Design and Uses of Prestressed Concrete Columns

by Raymond Itaya*

SYNOPSIS

At the present time, criteria for the design of prestressed concrete columns are not included in the PCI Building Code Requirements nor the ACI Building Code Requirements for Reinforced Concrete. The PCI Prestressed Concrete Column Committee has been studying the behavior of prestressed concrete columns for nearly two years. This paper attempts to summarize the knowledge to date and outline an approach to the design of prestressed concrete columns.

INTRODUCTION

Since columns are generally considered as members under compression, it might first appear that there is no justification for putting compression into the concrete by prestressing. Upon closer examination, however, columns are very often subjected to tensile stresses when bending moments due to wind and earthquake forces, eccentric loads, or frame action are applied to columns. Prestressing columns then can be considered as an extension of ordinary reinforced concrete columns where reinforcing steel is used to resist tension.

Prestressing introduces additional advantages to concrete columns. It transforms a cracked section into a non-cracked one, thus enabling the entire concrete section to resist bending moments. This becomes significant when bending predominates[9] (Fig. 1). Prestressing yields a homogeneous member with reliable buckling capacity which is important for slender columns. For precast columns subjected to transportation and erection stresses, prestressing supplies a higher resistance to cracking during handling. It is therefore clear that prestressed concrete columns will be found useful under many conditions. Figs. 2 and 3 illustrate the use of such columns where conventional reinforced columns would have been uneconomical, if not impossible.

Several possible types of prestressed concrete columns should be considered. Aside from the fully prestressed concrete columns, the combination of prestressed reinforcement and non-prestressed reinforcement offers advantages. The non-prestressed reinforcement does not appreciably strengthen the column under bending stresses in the working load range, but it is very effective

*Vice President
T. Y. Lin & Associates
Van Nuys, California

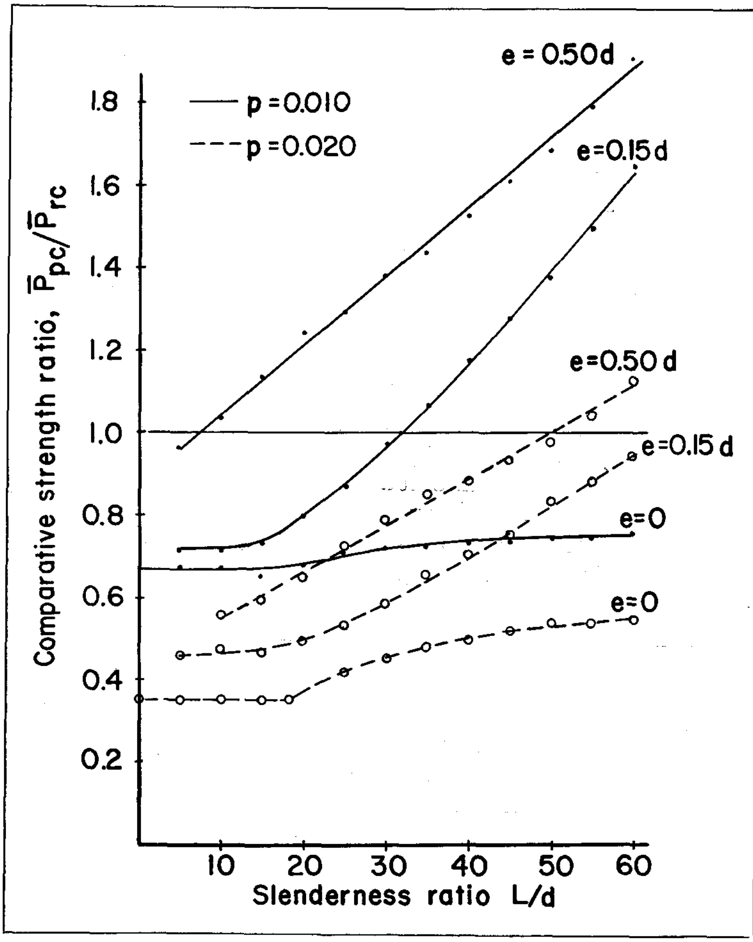

Fig. 1—Comparison of Prestressed and Reinforced Concrete Column Strengths

beyond cracking and into the ultimate load range, both in compressive and tensile resistance. Furthermore, the addition of non-prestressed reinforcement could change the mode of failure of the column and increase its ductility. Experimental and theoretical studies have already confirmed this[7,8], although applications are yet limited.

Another possibility is the three-dimensional prestressing of columns, combining spiral reinforcement with longitudinal prestressing. As is well known, tri-axial compressive strength of concrete can be up to ten times higher than the cylinder strength. The spiral reinforcement may be non-prestressed; it may be indirectly prestressed by the Poisson ratio effect resulting from longitudinal prestressing; or it may be chemically prestressed by expansive cements.

Realizing that the lack of knowledge concerning the design and behavior of prestressed concrete columns was largely responsible for their slow devolopment, the PCI formed a committee on prestressed concrete columns in 1963. The committee is evaluating the available data and theories to formulate cri-

Fig. 2—90-Ft. Prestressed Concrete Columns

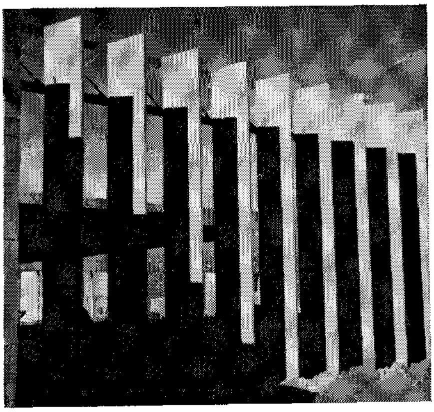

Fig. 3—Six-inch Wide Columns

teria for design of prestressed concrete columns. The committee believes that sufficient knowledge and data are already available so that safe and reasonable criteria can be set up to guide the engineer in the design of simple types of prestressed concrete columns. Additionl study and research, however, are much needed to refine the procedure and to produce more economical results. This paper is an attempt to summarize the knowledge to date (Ref. 1 to 9). While it represents the opinion of only the author, free use has been made of data and ideas from other members of the committee and their contribution is hereby acknowledged.

POSSIBLE DESIGN APPROACHES

For the design engineer, prestressed concrete columns present a real challenge. It is noted that for reinforced concrete columns, several major changes have been made in the ACI Code during the last three decades. The 1963 Code incorporated the results of extensive theoretical and experimental studies, but it is still far from perfect. A similar evolution may be foreseen for prestressed concrete columns with the exception that our knowledge of reinforced concrete columns may be utilized when dealing with prestressed ones.

Three approaches are possible for the design of prestressed concrete columns:

1. Rational and analytical approach.
2. A new set of code design clauses to be set up specifically for prestressed concrete columns.
3. Modification of ACI Code clauses for reinforced concrete columns so that they will be applicable to prestressed concrete columns.

In any of these three approaches, either the working stress or the ultimate strength method or a combination of both may be used.

RATIONAL AND ANALYTICAL METHOD

It is well known that the stresses in a prestressed concrete column can be rationally analyzed. For example, in Fig. 4 the stresses at any point in a prestressed concrete column section is given by

$$f = -\frac{F}{A_t} - \frac{P}{A_t} \pm \frac{Mc}{I_t} \pm \frac{P\Delta c}{I_t}$$

where

F = effective total prestress including all losses, except elastic shortening due to superimposed load.

P = superimposed load.

M = external moment at the section;
= Pe in Fig. 4.

c = distance to the extreme fiber from the centroid of the section.

A_t = area of the transformed section.

I_t = moment of inertia of transformed section.

Δ = deflection of the column at the section.

For a pin-ended column with uniform eccentricity, critical stresses occur at midheight of the column where the deflection is given by the well known secant formula,

$$\Delta = e\left(\sec\sqrt{\frac{PL^2}{4E_cI_t}} - 1\right)$$

For a given load eccentricity, this pin-ended column usually represents the worst possible condition in any building or bridge column unless the column is not laterally supported at the ends. Often it will be more economical to take into account the actual moment variation along the length of the column; but, as a first approximation and on the safe side, the engineer can always resort to this simpler approach. When the column is short and the deflection, Δ, is negligible, the solution becomes greatly simplified. Thus, the rational analysis of elastic stresses may not be a complicated process.

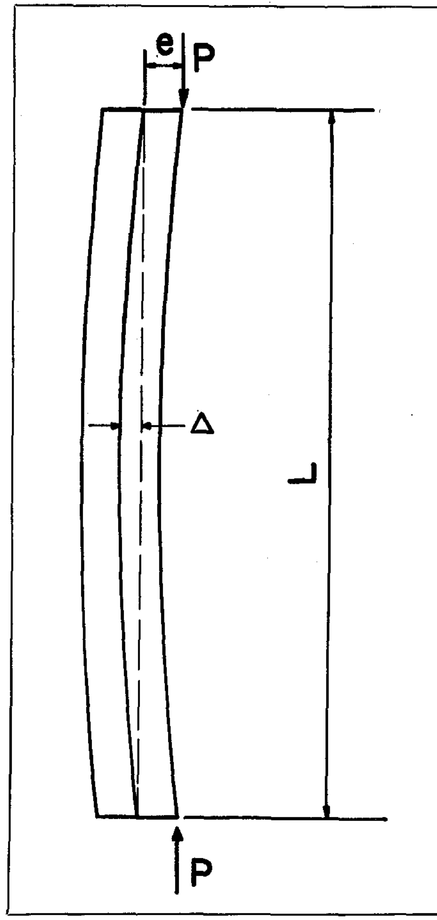

Fig. 4—Column Under Eccentric Load

Unfortunately, for certain columns, the elastic stresses are not the best measure of their strength, and plastic analysis is required to determine the deflection and buckling effects. A complete plastic analysis should include the plasticity of both steel and concrete, the cracking of concrete, and the moment curvature relationships of sections under combined axial loading and bending. While the basic theory of analysis is relatively straight forward, the execution becomes a rather tedious problem. The reliability of such an analysis has been proved by tests carried out at the University of California[4,7], University of Florida[2,3] and the University of Southern California[1]. Computer programs have been set up at the University of North Carolina and others[8,9].

The basic conditions of static equilibrium and geometrical compatibility for a prestressed column section under ultimate load are given by Fig. 5[6]. The static equilibrium of the section requires that for $\Sigma V = 0$,

$$P = C - T_1 - T_2$$

and for $\Sigma M = 0$,

$$M = (T_1 - T_2)\frac{y_t}{2} + Cy_c$$

By assuming a location for the neutral axis at ultimate load, setting ϵ_c as the ultimate strain in the concrete and f'_c as the ultimate stress of the concrete, and by assigning ultimate stress distribution curves for concrete, it is possible to compute the combination of P and M that results in this ultimate failure. For slender columns, the value of M just computed should include the effect of deflection, which can be computed by a numerical procedure, provided the load-moment curvature relationship of the column section is known.

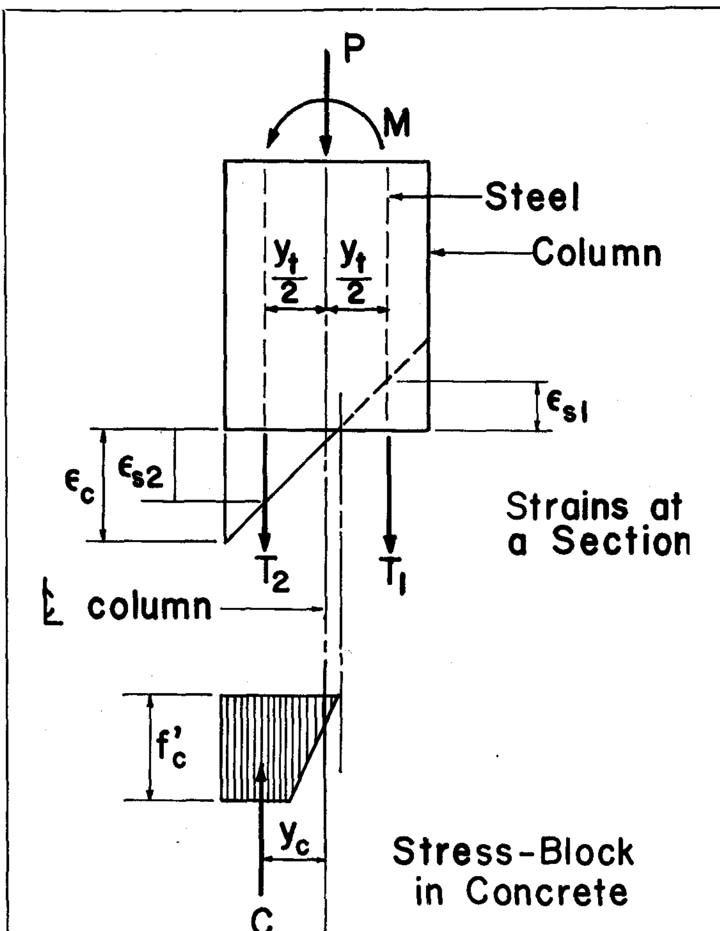

Fig. 5—Ultimate Strength Under Combined Axial Load and Moment

While the rational analysis will give stresses and the ultimate strength of prestressed concrete columns under combined axial load and bending, the problem of allowable stresses or factors of safety remains a difficult one.

NEW DESIGN CODE

Although studies for prestressed concrete columns have enabled the prediction of their behavior and strength, we do not yet have enough data to derive simple rules of design. Most engineers cannot afford the time to make a rational analysis, even though the theory is available. Computer analysis, such as the one carried out at the University of North Carolina will help, but will have to be extended to include more variables. As more data becomes available, it may be possible to derive simple design rules. However, the task is a highly complicated one including many variables. Recent work shows promise, but may require many more years of verification.

MODIFICATION OF THE ACI CODE

Now we come to a practical proposal which may enable the design of prestressed concrete columns to be immediately accepted. This will not give a perfect solution since it will be based on the 1963 ACI Code for Reinforced Concrete Columns. On the other hand, it contains allowable factors of safety which are accepted for reinforced concrete and should, therefore, be acceptable for prestressed concrete.

For short columns under axial load, the ACI Code formula for the allowable axial load on spiral columns is proposed:

$$P = A_g\,(.25f'_c + f_s p_g)$$

where f_s and p_g refers to the non-prestressed reinforcement. For tied columns, 85% of the allowable load for spiral columns may be used.

When the amount of prestress is high, it may appreciably decrease the ultimate strength of the columns. Therefore, when the effective prestress exceeds 0.15 f'_c the term f'_c in the formula should be reduced by 60% of the prestress in excess of 0.15 f'_c so that for spiral columns,

$$P = A_g\left\{ .25\,[f'_c - .6\,(f_{avg} - .15f'_c)] + f_s p_g \right\}$$

where

$$f_{avg} = \frac{F}{A_g}$$

The 60% is based on the decrease in prestress at the ultimate load.

For short columns subjected to axial load and bending and controlled by compression, the ACI Code interaction formula is suggested:

$$\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \text{ less than unity.}$$

The allowable F_a is computed as in the ACI Code,

$$F_a = .34\,(1 + p_g m)\,f'_c$$

The axial stress f_a is computed for external load only, unless the effective prestress exceeds $.15\,f'_c$, in which case 15% of the excess is added to the computation of f_a. The 15% is based on the 60% of the prestress at ultimate, multiplied by the factor 0.25 as for axial load only.

For short columns subjected to axial load and bending and controlled by tension, an ultimate strength approach is proposed. The interaction curve may be assumed to vary linearly between M_0 when the section is under pure flexure, to M_b when the axial load is N_b. The value M_0 is computed as for any prestressed section under flexure.

Further study is needed for the

determination of M_b and N_b at balanced failure. Limited tests and computer analyses indicate that at ultimate load, the value of N_b can be obtained from the following formula for rectangular sections[8]:

$$N_b = (.45 f'_c - f_{ce}) A$$

where f_{ce} = effective unit prestress in the concrete, considering only the case of uniform prestress.

The eccentricity e_b at balanced failure varies from about 0.25*d* for sections with no non-prestressed reinforcement, to about 0.5*d* for 3% non-prestressed reinforcement for a 12 inch thick column. "*d*" is the column thickness. How these values should be used for working stress design is yet to be determined.

For slender columns, reduction factors outlined in Chapter 9 of the ACI Code may be followed. Article 912 of the Code, limiting the dimension to eight inches, should not be applied to prestressed concrete columns since very often thin, prestressed columns are desirable and reliable if properly designed. For very long columns, the Euler load should be checked.

The PCI Committee on Columns will soon have to make a decision as to which approach among the aforementioned three should be recommended for prestressed concrete columns. Clearly, the rational approach is the most logical, but it is not the easiest. If the second approach is taken, it is conceivable that a simpler set of design rules may be set up than the ACI clauses for reinforced concrete columns. However, there will be the practical problem of getting the method accepted by the public, whereas if the third approach is taken, a proposal can be made within a few months if the effort is made.

CONCLUSION

In conclusion, it may be stated that prestressed concrete columns will be found useful and economical under certain conditions, such as columns with high slenderness ratios, columns subjected to appreciable bending moments, and precast columns. Since prestressed concrete columns can be rationally analyzed, any engineer who possesses a basic understanding of structural mechanics should be able to design any prestressed concrete column based on first principles, provided he has the time to perform the necessary calculations. Hence, it is only reasonable that prestressed concrete columns should be permitted when rational analysis can be presented.

In lieu of a rational analysis, approximate and safe methods of design can be made using the 1963 ACI Code for reinforced concrete columns with certain modifications. Additional research, both theoretical and experimental, is urged to determine the effects of many variables on these columns. The formulation of simple design rules and formulae based on these studies will lead to wider adoption and applications. Some of the variables to be considered are:

1. The amount and location of prestressed steel
2. The amount and location of non-prestressed steel
3. The shape of column
4. Spiral prestress and tri-axial prestress
5. Types of steel and concrete
6. Variation of moment
7. Eccentricity ratio
8. Slenderness ratio

In addition, the types of column connections, the joints between columns and girders, temperature, shrinkage and creep effects all require additional research.

Indeed, there remains a great deal to be done. But, we already have sufficient knowledge to produce safe designs, though not always optimum ones.

REFERENCES

1. Breckenridge, R. A., "A Study of the Characteristics of Prestressed Concrete Columns", University of Southern California, Los Angeles, 1953.
2. Jernigan, A. M. and Ozell, A. M., "Some Studies on the Behavior of Prestressed Concrete Columns", University of Florida, Gainesville, 1956.
3. Zia, P., "Ultimate Strength of Slender Prestressed Concrete Columns", University of Florida, Gainesville, 1957.
4. Lin, T. Y. and Itaya, R., "A Prestressed Concrete Column Under Eccentric Loading", *Journal of the Prestressed Concrete Institute,* Vol. 2, No. 3, December 1957.
5. Hall, A. S., "Buckling of Prestressed Columns", *Construction Review,* Sydney, Australia, June, 1963.
6. Lin, T. Y., *Design of Prestressed Concrete Structures,* Second Edition, John Wiley & Sons, Inc., New York, 1963.
7. Lakhwara, T. R., "Ultimate Strength of Partially Prestressed Concrete Columns Under Eccentric Loading", Graduate Student Research Report No. 94, Division of Structural Engineering and Structural Mechanics, University of California, Berkeley, 1963.
8. Sandrini, L. M., "Ultimate Strength of Partially Prestressed Concrete Columns Under Eccentric Loads—A Computer Analysis", Graduate Student Research Report No. 146, Division of Structural Engineering and Structural Mechanics, University of California, Berkeley, 1964.
9. Moreadith, F. L., "An Analytical Study of Ultimate Load Capacity of Long Hinged Prestressed Concrete Columns", Doctoral Thesis, Department of Civil Engineering, University of North Carolina, Raleigh, 1964.

Presented at the Tenth Annual Convention of the Prestressed Concrete Institute, Washington, D.C. September 1964.