3. In flexural members of ductile frames in earthquake areas, if the compression steel is yielding

$$\rho - 0.5\rho' \leqslant 0.5 \frac{0.85 f'_c \beta_1}{f_y} \frac{0.003 E_s}{0.003 E_s + f_y} \tag{6.26}$$

Table 6.1 shows the maximum steel contents allowed by Eqs. 6.24 to 6.26 for various steel and concrete strengths.

Table 6.1 Maximum Steel Contents for Ductility[a]

f_y, psi (N/mm^2):	40,000 (276)			60,000 (414)		
f'_c, psi (N/mm^2):	3000 (20.7)	4000 (27.6)	5000 (34.5)	3000 (20.7)	4000 (27.6)	5000 (34.5)
Max $(\rho - 0.75\rho')$ from Eq. 6.24	0.0278	0.0371	0.0437	0.0160	0.0214	0.0252
Max $(\rho - \rho')$ from Eq. 6.25	0.0186	0.0247	0.0291	0.0107	0.0143	0.0168
Max $(\rho - 0.5\rho')$ from Eq. 6.26	0.0186	0.0247	0.0291	0.0107	0.0143	0.0168

[a] From Reference 6.1.

Reference to Figs. 6.9 and 6.10 indicates the values of φ_u/φ_y that will be ensured by Eqs. 6.24 to 6.26 for the steel and concrete strengths given in Table 6.1. For sections without compression steel, Eqs. 6.25 and 6.26 will ensure $\varphi_u/\varphi_y > 3$ for $\varepsilon_c = 0.003$ and $\varphi_u/\varphi_y > 4$ for $\varepsilon_c = 0.004$. For sections with compression steel, a greater φ_u/φ_y ratio is ensured by Eq. 6.26. For example, if $\rho'/\rho = 0.5$, Eq. 6.26 will ensure $\varphi_u/\varphi_y > 4$ for $\varepsilon_c = 0.003$ and $\varphi_u/\varphi_y > 6$ for $\varepsilon_c = 0.004$. This increase in φ_u/φ_y values with compression steel will not occur when Eq. 6.25 is used.

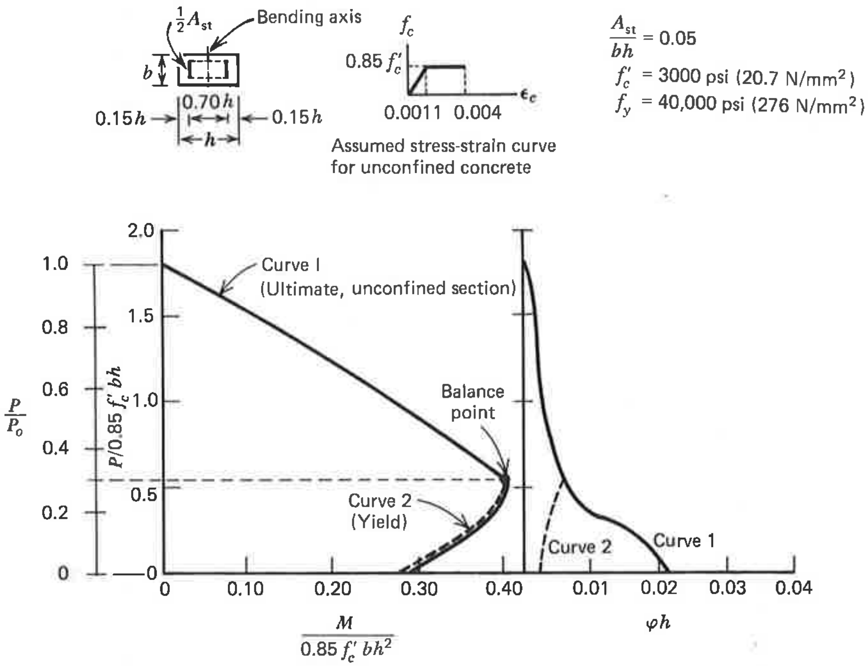
Thus some ductility will always be available from code-designed sections. The significance of the requirements of Eq. 6.25 and 6.26 are further discussed in other chapters.

6.4 DUCTILITY OF UNCONFINED COLUMN SECTIONS

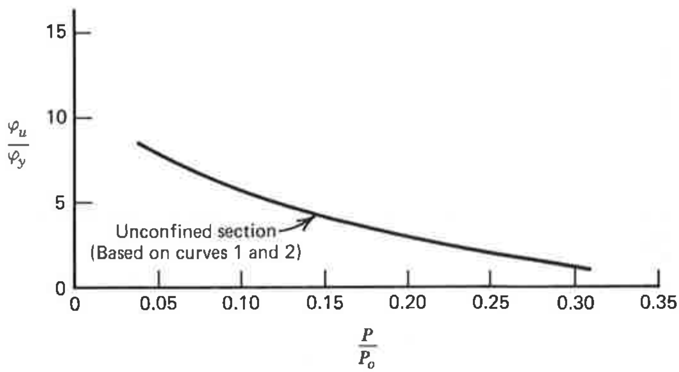
The axial load influences the curvature; hence there is no unique moment-curvature curve for a given column section, unlike the case of a given beam section. However, it is possible to plot the combinations of axial load P and moment M which cause the section to reach the ultimate capacity and the curvature φ corresponding to those combinations. Figure 6.12*a*, taken from Blume, Newmark, and Corning,[6.2] plots P against M (the interaction diagram) and P against φh for a column section having bars on two opposite faces. The details of the section and the assumed stress-strain curve for the concrete appear in the figure. Curve 1 of the P–M diagram indicates the combinations of P and M that cause the column to reach the useful limit of strain (0.004 for the concrete) without confinement. Curve 1 in the P–φh diagram shows the curvature of the section corresponding to the combinations of P and M when this ultimate condition is reached. Curves 2 give the combinations of P, M, and φh corresponding to the points at which the tension steel first reaches the yield strength. Curves 2 do not appear above the balance point because the tension steel does not reach the yield strength above that point. Below the balance point in the P–M diagram, curves 1 and 2 lie close together, indicating little change in the load capacity after yielding. Below the balance point in the P–φh diagram, curves 1 and 2 separate, and indicate the amount of inelastic bending deformation that occurs once yielding has started. The ratio φ_u/φ_y obtained from these two curves for the unconfined section is plotted against the column load ratio P/P_o in Fig. 6.12*b*, where P_o is the axial load strength of the column when no bending is present. At the balanced point, $P/P_o = 0.31$ for this section. It is evident that the ductility of the section is significantly reduced by the presence of axial load. For example, if the column load is 15% of the axial load capacity, the φ_u/φ_y value is reduced to about 4, and is smaller at higher load levels.

Pfrang, Siess, and Sozen[6.3] have also reported the results of an investigation into the inelastic deformations of reinforced concrete column sections. Of particular interest are the moment-curvature curves obtained for column sections with various levels of constant axial load (i.e., the column load was held constant at a particular level while the column was bent to failure). Curves for column sections with two different steel contents are presented in Fig. 6.13. The tensile strength of the concrete was ignored in the calculations, and the ultimate curvature was assumed to be reached when the maximum concrete strain was 0.0038. The curves illustrate again that at axial load levels greater than the balanced failure load, the ductility is negligible, being due only to the inelastic deformation of the concrete. At levels of load less than the balanced load, the ductility increases as the load level is reduced.

Because of the brittle behavior of unconfined columns at even moderate levels of axial compressive load, ACI 318-71[6.1] recommends that the ends of columns in ductile frames in earthquake areas be confined by closely spaced transverse reinforcement when the axial load is greater than 0.4 of the balanced load P_b.

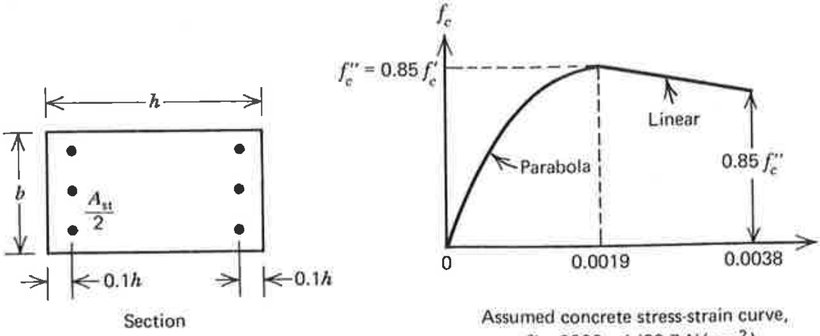


(a)



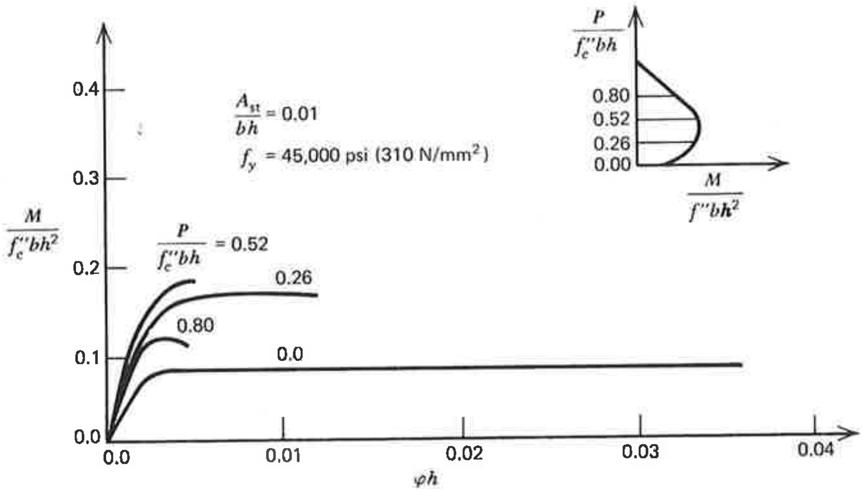
(b)

Fig. 6.12. Strength and ductility of a column section.[6.2] (a) Interaction diagrams. (b) Curvature ductility.



Assumed concrete stress-strain curve, $f_c' = 3000$ psi (20.7 N/mm²)

(a)



(b)

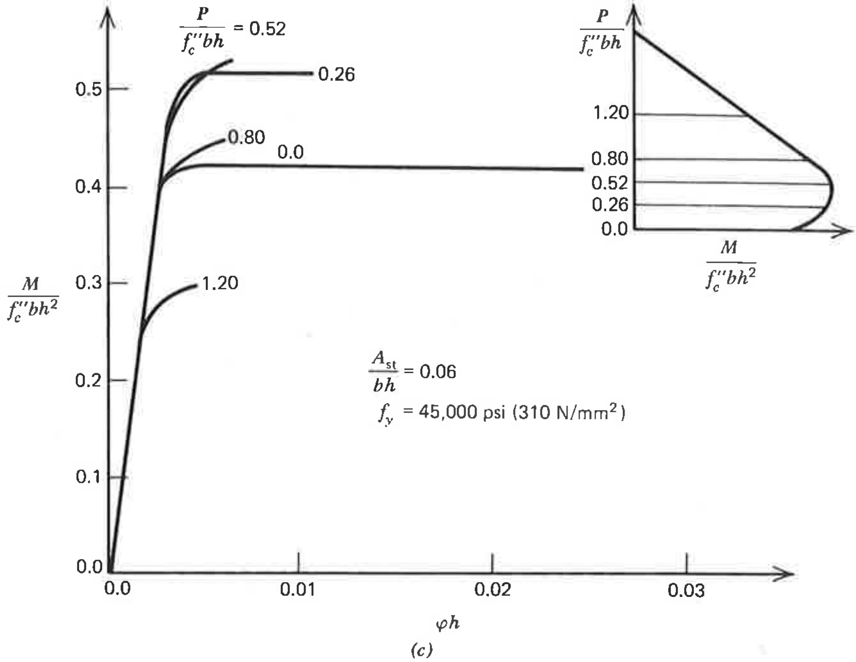


Fig. 6.13. Moment-curvature curves for column sections at various levels of axial load.[6.3]

6.5 MEMBERS WITH CONFINED CONCRETE

6.5.1 Effect of Confining the Concrete

If the compression zone of a member is confined by closely spaced transverse reinforcement in the form of closed stirrups, ties, hoops, or spirals, the ductility of the concrete may be greatly improved and a more ductile performance of the member at the ultimate load will result.

The stress-strain characteristics of concrete confined by transverse reinforcement were discussed in Section 2.1.3. At low levels of compressive stress, the transverse reinforcement is hardly stressed and the behavior of the concrete is unaffected by the reinforcement. At stresses approaching the uniaxial strength, the transverse strains in the concrete increase rapidly, because of progressive internal cracking, and the concrete expands against the transverse reinforcement. The restraining pressure applied by the reinforcement to the concrete considerably improves the stress-strain characteristics of the concrete at higher strains. Circular spirals confine the concrete more effectively than rectangular stirrups, ties, or hoops, because