SHEAR TRANSFER STRENGTH OF STEEL FIBER REINFORCED CONCRETE

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Abstract

Push-off tests were performed and a finite element model was adopted to study the influence of steel fibers on shear transfer strength of concrete. Nine push-off specimens were used. The specimens were divided into three groups each of a definable amount of steel fibers. Also, the amount of steel stirrups crossing the shear plan was variable. The results show that the use of steel fibers in combination with steel stirrups can minimize the required amount of stirrups and improve strength and ductility. Comparing test and theoretical results with the provisions of ACI-05 Code, it is concluded the ACI-05 shear-friction method gives a very conservative estimate of shear transfer strength of concrete.

مقاومة انتقال القص للخرسانة المسلحة بالألياف

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الخلاصة:

في هذا البحث تم القيام بدراسة نماذج خاصة (Push-off) وتبني موديل للعناصر المحددة لدراسة تأثير ألألياف الحديدية على مقاومة انتقال القص للخرسانة. تم فحص تسعة نماذج و قسمت النماذج إلى ثلاثة مجاميع حسب نسبة ألياف الحديد المستخدمة. كذلك كانت كمية حديد القص (الأترية) التي تقطع مستوى القص متغيرة. أظهرت النتائج أن استخدام ألياف الحديد بالاشتراك مع حديد القص بإمكانه أن يقلل كمية حديد القص اللازمة مع تحسين في المقاومة و المطيلية. كما تبين المقارنة بين النتائج العملية و النظرية لهذا البحث مع الفقرات الخاصة بقص-الاحتكاك (Shear-friction) في المدونة الأمريكية أن طريقة المدونة الأمريكية في حساب مقاومة انتقال القص تعتبر متحفظة جداً.

Introduction

Portland cement concrete can be considered as a brittle non-ductile material when subjected to tensile stresses. This has been solved since the nineteenth century by using steel reinforcing bars within the concrete to carry tensile loads.

Since the early 1960s, extensive research on steel fiber reinforced concrete (SFRC) showed that the addition of steel fibers can increase the tensile load capacity of concrete mix and keeps the crack width as small as possible.

The problem of shear behavior and ultimate shear strength of concrete members was examined many years ago. Many researches on fiber reinforced concrete beams indicate that fibers substantially improve the shear (diagonal tension) capacity of concrete beams. In some practical structures such as corbels, pre-cast concrete connections and interface between different concretes, shear stresses transfer at a definable plan. The push-off specimens are more suitable for studying shear transfer in such structures than conventional beams.

In this work, push-off specimens were used to investigate the influence of the addition of steel fibers on shear transfer strength and to study the possible amount of contribution of commercial percentages of steel fibers in carrying shear loads in contribution with reinforcing steel stirrups.

Failure Envelope of Concrete

For this study the formulation of the failure envelope proposed by William and Warnke (6) was adopted with the parameters; ft and fc. The failure criteria of concrete due to a multi-axial stress state can be expressed in the form

$$\frac{F}{fc} - S \geq 0 \tag{1}$$

where F: a function of principal stress state;

S: failure surface expressed in terms of principal stresses and some parameters, which are depending on fc, ft;

fc: uniaxial compressive (crushing) strength;

ft: uniaxial tensile strength.

Concrete Uniaxial Stress-Strain Relationships in Compression

For the nonlinear shear analysis of the test model, it is essential to understand the stress-strain behavior of FRC (fiber reinforced concrete) in compression. In this paper, the stress-strain relationship proposed by Khuntia et. Al, 1999 is used, which can be applied to both normal and high-strength concrete with or without steel fibers, and is given as

$$fc = E_c\, \varepsilon_c \left\{ Q + \frac{1-Q}{\left[1+\left(\frac{E_c\, \varepsilon_c}{K\, f'c} \right)^N \right]^{1/N}} \right\} \tag{2}$$

where:

$f'c$ = compressive stress of FRC at a strain of ε_c .

K, Q, and N are the nondimensional factors defined as follows:

$K=0.6+1.08/F^{0.16}$ ($K = 2.85$ for $F = 0$, i.e., for concrete without fibers)

$Q=(0.26-0.40/F^{0.28})Z^{1.4}$ ($Q =-0.9Z^{2.1}$ for $F = 0$)

$N =1.5Z^{0.58}$ ($N =1.5+(Z-1)^{0.8}$ for $F = 0$).

$Z = f'c / 28$ ($f'c$ in MPa).

Fiber reinforcing index $F = (V_f\, l_f /d_f)$, where V_f, l_f, and d_f are volume fraction, length, and diameter of the fiber, respectively.

$f'c$ = compressive strength of FRC.

Ec = elastic modulus of FRC, given by $Ec = Ec_{//} / 2 + Ec_{\perp} / 2$ (5); where $Ec_{//}$ is the elastic modulus of FRC in aligned condition (upper bound) equal to E_fV_f+ $Em(1-V_f)$ and $Ec_{\perp}$ is that in perpendicular fiber condition (lower bound) equal to $E_f\, Em/[Ef\,(1-Vf\,)+EmV_f\,]$. E_f and Em are the elastic modulus of fiber and matrix, respectively. For simplicity, the elastic modulus of FRC (Ec) can be taken equal to that of the matrix (Em).

A comparison of the behavior of FRC in compression with that of normal concrete is shown in **Figure (1-A)**. As shown in the figure, FRC possesses a partial confinement effect.

The strain corresponding to peak stress of FRC, ε_{of} , can be expressed as 1999

$$\varepsilon_{of} = \varepsilon_o + 0.00683 \frac{F^{0.65}}{\sqrt{f'c}} \tag{3}$$

where ε_o is the compressive strain of normal concrete at peak stress which equals 0.002 for normal-strength concrete, and can be taken as 0.002+($f'c$-28) * 0.72 * 10^{-5} for strengths greater than 28 MPa.
The value of ultimate compressive strain can be conservatively taken as twice that of strain at peak stress for all FRC strengths 1999.

Concrete Uniaxial Stress-Strain Rrelationships in Tension

The stress-strain response of a concrete member in uniaxial tension is initially almost linear elastic. Near the peak load, the response becomes softer due to micro cracking. For simplicity, the distribution of post-cracking tensile stress of FRC is assumed to be triangular (Khuntia, 1999). **Figure (1-B)** shows the typical stress-strain curve for concrete in tension with and without steel fibers.

Steel Stress-Strain Relationships in Tension and Compression

The stress-strain curve of reinforcing steel was modeled by an idealized bilinear curve identical in tension and compression as shown in **Figure (2)**.

Experimental Program

Push-off specimens were used in this work to study the enhancement on shear transfer strength due to the presence of steel fibers. The push-off specimens were 440mm in length, 200mm in width and were 100mm in thickness with 200mm shear plan length as shown in **Figure (3-a)**. Two variables were investigated; the first was the fiber content. Three steel fiber contents (Vf %) of (0.0, 0.5 and 1.0 %) by volume were used. While the second variable was the amount of shear reinforcement crossing the shear plans. One specimen from each group was designed without shear reinforcement crossing the shear plan. While the second specimen was designed with one 10mm diameter closed stirrup (2 legs) and the third specimen was reinforced with two 10mm diameter closed stirrup (4 legs), **Table (1)** summarizes the specimen's properties. Additional reinforcement was provided away from the shear plan to prevent failure other than the shear plan ,1972.

The used materials were as follows: ordinary Portland cement from Kubaisa factory; washed graded local natural sand from Al-Ukhaider; and crushed graded local gravel with maximum size of 19mm from Al-Nebaey region. The steel fibers were (Duramix type) with 0.5mm diameter and 30mm length (aspect ratio L/d= 60) and ultimate strength of 1177 MPa. A single concrete mix was used in this study with mix proportion by weight of (1: 1.5: 3) (Cement: Sand: Gravel) and with water cement ratio of 0.5. The concrete was mixed according to the fifth mixing procedure recommended by ACI 544.1R-82 ,1982.

The concrete was placed in the moulds in two layers and was externally vibrated using a table vibrator as recommended by ACI 544.2R-89 ,1989. All specimens including control specimens were prepared, cast and vibrated as recommended by ACI 544.2R-89 ,1989, and were tested at age of 28 days. The push-off specimens were loaded concentrically using a hydraulic testing machine as shown in **Figure (3-b)**.With each concrete mix, three 150mm cubes were prepared to test the compressive strength of concrete. Also, six (150×300 mm) and three (100×200 mm) cylinders were prepared to find the cylinder compressive strength, static modulus of elasticity and splitting tensile strength respectively.

Ansys Computer Program

A finite element model was proposed to represent the push-off specimens using the (ANSYS 5.4) finite element computer program. The out-put of this computer program was used to study the concrete shear transfer behavior and to compare with the experimental results.

The three-dimensional finite element representation mesh for the specimen using (ANSYS 5.4) software is shown in **Figure (4)**. The concrete is idealized by using (608) eight-noded brick elements (solid 65-reinforced element), steel reinforcement is idealized by using (184, 200, 216) two-noded bar elements (link 8- bar element). The total number of nodes is 945.

Ultimate Strength

The ultimate shear transfer strength is defined as the maximum shear that the test specimens can carry during the test. The shear transfer through the shear plane can be expressed as the ultimate force carried by the specimens divided by the area of the shear plane 1969, 1976.

v_u= ultimate shear stress (ultimate shear force/ area of shear plane)

In this research, the shear force equals the applied load and the shear plane area equals (200 x 100 mm). **Table (2)** shows the values of ultimate shear transfer strength of all specimens with other test data.

Results of Finite Element Model (Ansys Results):

By the comparison of experimental results with those of finite element model obtained by ANSYS, it is observed that the percentage error does not exceed 10.62% in the worst case. This percentage of error can be considered as an accepted percentage in the civil engineering field. Also, it is noticed that the percentage error increases as the shear steel quantity increase. This result can be attributed to the decreasing degree of representation of the steel stress-strain model to the actual behavior as steel stress increase.

The deformed shape of specimen Number A0 at stress level of 2 MPa is shown in **Figure (5)**. The vertical stress in Y-direction at load equals 4.8 MPa is shown in **Figure (6)**. From this figure it can be seen that the maximum vertical stresses occur near the opening of specimen.

Effect of Investigated Parameters

Based on the investigated parameters and the obtained results in this study, the effect of steel reinforcing stirrups and steel fibers on the shear transfer strength of push-off specimens both individually and in combination are discussed here.

Effect of Shear Reinforcement

Figure (7) shows the shear transfer strength values for the three groups of specimens which have different fiber contents. It is shown that for each group, the shear transfer strength increases as the number of stirrup legs increase. The shear transfer strength for group A specimens (without steel fibers), increases from 5.9 MPa for specimens without shear reinforcement to 9.5 MPa for specimens reinforced with 2 legs of 10mm diameter stirrups. While when 4 legs are used instead, the shear transfer strength increases to 11.65 MPa. Similar sequences of increase are recorded for group B and group C specimens as shown in **Figure (7)** and recorded in **Table (2)**. This means that for group A specimens, a shear strength increase of 61% and 97.5% occurs when the push-off specimens are reinforced with 2 and 4 stirrup legs respectively. **Figure (8)** shows that the percentage increase in shear transfer strength ranges between 61% and 78.4% for push-off specimens with two legs of 10mm diameter closed stirrups and ranges between 97.5% and 116.2 for 4 legs of stirrups.

Effect of Steel Fibers

As mentioned previously, two fiber contents of 0.5 % and 1.0 % are adopted in this study in addition to the reference specimens. The effect of the addition of fibers on shear transfer strength of push-off specimens is shown in **Figures (9) and (10)**. **Figure (9)** shows that the shear transfer strength increases as the fiber content increases. The shear strength of push-off specimens without shear reinforcement (group A) increases from 5.9 MPa for specimens without fibers to 6.57 MPa and 7.4 MPa for specimens with 0.5 % and 1.0 % fiber content. For group B specimens the sequence is (9.5, 11.1 and 13.2 MPa) for fiber contents of (0.0, 0.5 and 1.0 %) respectively. Similar sequence is noticed for group C specimens. The percentage increase in shear transfer strength due to the addition of steel fibers of (0.5 % and 1.0 %) is in the range of (11.3 % to 16.8 %) and (25.4 % to 38.9 %) respectively.

This increase in shear transfer strength is an expected result since shear failure occurs mostly as direct shear cracks propagated and increased in width, and because the steel fibers show several potential advantages such as; (1) the fibers are randomly distributed through the volume of concrete at much closer spacing than can obtained with reinforcing bars; (2) the first crack tensile strength and the ultimate tensile strength are increased by the presence of fibers; and (3) the shear friction is increased,1988.

By the comparison of ANSYS results with the experimental results, it is shown that ANSYS results are generally higher than those obtained experimentally. Also, it is noticed that the percentage difference increases as the fiber content increases.

Combined Effect of Reinforcing Stirrups and Steel Fibers

It is reported previously in this paper that the percentage increase in shear transfer strength gained by using 1.0 % of steel fiber does not exceed 26 % compared to plain concrete specimens. While the use of two legs of 10 mm diameter closed stirrups (ρf_y = 3.66 MPa), results in an increase in shear transfer strength exceeding 60 % compared to plain concrete specimens. And when four legs 10 mm diameter closed stirrups (ρf_y = 7.32 MPa) are used, shear transfer strength increases by about 100 %. This may confirms that fibers can not be used individually to resist applied loads without using conventional steel reinforcing bars.

On the other hand, it is noticed that using steel fibers in combination with reinforcing steel bars can results in further improvement in shear strength of push-off specimens. Where, shear strength increases by about 124% when two legs of 10 mm diameter stirrups are used in combination with 1.0 % of fibers, and increases by about 172 % when four legs of 10 mm stirrups are used in combination with 1.0 % of fibers as compared to plain un-reinforced specimens. Another noticeable result is that the use of two legs of 10 mm stirrups in combination with 1.0 % of steel fibers results in higher shear stresses at failure than using four legs of stirrups without fibers. The shear strength of push-off specimens which reinforced with four legs of stirrups without fibers is 11.65 MPa, while for specimens reinforced with two legs with 1.0 % of steel fibers, shear strength is 13.2 MPa.

Test results of this study confirm that steel fibers significantly increase shear capacity of concrete especially when work in combination with conventional stirrups. Also, it confirm that 1.0 percent of steel fibers can replace a part of steel stirrups reaching moderately higher shear stresses at failure and improving crack propagation resistance showing higher ductility at failure. However, the steel reinforcement can be placed and distributed in the required orientations and spaced in the required distances to withstand the design loads, while this can not be ensured when steel fibers is used instead, since steel fibers are randomly distributed in the concrete matrix and spread in different positions and orientations, which lead to the conclusion that steel fibers can not be used simply in place of conventional steel bars, it can be used in combination with steel bars to increase concrete ductility, help keeping the crack as small as possible and improve the shear capacity of concrete members.

Comparison of the study results with the aci-05 code shear-friction provisions.

Depending on the finite element model obtained by the ANSYS computer program , many shear transfer strength results were obtained using two different bar diameters, three different steel yield stresses and three fiber contents as shown in **Table (3). Figure (11)** shows a comparison between the experimental and the finite element results of this study with the ACI-318m-05 Code (1) shear-friction design method. It is noticed that the lowest shear transfer strength in this study (specimen A0: no stirrups and no fibers) is higher than the maximum shear transfer strength limited by ACI-318m-05 Code. Section 11.7.5 of ACI-318m-05 Code limits the maximum shear transfer strength V_n by $0.2 f_c'$ or 5.5 MPa times the area of concrete section resisting shear transfer. While in this study, it is found that the shear transfer strength for specimen without reinforcement and fibers is about 6.0 MPa which exceeds the maximum shear transfer strength limited by ACI-318m-05 Code. The shear transfer strength for reinforced specimens without fibers ranges from 8.6 MPa for ρf_y of 1.61 MPa to 12.9 MPa for ρf_y of 7.58 MPa which confirms that the ACI-318m-05 Code shear-friction design method is too conservative. When the ACI-318m-05 Code shear-friction design method is compared with the results of fiber reinforced specimen results, the gap becomes wider. The shear transfer strength for 1% fiber reinforced concrete ranges between (11.7 and 18 MPa) for ρf_y of (1.61 and 7.58 MPa) respectively. The aim of the limitation of the maximum shear transfer strength of the ACI-318m-05 Code to 5.5 MPa is to limit the amount of steel required to resist the shear transfer stresses.

Depending on the results of this study, it can be concluded that the ACI-318m-05 Code shear friction design method is too conservative. Modifications can be made to this method by taking into account the shear friction resistance of concrete (initial point of the design lines) and raising the upper limit of shear transfer strength to about 8 MPa, which results in conservative design lines with which lower quantities of steel reinforcement can be used to carry higher shear transfer stresses.

Conclusions:

1- Shear transfer strength of concrete enhances noticeably when steel fibers are used. The percentage increase in shear transfer strength was in the range of 25.4% to 38.9% when 1% of duramix type steel fibers are added.

2- The use of 1% of steel fibers can replace a part of steel stirrups reaching moderately higher shear strength and showing higher ductility by improving the crack propagation resistance. The use of two legs of 10mm diameter stirrups in combination with 1% of steel fibers results in a higher shear stresses at failure than using four legs without fibers. The shear transfer strength of specimens reinforced with four stirrups legs was 11.65 MPa, while it was 13.2 MPa for specimens with two legs of stirrups and 1% of steel fibers.

3- Comparing the experimental and the finite element model results of this study with the ACI-318m-05 Code shear-friction provisions, it can be concluded that the ACI-318m-05 Code shear-friction design method gives a conservative estimate of shear transfer strength of concrete.

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Table (1): Push-off specimen properties.

Specimen No.	V_f %	No. of Shear Legs	Shear Parameter(ρf_y) (MPa)	f_{cu} (MPa)	f'_c (MPa)	Splitting Strength (MPa)	E_c (GPa)
A0	0.0 %	0	0	28.9	23.3	2.85	22.8
A1		2	3.66				
A2		4	7.32				
B0	0.5 %	0	0	30.6	23.8	3.04	24.1
B1		2	3.66				
B2		4	7.32				
C0	1.0 %	0	0	29.7	23.9	3.22	28.5
C1		2	3.66				
C2		4	7.32				

Table (2): Experimental and ANSYS shear transfer strength results.

Specimen No.	V_f %	No. of Shear Legs	Shear Parameter ρf_y (MPa)	Shear Transfer Strength (MPa)	Shear Transfer Strength by ANSYS (MPa)	Error %
A0	0.0 %	0	0	5.9	6.05	2.5
A1		2	3.66	9.5	10.0	5.27
A2		4	7.32	11.65	12.7	9.01
B0	0.5 %	0	0	6.57	6.8	3.5

B1		2	3.66	11.1	11.8	6.31
B2		4	7.32	13.47	14.9	10.62
C0	1.0 %	0	0	7.4	7.6	2.7
C1		2	3.66	13.2	14.0	6.06
C2		4	7.32	16.06	17.65	9.9

Table (3): Results obtained by the ANSYS computer program.

Steel Type	As (mm^2)	As*fy	ρfy (MPa)	V_f %	Shear Transfer Strength by ANSYS (MPa)
2Lϕ8	100.5	280*100.5	1.61	0	8.6
				0.5	9.8
				1.0	11.7
2Lϕ8	100.5	350*100.5	2.01	0	8.8
				0.5	9.6
				1.0	11.7
2Lϕ8	100.5	420*100.5	2.412	0	8.9
				0.5	10
				1.0	12.1
4Lϕ8	201	280*201	3.216	0	10.3
				0.5	12.0
				1.0	14.0
4Lϕ8	201	350*201	4.02	0	10.9
				0.5	12.5
				1.0	14.9
4Lϕ8	201	420*201	4.824	0	10.8
				0.5	12.9
				1.0	15.65
2Lϕ10	158	280*158	2.528	0	9.8
				0.5	11.0
				1.0	13.0
2Lϕ10	158	350*158	3.16	0	9.6
				0.5	11.4
				1.0	13.7
2Lϕ10	158	420*158	3.793	0	10.1
				0.5	11.95
				1.0	14.1
4Lϕ10	316	280*316	5.056	0	11.55
				0.5	13.65
				1.0	16.25
4Lϕ10	316	350*316	6.32	0	12.3
				0.5	14.35

				1.0	17.35
4Lϕ10	316	420*316	7.584	0	12.9
				0.5	15.05
				1.0	18.0

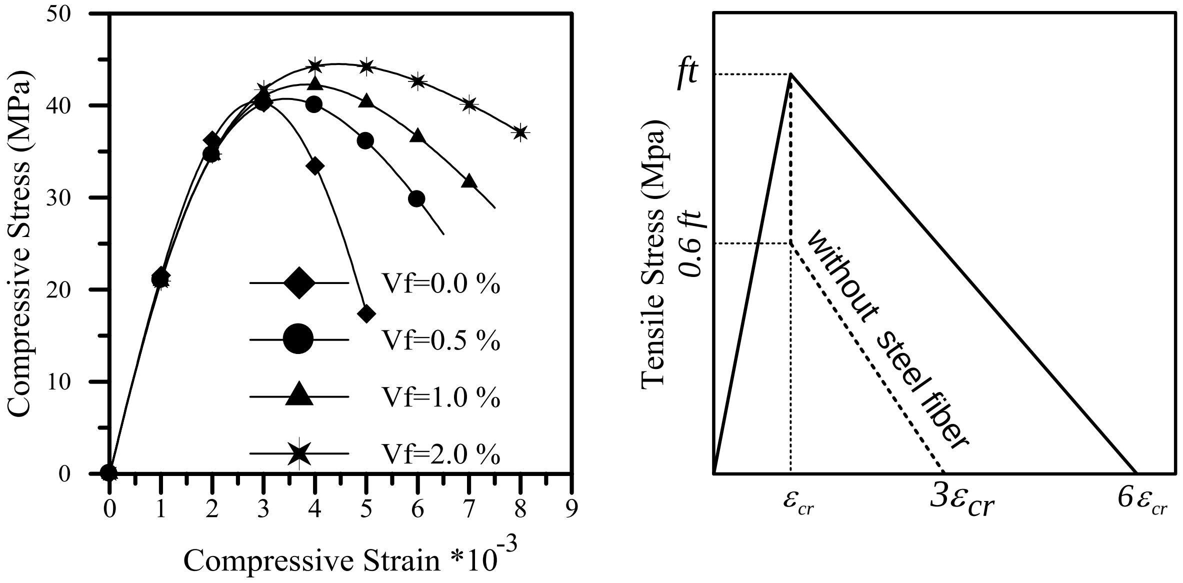

Figure (1): Uniaxial stress-strain of concrete: (A) compression; (B) tension.

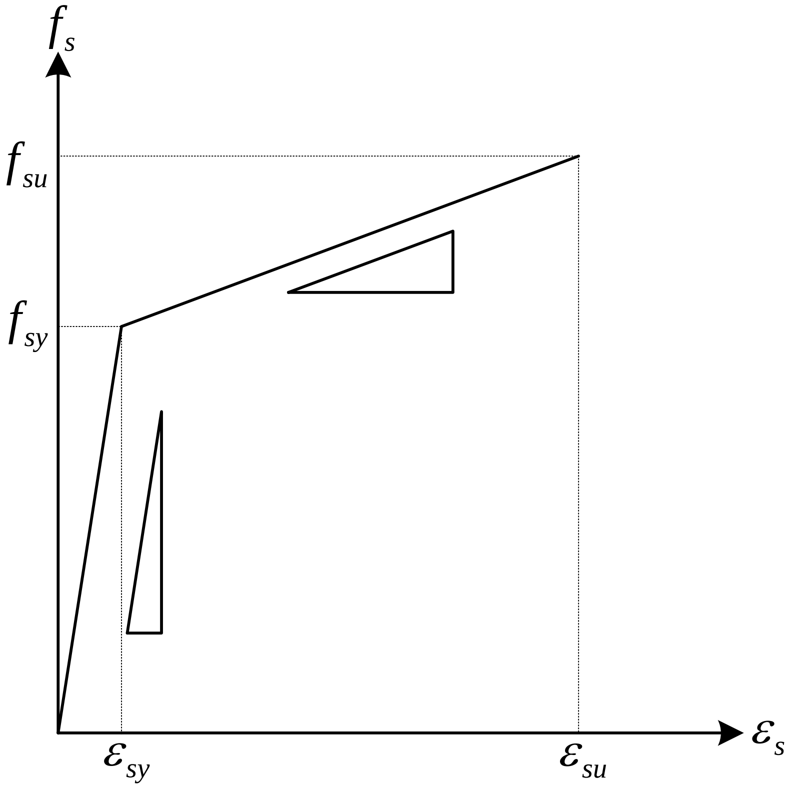

Figure (2): Idealized stress-strain for steel bars.

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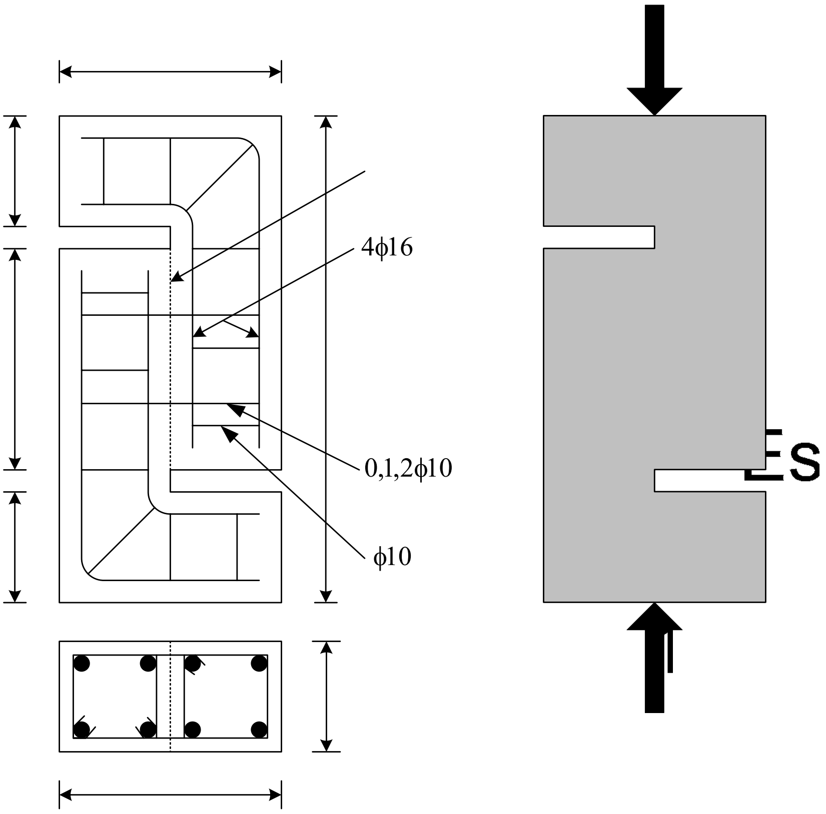

Figure (3) (A) Dimensions and reinforcement details of push-off specimen. (B) Loading arrangement of push-off specimens.

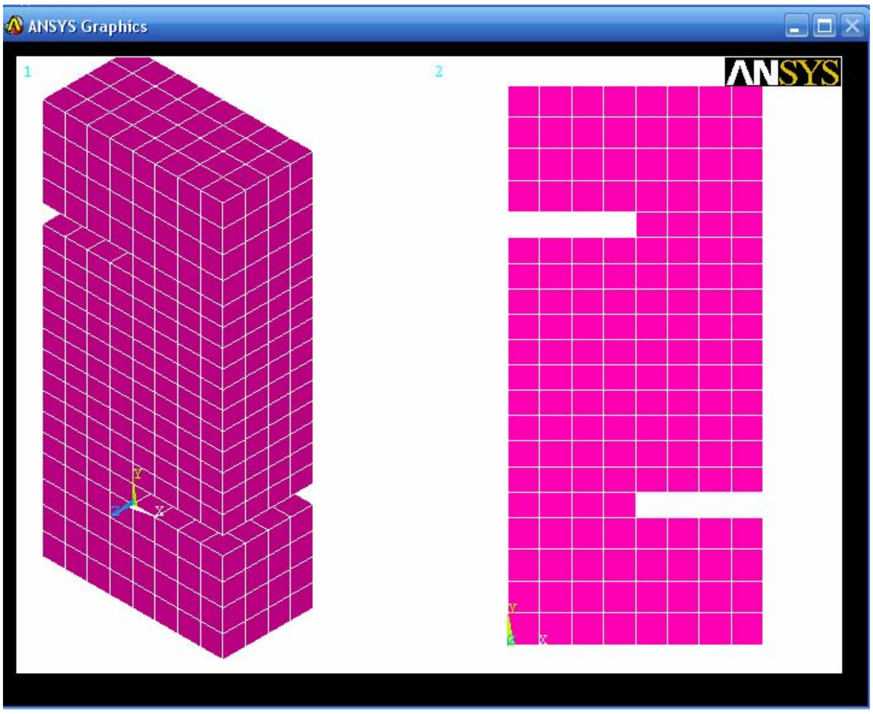

Figure (4) Finite element mesh of test specimen

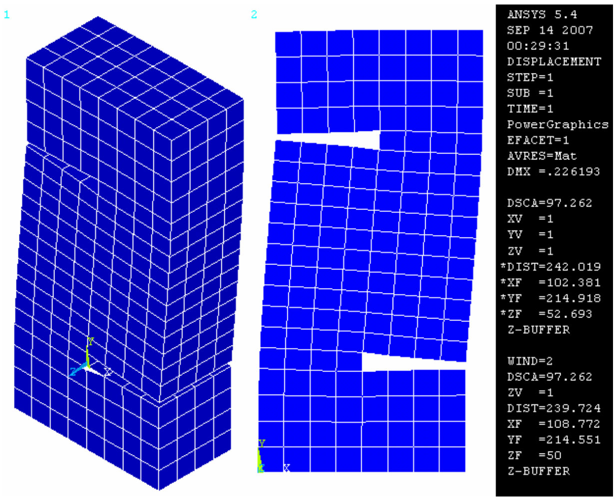

Figure (5) Deformed shape of specimen number A0 at a stress level of 2 MPa.

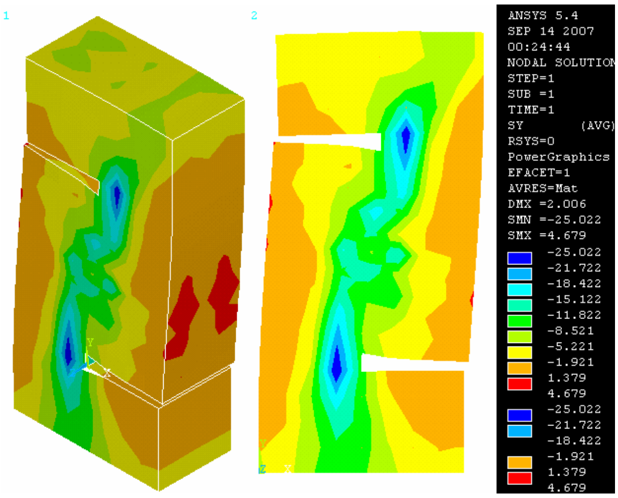

Figure (6) Stresses in y direction of specimen number A0 at a stress level of 4.8 MPa.

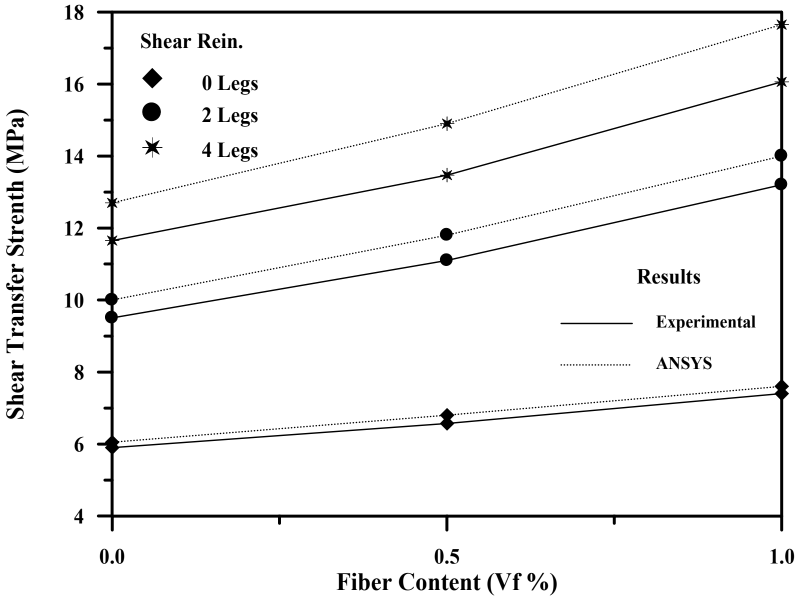

Figure (7) Shear transfer strength-fiber content curves for different shear reinforcements.

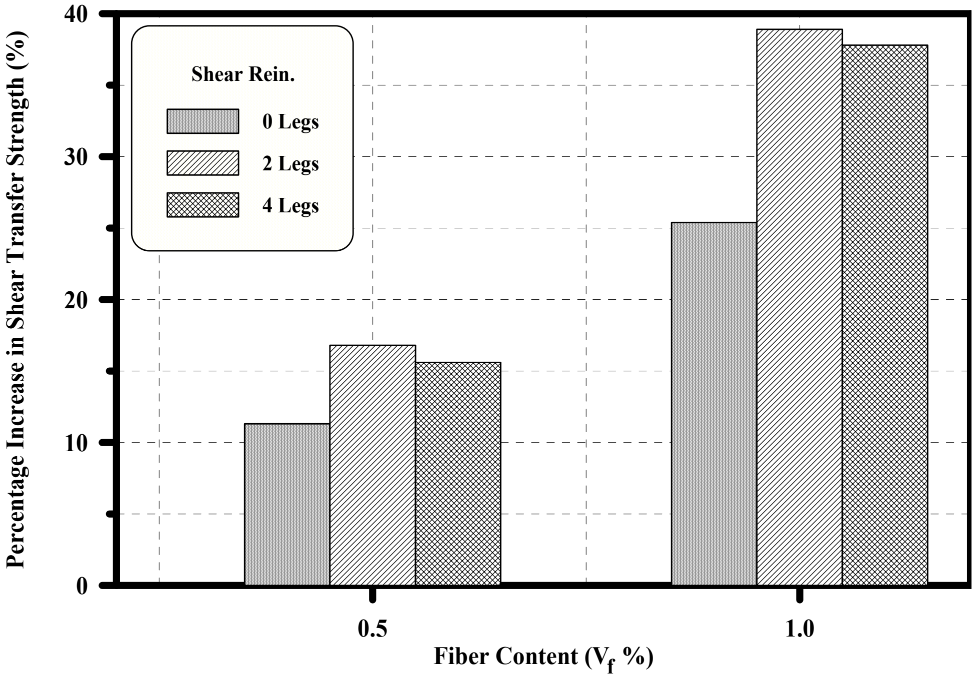

Figure (8) Percentage increase in shear transfer strength-fiber content relationship for different shear reinforcements

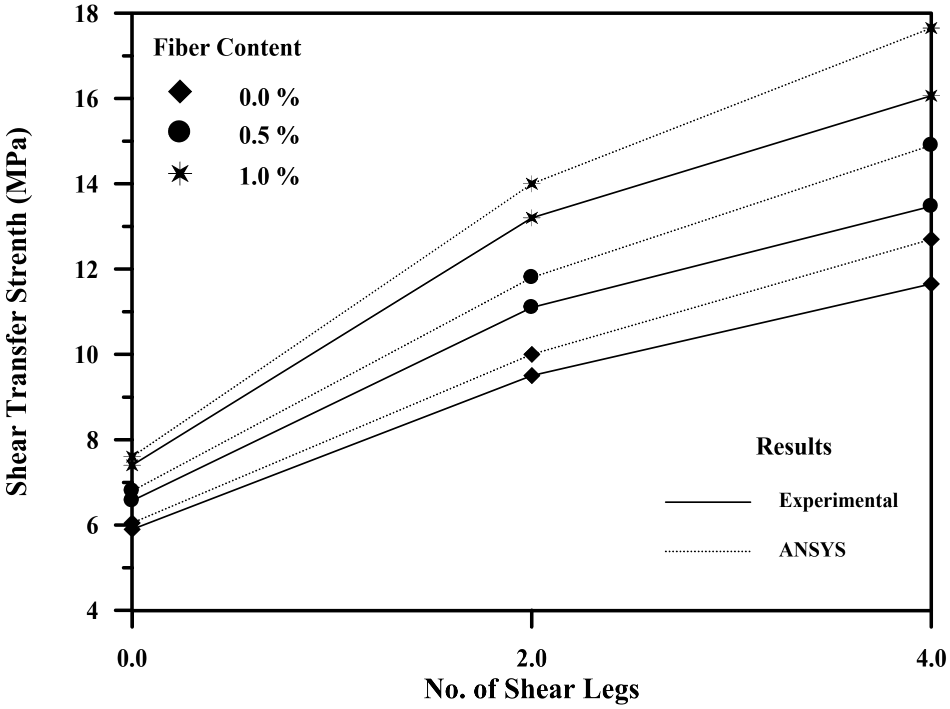

Figure (9) Shear transfer strength-number of shear stirrup legs curves for different fiber contents.

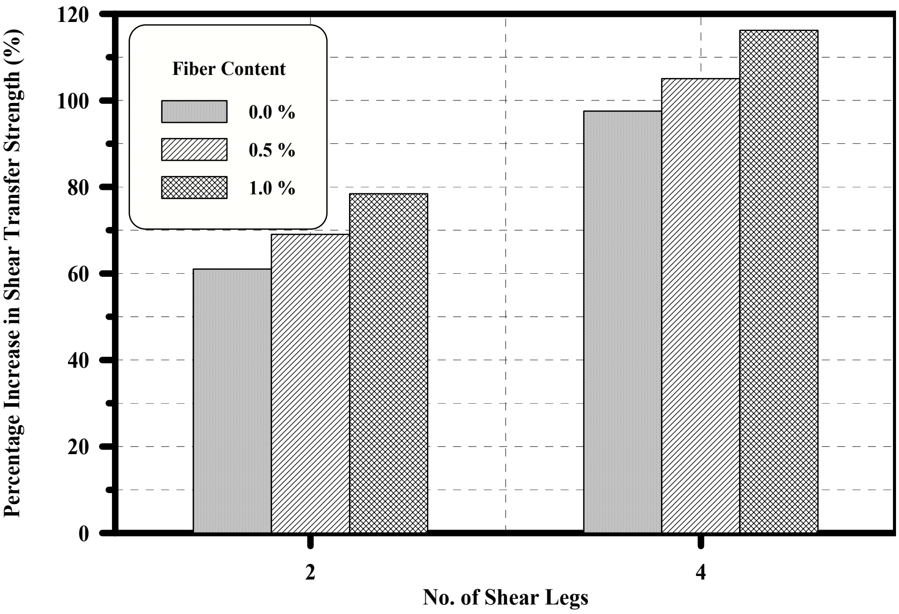

Figure (10) Percentage increase in shear transfer strength-number of shear stirrups legs relationship for different fiber contents

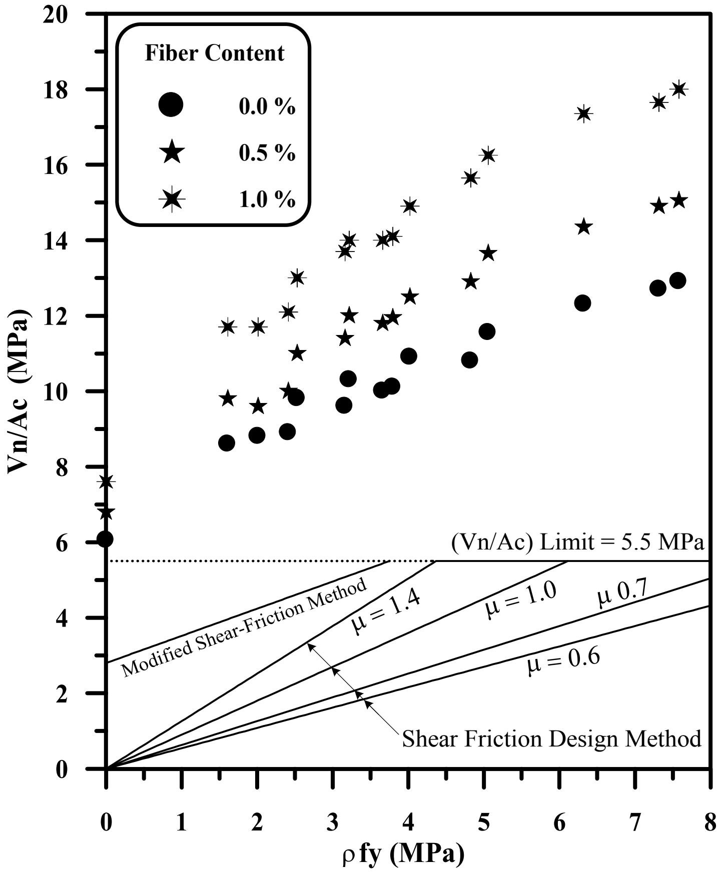

Figure (11) Results of this study versus ACI-318m-05 Code shear friction design method.