Steel cross-bracing in seismic resistant structures

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ABSTRACT: Various forms of bracing, including simple tension rods, compression members and multiphase bracing are reviewed. Accurate mathematical representations of the hysteretic response curves are developed. Incorporation of the inelastic characteristics of bracing members into a computer based model of a moment resistant plane frame allows analysis of the post-elastic behavior of general cross-braced frames under earthquake action. The inclusion of bracing elements in selected representative elastic rigid-jointed plane frames is shown to reduce both the displacement and the loads induced in the main frame by seismic action whilst confining energy dissipation to preselected sacrificial elements. Inclusion in the design process of the material presented should enable more reliable use to be made of the attractions of an initially laterally stiff structure incorporating compressive braces which is capable of degrading to a more flexible, yet still load resistant, configuration.

1. INTRODUCTION

The unsatisfactory behavior of cross-braced steel frameworks in past earthquakes has resulted in building codes requiring the application of significant penalties to the design of structural configurations which rely on cross-bracing as a major contribution to lateral resistance.

To some extent the recorded poor performance reflects a lack of clear understanding of the properties of braces and a consequent inability to predict accurately their response to cyclic axial loading.

If valid models of bracing elements were generally available to designers it seems probable that confidence would increase to the extent that much greater use would be made of the valuable increase in drift control which cross-bracing provides to otherwise flexible structures.

In this paper the various forms of bracing are reviewed. Their behavior is examined when the structure in which they are incorporated is subjected to cyclic lateral loading. Several configurations of bracing are investigated in an attempt to establish choices which will minimize the effects of seismic loading.

1.1 The Tension Brace

The simplest form of brace is a diagonal wire or rod which can resist tension but which buckles under very small compressive load. Such braces are common in elevated water tower structures (see figure 1) where pairs of crossed braces are characterised by no structural connection at the cross-over position. Provided that adequate attention is given to detailing the end connections, the braces can be accurately modeled as exhibiting a linear force/deflection relationship up to yield and a second linear relationship, of reduced axial stiffness, representing the true force, true deflection curve (Kalpakjian, 1967) between the initial elastic limit and the end of the useful contribution of the brace to the strength of the structure.

Pairs of diagonally opposed simple tension braces may be subjected to initial pretension. The value of lateral stiffness contributed by the braces is then effectively doubled so long as both members remain tensioned. When as a result of sidesway, one of the braces becomes slack, the cross bracing stiffness characteristics return to that of a single tension brace. Effectively this pre-tensioned configuration confers bilinear load/deflection characteristics on the bracing system without the necessity for permanent yield occurring yet provides a practical solution to the problem of installing tension cross braces to be "just tight" under zero lateral load.

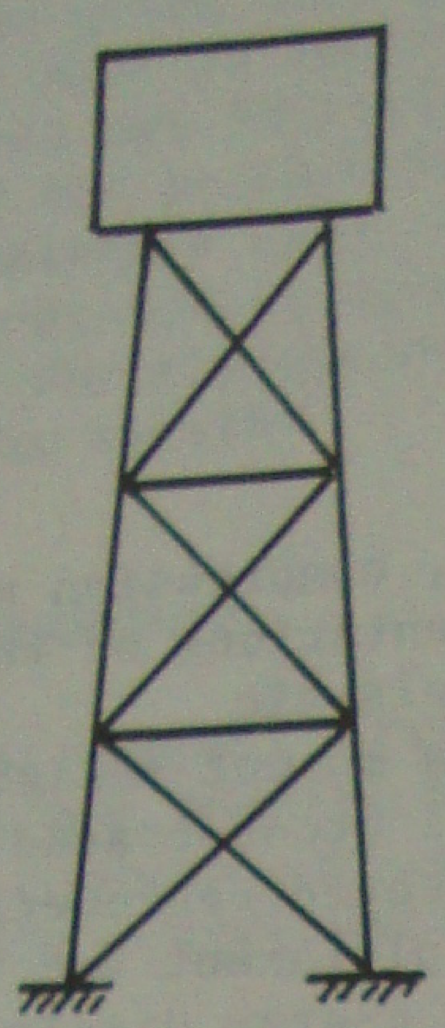

Figure 1. Cross-braced tower.

1.2 The Compression Brace

The compression brace may be considered to act in one of two basic forms. In the first it is assumed that the member yields in axial compression. In the second the member is assumed to buckle elastically. This second case neglects the dissipation of energy provided by inelastic deformation, an important consideration in seismic resistant design. The load/deflection relationships for each of the two compression brace models, coupled with a yielding tension brace behavior, are shown in Figure 2.

Several investigators have proposed models which incorporate reversed elastic and inelastic distortions, including buckling effects where appropriate. The most detailed (Higginbotham, 1973) proved to be so complex as to be difficult to apply to large structures consequently a series of simplified versions have been proposed (Nilforoushan, 1973; Singh, 1977). In these the force/displacement relationship is modeled as a series of straight lines which approximate the theoretically derived hysteresis loops, see Figure 3. A refinement of this approach involving an iterative procedure to model the compressive part of the curve has been proposed (Haroun, 1983).

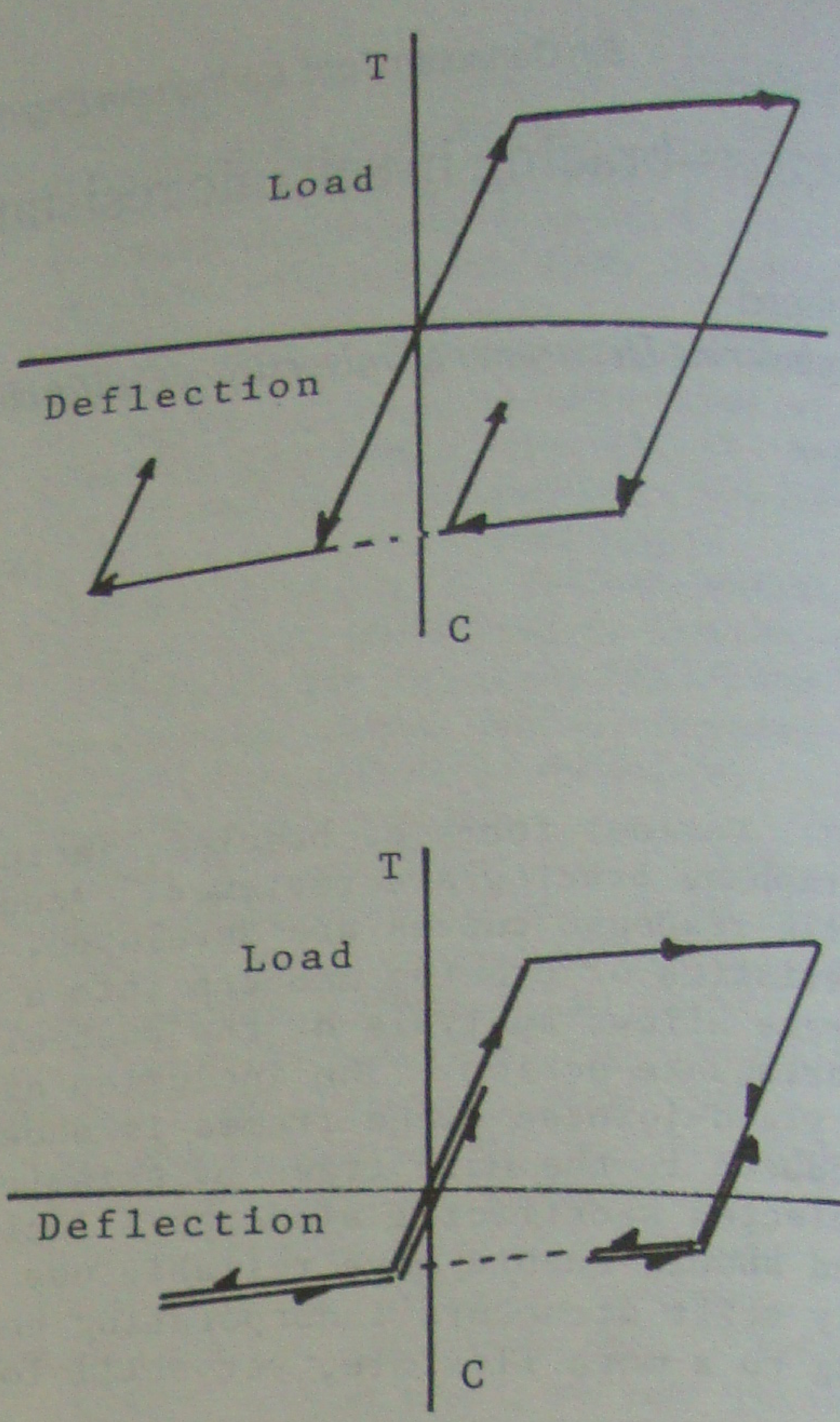

Figure 2. Inelastic behavior of truss elements.

Reasonable verification of the mathematical models has been provided by the results of experimental cyclic load tests (Kahn, 1976).

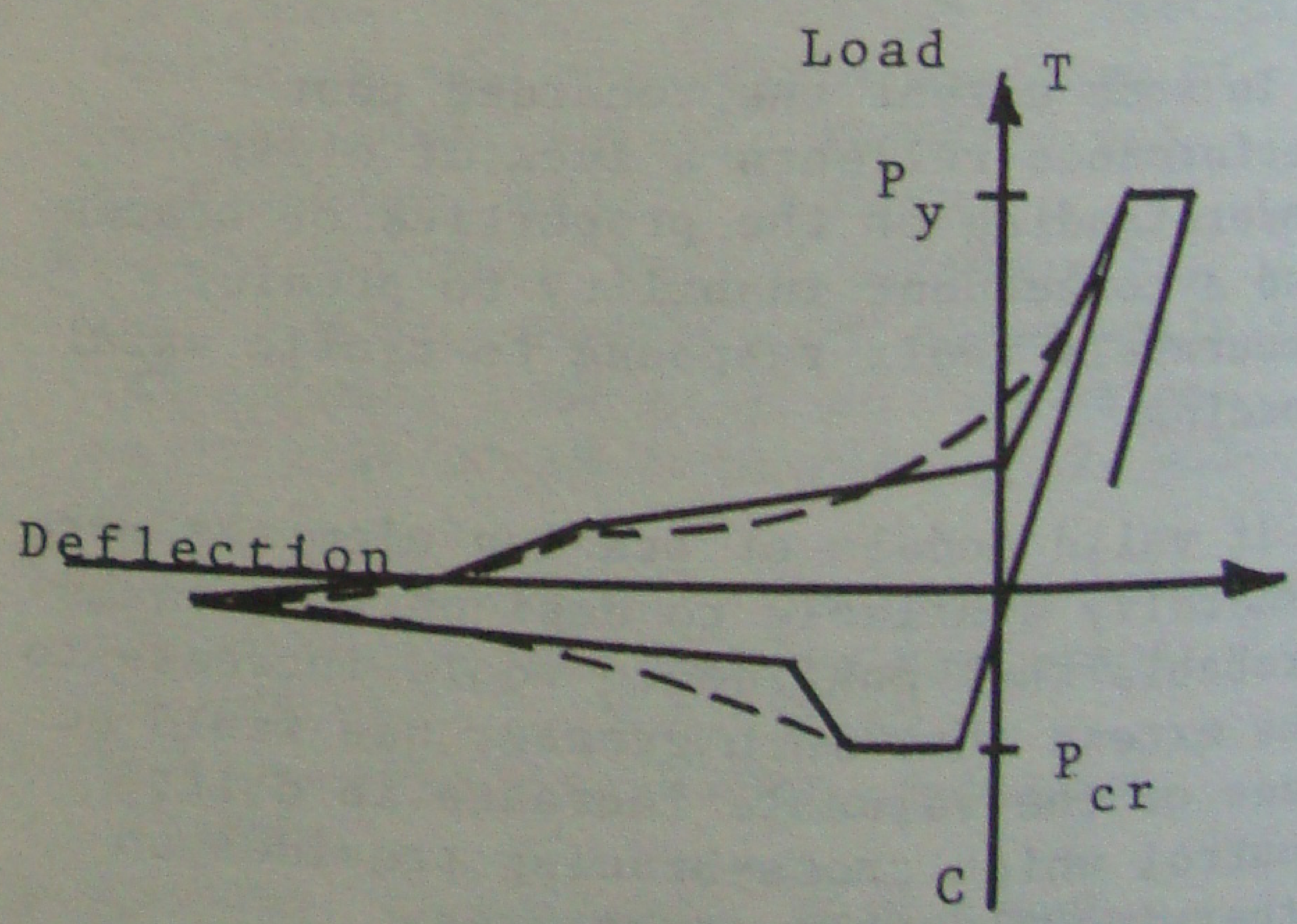

Figure 3. Linear simplification of force-deformation curve.

1.3 Multiphase Bracing

Combinations of diagonal braces so that two or more of different load/deflection characteristics act in parallel allow an almost infinite range of lateral load responses to be achieved. Tests including that depicted in Figure 4 have shown (Shepherd, 1973a) that it is possible to construct a frame with tension braces which is initially stiff under lateral load, is significantly more flexible at larger sidesway, is capable of exhibiting ductile behavior and is able to stiffen up again prior to collapse. Since these characteristics are in demand by designers of earthquake resistant structures the use of multiphase cross braced frames appears to have significant potential.

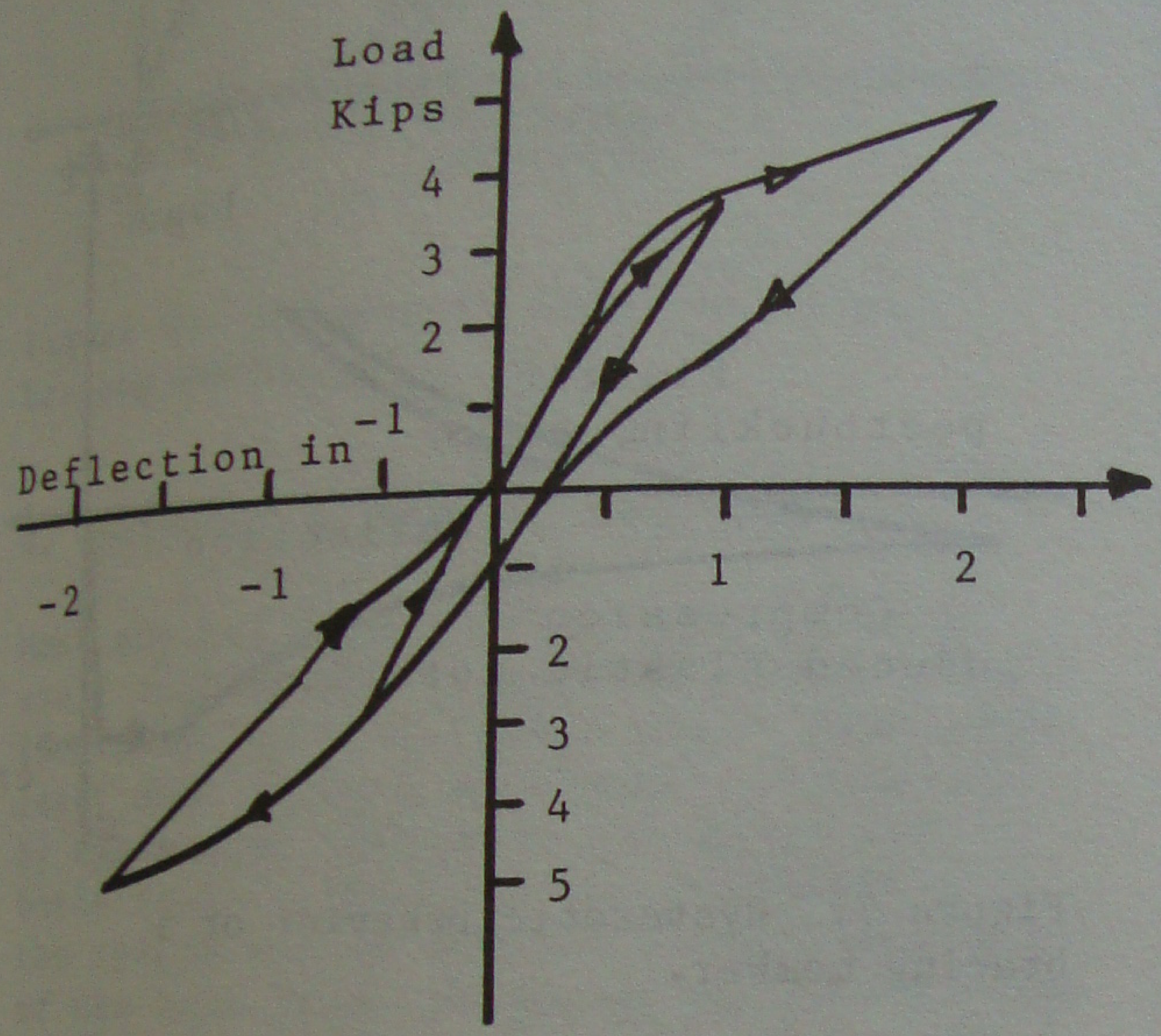

Figure 4. Sidesway stiffness of a portal frame braced with parallel diagonally opposite rods.

2. MATHEMATICAL REPRESENTATION

2.1 The Tension Brace

In the elastic range the axial stiffness K may be predicted using the expression

$$K = \frac{A_o E}{L_o} \qquad \text{(i)}$$

where A_o is the original cross sectional area of the brace
E is the elastic modulus
L_o is the original length

The post yield axial stiffness may be predicted on the basis of the post-yield true force, true deflection relationship namely

$$\text{The true force} = \frac{A_o L_o}{L_i} K_o (\varepsilon_i)^n \qquad \text{(ii)}$$

where L_i is the brace length when the true force is determined
K_o is the strength coefficient
ε_i is the true strain
and n is the strain hardening coefficient.

Using equations (i) and (ii) essentially bilinear load/deflection models of axially loaded steel tension braces may be derived. An example of the second section of the load/deflection relationship is shown in Figure 5.

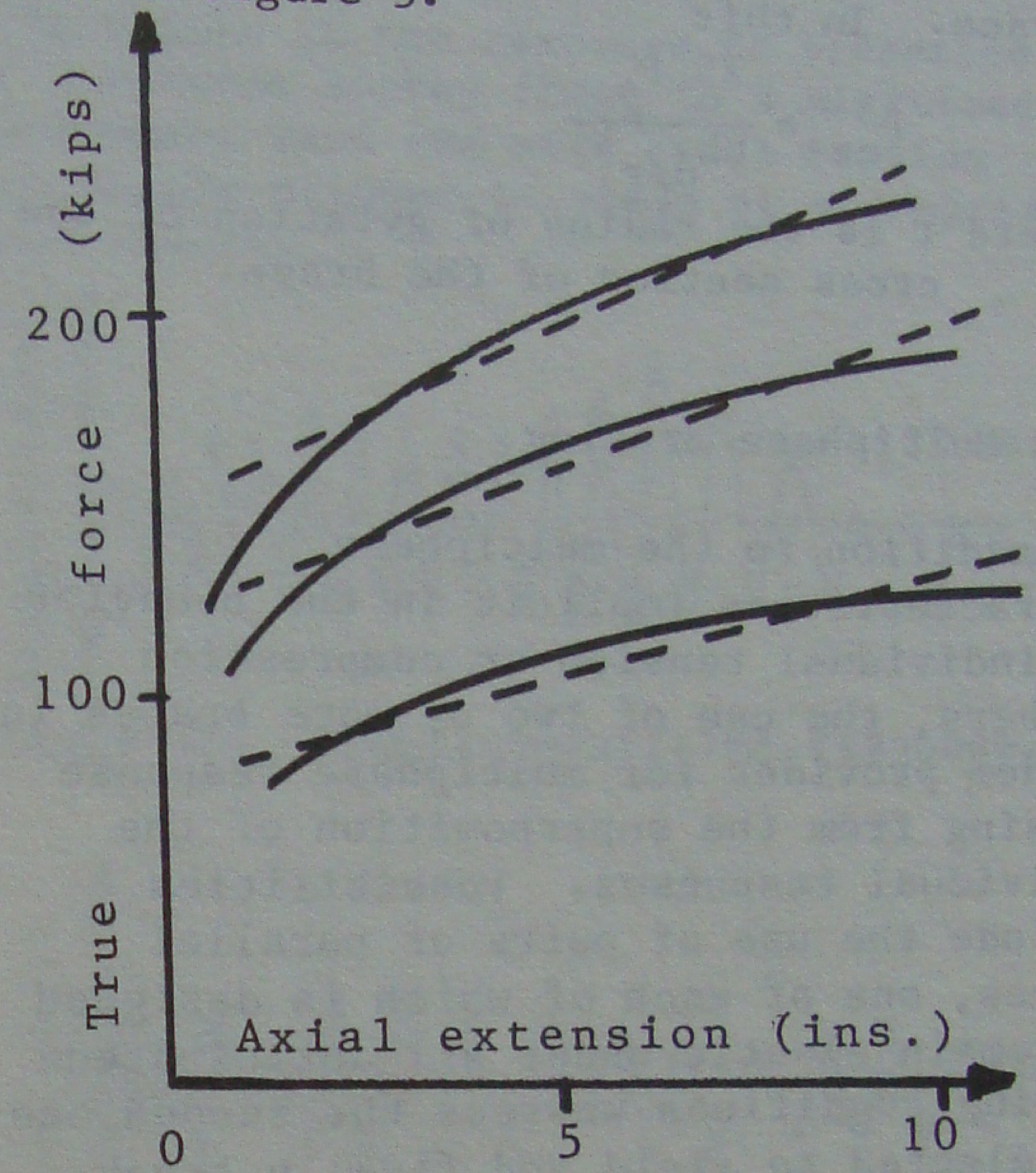

Figure 5. True force/time deflection curves for bracing rods.

2.2 The Compression Brace

The assumption of pin ended, one dimensional braces allows simplification of the mathematical model. Up to onset of lateral deflection expression (i) will provide a representation of the stiffness characteristic. Subsequently a constant applied compressive load P_{cr} ban be predicted using the Euler approach.

$$\text{Then } P_{cr} = -\pi^2 \frac{EI}{L_o^2}$$

where I is the second moment of area of the member's cross section.

At the onset of yield at the midlength of the compressed brace a modified plastic moment M_{np} may be considered to exist.

$$M_{np} = M_p \left\{ 1 - \left(\frac{P}{P_y}\right)^2 \right\}$$

where M_p is the plastic moment of the section
P is the axial load on the member
and P_y is the axial yield load of the member.

The overall compressive axial stiffness is then predicted on the basis of its deflection being composed of two components, the first arising from elastic axial deformation and the second from the lateral deflection.

The simplification proposed by Singh involves the use of a linear segment for the compression characteristic of a brace. In this

$$P_{cr} = \frac{25\, P_y}{(L_{o/r})}$$

where r is the radius of gyration of the cross section of the brace.

2.3 Multiphase Bracing

In addition to the multiphase characteristics implicit in the behavior of individual tension or compression members, the use of two or more braces in tandem provides for multiphase response arising from the superposition of the individual responses. Possibilities include the use of pairs of parallel braces, one of each of which is designed to remain elastic under all anticipated loading conditions whereas the second one is selected to yield and finally break under the severest expected applied loads. The mathematical representations of such systems may be compiled by compounding the individual stiffness terms presented above.

3. HYSTERETIC RESPONSE CURVES

Using the considerations presented earlier it is possible to generate (Haroun, 1986) hysteretic response plots appropriate to a range of possible phase change sequences. In Figure 6 changing from elastic state to buckling on a straight line, reversing, returning to the elastic state followed by plastic yielding and elastic unloading is shown.

The change from buckling to compression induced plastic rotation followed by reversal to elastic post buckling, to tension induced plastic rotation, to yield and to unloading is shown in Figure 7.

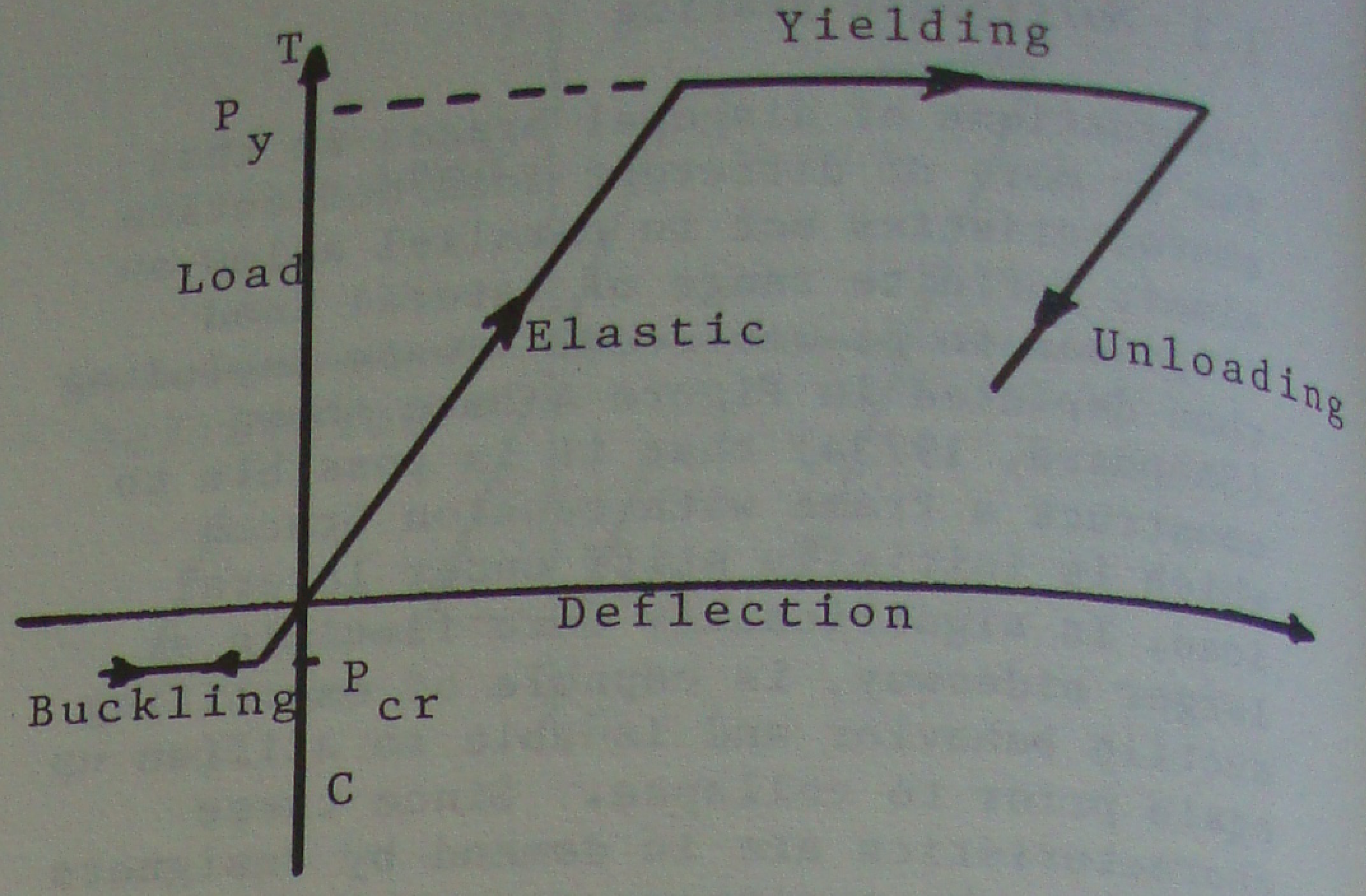

Figure 6. Hysteretic behavior of a bracing member

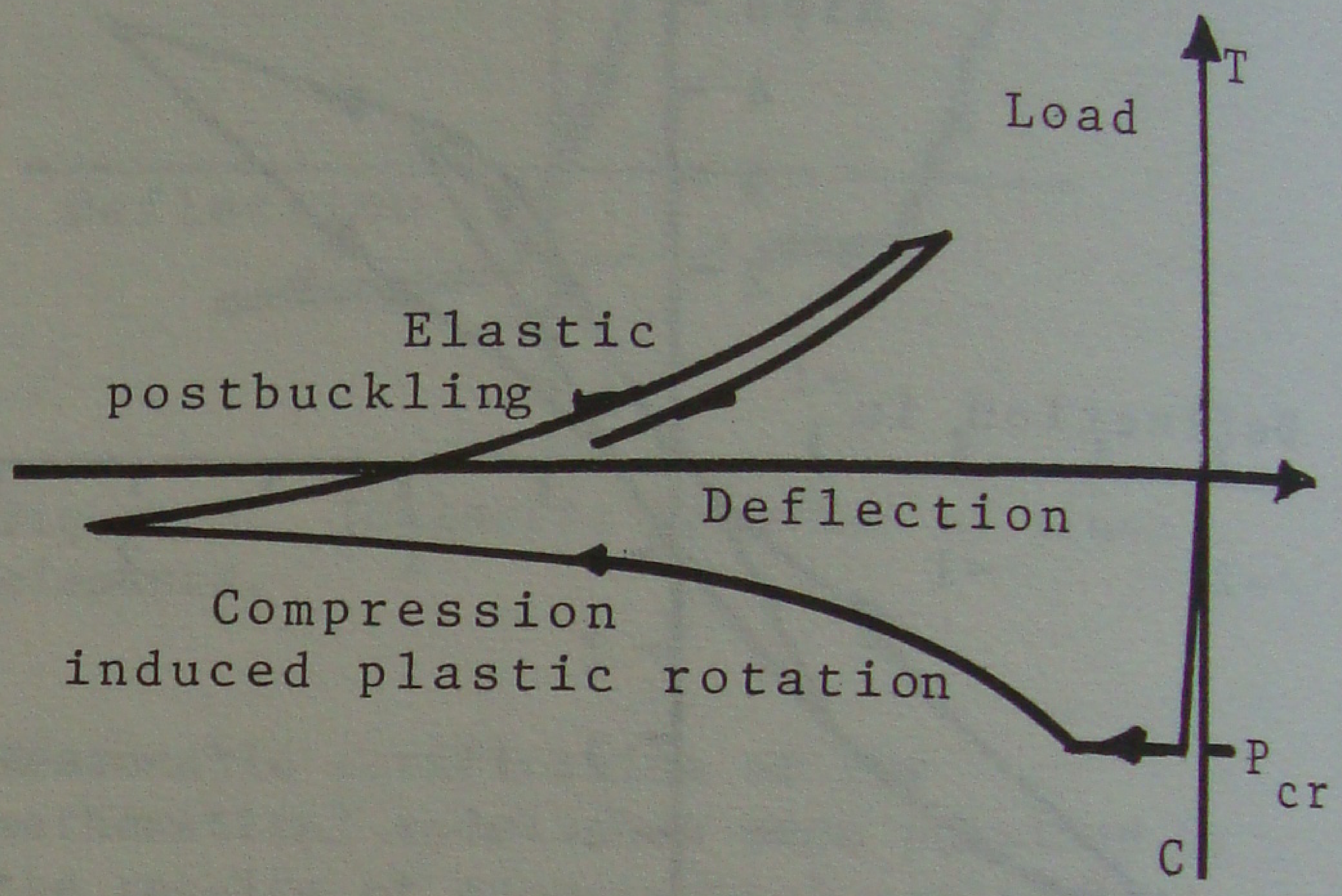

Figure 7. Hysteretic behavior of a bracing member.

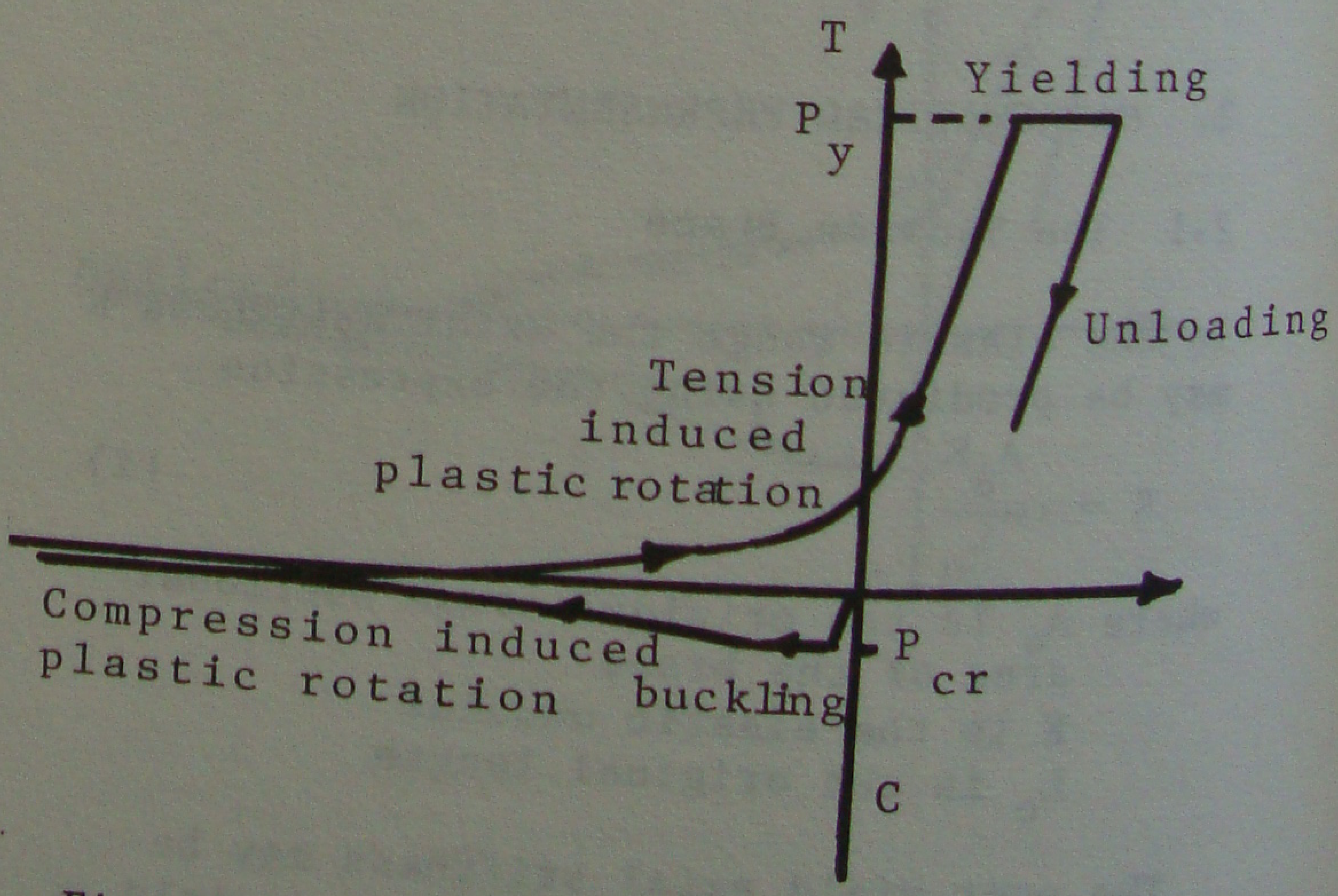

Figure 8. Hysteretic behavior of a bracing member.

In Figure 8 the change from buckling to compression induced plastic rotation is shown, followed by reversal to elastic post buckling and tension induced plastic rotation with a second reversal to inelastic post buckling. Two typical deformation cycles of a bracing element are shown in Figure 9.

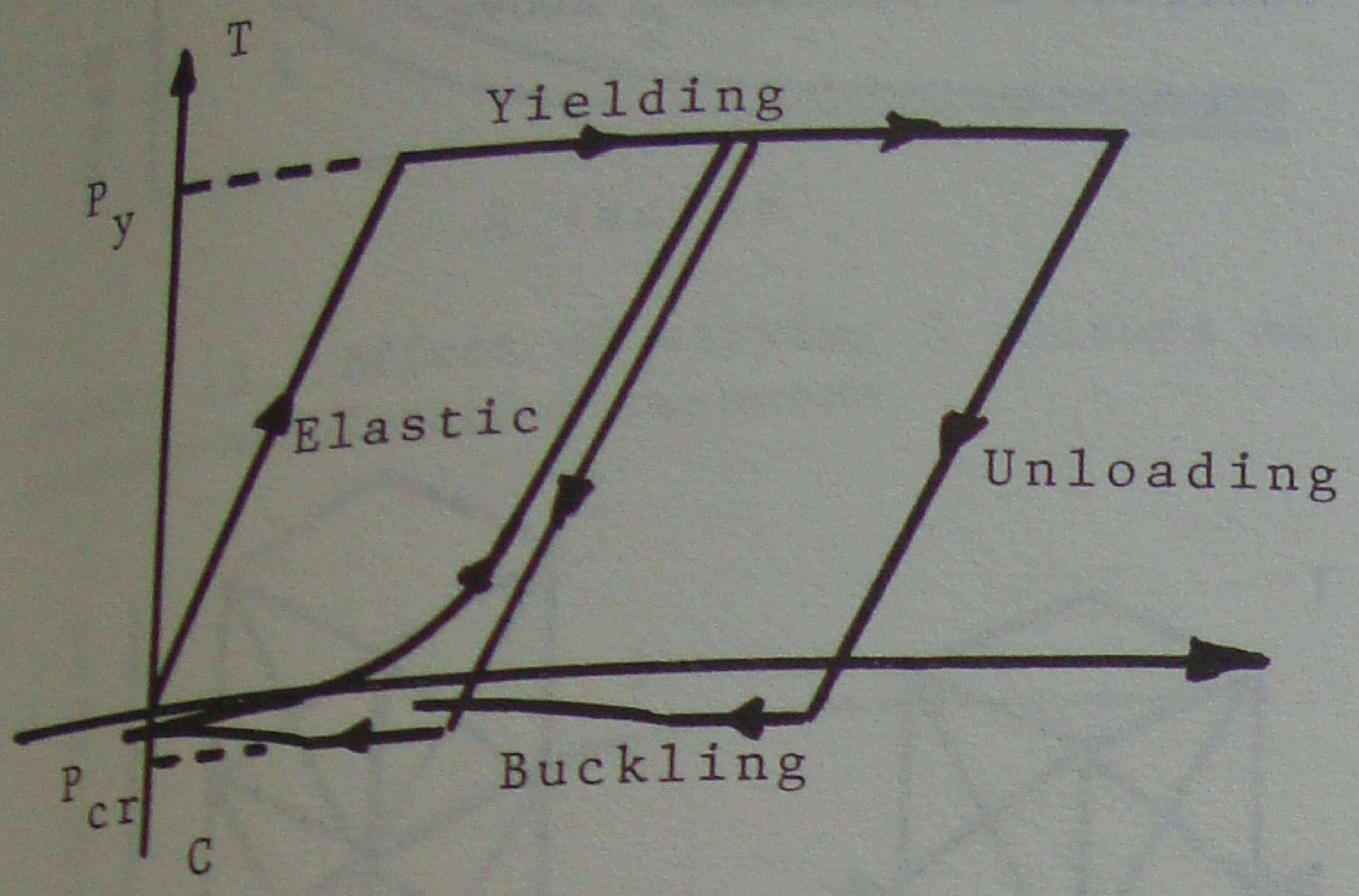

Figure 9. Hysteretic behavior of a bracing member.

4. RESPONSE TO SEISMIC EXCITATION

Most applications of diagonal braces in civil engineering structures involve their incorporation into frames which possess at least some lateral stiffness contributed by the moment resistant joints of the basic frame. The over all stiffness of the system can be derived by superposition of the base frame stiffness on the bracing stiffness. Matrix techniques allow this to be accomplished relatively efficiently.

The response to time varying loads such as those arising in earthquakes can then be determined by standard numerical integration techniques (Clough, 1975). The non-linear stiffness characteristics are handled by assuming linear stiffness properties over the short time intervals used in the integration with adjustment to the stiffness, as appropriate, at each time step. The process may be summarised as the computer based numerical solution of the equations

$$[M] \cdot \{\Delta\ddot{x}\} + [C] \cdot \{\Delta\dot{x}\} + [K] \cdot \{\Delta x\} = -[M] \cdot \Delta\ddot{x}_g$$

where M is a discrete standard mass

$\Delta\ddot{x}$ is an incremental acceleration

C is the velocity proportional damping

$\Delta\dot{x}$ is an increment of velocity

K is the system (lateral) stiffness

Δx is an increment of displacement

$\Delta\ddot{x}_g$ is an increment of base acceleration.

This technique has been applied (Shepherd, 1973b) to the analysis of a cross braced water tower frame (Moran, 1958).

In Figure 10 the response is presented of the three storey frame to a digitised earthquake when the mild steel tension braces are allowed to yield at appropriate load levels.

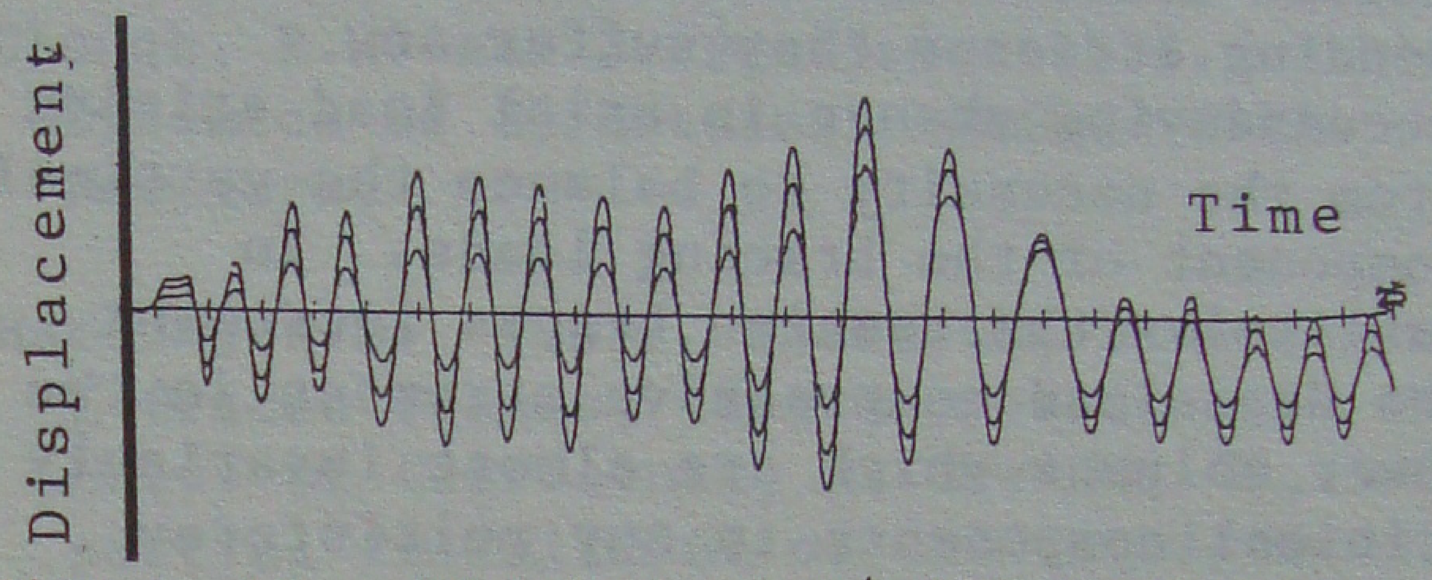

Figure 10. Displacement/time response.

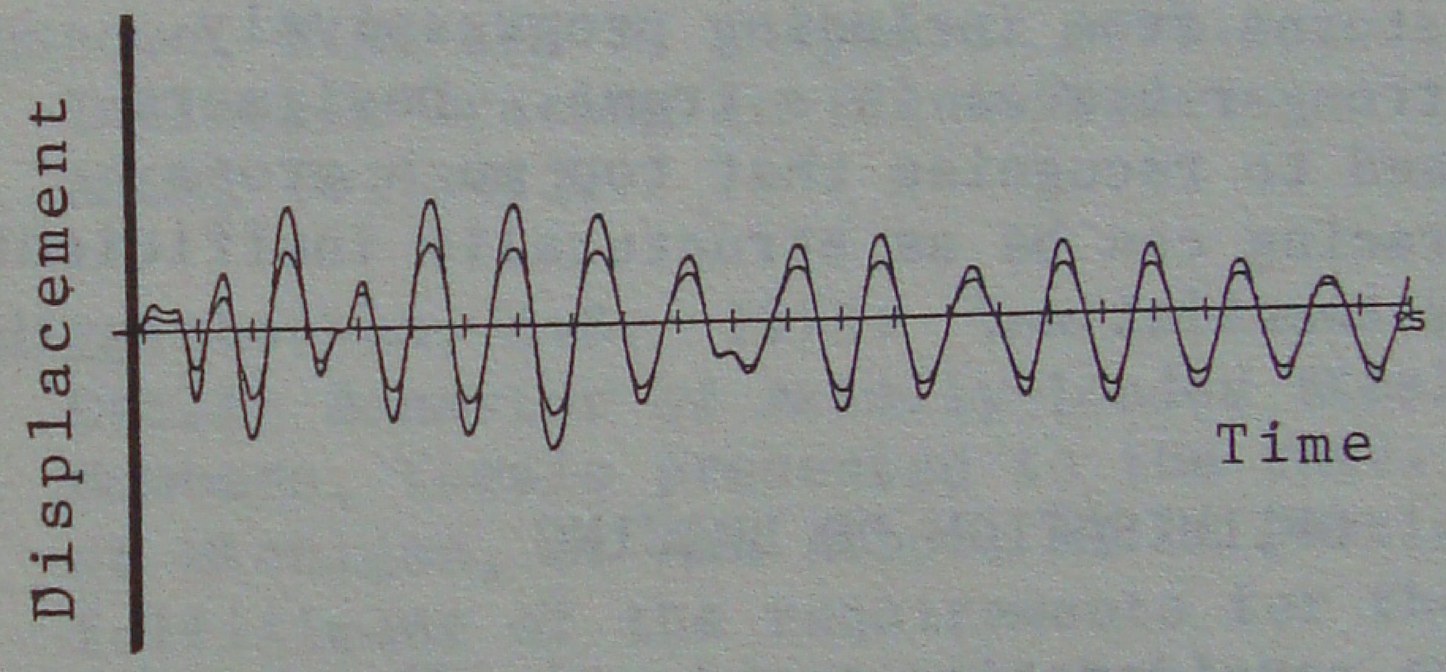

Figure 11. Displacement/time response.

The response of a similar frame but with miltiphase sacifical bracing of total weight approximately equal to that of the first set of braces is shown in Figure 11. Significant reduction in the seismic induced movement is evident in the case where the response was broken up by the multiphase sacrificial bracing members.

More recently (Haroun, 1986) the method has been applied to the analysis of a single storey portal frame in which the cross-bracing could act in both compressive and tensile modes. Again it has been demonstrated that the response of the structural system in which the bracing system is modeled more realistically is significantly less than the response of the equivalent infinitely elastic system.

5. BRACING LIMITATIONS

The sparse application of bracing systems in past practice reflects some less than satisfactory structural characteristics. Details, noticeably end connections, require special attention if premature failure is to be avoided. Such unanticipated fractures can leave an otherwise satisfactorily balanced structural system vulnerable to catastrophic torsional response. The use of parallel braces, at least one of which is designed to exhibit significant ductility, can prevent the worst features of torsional imbalance occurring.

The reduction in the deflections of frames afforded by bracing does introduce an adverse consequence in that although column members benefit from a reduction in bending stresses they suffer an accompanying change in axial load arising from the necessity to balance the vertical component of the bracing loads. In particular the tension braces increment the dead load compressive stresses in the lower columns which are almost invariably critical components in any multistorey structural system. This consideration leads to the concept of diminishing returns from including progressively stronger braces in a frame. Designers need to recognise that too much cross-bracing can be as structurally inefficient as too little.

6. OPTIMISATION OF BRACING

The consideration previously discussed prompted a pilot investigation of the proportion of cross bracing which becomes counter productive when incorporated in a rigid jointed plane frame. Three space frames were modeled. Each was one bay wide and one bay in width. The dimensions of the one, two and three bay frames are shown in figure 12.

The variable S was selected to represent the ratio of initial axial stiffness of the bracing member to that of the column member at any chosen level. Thus an unbraced bay has S equal to zero whereas a bay with the braces each equal in axial stiffness to the corresponding column has an S value of unity.

Seven pairs of single cross braces were modeled, in turn, in each of the three frames; all bays in each frame being braced similarly for any one case. S values of 0.0, 0.1, 0.2, 0.3, 0.50, 0.75 and 1.00 were used. The twenty-one structures were analysed to determine the maximum top level lateral displacement and the minimum axial force in a lower column using the techniques discussed earlier in this paper. The digitised ground acceleration of the El Centro 1940, E-W. component was used as input and the braces were allowed to buckle and yield as outlined in section 3 above.

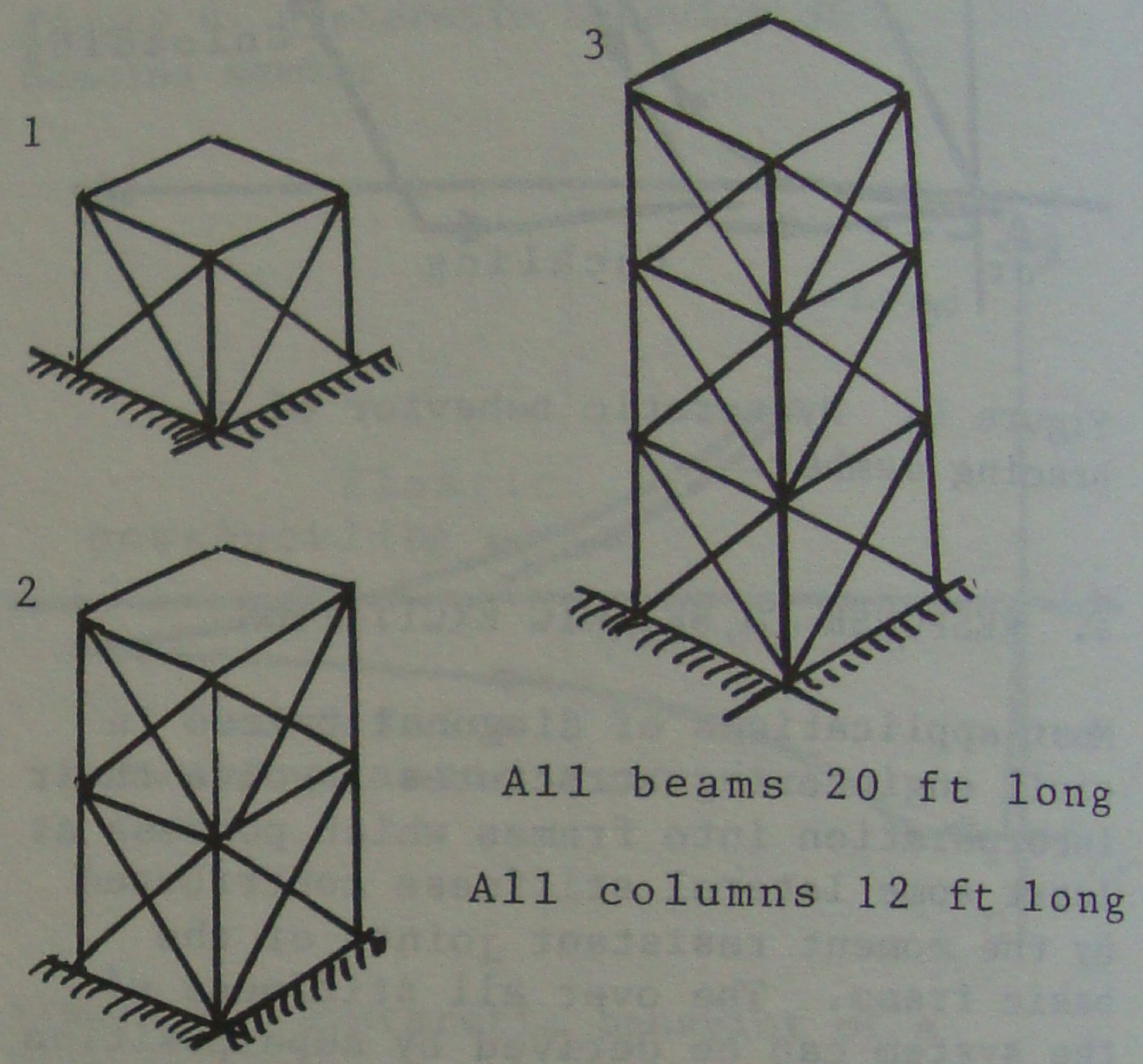

Figure 12. The frames modeled.

The analysis results are summarised in Figures 13 and 14. Examination of Figure 13 indicates that significant reductions in response are obtained for relatively low S values. Figure 14 confirms that higher S values are detrimental to the column axial load demands. Although care must be exercised in forming any general conclusions from such a limited study, the results tend to confirm the intuitive view that a relatively small proportion of bracing, of the order of S equal to 0.25, will result in a more structurally efficient seismic resistant structure that achieved by a much more generous provision of bracing. One obvious reason is that inelastic action, with subsequent absorption of input energy, is achieved only when the braces do reach yield.

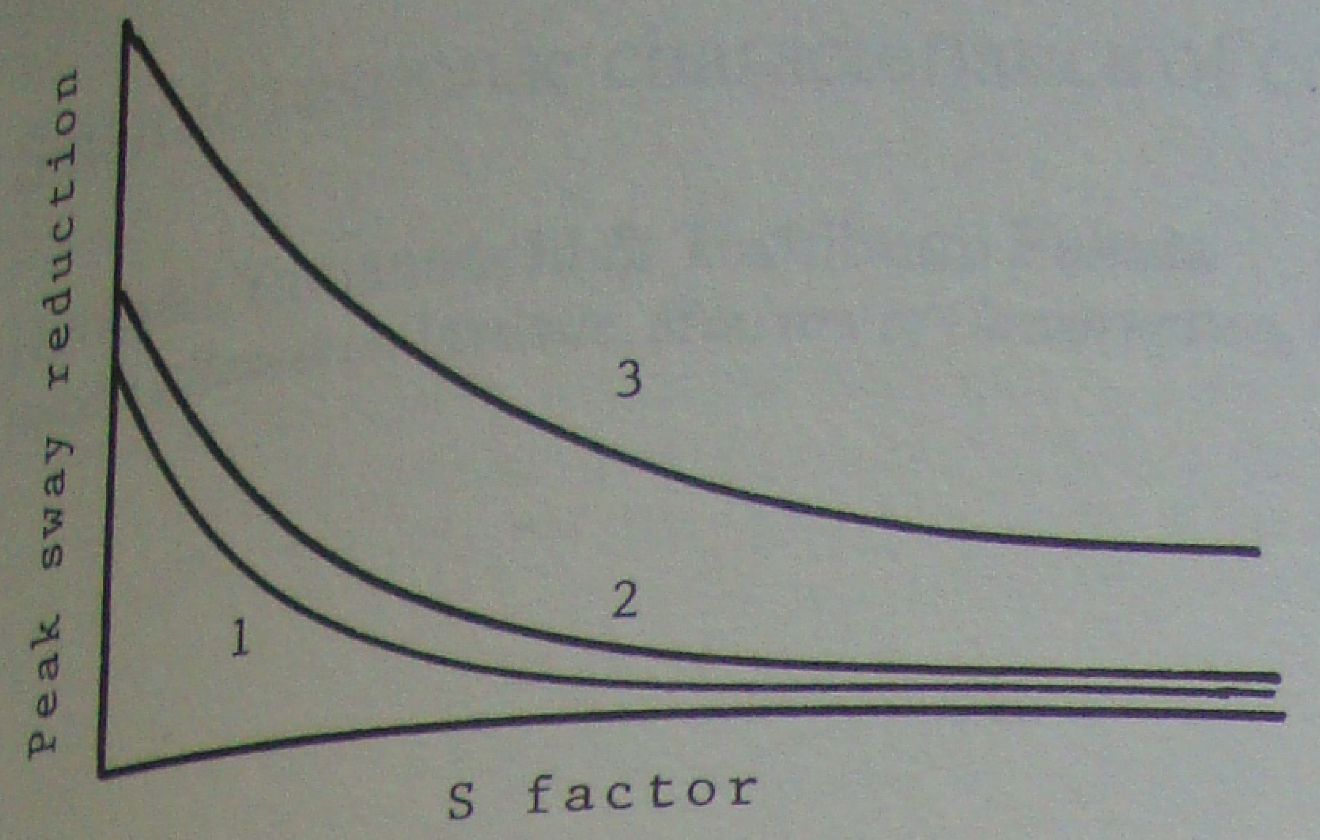

Figure 13. Effect of varying S factors on maximun acceleration response.

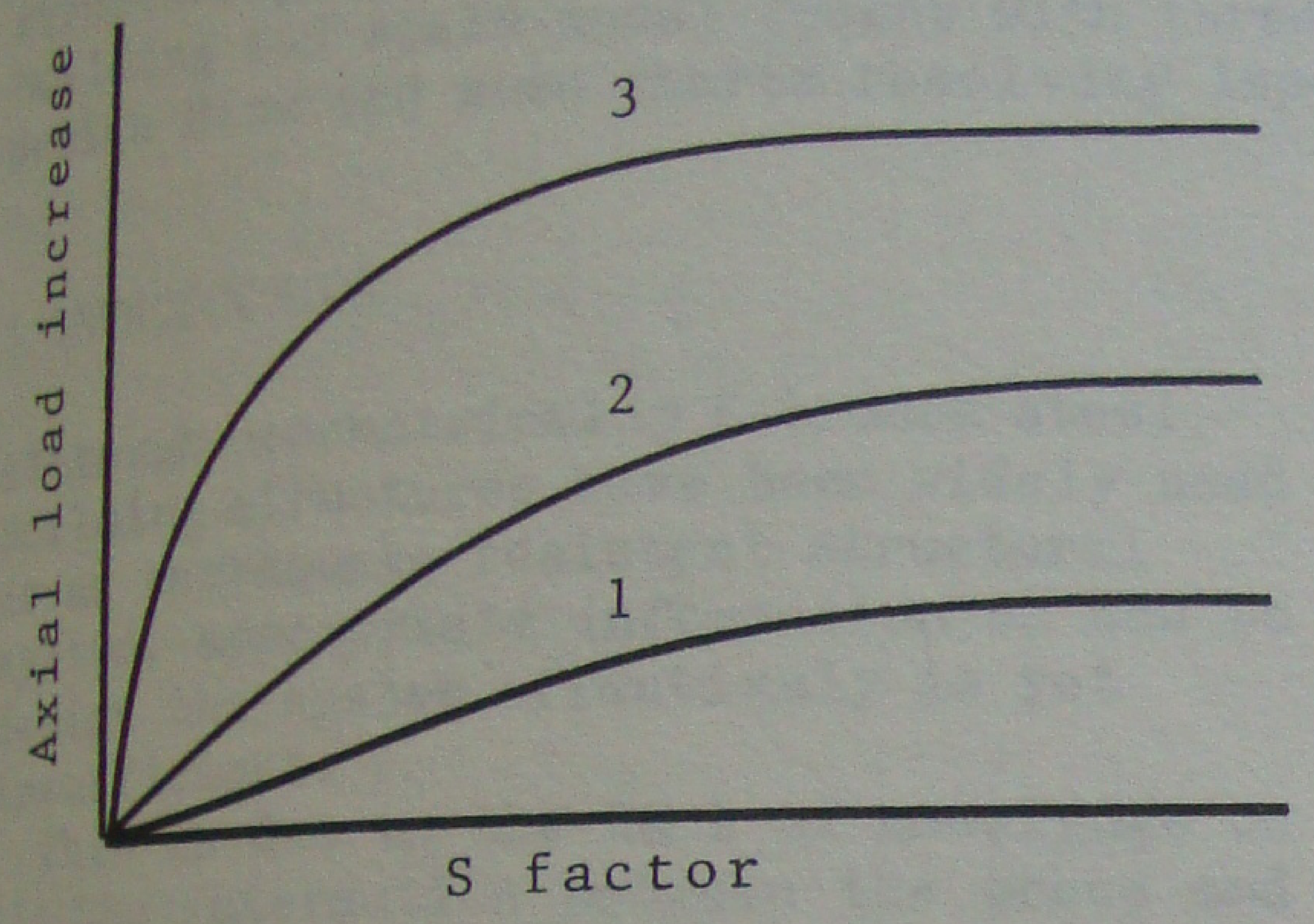

Figure 14. Effect of varying S factors on maximum axial column load.

7. CONCLUSIONS

The uncertainty regarding the reliability of bracing under seismic loading has influenced design codes. The Uniform Building Code typifies this in the use of a large structural type magnifier in the horizontal design load requirement for elevated water tank support structures when they are of cross-braced leg configuration. In cases where a designer has the option of conducting a more sophisticated analysis as part of the earthquake resistant design process than blind compliance with the letter of the applicable code would necessitate, the tools to facilitate this are currently available. Mathematical models can be used with confidence to predict seismic response and to refine the design.

The results of a limited investigation of the optimum strength of bracing confirm previous veiws that over-strong bracing can be detrimental to the response of a structure to earthquake loading.

It seems probable that continued improvement in the awareness of the benefits and disadvantages of bracing in economically providing gains in rigidity of essentially flexible structures will prompt its return to favor in seismic resistant construction.

8. ACKNOWLEDGEMENTS

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