Seismic design of RC column and wall sections : Part II – Proposal for limiting strain in steel

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In a companion paper[1]*, the philosophy of flexural limit state design of reinforced concrete sections as per the current Indian Standard was examined. This paper proposes a limiting strain state for steel in the limit state method of design keeping in mind results of a numerical investigation that considers variations in the properties of column sections, namely geometry, location of longitudinal steel, and percentage of longitudinal steel. Two performance pointers, namely, section ductility and strain energy stored in cross-section, are the focus of investigation.*

Keywords: *Concrete, columns, walls, limiting strain, ductility, longitudinal steel, seismic design*

The philosophy of limit state design of reinforced concrete (RC) structures in the Indian concrete code[2] proposes that the structure should safely withstand all possible loads throughout its design life by satisfying certain specified acceptable limit states of collapse and serviceability. The possibility of a structure attaining one of its limit states is determined using the probable variations in material strengths and loads. The limit state design[2,3] and strength design methods[4] specify appropriate partial safety factors obtained from statistical analysis. Different load factors are specified for the load combinations.

The desirable seismic response of an RC column section is achieved by satisfying the strength and deformation demands during strong earthquake shaking. This is ensured by flexural yielding of longitudinal tension reinforcement and subsequent ductile behaviour of section under actual seismic conditions. This is the desired limit state of collapse in flexure. This study investigates the limiting strain in reinforcing steel that will assure a reasonable section ductility and energy dissipation. As mentioned in the companion paper, the observations and conclusions of these companion papers are valid for ensuring ductile response in RC members particularly in seismic zones III, IV and V.

Limiting strain states

An RC section reaches limit state of collapse in flexure when either the compressive strain in the extreme fibre of concrete or the tensile strain in the extreme layer of steel reaches the specified limiting value. The Indian concrete code[2] recommends 0.0035 as the limiting compressive strain in concrete, while the New Zealand and American codes[3,4] recommend 0.003. Although the American bridge codes[5,6] specify the limiting compressive strain as 0.003, the ATC Standard[7] prescribes 0.004 for estimating the design flexural strength in ductile columns that undergo subsequent increase in strengths after yielding; for columns other than ductile ones, the limiting compressive strain in ATC Standard[7] is also specified as 0.003. While in the New Zealand NZS 3101[3], the yield strain $\varepsilon_y = \frac{f_y}{E_s}$ is specified as the limit state of strain in steel, in the ACI 318[4], a minimum tensile strain of 0.005 is prescribed in the longitudinal steel for tension-controlled sections. Similarly, the Indian code specifies a minimum value of strain in the extreme layer of steel as $0.002 + \frac{f_y}{1.15 E_s}$.

In addition to the limit states, the balanced strain condition is also specified as the simultaneous tensile yielding of extreme steel layer and compressive crushing of extreme concrete fibre[4]. To ensure ductile behaviour of RC columns and bridge piers, the axial compressive force and the amount of reinforcement are also restricted in various codes of practice, as discussed in the companion paper[1].

Balanced section

For flexural limit state design, the Indian concrete code[2] specifies the limiting strain of concrete as 0.0035, *Fig* 1*(a)*. As the tensile strain in the extreme layer of steel is specified to be a minimum value of $0.002+\frac{f_y}{1.15E_s}$, there is no balanced strain condition specified in the Indian code provisions; the tensile strain in reinforcement is permitted to reach any value more than the specified minimum. Also, the precedence of flexural yielding of steel over crushing of concrete, is not ensured by the design procedure. Thus, the under-reinforced design of RC columns is not ensured as per the Indian code provisions.

For flexural design of any RC column section, the balanced axial load needs to be specified to ensure that

(i) the design of the section is under-reinforced, and

(ii) the response of the section is ductile. The force equilibrium equation at balanced strain conditions gives the balanced compressive load, P_b, on the section as

$$P_b = C_c + C_c - T \qquad (1)$$

where,

C_c = contribution of concrete in compression

C_s = contribution of steel in compression

T = tension in steel.

If P_{uz} is the code-specified ultimate compression capacity given by

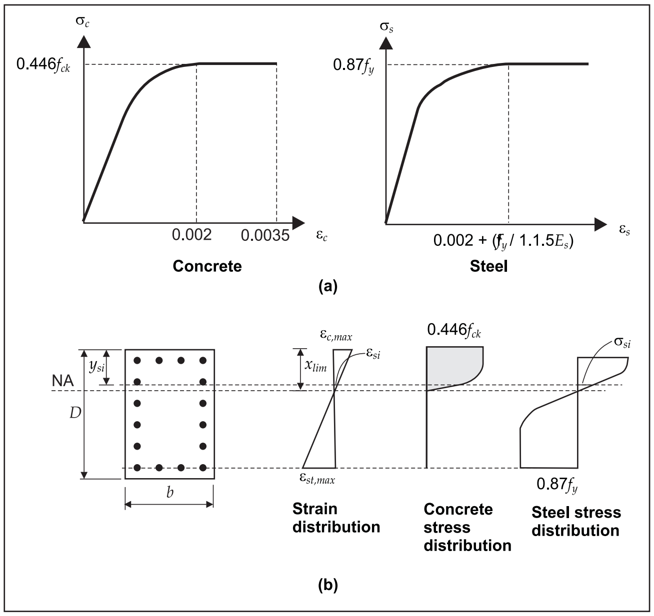

Fig 1 *(a)* Flexural limit states for concrete and steel *(b)* Limit state of collapse in flexure for a balanced section

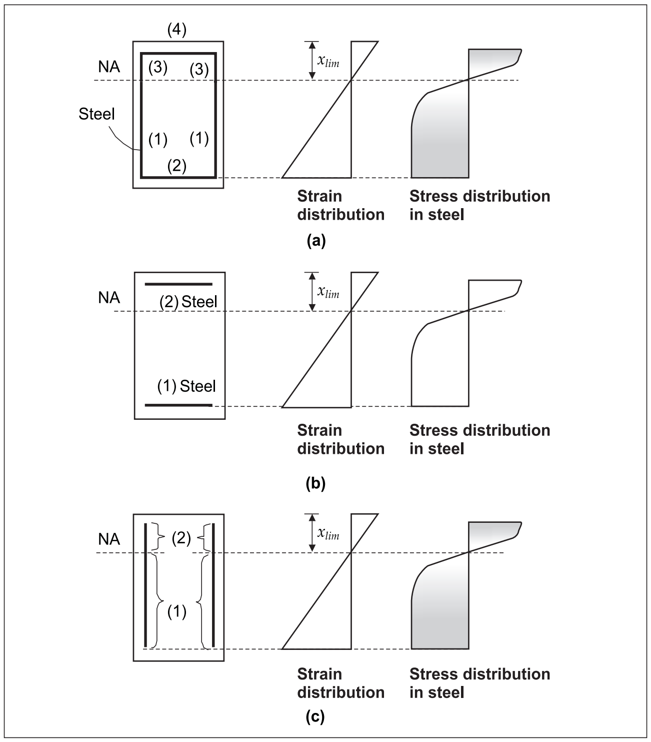

Fig 2 Calculation of forces in steel with *(a)* Case A: reinforcement on four sides, *(b)* Case B: reinforcement on two faces along width *(c)* Case C: reinforcement on two faces along depth

$$P_{uz} = 0.45 f_{ck} bD + 0.75 f_y A_{sc} \qquad ...(2)$$

where,

b = width of section

d = depth of section

f_{ck} = grade of concrete

f_y = yield strength of steel

A_{sc} = total area of vertical reinforcement.

then define a balanced axial load factor λ such that $\lambda = P_b / P_{uz}$.

For good under-reinforced design of a column section, λ needs to be as large as possible and the actual compressive axial load, P on the section needs to be less than the balanced axial load, P_b; this will ensure flexural yielding of steel and subsequent ductile response of the column.

The variation of, λ, with section depth, D, is obtained for given section width b, percentage and distribution of longitudinal steel and material properties of the section. λ is calculated by the following step-wise procedure.

Step 1: Obtain the balanced strain distribution by defining the limiting compressive strain, $\varepsilon_{c,\max}$, at the extreme fibre of concrete and the limiting tensile strain , at the extreme steel layer, *Fig* 1*(b)*.

Step 2: Obtain C_c, C_s, and T from the given design stress-strain curves. Calculate P_{uz} from the section properties using Equation (2).

Step 3: Obtain λ from Equation (1) as

$$\lambda = \frac{C_c + C_s - T}{P_{uz}} \qquad ...(3)$$

The implications of parameters $\varepsilon_{st,\max}$ and λ are discussed in detail in the section below. The conclusions of the numerical study are used to propose a limit-state of strain for steel.

Numerical study

Column sections of different widths and depths were considered. The grade of concrete was taken as M20 and the reinforcement Fe 415. In all sections, 0.8 percent vertical reinforcement was provided, which is the minimum percentage of steel specified for RC columns[2]. For Fe 415 grade of reinforcement, the code-specified minimum value of tensile strain[2] in the extreme layer of steel is 0.0038. For fixing the balanced strain condition, the limiting tensile strain in the extreme layer of steel was assumed as 0.01; thus, a limited degree of ductile behaviour of reinforcement is allowed beyond the code-specified minimum strain value of 0.0038. The limiting compressive strain in the extreme concrete fibre was kept same as the code-specified value of 0.0035.

Three types of vertical steel distributions were used, *Fig* 2, namely

- *(i)* Case A: steel on all four sides
- *(ii)* Case B: equal steel on two faces along width
- *(iii)* Case C: equal steel on two faces along depth.

For the preliminary study of sections, the vertical steel was assumed as a continuous distribution instead of discrete bars. The volumetric ratio of vertical steel was converted to an equivalent linear distribution of steel along the appropriate sides. The code-specified stress-strain distribution of steel with the assumed limiting strain was discretised into seven linear segments, *Fig* 3. C_s and T were obtained by integrating the stress distribution over the linear segments. The variation of λ with the depth of section was obtained for assumed different widths and different distributions of steel, *Fig* 4. The salient results of the numerical study with different distributions of longitudinal steel are given below.

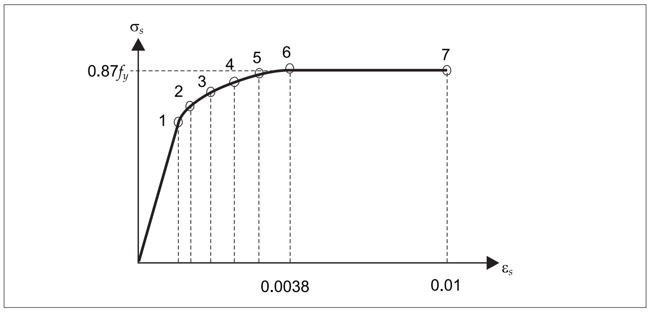

Fig 3 Discretisation of design stress-strain curve for steel

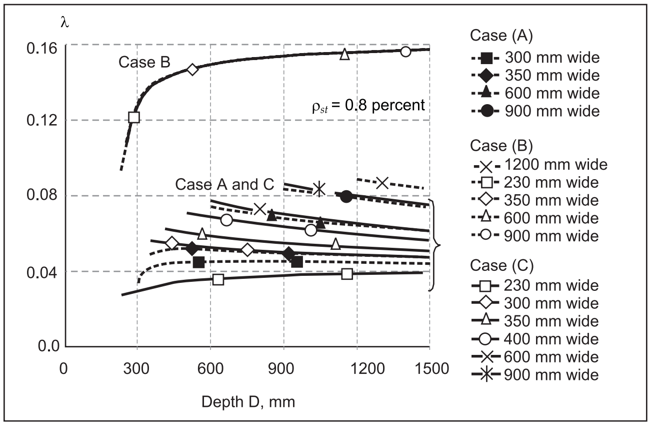

Fig 4 Effect of vertical steel distribution on balanced axial load capacity of column sections

- *(i)* The balanced axial loads obtained in Case B are more than those obtained in Cases A and C.
- *(ii)* In Case A with 230 mm width of section, the balanced axial load factor, λ, reaches only 0.04 and that too at higher depths. Thus, the under-reinforced failure region on $P_u - M_u$ interaction curve is very small.
- *(iii)* In Cases A and C, λ decreases with increasing depth of the section particularly for wide columns.
- *(iv)* In case B, the balanced axial load capacity increases rapidly for small depths, but reaches an upper bound value of 0.16 at large depths.

For a particular cross-sectional area (300 mm width and 500 mm depth) and equal distribution of longitudinal steel on two faces along width (Case B) in the RC column, the variation of λ with the limiting tensile strain, $\varepsilon_{st,\max}$, in longitudinal steel is investigated, *Fig* 5. The salient observations are given below.

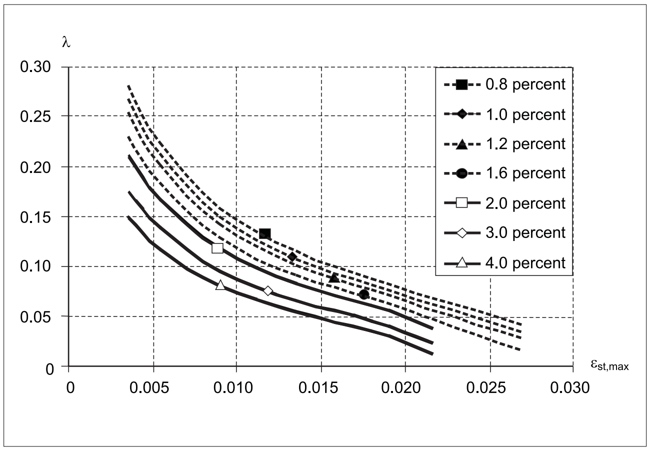

Fig 5 Effect of limiting strain in longitudinal steel on balanced axial load capacity of 300x500mm sections

(i) With increasing amounts of longitudinal steel, the balanced axial load capacity of RC columns decreases with the increasing $\varepsilon_{st,\max}$.

(ii) With an assumed percentage of longitudinal steel and a limiting tensile strain, $\varepsilon_{st,\max}$, for the longitudinal steel, the axial load on the section needs to be restricted for ensuring under-reinforced behaviour.

Strain energy

The strain energy stored in a RC section under flexure is a performance pointer towards the ductile behaviour of the section. The following step-wise procedure was employed to generate the axial force-strain energy curve.

Step 1: The depth of neutral axis, *x*, was chosen (*x* is varied from $-\infty$ to $+\infty$). When *x* was found to be, in the range $[-5D,+5D]$, a large number of values of *x* were chosen to obtain the smooth interaction curves.

Step 2: The region in which *x* lies, that is, region AB if $-\infty < x < -0.5D$, region BC if $-0.5D \le x < x_b$, region CD if $x_b \le x < +0.5D$ and region DE if $+0.5D \le x < +\infty$.

Step 3: For the area of concrete, the strain energy stored in a single fibre for deforming up to a strain level, ε_c , is given as $\int f_c bdx$. Then the total energy stored in concrete over the whole cross-section would be $\int \left(\int f_c bdx \right) d\varepsilon$.

Step 4: For the longitudinal steel, the strain energy was computed as the area under the stress-strain curve of steel upto the strain level prevalent in the longitudinal steel under consideration.

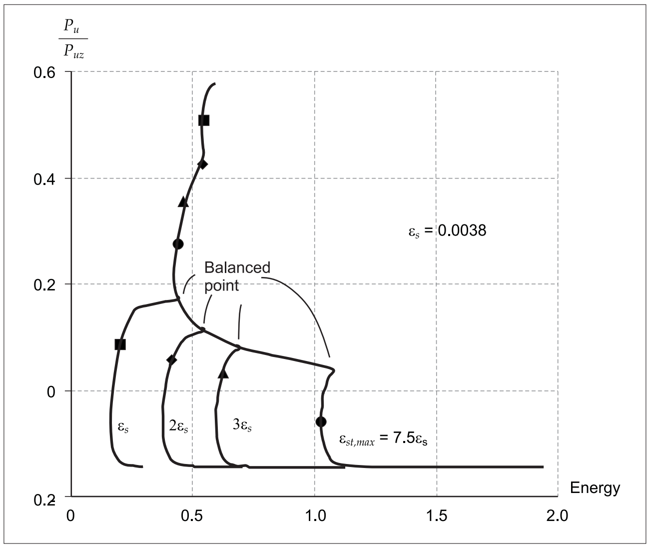

Fig 6 Effect of limiting strain of longitudinal steel on the strain energy capacity of column sections

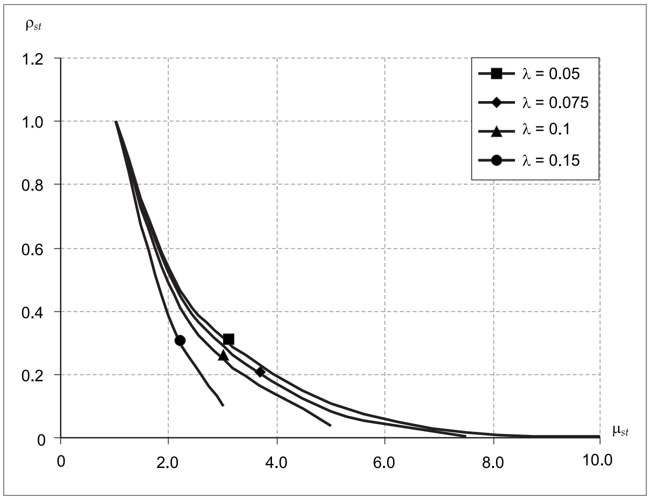

Fig 7 Effect of balanced load factor on longitudinal steel ratio of column sections

Step 5: The total strain energy stored in the section is the sum of the energies obtained in Steps 4 and 5.

The axial load-strain energy interaction curve is obtained for the RC section of size 300 mm × 500 mm and longitudinal steel 0.8 percent, *Fig* 6. The salient observations are that:

(i) the strain energy capacity increases with the increasing limiting tensile strain in steel.

(ii) the strain energy capacity of the section is higher for axial compressive loads below the balance point than for the loads above it, if $\varepsilon_{st,\max}$ is larger than 0.0076.

(iii) with increasing limiting strain, $\varepsilon_{st,\max}$, in steel, the maximum axial load for the under-reinforced design regime gets reduced.

Strain ductility

Strain ductility capacity of an RC section is obtained as the ratio of the maximum permissible tensile strain, ε , in the longitudinal steel and the tensile strain, ε_s , in the longitudinal steel specified as $\varepsilon_s = 0.002 + \frac{f_y}{1.15E_s}$. In the numerical study, the limiting strains, $\varepsilon_{st,\max}$, in longitudinal steel are varied as multiples of ε_s . For the balanced strain condition, the limiting compressive strain in concrete taken as 0.0035 corresponding to each value of $\varepsilon_{st,\max}$. The steel ratio, ρ_s , was obtained as the ratio of the area of steel required for a strain level of $\varepsilon_{st,\max}$ and the area of steel required for a strain level of ε_s . The steel area ratio-strain ductility curve was obtained for section of size 300 mm × 500 mm with longitudinal reinforcement distributed equally on two opposite sides, *Fig* 7. The salient observations are that:

(i) with increase in axial load, the strain ductility capacity decreases for the same steel ratio

(ii) for the same axial load level, the amount of longitudinal steel required decreases to obtain the desired ductility of the section.

Conclusions

The salient conclusions of the numerical study are as follows.

(i) For 230-mm wide RC building columns, the code-specified minimum percentage of steel does not ensure under-reinforced design.

(ii) Column sections with concentrated longitudinal steel at the tension and compression faces offer more desirable seismic behaviour than those with distributed steel.

(iii) The balanced strain conditions need to be incorporated in the flexural limit state design philosophy of IS 456, to ensure the desirable ductile response of the section.

(iv) The strain energy capacity of an RC column section reflects the effect of the limiting tensile strain in longitudinal steel in the under-reinforced design regime.

(v) The amount and distribution of longitudinal steel and the balanced axial load factor of an RC column section determine the ductility capacity of the section.

(vi) The proposed limiting strain in tension for steel is $\varepsilon_{st} = 2\varepsilon_s = 0.0076$. This provides reasonably uniform energy dissipation for all levels of axial load.

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