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Design of confinement reinforcement for RC columns

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Transverse reinforcements in columns in the form of hoops, cross-ties, or spirals play an important role in safeguarding the columns, especially when they are subjected to strong earthquakes or accidental lateral loads. They are required in any column—whether they are parts of a moment resistant frame or the gravity system in order for them to deform laterally and provide the required ductility. The current equations for confinement reinforcement in IS 13920 code do not provide consistent level of safety against deformation and damage associated with flexural yielding during earthquakes. Hence an equation for the design of confinement reinforcement for ductile earthquake resistant rectangular and circular columns is suggested for inclusion in the next revision of the code. These equations take into account the various parameters that affect the performance of confining reinforcement, such as effective confining pressure or ratio of concrete strength to tie strength, axial load level, unconfined cover concrete thickness, longitudinal reinforcement and spacing, and curvature ductility factor. Some detailing of these reinforcements is also discussed.

Reinforced concrete columns are the main load bearing elements of any structure. They support the beams and slabs and transfer the loads to the foundations. Hence they have to be designed and detailed adequately to resist both gravity and lateral loads. In India columns are more abused than other structural elements; minimum size

as per codes not provided, rebars are kinked for better alignment (see Figure 1a), they are made porous due to the difficulty of concreting and vibrating in narrow, tall formwork, they are not cured properly, due to the difficulty of curing vertical elements (see Figure 1b), only minimum transverse reinforcement are provided and only 90° hooks are provided (See Figure 1c). However, we do not witness many failures because the working loads are only about 67% of the failure loads and also due to the partial safety factors of materials. However, during earthquakes or accidental lateral loading, plastic hinges will form in columns and beams. With inadequate design, detailing or construction, the columns are bound to fail, as we have witnessed in several earthquakes (e.g., like the ones in Bhuj, and Haiti). In order to prevent plastic hinges to form in columns, traditionally codes suggest designers to adopt the concept of 'strong column and weak axis', in which columns are proportioned in such a way that the flexural capacity of column is at least 20% more (only 10% more as per clause 7.2.1 of the draft IS 13920) than the flexural capacity of beams meeting the column. It is important to appreciate that during severe earthquakes some column hinging and some yielding of columns will occur even if the strong column-weak beam philosophy is followed. Hence it is important to design the transverse reinforcement of columns and detail them to provide the required amount of ductility.



Figure 1. Columns not properly designed or executed: (a) Kinking of longitudinal bars, (b) Insufficient curing, (c) Minimal transverse reinforcement

Purpose of transverse reinforcement

Transverse reinforcement are specified in design codes for beams and columns to serve the following four functions: (a) to prevent buckling of longitudinal reinforcing bars, (b) to resist shear forces and to avoid shear failure, (c) to confine the concrete core to provide sufficient deformability (ductility), (d) to clamp together lap splices-after splitting cracks form parallel to the splices, ties or spirals restrain slip between the spliced bars. Note that none of these functions are effective till the concrete cracks or spalls; All are critical for the column to maintain vertical or lateral capacities under earthquake displacements in the post-yield range. The article addresses mainly the confinement requirements.

Need to revise confining reinforcement provisions of IS 13920

In a recent paper Ranjith and Jain outlined the importance of revising the clauses related to confinement reinforcement for columns and shear walls in IS 13920.^{1,2} They suggested that the provisions be revised in line with ACI 318-08.³ However it may not be a good idea to revise it based on ACI 318-08 provisions. Even though ACI 318 code is being revised every three years (the 2011 version of the code is due for publication in a few weeks), the particular clause (clause 21.6.4.4) of ACI code has not been revised recently!

Because the pressure on the sides of the hoops causes the sides of hoops to deflect outward, rectangular hoops are often less efficient than spirals in confining the core

of concrete column (see Fig. 2 and 3). The equation for required area of rectangular hoops, as given in equation 2.4 of ACI code is based on the equation for spirals derived by Richart et al in 1929, as shown below⁴.

Based on the results of extensive experimental program, Richart et al, assumed that the strength gain in core concrete as⁴

$$f_{cc} = f_{cp} + 4.1f_l \quad \text{.....(1)}$$

Where f_{cc} = strength of confined core concrete, f_{cp} = compressive strength of plain concrete in column ($f_{cp} \approx 0.85f_c$), and f_l = passive compressive pressure provided by transverse reinforcement. The design criterion adopted in ACI 318 for column confinement is based on the premise that confined columns should maintain their concentric load carrying capacities even after spalling of concrete cover. Thus, equating the concentric capacity of cover concrete to strength gain in the core, we get

$$0.85f_c'(A_g - A_c) = 4.1f_l(A_c - A_s) \quad \text{.....(2)}$$

Where f_c' is the compressive cylinder strength of concrete, A_g = gross area of column cross-section, A_c = area of concrete core within perimeter transverse reinforcement (commonly taken as centre-to-centre), and A_s = area of longitudinal steel reinforcement.

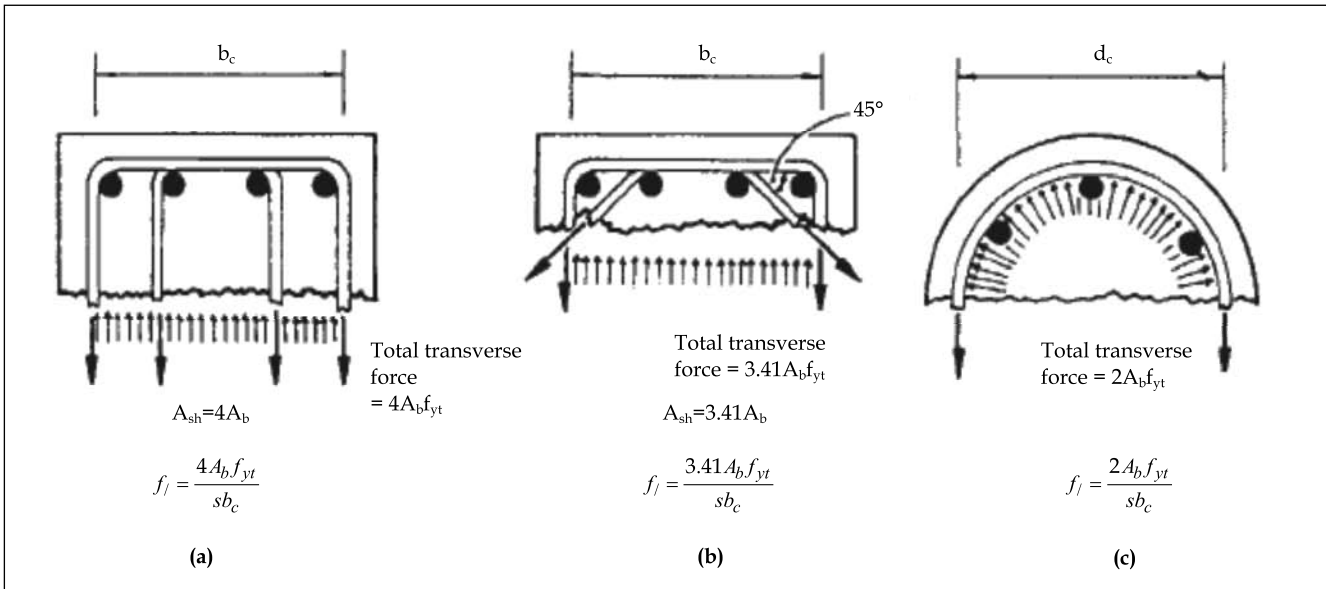


Figure 2. Confining stresses provided by different arrangements of transverse reinforcement¹⁵

The lateral pressure f_l for spirally reinforced circular column at yield is given by

$$f_l = \frac{2A_{sp}f_{yt}}{sb_c} \quad \dots\dots(3)$$

Where A_{sp} = area of spiral reinforcement, f_{yt} = yield strength of transverse reinforcement, s = centre-to-centre spacing of transverse reinforcement along column height, and h = column sectional dimension.

Substituting f_l into equation 2 and dividing both sides by $2.05 f_{yt}A_c$

$$0.415 \frac{f'_c}{f_{yt}} \left(\frac{A_g}{A_c} - 1 \right) = \frac{4A_{sp}}{sb_c} - \frac{4A_{sp}A_s}{sb_cA_c} \quad \dots\dots(4a)$$

Denoting $[4A_{sp}/(sh)]$ as ρ_{st} and rearranging, we get,

$$\rho_{st} = 0.415 \frac{f'_c}{f_{yt}} \left(\frac{A_g}{A_c} - 1 \right) + \frac{4A_{sp}A_s}{sb_cA_c} \quad \dots\dots(4b)$$

The above equation was adopted in ACI code after dropping the last term and changing the coefficient 0.415 to 0.45, as³

$$\rho_{st} = 0.45 \frac{f'_c}{f_{yt}} \left(\frac{A_g}{A_c} - 1 \right) \quad \dots\dots(4c)$$

For large columns, the ratio of cross-sectional area to confined core area (A_g/A_c) may approach unity, and the above equation results in small values ρ_{st} . Hence a lower-bound expression is provided by setting a limit to the (A_g/A_c) ratio, as below³.

$$\rho_{st} = 0.12 \frac{f'_c}{f_{yt}} \quad \dots\dots(4d)$$

The confinement steel requirements for square and rectangular columns were derived as an arbitrary extension of the above formulae, recognising that rectangular/square hoops are not as effective as spirals. It was assumed that the rectangular/square hoops will be 75 percent as effective as circular spirals. Thus the constants in equation 4c and 4d were changed to give hoops with about one-third more cross-sectional area than those of spirals, to give the following formulae.³

$$\rho_{st} = 0.3 \frac{f'_c}{f_{yt}} \left(\frac{A_g}{A_c} - 1 \right) \quad \dots\dots(5a)$$

$$\rho_{st} = 0.09 \frac{f'_c}{f_{yt}} \quad \dots\dots(5b)$$

Thus the strength enhancement in the core ($f_{cc}-f_{cp}$) implied by these formula are $3.8f_l$ and $2.8 f_l$ for circular column with spirals and rectangular or square columns

respectively (as against $4.1 f_t$ as suggested by Richart et al).⁴ Equations 4d and 5b govern for large-diameter columns, and are intended to ensure adequate flexural curvature capacity in yielding regions.^{5,6} These equations are not new and are present in ACI 318 even in the 1999 or may be in still earlier versions of the code.

Parameters that affect the amount of confinement reinforcement

The state of knowledge on concrete confinement has improved substantially since the pioneering work of Richart et al in 1929, and a large volume of experimental data has been generated and a number of improved analytical models have been developed. Various design parameters, that are overlooked by the ACI code have been identified and studied.^{7,8} A good review of the research in this area is provided by Sakai and Sheikh;⁹ and Sharma et al.¹⁰ Due to space limitations, only a few of these important papers, which formed the basis of New Zealand and Canadian codes, are cited here.¹¹⁻¹²

The following parameters are found to affect the required amount of confinement reinforcement.⁵⁻⁹

1. *Effective confining pressure or ratio of concrete strength to tie strength:* The required A_{sh} will be proportional to $s_b f_c' / f_{yt}$. Note that as the yield strength is increased, the quantity of required confining reinforcement will be reduced. Based on the assumption of how much strain will occur in transverse reinforcement, limits are often placed on the value of f_{yt} that can be used in the calculations (see Table 1). As high strength concrete is more brittle than normal strength concrete, it may require more confining steel.
2. *Axial load level:* It has been well established that columns with low compressive axial loads may require less confinement than those with high axial loads. The Canadian and New Zealand codes include the effect of axial load. Elwood et al. suggest that it is enough to include the term $P_u / A_g f_c'$ (which is having a range of 0.1-0.7) in the equation, since the inclusion of the term $A_s f_{yt}$, as done in the Canadian code, does not appreciably change the value of confining reinforcement.⁸ The moment-curvature response of members subjected to axial tensions would be dominated by the behaviour of longitudinal reinforcement; hence columns with axial tension are not critical as they will sustain large ultimate curvatures.
3. *Unconfined cover concrete thickness:* As the load is increased, the unconfined concrete in the cover portion of the column will begin to spall, when the compressive strain in concrete reaches about 0.003 to 0.005, resulting in loss of strength. This loss will be considerable when the area of unconfined concrete cover is a larger proportion of the total concrete. Hence this effect has to be included in the confinement provisions, by specifying the ratio A_g / A_c , where A_g is the gross area and A_c is the area of confined core (the normal range for this

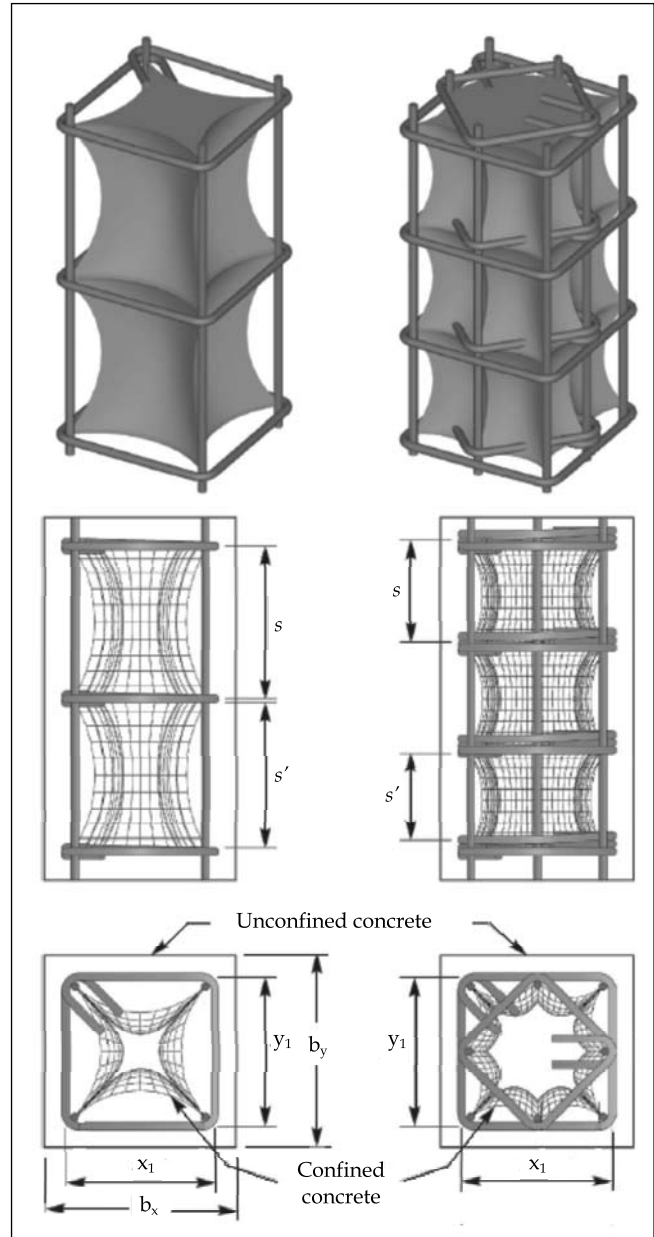


Figure 3. Confinement of concrete in rectangular or square columns⁶

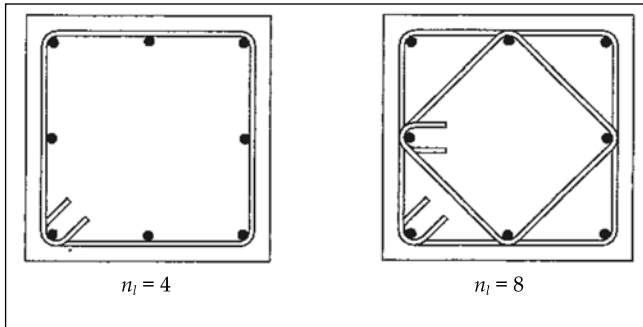


Figure 4. Consideration of the effect of longitudinal rods in confinement

ratio is 0.7-0.81). The fact that A_{sh} will be directly proportional to A_g/A_c has been confirmed using moment-curvature studies.^{5,13} However ACI (as well as IS 13920) equations, as shown earlier, were set up to equate the concentric capacity of cover concrete to strength gain in the core, rather than considering the effect of A_g/A_c on lateral deformation capacity. Hence ACI and IS codes have a factor of $(A_g/A_c - 1)$ instead of A_g/A_c . For larger columns to have sufficient confinement, the ratio A_g/A_c should not exceed 1.3.

4. *Longitudinal reinforcement and spacing:* It has been found from experiments that the amount and transverse support of longitudinal reinforcement will also influence the confinement of concrete core (see also Figure 3). Canadian and New Zealand codes allow for this, though the approach taken and the resultant impact on the requirements are different in these codes.⁸ The Canadian code and the proposed equation, recognizes the fact that when more longitudinal bars are restrained by hoops or cross-ties, effectiveness of confinement is improved, since the confined concrete arches horizontally between restrained longitudinal bars (see Figure 3). In both these equations, this effect is reflected in the factor k_n , which relates to the number of longitudinal bars restrained by corners of hoops or hooks of seismic cross-ties, (n_l), as shown in Figure 4. The k_n factor also encourages good column detailing for confinement as well as providing effective restraint to prevent bar buckling.⁸ Note that when longitudinal reinforcement ratio is high, steel congestion problems will arise, and hence a larger size of column is preferable in such cases. The required confining reinforcement increases when flexural steel content ρ_l decreases (see NZS 3101 equation in Table 1).

5. *Curvature ductility factor:* It is well known that the quantity of confining reinforcement provided in the potential plastic hinge zones of columns has a significant effect on the curvature ductility factor $\mu_\phi = \Phi_u/\Phi_y$. Columns are considered to have adequate ductility, if they are able to sustain a curvature ductility factor μ_ϕ of approximately 20.^{5,13} This order of curvature ductility should enable the plastic hinges at the bases of columns to undergo sufficient plastic rotation to reach a displacement ductility factor of 4 to 6 (see Figure 5). For frames where limited ductility is sufficient, should be able to sustain a curvature ductility factor μ_ϕ of approximately 10.¹⁴

The relationship between the curvature and displacement ductility was derived by Park and Paulay, neglecting $P-\Delta$ effect, rebar slip and shear deformations as given below:¹⁵

$$\mu_\Delta = 1 + 3(\mu_\phi - 1) \frac{L_p}{L} \left(1 - 0.5 \frac{L_p}{L} \right) \quad \dots\dots(6)$$

where μ_Δ = displacement ductility ($=\Delta_u/\Delta_y$), μ_ϕ = curvature ductility ($=\Phi_u/\Phi_y$), L = length of column and L_p = plastic hinge length. The plastic hinge length, L_p , will be typically in the range of 0.5 to 1.5 times the member depth, h .¹⁶

Comparison of different codal equations^{2-3,11-12}

A comparison of various code equation is provided in Table 1. Also included are the equations as suggested by

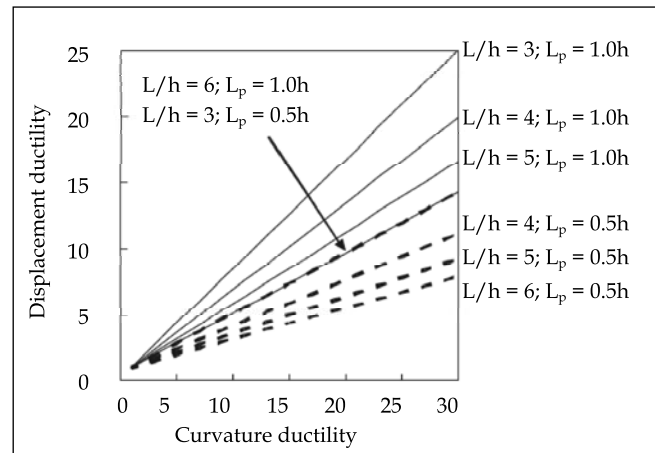


Figure 5. Relationship between curvature and displacement ductility¹⁷

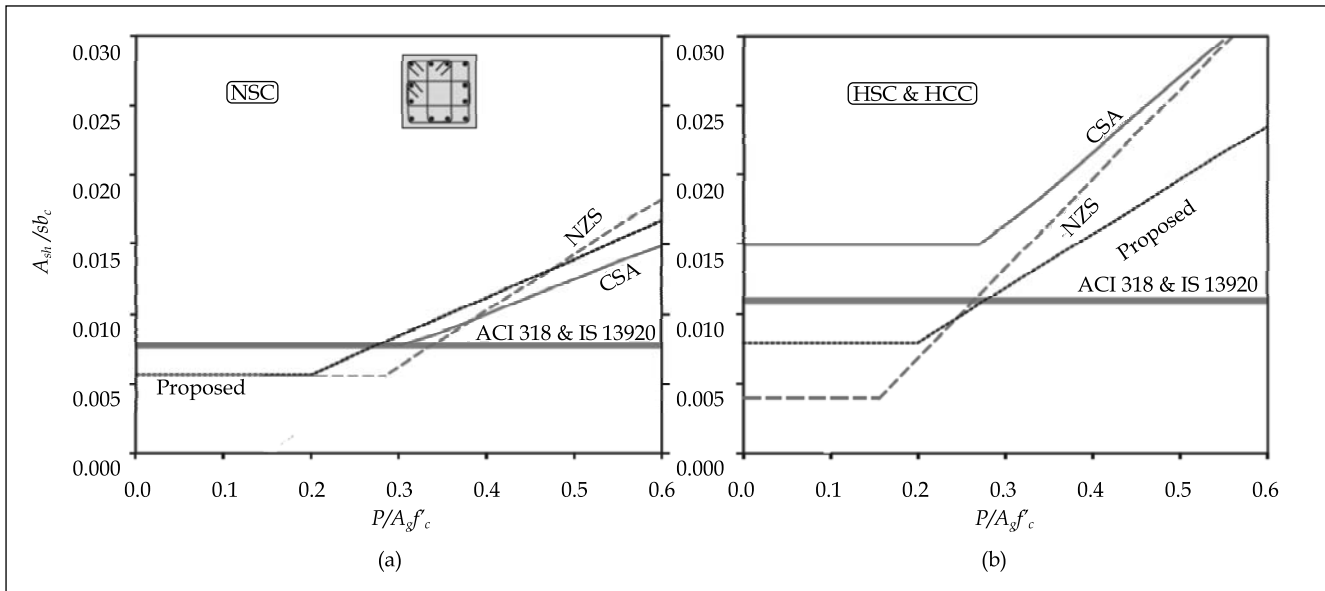


Figure 6. Comparison of confinement provisions (a) $f'_c = 35$ MPa and $f_{yt} = f_y = 415$ MPa; (b) $f'_c = 82.5$ MPa, $f_{yt} = 689$ MPa, and $f_y = 517$ MPa (Adapted from Elwood et al⁸)

Li and Park for high strength concrete columns and by Elwood et al.^{14,8} The equation developed by Elwood et al. is proposed for the Indian code, as it incorporates all the parameters discussed above and found to correlate with experimental results and provides adequate safety and ductility.⁸

A comparison of the four codal equations, along with the proposed equation is provided in Figure 6, for a column of size 600 mm x 600 mm, with a core size of 525 x 525 mm ($A_g/A_c = 1.3$) and reinforced with 12 numbers of 30 mm diameter longitudinal bars.

Note that IS 13920 gives area of one leg only. Hence the value of $A_{sh}sb_c$ is calculated as below for normal strength concrete (NSC):

For the arrangement of hoops shown in Figure 6, $h = 525/3 = 175$ mm

Area of one leg of hoop =

$$0.18 \times 175 \times \frac{35/0.8}{415} \times 91.3 - 1.0) s = 0.9962s \text{ mm}^2$$

There are 4 numbers of legs, hence we get

$$\frac{A_{sh}}{sb_c} = \frac{0.9962 \times 4}{525} = 7.59 \times 10^{-3}$$

Similarly, the above value for high strength concrete (HSC) and high strength steel (HSS) has been calculated and compared with other codal values in Figure 6. Elwood et al. also compared the proposed equation with the available experimental results and found that this equation results in improved performance.⁸

Confinement of circular columns:

Based on the reasoning given earlier, the following confinement equation is proposed for circular columns⁸:

$$\rho_s = 0.44k_p \left(\frac{f_{ck}}{f_{yt}} \right) \left(\frac{A_g}{A_c} \right) \quad \dots\dots(13)$$

where, ρ_s is the volumetric ratio of transverse reinforcement, $k_p = 0.8 P_u/A_g f_{ck} \geq 0.2$. Note that the

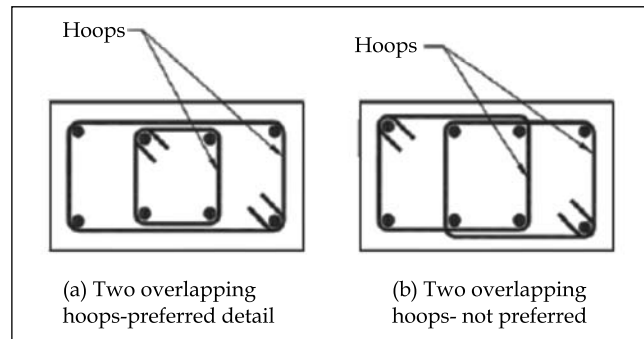


Figure 7. Confinement using hoops¹²

Table 1. Summary of confinement equations for rectangular columns as per different codes

Reference	$A_{sh}/sb_c =$	Deformation parameter	Comments
IS 13920:1993 ²	$0.18 \frac{f_{ck}}{f_{yt}} \left(\frac{A_g}{A_c} - 1.0 \right) * (7)$	None	$f_{yt} \leq 415 \text{ MPa}$ $h < 300 \text{ mm}$
ACI 318-08 ³	$0.3 \frac{f'_c}{f_{yt}} \left(\frac{A_g}{A_c} - 1.0 \right) (8a)$	None	$f_{yt} \leq 689 \text{ MPa}$ $\frac{A_{sh}}{sb_c} \geq 0.09 \frac{f'_c}{f_{yt}} (8a)$
NZS 3101-06 ¹²	$\left[\frac{1.3 - \rho_l m}{3.3} \frac{A_g}{A_c} \frac{f'_c}{f_{yt}} \frac{P}{0.85 f'_c A_g} \right] - 0.006$ where $m = \frac{f_{yt}}{0.85 f'_c} (9a)$	μ_Φ (with $\mu_\Phi = 20$)	$\frac{A_{sh}}{s} \geq \frac{\sum A_b}{96 d_b} \frac{f_y}{f_{yt}} (9b)$ $\rho_l m \leq 0.4;$ $\frac{A_g}{A_c} \leq 1.5$ $f_{yt} \leq 800 \text{ MPa}$ (based on Watson, Zahn, and Park)
Li and Park ¹⁴	$\left[\frac{(\phi_u / \phi_y) - 30 \rho_l m + 22}{\lambda} \frac{A_g}{A_c} \frac{f'_c}{f_{yt}} \frac{P}{0.85 f'_c A_g} \right]$ where $m = \frac{f_{yt}}{0.85 f'_c} (10)$	μ_Φ (with $\mu_\Phi = 20$)	$\rho_l m \leq 0.4;$ $\frac{A_g}{A_c} \leq 1.5$ $f_{yt} \leq 900 \text{ MPa}$
CSA A23.3-04 ¹¹ (Clause 21.4.4.2)	$0.2 k_n k_p \frac{A_g}{A_c} \frac{f'_c}{f_{yt}}$ where $k_n = \frac{n_l}{(n_l - 2)}$ and $k_p = \frac{P}{P_0} (11a)$	μ_Δ (with $\mu_\Delta \geq 4$)	$f_{yt} \leq 500 \text{ MPa}$ $\frac{A_{sh}}{sb_c} \geq 0.09 \frac{f'_c}{f_{yt}} (11b)$ (based on Paultre and Légeron)
Elwood et al. 2009 ⁸ (proposed for IS code)	$0.3 k_n k_p \frac{A_g}{A_c} \frac{f'_c}{f_{yt}}$ where $k_n = \left(0.6 + 0.4 \frac{n}{n_l} \right) \left(\frac{h_x + 12}{20} \right)$ and $k_p = \frac{0.8 P_u}{A_g f_{ck}} \geq 0.2 (12)$	μ_Δ (with $\mu_\Delta \geq 3$)	$f_{yt} \leq 689 \text{ MPa}$ $\frac{A_g}{A_c} \leq 1.3$ $\left(\frac{h_x + 12}{20} \right) \geq 1.0$

*In IS code h is used instead of b_c , where h is the longer dimension of the rectangular confining hoop measured to its outer and gives area of one leg only. ΣAb = Sum of the areas of longitudinal bars; A_c = area of concrete core within perimeter transverse reinforcement, and A_g = gross area of column, A_{sh} = total cross-sectional area of transverse reinforcement (including cross hoops) with spacing s and perpendicular to dimension b_c , b_c is the cross-sectional dimension of column core measured to the outside edges of transverse reinforcement composing area A_c , d_b = diameter of longitudinal bar, f'_c = specified cylinder compressive strength of concrete, f_{ck} = specified cube compressive strength of concrete, f_{yl} = specified yield strength of longitudinal reinforcement, f_{yt} = specified yield strength of transverse reinforcement, h_x = center-to-center horizontal spacing of cross ties or hoop legs, m = mechanical reinforcing ratio ($m = f_{yl} / 0.85 f'_c$); n = total number of longitudinal bars, n_l = number of longitudinal bars laterally supported by corner of hoops or by seismic hooks of crossties that are ≥ 135 degrees; P_0 = nominal axial load strength at zero eccentricity [$P_0 = 0.85 f'_c (A_g - A_c) + A_s f_{yl}$], P_u = factored load on column, s = centre-to-centre spacing of transverse reinforcement along column height, μ_ϕ = maximum considered earthquake curvature ductility ratio, μ_Δ = maximum considered earthquake drift ductility ratio, ρ_l = total area of longitudinal reinforcement divided by A_g

term k_n is not required for circular columns, as spirals provide effective confinement than rectangular hoops.

It should also be noted that very high strength concrete is extremely brittle when not confined adequately and the required confinement may be considerably greater than for NSC columns.¹⁴

Detailing of transverse reinforcement

In addition to the quantity of confinement steel, their arrangement is also important for their effectiveness. The minimum diameter of transverse reinforcement should be 8 mm for longitudinal bars less than 25 mm and 10 mm for longitudinal bars greater than 25 mm. Clear spacing between spirals shall not exceed 75 mm, nor be less than 25 mm. At both ends of the column, hoops shall be provided at spacing s_o over a length l_o measured from the joint face. Spacing s_o shall not exceed six times the diameter of the smallest longitudinal bar enclosed or 1/4 of the smallest cross-sectional dimension of the column, but need not be less than 75 mm nor more than 100mm as per IS 13920. Length l_o shall not be less than the largest of (a) one-sixth of the clear span of the column; (b) maximum cross-sectional dimension of the column; and (c) 450 mm. The first hoop shall be located not more than $s_o/2$ from the joint face. Outside the length l_o , Vertical spacing of ties shall not exceed 16 times smallest diameter of longitudinal bar, the least dimension of the compression member or 300mm, according to IS 456. But during the September 1999 Athens earthquake, it was found that several columns failed by shear at the location of the point of infection near the mid-height of columns.¹⁸ Hence it may be advisable to provide confining reinforcement throughout the column length at least in the ground floor columns.

The ACI permits the use of cross-ties having 135° hook at one end and 90° hook at the other end provided these cross-ties are alternated on the same longitudinal bar. However IS 13920 does not allow such arrangement and insists that both the ends of cross-ties should have 135° only. The arrangement as suggested in the ACI code is easy to implement at site and hence may be adopted in IS 13920 also.¹

The arrangement of hoops (type II) shown in Figure 7b is not preferable according to NZS 3101-2006. This code also states that not all longitudinal bars need to be laterally supported by a bend in a transverse hoop or cross-tie.

Rohit et al. recently reviewed column and wall detailing provisions of IS codes critically by comparing them

with International standards, and suggested possible improvements.¹⁹

Summary and conclusions

Columns have to be properly designed, detailed and constructed such that they perform as desired during strong earthquakes. Properly designed and detailed confining transverse reinforcements prevent buckling of longitudinal bars, avoid shear failure and provide sufficient ductility. The formula provided in IS 13920:1993 code has to be revised as it does not consider all the parameters that affect the behaviour. Hence an equation has been proposed, which considers all the parameters and found to correlate with the existing experimental results as well as provides sufficient deformation ductility. This equation can be applied to NSC and HSC also. A few detailing methodologies for the efficient functioning of confining reinforcement are also presented.

Dedication

This paper is dedicated to the memory of Prof. D.S. Prakash Rao, whose contribution to RC design and detailing was phenomenal.

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