Evaluation and enhancing the punching shear resistance of flat slabs using HSC

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The use of high-strength concrete, with strength exceeding 40 MPa, in reinforced concrete slabs, is becoming popular in India and other countries. Current design provisions of major codes throughout the world are based on empirical relationships developed from tests on low-strength concrete. In this paper, the existing recommendations in design codes for punching shear failure of slabs are reviewed. Though the Indian code formulae predict the punching shear resistance of high strength concrete slabs as compared to the experimental results, they do not consider the reinforcement ratio and size effects. Hence, a formula similar to that of CEB-FIP code formula is suggested. Out of the several methods to enhance the punching shear capacity, the stud shear reinforcement is found to increase the load carrying capacity, punching shear strength and ductility of flat slabs. Recent provisions in the American code allow 100 percent enhancement of shear capacity if shear stud reinforcements are used.

Keywords: *BIS provisions, steel shear reinforcement, punching shear, flat slabs, high-strength concrete, stud reinforcement*

A number of structures including bridges are being built with high-strength concrete (HSC)/high performance concretes (HPC) with strengths exceeding 60 MPa, due to the number of advantages offered by them. HSC members exhibit, in some instances, different failure mechanisms and simply extrapolating models and equations meant for normal strength to HSC may lead to unsafe designs[1].

The use of HSC improves the punching shear resistance allowing higher forces to be transferred through the slab-column connection. Inspite of its wide use, only a few research projects have been conducted on the punching shear resistance of HSC slabs. The empirical expressions given in most of the design codes are based on the experimental results from slabs with concrete strengths up to 40MPa.

Hence in this paper, the evaluation of punching shear resistance of flat slabs with respect to some of the major codes of practices are compared with some of the published experimental data. Methods adopted to enhance the punching shear strength of flat slabs are also discussed.

The concrete flat slab system is a slab and column structure without drop panels and column capitals at the slab and column connection. The flat plate structure is advantageous over other slab systems because of the significant savings in construction cost (due to the elimination of beams and adoption of simple form work) and the resulting aesthetic appearance, especially from the slab's soffit. Moreover, the elimination of beams reduces the overall height of individual floors in a multi-storey building – creating additional floor space for a given building height. Due to the above advantages, such flat slab systems are widely used for multi-storey structures such as office buildings, car parks, etc, in several countries.

Flat plate slabs exhibit higher stress at the column connection and are most likely to fail due to punching shear rather than flexural failure, especially when a high reinforcement ratio is used.

The catastrophic nature of the punching shear problem around the column-slab junction poses a critical problem to the engineers concerned. It has to be noted that the punching

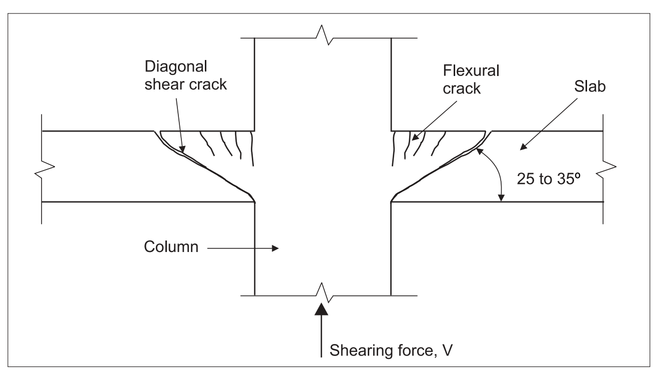

Fig 1 Flexural and shear cracks in the flat slab near the vicinity of column

Fig 2 A typical punching shear failure of a bridge deck[4]

shear failure will occur at a load well below the flexural capacity of the slab, due to the concentration of shear forces and the unbalanced bending and twisting moments. Such a concentration of shear force and moments leads to unsymmetrical stress distribution around the column-slab connections. The local and brittle nature of the punching shear failure is in the form of crushing of concrete in the column periphery before the steel reinforcement reaches the yield strain. Thus, the column will be seen punching through the slab along a truncated cone caused by diagonal cracking around the column, *Fig* 1. A typical punching shear failure of a bridge deck during testing is shown in *Fig* 2. The observed angle of failure surface was found to vary between 26^{o} and 36^{o} for normal strength concrete and 32^{o} and 38^{o} for HSC[2].

Errors in predicting the punching shear have shown to lead to catastrophic failure. One such failure is the collapse of the six-year old, five-storey Sampoong Department store (originally designed as an office block and later converted to department store with reckless structural modifications) in Seoul, Korea in 1995. This collapse under service conditions killed 498 people[3].

In view of the complexities of the three-dimensional behaviour of the column-slab connections and the uncertainty of shear transfer mechanism, this problem has been studied by a number of researchers all over the world[4–9]. However, it is interesting to note that not much work has been done in India. Moreover, till now, most of the flat slab constructions built in India have drop panels or column capitals, probably to avoid this problem.

Provisions in codes of practice

Codes of practice of several countries present formulae, where the design punching load is a product of design nominal shear strength and the area of a chosen critical failure surface. Depending on the code of a country, the critical section for checking punching shear in slabs is taken at 0.5 to 2 times the effective depth from the edge of the load or the reaction. Influences of reinforcement, slab depth and other parameters are considered by the application of different modification factors. The methods do not reflect the physical reality of the punching phenomenon, but can, when properly calibrated, lead to reasonable predictions[2,10].

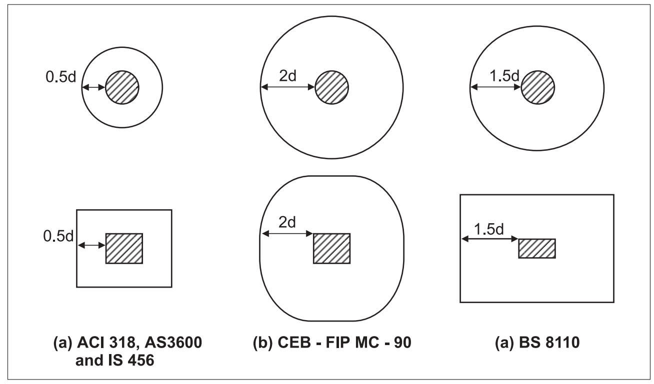

Fig 3 Critical perimeters specified in different codes

Generally the punching shear strength values specified in different codes vary with concrete compressive strength f_c or f_{ck} and are usually expressed in terms of f^{n}_{ck}. In the Indian code IS 456, the punching shear strength is expressed as proportional to $\sqrt{f_{ck}}$. Though the Indian code includes up to M80 grade concrete in *Table* 1, most of the equations are applicable to normal strength concretes up to a grade of M40 only[1, 11]. The square-root formula in the Indian code is adopted from the ACI 318 code[12]. The formulae available in different code of practices are discussed briefly in the following section.

ACI code provisions[12]

ACI 318 code provisions (clause 11.12.2.1) for punching shear are derived from Moe's work on low strength concrete[13]. The ultimate shear strength for slabs without pre-stress is given by

$$V_{uo} = ud\,(v_n) \qquad \text{...(1)}$$

where,

u = length of the critical perimeter, taken at a distance of $d/2$ from the column, mm (*See Fig* 3)

d = effective depth of slab, mm

v_n = punching shear strength, MPa, shall be the smallest of:

Table 1: Variables considered in References 2 and 19

	Type	Diameter/ width, mm	f_c, MPa	Column diameter/ width, mm	Slab depth/effective depth, mm	Slab reinforcement, percent
Marzouk and Hussin[2]						
HS2	Square	1500	70.2	150	120/95	0.842
HS7	Square	1500	73.8	150	120/95	1.193
HS3	Square	1500	69.1	150	120/95	1.473
HS4	Square	1500	65.8	150	120/90	2.370
HS5	Square	1500	68.1	150	150/95	0.640
HS12	Square	1500	75	150	90/70	1.524
HS13	Square	1500	68	150	90/70	2.000
HS14	Square	1500	72	220	120/95	1.473
HS15	Square	1500	71	300	120/95	1.473
Osman, Marzouk and Helmy[19]						
HSLW 0.5 P	Square	1900	76.10	250	120	0.5
HSLW 1.0 P	Square	1900	73.40	250	115	1.0
HSLW 1.5 P	Square	1900	75.50	250	115	1.5
HSLW 2.0 P	Square	1900	74.0	250	115	2.0

$$(i)\ v_n = \left(1+\frac{2}{\beta_c}\right)\frac{\sqrt{f_c'}}{6} \qquad ...2(a)$$

$$(ii)\ v_n = \left(\frac{\alpha_s d}{u}+2\right)\frac{\sqrt{f_c'}}{12} \qquad ...2(b)$$

$$(iii)\ v_n = \frac{\sqrt{f_c'}}{3} \qquad ...2(c)$$

where,

α_s = 40 for interior columns, 30 for edge columns and 20 for corner columns

β_c = ratio of longest column dimension to shorter column/capital dimension.

In the comparison presented in this paper, the measured strength at the day of the test is substituted for f'_c or f_{ck}.

The Australian code AS 3600 (clause 9.2.3) provisions are similar to Equations (1) and (2)[14].

Indian code provisions[11]

The Indian code provisions are also based on the American code. As per the Indian code, the ultimate shear strength for slabs without prestress is given by (clause 31.6.3.1 of the code)

$$V_{uo} = ud\tau_c \qquad ...(3)$$

where,

$$\tau_c = k_s\,(0.25\sqrt{f_{ck}}\,) \qquad ...(4)$$

$$k_s = 0.5 + \beta c \leq 1.0 \qquad ...4(a)$$

The other terms have been defined already.

British code provisions[15]

The British code provisions are based on the work by Regan[16]. As per the British code BS 8110, the ultimate shear strength of slabs without pre stress is given by

$$V_{uo} = ud\tau_c \qquad ...(5)$$

where,

$$\tau_c = \frac{0.79}{\gamma_m}\left(\frac{100A_s}{bd}\right)^{\frac{1}{3}}\left(\frac{400}{d}\right)^{\frac{1}{4}} \qquad ...(6)$$

γ_m = partial safety factor for concrete under shear taken as 1.5

A_s = longitudinal tension reinforcement

b = breadth of section

d = effective depth of section.

If the concrete grade is other than M25 (up to a maximum of M40), the shear stress given by equation (6) is multiplied by the factor $(f_{ck}/25)^{1/3}$. It is to be noted that in the British code, the critical section for shear is considered at 1.5 d from the face of the column, *Fig* 3.

CEB-FIP MC-90 model code[17]

The CEB-FIP model code MC - 90 provisions are similar to the British code provisions and the punching shear resistance, F_{sd}, is expressed as proportional to $(f_{ck})^{1/3}$, where f_{ck} is the characteristic compressive strength of concrete. Unlike the codes stated previously, the highest concrete grade considered in MC 90 is M80, which corresponds to f_{ck} equal to 80MPa. The punching shear resistance is given by

$$F_{sd} = 0.12\xi\,(100\rho f_{ck})^{1/3}\,u_1 d \qquad ...7(a)$$

where,

The size – effect coefficient, ξ

$$\xi = 1+\sqrt{\frac{200}{d}} \qquad ...7(b)$$

u_1 = length of the critical perimeter at 2d from the column, *Fig* 3

$$\rho = \sqrt{\rho_x \rho_y} \qquad ...7(c)$$

In the ultimate limit state the partial safety factor is 1.5. For the calculation of punching load capacity, Equation (7) is multiplied by 1.5, which gives Equation (8)

$$F_{sd} = 0.18\xi\,(100\,\rho f_{ck})^{1/3}\,u_1 d \qquad ...(8)$$

In the comparison of this study, measured concrete strength is taken as f_{ck}.

Euro code 2 provisions[18]

The Eurocode provisions are similar to the British code provisions. As per Eurocode, the punching shear strength of the slab is given by[18]

$$V_{Rd,c} = \frac{0.18}{\gamma_c k}\left(100\rho_1 f_{ck}\right)^{\frac{1}{3}} + 0.10\sigma_{cp} \geq \left(V_{\min} + 0.10\sigma_{cp}\right) \qquad ...9(a)$$

where,

$$k = 1+\sqrt{\frac{200}{d}} \leq 2.0,\ d \text{ in mm} \qquad ...9(b)$$

$$\rho_1 = \sqrt{\rho_{ly}.\rho_{lz}} \leq 0.02 \qquad ...9(c)$$

ρ_{ly}. ρ_{lz} relate to the bonded tension steel in x and y directions respectively. The values ρ_{ly} and ρ_{lz} should be calculated as mean values taking into account a slab width equal to the column width plus 3d each side.

$$\sigma_{cp} = \frac{\sigma_{cy}+\sigma_{cz}}{2} \qquad ...9(d)$$

γ_c = partial safety factor for concrete

σ_{cy}, σ_{cz} = normal concrete stresses in the critical section in Y and Z directions (MPa, positive if compression), respectively

$$V_{min} = 0.035\,k^{3/2}\,f_{ck}^{1/2} \qquad ...9(e)$$

Comparison of test results with code predictions

A review of the literature revealed that only a few experimental studies are available on punching shear strength of high-strength slabs[2, 19-21].

Table 2: Comparison of experimental and predicted punching shear strengths, P_{code}/P_u

	Experimental P_u, kN	IS 456	BS 8110	CEB-FIP
Marzouk and Hussein[2]				
HS2	249	1.17	1.08	1.16
HS7	356	0.84	0.86	0.93
HS3	356	0.81	0.90	0.97
HS4	418	0.63	0.82	0.88
HS5	365	1.16	0.98	0.71
HS12	258	0.78	0.85	0.90
HS13	267	0.71	0.87	0.95
HS14	498	0.77	0.76	0.81
HS15	560	0.84	0.78	0.83
Osman, Marzouk and Helmy[19]				
HSLW 0.5 P	303.70	1.58	0.99	1.33
HSLW 1.0 P	473.50	0.96	0.76	1.05
HSLW 1.5 P	538.54	0.85	0.74	1.05
HSLW 2.0 P	613.40	0.75	0.65	1.02

In these studies, tests were conducted on square or circular slabs supported by column stubs or loading plates. A brief description of the research studies is given below. A considerable variety of concrete strengths, slab reinforcement ratios and slab depths were represented in these studies.

Marzouk and Hussein tested 17 square specimens to investigate the punching shear behaviour of HSC slabs[2]. The structural behaviour with regard to the deformation and strength characteristic of HSC slabs of various thicknesses and different reinforcement ratios (0.49 – 2.33 percent) were studied.

Osman, Marzouk and Helmy tested four slabs to study the behaviour of high-strength light weight concrete slabs under punching loads[19]. These slabs were having concrete of compressive strength higher than 70 MPa with steel ratios ranging from 0.5 to 2.0 percent. They found that the specimen with 0.5 percent reinforcement failed under flexural mode whereas the other specimens failed under punching shear. They also found that for high strength light weight concrete (HSLW) the angle of failure surface was between 25^o and 29^o.

Ramdane tested 18 circular slabs of 125 mm thickness and 1700 mm in diameter[20]. They were divided into three groups in terms of main steel ratio with different concrete cylinder strengths varying from 32 to 102 MPa. The slabs were equally reinforced in orthogonal directions and were without shear reinforcement.

Hallgren and Kinnunen tested 10 circular HSC slabs, supported on circular concrete column stubs[21]. The total diameter of the slabs was 2540 mm and the diameter of the circle along which the load was uniformly distributed was 2400 mm. The slabs had a nominal thickness of 240 mm with an effective depth of 200 mm. The compressive strengths of HSC specimens were between 85 and 108 MPa. All slabs were provided with two-way flexural reinforcement consisting of deformed bars with a mean flexural reinforcement ratio of 0.003 to 0.012. Three slabs had shear reinforcement.

Table 1 shows the test variables of Reference 2 and 19. *Table* 2 compares the experimental ultimate loads, P_{test}, of the slabs to the values predicted by IS 456, BS 8110 and CEB-FIP MC-90. In these expressions, the limits with respect to the concrete strength have been ignored. It should also be noted that the partial safety factors in the codal equations were omitted for verification purpose. The capacity reduction factor is assumed to be equal to 1. Since AS 3600, ACI 318 and IS 456 formulae are similar, the IS 456 values only are shown in *Table* 2. Similarly the Eurocode values are similar to that of CEB-FIP code.

From *Table* 2, it may be observed that IS 456 (as well as ACI 318 and AS 3600) code formulae are conservative in predicting the punching load whereas the CEB-FIP formula and BS 8100 formula are less conservative (It has to be noted that the tests of Reference 19 are on HSLW concrete. The ACI code requires that for semi-light weight (sand-light weight) concrete, the shear stresses obtained by Equation (2) are to be multiplied by a reduction factor equal to 0.85. BS 8110 similarly adopts a reduction factor of 0.80). Comparison of the code formulae with the test results of Reference 19 shows that the ACI code is conservative for steel ratios ≥ 1.0 percent. Due to the reduction factors specified by ACI and BS codes for the light weight concrete, the values are conservative for steel ratios ≥ 1.0 and hence Osman *et al* suggested that the reduction factors in both the codes be changed to 0.95 for HSLW concrete[19]. The CEB-FIP expression is less conservative and more consistent compared with the test results of HSLW concretes.

Similar comparisons were made by Ngo, who compared ACI 318-95, AS 3600 and CEB-FIP formulae with test results of References 2, 19, 20 and 21 and concluded that AS 3600 and ACI 318 formulae are applicable to HSC[4]. He also found that CEB-FIP formula is less conservative and should be applied to concretes with strength up to 80 MPa.

It has to be noted that ACI, Indian and Australian code equations assume that the punching shear stress is proportional to square root of the concrete compressive strength, whereas the European codes (Eurocode 2, BS 8110 and CEB-FIP) assume that it is proportional to the cubic root of concrete compressive strength. The test results also indicate that the punching shear capacity of the connection increases as the steel reinforcement ratio is increased. Hence, it is suggested that the Indian code formula should be changed similar to the CEB-FIP code, which gives consistent results for normal and high strength concrete (normal and light weight) and also considers size effect and contribution of reinforcement ratio.

Enhancing the punching shear strength of flat slabs

The punching shear resistance of reinforced concrete (RC) flat slabs can be enhanced by various means. (Enhancement is necessary especially in flat slabs located in seismic areas. During an earthquake, the unbalanced moment transferred between slabs and column may produce significant shear stresses that will increase the likelihood of brittle fracture).

The enlargement of column cross-section and thickening of the portion of the slab around the column (by use of drop panels or column shear capitals) will enhance the shear

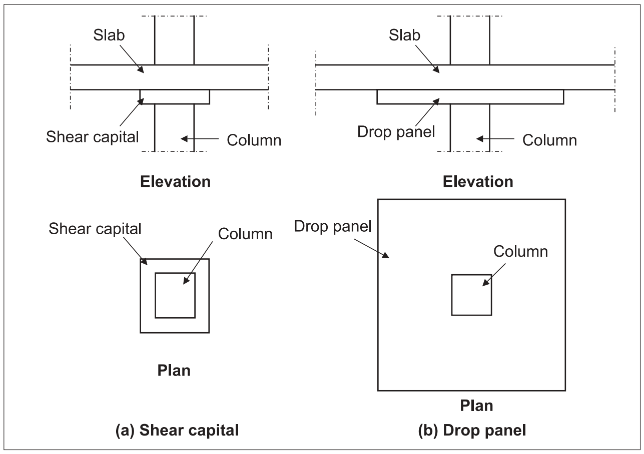

Fig 4 Definition of shear capital and drop panel

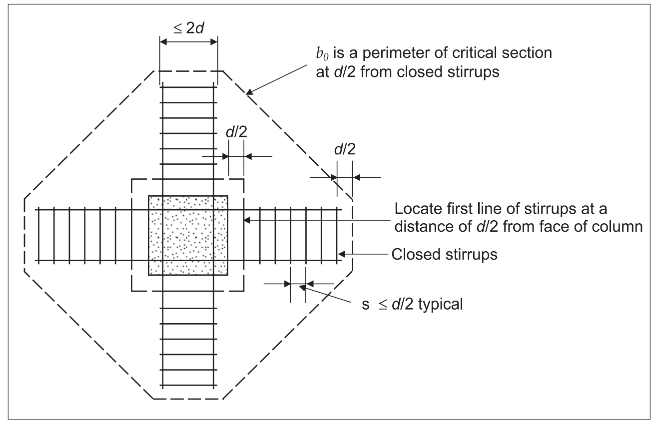

Fig 5 Shear reinforcement in the form of stirrups

resistance, *Fig* 4. From the economic and aesthetic point of view, such solutions are not feasible, since large columns will reduce the floor space and thicker slabs will increase dead load and subsequently the cost of foundations. Also, Megally and Ghali showed that the failure of shear capital is accompanied by sudden separation of the shear capital from the slab, along with brittle failure and do not recommend the use of shear capitals to increase the punching shear resistance especially in earthquake zones[22] (for the shear capital to be effective, their length should be greater than four times slab thickness plus the largest column dimension, and should also be reinforced like drop panels[22]).

Amongst various methods used to enhance punching shear of flat slabs, the shear stud reinforcement is found to provide an economic and aesthetic solution.

It can be seen from *Table* 2 that increasing the amount of flexural reinforcement and the concrete compressive strength will have some beneficial effect. However, increasing the flexural reinforcement is less effective in increasing ductility (which is an important criteria in earthquake zones).

Provision of spandrel beams along the edges of the slab will improve the punching shear capacity of the slab[23]. However, the existence of spandrel beams will complicate the already complex punching shear performance of the column-slab connection.

In view of the above, many researchers have found that the introduction of shear reinforcement is more economical and reduces the chances of brittle failure at slab-column connection [24-30]. The performance of several types of shear reinforcements such as inclined stirrups, structural shear heads (in the form of steel I-or channel sections), bent – up bars, hooked bars and welded-wire fabric have been tested extensively in the last three decades [24-30]. It has been found that the introduction of such shear reinforcement results in ductile failure caused by yielding of flexural reinforcement and improves the punching shear resistance.

Conventional shear reinforcement, in the form of stirrups has been found to be expensive, since it complicates the placement of the flexural reinforcement in thin slabs, *Fig* 5. Moreover with stirrup legs, the anchorage is provided by means of hooks, bends and longitudinal slab flexural reinforcement, lodged at stirrup corners[12]. Before the force in a stirrup leg reaches its yield strength, the concrete within the hooks or bends crushes or splits, causing slip and thus preventing development of the full strength of the stirrups[22]. Since the length of the vertical leg of stirrup in the slab is relatively short, a small slip causes a large drop in force[22]. Due to these reasons, ACI 318-02 commentary (clause 11.12.3) discourages their use in slabs thinner than 250mm.

In order to solve this problem, the research team in the university of Calgary, Canada has developed three types of pre-assembled shear reinforcing units, namely, the I-segment, headed shear stud and welded wire fabric[25]. In addition they have developed a type of shear reinforcement called stud-shear reinforcement[26], *Figs* 6 and 7. Though this stud-shear reinforcement has been in use in the international market for the past few years, it is not yet available in the Indian market.

The stud has an anchor head and a steel strip welded to its top and bottom respectively, *Fig* 7. Thus, the anchorage is achieved mechanically by the forged heads or by the steel strip. The full yield strength of the stud was found to be developed without appreciable slip, due to the anchor head which has an area equal to 9 to 10 times the cross-sectional area of the stud[31]. The steel strip, also called the rail, acts as an anchor and

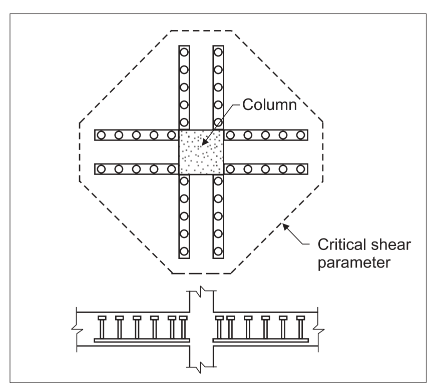

Fig 6 Stud shear reinforcement

spacer, holding the studs in a vertical position at the appropriate spacing in the formwork until the concrete is cast. Several tests have been conducted which confirmed that the use of shear studs increase the load-carrying capacity, punching shear strength and ductility of flat slabs[29-31]. The tests also revealed that such studs are easy to install, reduce congestion and do not interfere with flexural reinforcement.

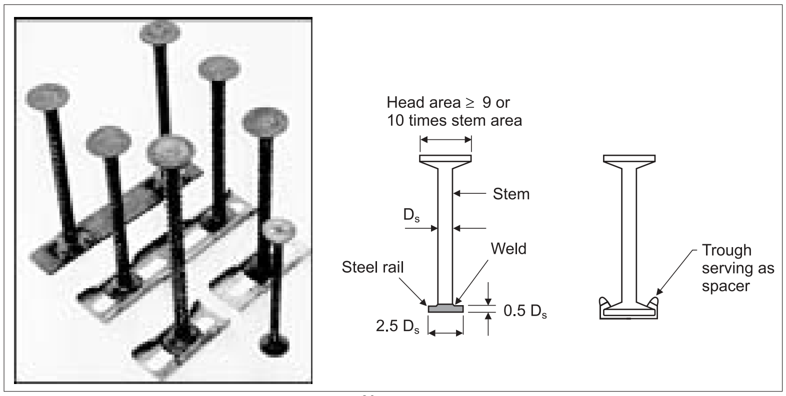

Fig 7 Details of double headed studs[26]

Punching shear stress in the presence of shear reinforcement

As discussed above, when the shear capacity of slab calculated using Equation (1) exceeds the applied shear, the punching shear strength can be augmented by a shear capital, a drop panel or by using shear reinforcement. When shear reinforcement is present, *Fig* 5, the nominal shear stress, v_n , is given by the ACI code as[12,22],

$$v_n = v_c + v_s \leq \frac{\sqrt{f_c'}}{2} \qquad \text{...(10)}$$

where,

v_s = nominal shear stress provided by shear reinforcement

v_c = nominal shear stress of concrete in the presence of shear reinforcement.

The formulae for calculating the capacity of concrete and the capacity of shear reinforcement are:

$$v_s = \frac{A_v f_{yv}}{us} \leq \frac{\sqrt{f_c'}}{3} \qquad \text{...11(a)}$$

$$v_c \leq \frac{\sqrt{f_c'}}{6} \qquad \text{...11(b)}$$

where,

A_v = cross-sectional area of the shear reinforcement on one peripheral line parallel to the column faces, *Fig* 8

s = spacing between peripheral lines

f_{yv} = specified yield strength of shear reinforcement.

Since Indian code provision (Equations 3 and 4) are similar to those of ACI code provisions, the above equations (Equations 10 and 11) can be directly adopted in the Indian code.

For most slab-columns without shear reinforcement, Equation 2*(c)* will govern the capacity of the concrete. Equations 2*(c)* and 10 indicate that the maximum enhancement of punching strength with shear reinforcement does not exceed 50 percent. However, ACI 421.1R-99 allows v_n to reach $\frac{2}{3}\sqrt{f_c'}$ if stud shear reinforcement is used, representing 100 percent increase[31]. It also considers $v_c = 0.25\sqrt{f_c'}$ instead of $\frac{1}{6}\sqrt{f_c'}$. Generally, when shear reinforcement is provided, the critical section for punching shear gets shifted further from the column. Hence, the Indian code requires that the shear strength should be investigated at successive sections (at intervals of 0.75*d* as per the Explanatory hand book) away from the column till the shear stress does not exceed $\frac{\sqrt{f_{ck}}}{8}$. The Indian code suggests that the shear stress carried by the concrete shall be assumed to be $0.5t_c$ (which will be $\frac{1}{8}\sqrt{f_c'}$) and reinforcement shall carry the remaining shear. This is conservative compared to the ACI code provision. Indian code also recommends that the spacing of stirrups should not exceed 0.75*d* and must be continued to a distance *d* beyond the section at which the shear stress is within allowable limits. References 32 and 33 provide more details about methods of design and worked out design examples.

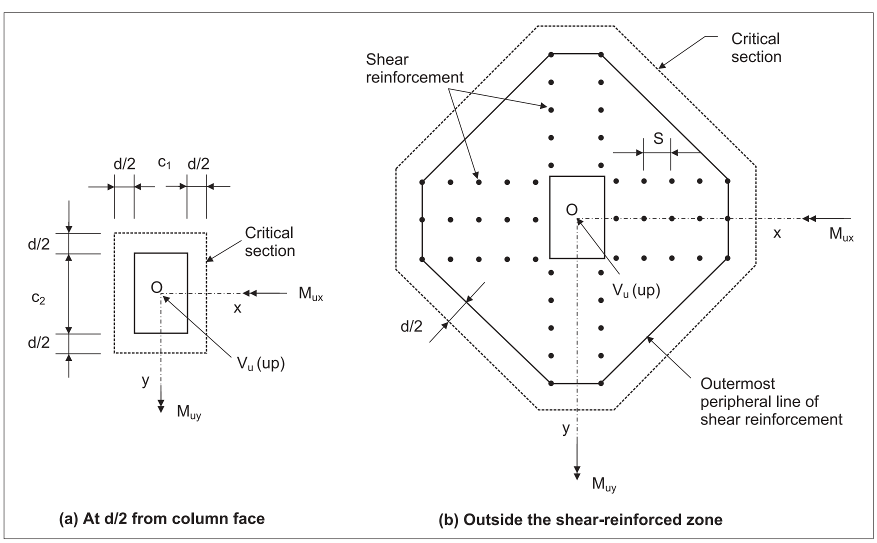

Fig 8 Critical sections for punching shear of an interior slab-column connection

Summary and conclusions

RC flat slab systems are popular in several countries of the world, due to the advantages offered by them. The use of HSC has necessitated the re-evaluation of the formulae used in code of practices, which are based on the tests on normal strength concrete. A comparison of the provisions of various codes of practices with the available test data shows that Indian code (ACI and Australian codes have similar provisions) provisions are applicable to HSC also. However, these provisions do not consider reinforcement ratio and size effects. The European codal provisions which include these parameters also and based on cube root of compressive strength of concrete are found to predict the punching shear strength of flat slabs consistently for high strength normal weight and high strength light weight concretes. Hence, the provisions of CEB-FIP model code equations are proposed to be adopted by the Indian code.

Out of the various methods to enhance the punching shear strength of flat slabs, the shear stud reinforcement (SSR) is found to provide economic and aesthetic solution. They not only enhance the shear capacity but also result in flexural failure of the slab and thus increasing the ductility of flat slab, which is very important in earthquake prone zones. SSR are also easy to install, reduce congestion and do not interfere with flexural reinforcement. Hence, they are suggested for use in flat slabs. American code provides design equations for flat slabs with SSR. Since the Indian code provisions are based on American code provisions, Equations (10) and (11) can be adopted in the Indian code also. Using these equations, the punching shear strength of flat slabs is enhanced by 100 percent.

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