout of steel fibers from the concrete before complete separation and failure of concrete occurs.

7- The beneficial effect of steel fibers on enhancing the ultimate shear failure load of continuous high strength concrete beams becomes more significant as the shear span to depth ratio decreases.

8- The ultimate shear failure load for continuous high strength concrete beams decreases significantly with an increase in the shear span to depth ratio.

9- The shear failure for continuous high strength concrete beams without steel fibers is catastrophic, sudden, and explosive, associated with a loud noise. The failure of beams having steel fibers of low volume content is less catastrophic. The failure of beams having steel fibers of moderate and high volume content is much more ductile especially with large values of shear span to depth ratio.

10- The cracking pattern of continuous high strength concrete beams with steel fibers has several diagonal cracks which are more closer than that in the case of beams without steel fibers. This indicates a redistribution of stresses beyond cracking. The effect of steel fibers becomes more significant after the formation of shear cracks.

11- The models found in the literature which were originally developed for estimating the ultimate shear strength of simply supported steel fiber high strength concrete beams are not applicable in the case of continuous beams. More experimental data is needed to enable the development of a reliable empirical equation for estimating the ultimate shear strength of steel fiber high strength concrete continuous beams.

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