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Shear Capacity of High-Strength Fiber Reinforced Concrete Beam-Column Joints

Dr. Kaiss Sarsam* & Zaid Muhammad Kani Al-Azzawi**

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Abstract

This work examines the work of 13 high-strength concrete (HSC) beam-column joints (BCJ)-with and without steel fibers. Several shear design methods (with modification for fiber content, where applicable) were found to be conservative within a range of the following variables: 1) concrete compressive strength, 2) type and volume fraction of steel fibers, 3) content of hoops in the joint, and 4) column axial load. The coefficient of variation (COV) of the ratio of test strength to design strength (V_{TEST} / V_{rDES}) was found to be appreciably low for two of the five existing safe design methods. A conservative design method, which lowers the COV even further to a value of 7.8 percent, is proposed for HSC joints, with and without steel fiber reinforcement.

Keywords: Beam-column joints; Fiber reinforcement; High-strength concrete; Hoops; Shear strength.

التحمل بالقص للمفاصل بين الأعمدة والعتبات المصنوعة من خرسانة عالية المقاومة والمسلحة بالألياف

الخلاصة

يشمل البحث نتائج اختبار 13 مفصل بين العمود والعتبة مصنوعة من خرسانة عالية المقاومة والتي فشلت بالقص في المفصل - مع أو بدون الألياف الحديدية. يبين البحث بأن تطبيق عدة طرق متوفرة حالياً للتصميم يؤدي إلى تصاميم أمينة للمفاصل، وذلك بعد إضافة تعديل عليها عند وجود الألياف. تشمل هذه النتائج متغيرات أساسية: مقاومة الخرسانة للإنضغاط، نوع وكمية الألياف الحديدية، كمية الأطواق في المفصل ومقدار الحمل المحوري للعمود.

يظهر البحث بأن معامل التغاير للنسبة بين تحمل المفصل للقص بالاختبار إلى التحمل المصمم عليه أقل بكثير في إثنين من طرق التصميم الأمينة المتوفرة حالياً مقارنة بالطرق الثلاثة الأخرى الأمينة. يقدم البحث طريقة أمينة مقترحة لتصميم المفاصل المصنوعة من الخرسانة عالية المقاومة في الحالتين: إحتوائها على الألياف الحديدية أو بدونها. تؤدي الطريقة المقترحة إلى معامل تغاير أقل، قيمته 7.8 %.

Introduction

The use of high-strength concrete (HSC) in construction has steadily increased over the past years leading to the reduction of member sizes. Several studies have demonstrated the economy of using HSC in low-rise, mid-rise and high-rise buildings(1). The increasing use of HSC has raised the concern over the applicability of the current empirical methods, which were developed from experimental data on specimens having compressive strength below 40 MPa(1).

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* Building & Construction Engineering Department, University of Technology/ Baghdad.
** College of Engineering, University of Anbar/ Anbar

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

HSC, as a material in compression may be brittle, and as the concrete strength increases the post peak portion of the stress-strain diagram almost vanishes or descends steeply(2-6). The decrease in ductility could be a serious drawback for HSC. Research indicates that steel fibers are more effective in increasing both strength and ductility of HSC than those of normal-strength concrete (NSC)(7). This is due to the improved bond characteristics associated with the use of fibers in HSC as compared to NSC.

The use of fibers to improve the characteristics of construction materials is well established(8-11). The addition of fibers transforms concrete into a more ductile material. The randomly oriented fibers arrest the concrete microcracking mechanism and limit crack propagation, thus improving strength and ductility.

The beam-column joint (BCJ) is one of the most critical areas of a framed structure, where failure is often initiated because of high shearing forces. The increasing use of HSC in columns(1) made the HSC joint design of paramount importance in the design of framed buildings. To dissipate the energy introduced by the loading, the BCJ region should be designed with sufficient strength and ductility to allow a plastic hinge to develop in the beam rather than in the column.

A BCJ is currently designed to withstand a large shearing forces by closer spacing of joint hoops(12). However the spacing reduction may prevent concrete from flowing around the reinforcing bars during construction, causing inadequate bond between the steel and concrete and possible voids within the joint core. Test results(13-15) have shown that the shear capacity and ductility of the BCJ region is increased when steel fiber reinforced concrete (SFRC) is used. Thus, the hoop reinforcement in the joint may be reduced or eliminated by using SFRC in the BCJ region.

Research Significance

HSC joint tests with and without fibers are compared with several simple design methods, including code design originally developed mainly from NSC research. All existing design methods [Eqs. (2-7)] are identical to their respective requirement for shear design, except for the addition of a term for steel fiber contribution, where applicable. A proposed method is introduced that leads to a conservative design.

Experimental Program

Full details of test specimens and material properties are available in reference 17. Table 1 and Fig. 1 give specimen details.

All reinforcing bars were deformed, except the 4mm hoop bars (Table 1) which were plain. Yield strengths of the 4-, 8-, 12-, 16-, and 18-mm bars were 557, 466, 440, 507, and 531 MPa, respectively. Mix proportions by weight of 1:1.24:1.86:0.285:0.05 were used respectively for the cement, sand, gravel, water, and superplasticizer. Steel fibers of 1100 MPa tensile strength were used. The straight fibers had a length of 25.4mm, a diameter of 0.4mm and an aspect ratio (***L/D***) of 63.5; while the hooked fibers had a length of 50mm, a diameter of 0.5mm and an aspect ratio of 100.

Special bearing assemblies (rollers and hinges) were made to facilitate the application of the loads to the test specimens in the testing rig. The column was loaded to a prespecified compression load N_u prior to any beam loading. This axial load was kept constant in each BCJ test.

Experimental Results

All of the 13 BCJs failed in joint shear. Fig. 2 shows the joint failure of specimens SP-1, SP-3, SP-8, SP-9, SP-10, and SP-13. Firstly, the beam flexure tension cracks started in a similar way for all 13 specimens, near the beam-joint interface and expanded into the beam. Secondly, the joint diagonal cracks appeared, for all specimens, nearly parallel to the joint diagonal. For BCJs without fibers, there was a central dominant crack with a few additional cracks to its side (e.g. specimens SP-1 & SP-8) as shown in Figs. 2(a) and 2(c). However, the crack patterns were significantly different from those in BCJs with fibers with several more cracks. The crack size in BCJ's with fibers was much smaller than that on BCJs without fibers (e.g. specimens SP-3 &SP-10) as shown in Figs. 2(b) and 2(e).

The existence of a hoop did not prevent a brittle type failure, as can be seen when comparing SP-8 failure [Fig. 2(c)] which had no fibers with SP-9 [Fig. 2(d)] which was identical except for 1.0% hooked fibers (each had a single 8mm central hoop in the joint). The latter had a greater number of smaller size cracks at failure than the former. In addition, the integrity at failure of SP-9 was significantly better than that of SP-8. This indicates that repair after damage (retrofitting) could be easier if the BCJ with fibers is used.

The expected influence of the column axial load in increasing the joint diagonal cracking angle with the horizontal can be clearly seen by comparing the failure of SP-3 [Fig. 2(b)] and SP-13 [Fig. 2(f)]. The cracks in the latter with a column compressive stress of 6.41 MPa were more vertical in the joint as compared with the former that has a column compression stress of 3.21 MPa.

The behavior of each of the 13 BCJs indicates no anchorage distress in the beam and column reinforcement at failure. The BCJ failure load capacity (V_{TEST} of Table 1) is based on equilibrium at the column-beam interface. The exerted external moment at failure (M_{max} in the beam) is equated to the internal resisting moment of the beam cross-section at the beam-column interface. Then the forces (tension and compression) are added algebraically to obtain a net zero axial force in the interface. The contribution of the fibers is included in the tension zone of the cross-section. Detailed calculations of V_{TEST} are presented in reference 17.

Evaluation Of Experimental Results

Joint strength design equations:

Regression analysis of the results of the 13 BCJ tests of this work under monotonic loading has resulted in the proposed Eq. (1). As will be seen later, Eq. (1) leads to an improved conservative strength prediction of HSC joints, with and without fiber. In all of the following [Eqs. (1-7)] the symbols are defined in the "Notation" except where necessary [e.g. Eqs. (1-A), (1-B), etc.].

$$V_{rPROP} = \left[\sqrt{f'_{cf}} + 10F + 24 r_d\right].\left(\frac{d_c}{d_b}\right).\sqrt{1+0.29\frac{N_u}{A_g}}.b_c.d_c + \frac{1}{b}.A_{st}.f_{yv} \quad \ldots\ldots \quad (1)$$

where

$$F = V_f.\frac{L}{D}.d_f \quad \ldots\ldots \quad (1\text{-}A)$$

The fiber influence (V_F) is defined as follows:

$$V_F = (10F).\left(\frac{d_c}{d_b}\right).\sqrt{1+0.29\frac{N_u}{A_g}}.b_c.d_c \quad \ldots\ldots \quad (1\text{-}B)$$

Because the following methods [Eqs. (2) to (6)] do not include the influence of the fiber fraction, an additional term is added [Eq.(1-B)]. In Eqs. (2) to (6), the value of f'_{cf} is substituted into the value of f'_c where applicable. The design methods modified with Eq. (1-B) are defined as follows:

Modified Sarsam's method(18)

$$V_{rSARS} = [5.43\left(f'_c.r_c\right)^{1/3}.\left(\frac{d_c}{d_b}\right)^{4/3}.\sqrt{1+0.29\frac{N_u}{A_g}}.b_c.d_c + 0.87A_{st}.f_{yv}] + V_F \quad \ldots\ldots \quad (2)$$

Modified ACI-ASCE COMM.352 method(19)

$$V_{rC352} = 0.85[1.4\times 0.29\sqrt{f'_c\left(1+0.29\frac{N_u}{A_g}\right)}.b'.d_c + \frac{A_{sv}.f_{yv}.d_c}{S_v}] + V_F \quad \ldots\ldots \quad (3)$$

Modified Meinheit's method(16)

$$V_{rMEIN} = V_c + V_s = 0.97[x.\left(f'_c\right)^{2/3}.b_c.d_c] + V_F \quad \ldots\ldots \quad (4)$$

where:

$$x = 1 + 6r_s \le 1.6 \quad \ldots \quad (4\text{-}A)$$

$$r_s = \frac{A_h\left(2b'+2h'\right)}{S_v.b'.h'} \quad \ldots \quad (4\text{-}B)$$

and

$$V_{rMEIN} \le 1.66\sqrt{f'_c}.b_c.d_c \quad \ldots \quad (4\text{-}C)$$

Modified British Standard method(20)

$$V_{rBS} = [0.79\left(\frac{100A_s}{b_c.d_c}\right)^{1/3}.\left(\frac{400}{d_c}\right)^{1/4}.\frac{1}{1.25}b_c.d_c + \frac{0.87A_{sv}.f_{yv}.d_c}{S_v}] + V_F \quad \ldots\ldots \quad (5)$$

Modified ACI code method(21)

$$V_{rACI} = 0.85[\frac{\sqrt{f'_c}}{6}.\left(1+\frac{N_u}{14A_g}\right).b_c.d_c + \frac{A_{sv}.f_{yv}.d_c}{S_v}] + V_F \quad \ldots\ldots \quad (6)$$

Modified Beckingsale's method(22)

$$V_{rBECK} = 0.85[0.25\left(1+\frac{f'_c}{25}\right).\sqrt{\frac{N_u}{A_g}-2.5}.b_c.h_c + A_{st}.f_{yv}] + V_F \quad \ldots\ldots \quad (7)$$

Comparison of design methods:

Table 2 compares the seven design methods for all HSC specimens. Considering a ratio of $V_{TEST}/V_{rDES} \geq 1.0$ as conservative, all design equations except Eq. (4) lead to a safe design. The percent coefficient of variation (COV) corresponding to Eqs. (7, 6, 5, 3, 2 and 1) are: 54.8, 37.6, 35.1, 16.1, 11.0 and 7.8, respectively.

Influence of major parameters

The prediction accuracy of the three conservative design methods with the lowest COV percentage is compared in Figs. 3 through 6. Fig. 3 shows the influence of the fiber factor (***F***) on the safety of prediction (ratio of $\boldsymbol{V_{TEST}} / \boldsymbol{V_{rDES}}$). It can be seen that the predictions of the modified methods of Sarasm [Eq. (2)] and Committee 352 [Eq. (3)] indicates significant drops in their safety margins with increasing ***F*** values. In contrast, the proposed Eq. (1) does not show any significant change in safety with rising ***F*** values. Similarly, Fig.4 indicates that both Eqs. (2) and (3) lead to significant drops in safety factor with rising f'_{cf} values, in contrast with the proposed Eq. (1).

Fig. 5 shows that the three design methods show no significant change in the safety factor with the hoop force value ($A_{st} \cdot f_{yv}$). However, the proposed Eq. (1) shows little scatter in the predictions compared to those predicted by Eqs. (2) and (3). Similarly Fig. 6 shows that predictions obtained using Eqs. (2) and (3) are scattered in contrast to those obtained when using the proposed Eq. (1).

Conclusions

Based on the thirteen HSC joint tests, the following conclusions can be made:

1- HSC joints without fibers exhibited sudden modes of failure, even for specimens with hoops that fractured. Therefore, it is not recommended to construct HSC joints without fibers unless the designer ensures that the failure would be outside the joint by considering all the design variables including overstrength of the adjoining members(23).

2- The addition of fibers in the BCJs helped to keep significantly better integrity of specimens at failure load, in contrast with joints without fibers.

3- The observed large number of smaller size cracks for specimens with steel fibers have led to more ductile behavior as compared to BCJs without fibers.

4- Table 1 shows that there may be an upper limit to the usefulness of $\boldsymbol{V_f}$ for both straight and hooked fibers. Using 0.5% and 1.0% for $\boldsymbol{V_f}$ succeeded in strengthening the joint. In contrast, using 1.5% for $\boldsymbol{V_f}$ led to a drop in strength compared to BCJs with 1.0% for $\boldsymbol{V_f}$.

5- All 13 HSC joints could be safely designed using 6 of the 7 methods. The exception is reference 16, which leads to 12 unsafe strength predictions.

6- The severe loading (reversible cyclic) regime of testing in New Zealand(22) has led to exceedingly conservative design requirements. For example the mean of the shear design values obtained by using Eq. (7) (Table 2) is 3.8 times that of the mean of the shear design values obtained by using Eq. (1).

7- Both BS(20) and ACI(21) design methods, which are essentially based on beam (rather than BCJ) shear tests, give rather high COV values of 35.1% and 37.6% respectively.

8- The proposed method [Eq. (1)] gives the lowest COV among the three BCJ design methods- Eqs. (1-3). These COV values for HSC joints (with or without fibers) were 16.1%, 11.0% and 7.8% for Eqs. (3), (2) and (1) respectively.

9- Based on this work, using steel fibers for HSC joints with an upper limit of 1.0% volume fraction has proved to be successful in improving both the ductility and strength of BCJs. This applies to joints with and without hoops.

10- Current existing design methods, except reference 16, were found to be conservative for HSC joint design, with and without fibers.

Further Research

Further research is indicated in the following:

1- Influence of a large amount of hoop reinforcement in HSC joint.
2- Influence of different beam-to-column relative dimensions.
3- Behavior of ultra high-strength concrete (UHSC) joints- exceeding 100 MPa in compressive strength.
4- Influence of very high column compression load on BCJ behavior.
5- Influence of column tensile load on BCJ behavior.
6- Influence of reversible cyclic loading on fiber reinforced HSC joint behavior.
7- Influence of prestressing on fiber reinforced BCJ behavior.

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Notations

A_g = gross cross-section area of the column at the joint.
A_h = cross-sectional area of one leg of a hoop.
A_s = area of tensile reinforcement
A_{sc} = area of two layers of column longitudinal reinforcement at two opposite faces- i.e. not including intermediate bars.
A_{so} = area of the layer of column longitudinal reinforcement furthest away from the maximum column compression face.
A_{st} = total area of hoops crossing the diagonal plane from corner to corner of the joint between the beam compression and tension reinforcement
A_{sv} = cross-sectional area of one layer of hoops perpendicular to the member longitudinal reinforcement.
b' = external width of hoops.
b_c = width of column section at the joint.
D = fiber diameter.
d_b = distance from extreme beam compression fiber to centroid of tension reinforcement.
d_c = distance from extreme column compression face to centroid of the layer of column steel furthest away from this face.
d_f = fiber bond factor,
= 0.5 for hooked fibers,
= 0.25 for straight fibers.
F = fiber factor- Eq. (1-A).

f'_c = concrete compression strength based on 150 x 300 mm cylinders.
f'_{cf} = fiber reinforced concrete compression strength based on 150 x 300 mm cylinders.
f_{yv} = yield strength of hoops.
h' = external depth of hoops.
h_c = total depth of column.
L = fiber length.
N_u = column axial load
S_v = spacing of hoops.
V_c = shear force resistance of hoops.
V_F = shear force resistance of fibers- Eq. (1-B).
V_f = fiber volume fraction
V_{rACI} = design joint shear resistance by Eq. (6)*.
V_{rBECK} = design joint shear resistance by Eq. (7)*.
V_{rBS} = design joint shear resistance by Eq. (5)*.
V_{rC352} = design joint shear resistance by Eq. (3)*.
v_{rDES} = design joint shear resistance*
V_{rMEIN} = design joint shear resistance by Eq. (4)*.
V_{rPROP} = design joint shear resistance by Eq. (1)*.
V_{rSARS} = design joint shear resistance by Eq. (2)*.
V_s = shear force resistance of hoops.
V_{TEST} = BCJ failure load capacity.
β = constant factor,
= 1.0 with one layer of hoops in the middle of the joint,
= 1.5 with more than one layer of joint hoops.
ρ_c = $A_{so}/(b_c . d_c)$.
ρ_d = $A_{sc}/(b_c . h_c)$.

* All V_r values include the appropriate material reduction factors.

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Table(1) Test details and results

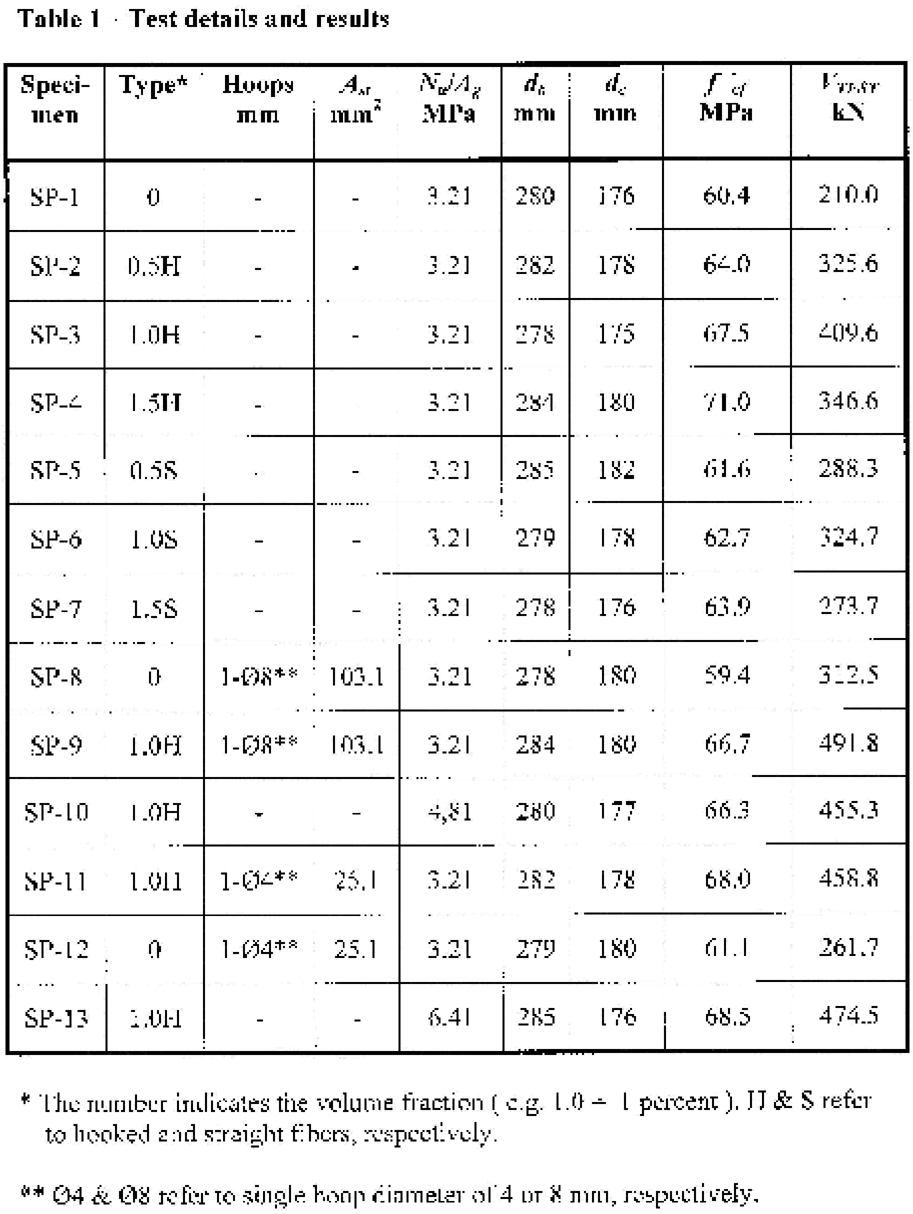


Table 1 · Test details and results

Speci-men	Type*	Hoops mm	A_{st} mm^2	N_u/A_g MPa	d_b mm	d_c mm	f'_{cf} MPa	V_{TEST} kN
SP-1	0	-	-	3.21	280	176	60.4	210.0
SP-2	0.5H	-	-	3.21	282	178	64.0	325.6
SP-3	1.0H	-	-	3.21	278	175	67.5	409.6
SP-4	1.5H	-		3.21	284	180	71.0	346.6
SP-5	0.5S	-	-	3.21	285	182	61.6	288.3
SP-6	1.0S	-	-	3.21	279	178	62.7	324.7
SP-7	1.5S	-	-	3.21	278	176	63.9	273.7
SP-8	0	1-Ø8**	103.1	3.21	278	180	59.4	312.5
SP-9	1.0H	1-Ø8**	103.1	3.21	284	180	66.7	491.8
SP-10	1.0H	-	-	4.81	280	177	66.3	455.3
SP-11	1.0H	1-Ø4**	25.1	3.21	282	178	68.0	458.8
SP-12	0	1-Ø4**	25.1	3.21	279	180	61.1	261.7
SP-13	1.0H	-	-	6.41	285	176	68.5	474.5

* The number indicates the volume fraction (e.g. 1.0 = 1 percent). H & S refer to hooked and straight fibers, respectively.

** Ø4 & Ø8 refer to single hoop diameter of 4 or 8 mm, respectively.

Table (2) Comparison between v_{TEST} and v_{rDES}

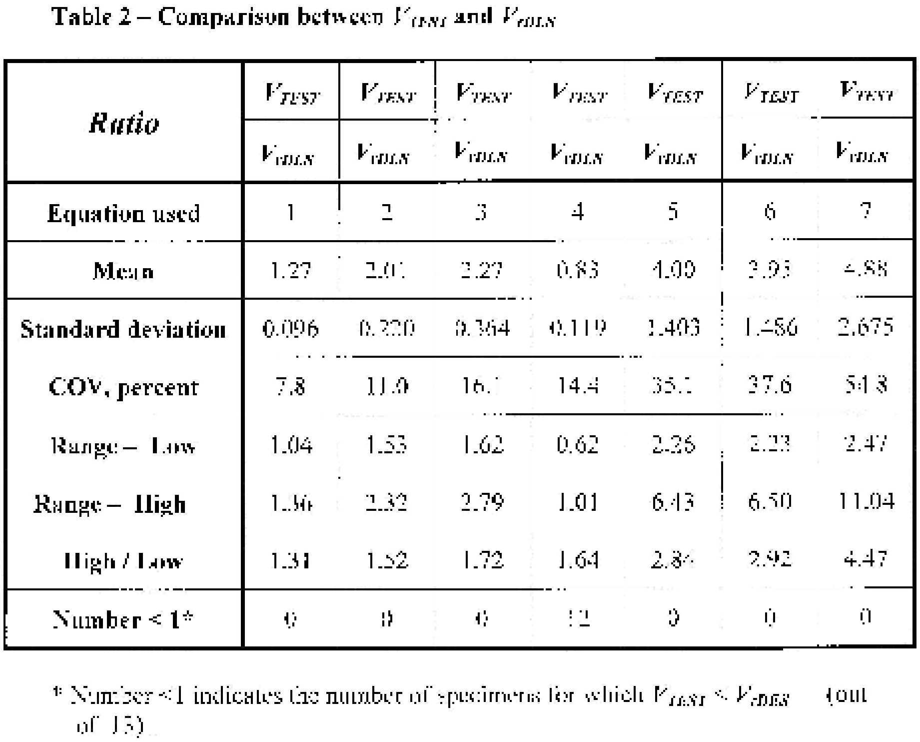
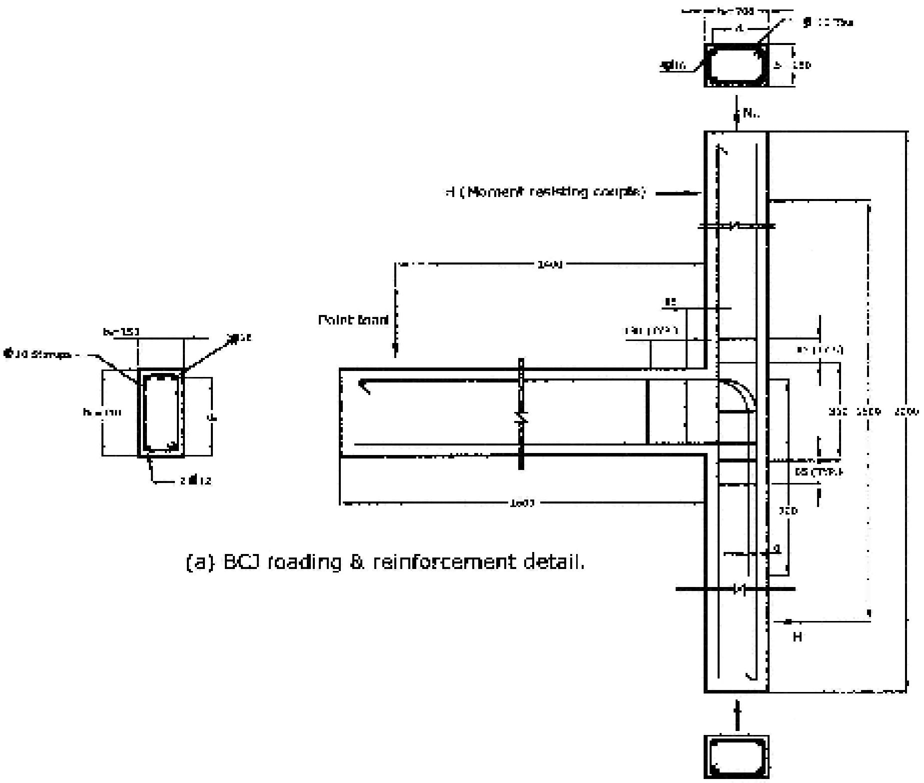


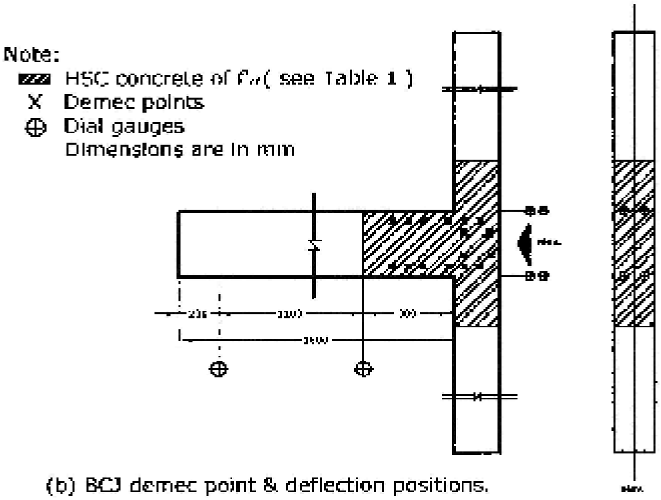
Table 2 – Comparison between V_{TEST} and V_{rDES}

Ratio	$\frac{V_{TEST}}{V_{rDES}}$	$\frac{V_{TEST}}{V_{rDES}}$	$\frac{V_{TEST}}{V_{rDES}}$	$\frac{V_{TEST}}{V_{rDES}}$	$\frac{V_{TEST}}{V_{rDES}}$	$\frac{V_{TEST}}{V_{rDES}}$	$\frac{V_{TEST}}{V_{rDES}}$
Equation used	1	2	3	4	5	6	7
Mean	1.27	2.01	2.27	0.83	4.00	3.93	4.88
Standard deviation	0.096	0.220	0.364	0.119	1.403	1.486	2.675
COV, percent	7.8	11.0	16.1	14.4	35.1	37.6	54.8
Range – Low	1.04	1.53	1.62	0.62	2.26	2.23	2.47
Range – High	1.36	2.32	2.79	1.01	6.43	6.50	11.04
High / Low	1.31	1.52	1.72	1.64	2.84	2.92	4.47
Number < 1*	0	0	0	12	0	0	0

* Number <1 indicates the number of specimens for which $V_{TEST} < V_{rDES}$ (out of 15)



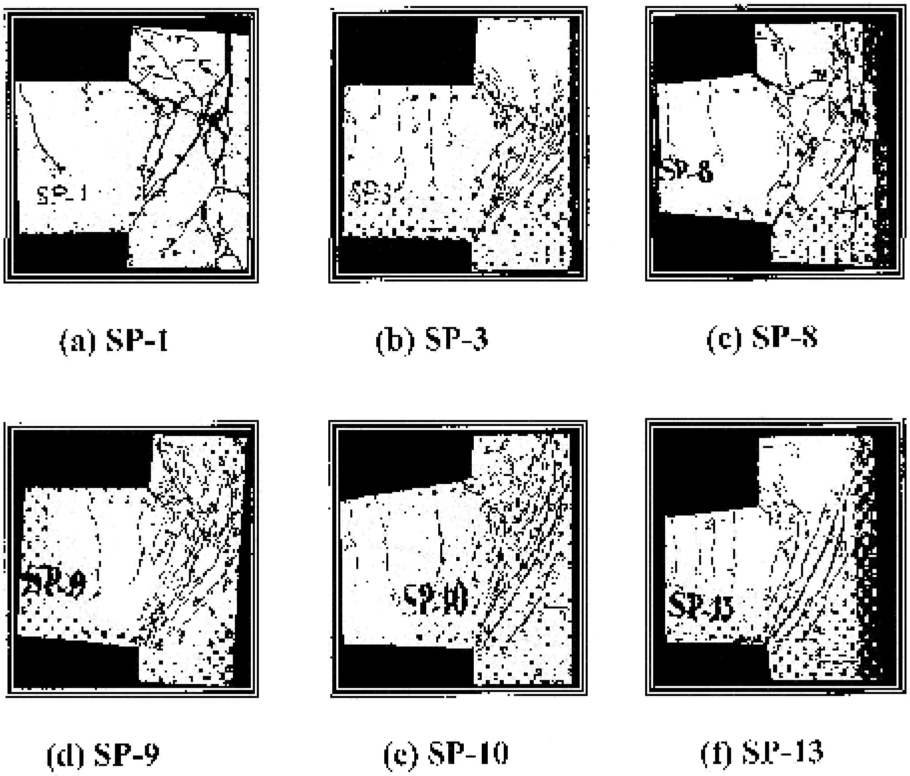
(a) BCJ loading & reinforcement detail.



(b) BCJ demec point & deflection positions.

Fig. 1- Specimen details

Figure (1) Specimen details



(a) SP-1 (b) SP-3 (c) SP-8

(d) SP-9 (e) SP-10 (f) SP-13

Figure (2) Specimens after failure

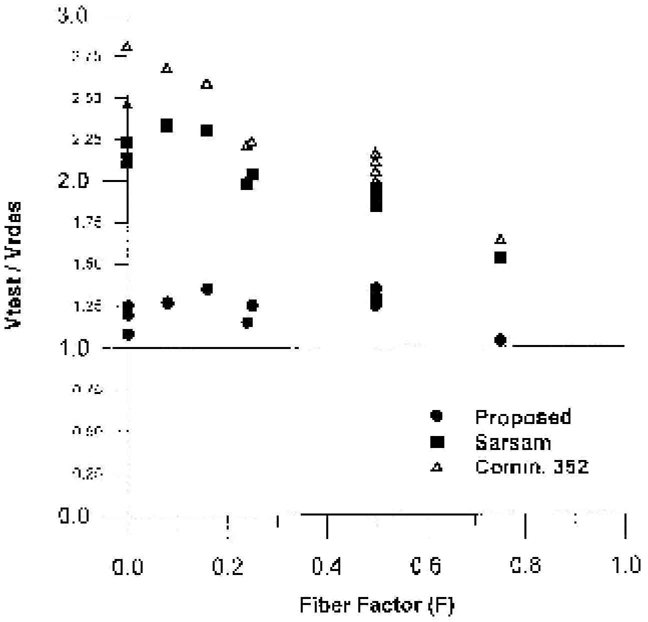


Fig. 3 - Effect of fiber factor

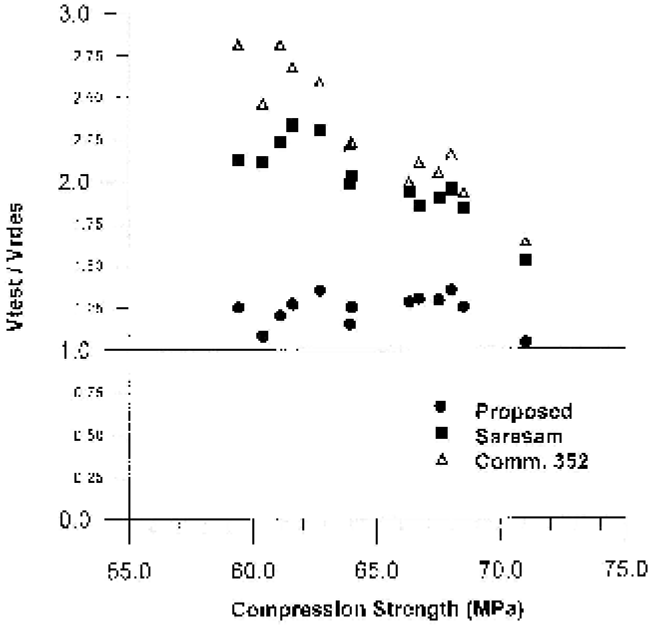


Fig.4 - Effect of compression strength

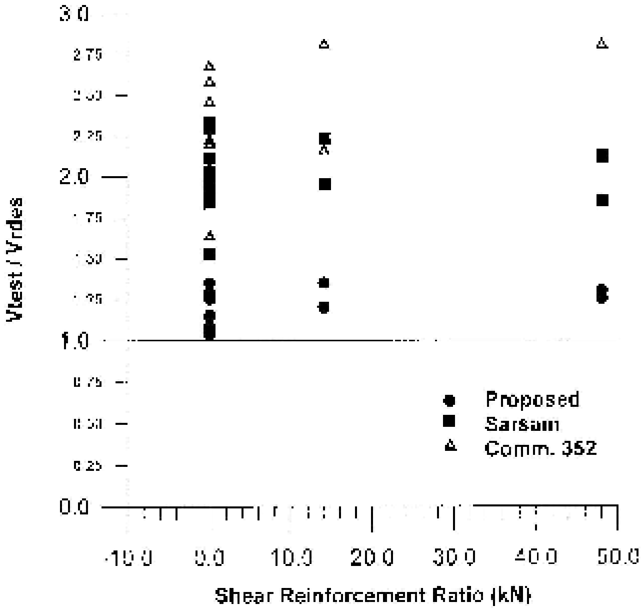


Fig. 5 - Effect of shear reinforcement force (kN)

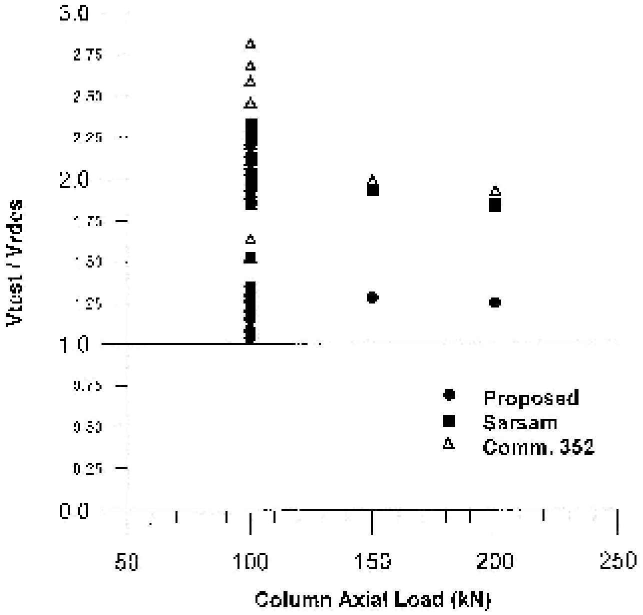


Fig. 6 - Effect of column axial load (kN)