PRELIMINARY PLASTIC DESIGN OF
MULTI-STORY FRAMES
BY COMPUTER

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1. INTRODUCTION

Research into the plastic design of multi-story steel frames has progressed to the point where fairly complete methods for the analysis and design of such frames are available.¹,² A design manual for the plastic design of braced frames presents the results of this work as applied to braced frames in a form suitable for design office use.³ Some buildings have already been built from designs using the methods for braced frames now available.⁴

A designer attempting to design an unbraced multi-story frame by the methods presented in Ref. 1 might consider the methods too tedious to be practical for his use. This paper will discuss two computer programs which have been prepared to aid in the preliminary design of unbraced multi-story frames by reducing the amount of routine calculations performed by the designer and by eliminating the need for certain graphical plots.

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*Superscripts within text refer to corresponding items in reference list at end of paper.
The first of the two programs to be discussed is a program in FORTRAN language for the preliminary plastic design of unbraced frames. This program operates with a small amount of input information to tabulate design data for every member of a frame and provide a set of forces and bending moments for each member which will be used by the designer to select section sizes from available design tables. In its effect this portion of the design could be compared to an allowable stress design prepared using the familiar portal or cantilever methods of analysis. The amount of work to perform this portion by hand plastically would be comparable to that for those elastic methods. The very fact that the procedure is so easy to do is an indication that it should be a task for the computer rather than an engineer.

The second program to be described is also in the FORTRAN language. This program analyzes individual stories of a trial frame by the sway subassemblage method. It computes coordinates of a load versus sway plot in the elastic and inelastic range, a procedure which formerly required calculating and plotting a curve for each column in a story and then summing the ordinates.

This paper will assume that the potential user of such a program is initially most concerned with just what information the designer will have to prepare for submission to the computer and what results will be returned to the designer as output. Therefore computation procedures and programs will only be briefly outlined and primary attention will be given to the input and output phases.
of the programs. Complete printouts of the programs are presented in Refs. 8 and 9 which may be obtained at the cost of reproduction from Fritz Engineering Laboratory, Lehigh University.

2. PRELIMINARY DESIGN OF UNBRACED FRAMES

The first program, Preliminary Design of Unbraced Frames, is partitioned into two phases, primarily so that relatively large size frames can be handled on a relatively small computer. Phase I is a program for tabulation of design data which provides a punched card output for use as input data for Phase II. Phase II uses the data of Phase I to compute values of moment for all girders and moment and thrust for all columns for three cases of loading most considered in design.

The program as now available is dimensioned to handle regular-shaped, rectangular frames up to eight bays and 48 stories. With minor modifications it has been run successfully on several computers such as: GE 225, IBM 360, CDC 8130, and CDC 6400.

2.1 Phase I--Tabulation of Design Data

Phase I of the program accepts data about the geometry of the structure and the general load patterns and translates this into loads on individual members based on the tributary areas supported by the members. Figure 1 shows the shape of frame which can be handled by the program and the dimensions which must be input by the designer. In the proper format, the designer must input the number of stories, the number of bays, the bent spacing, bay spans,
Fig. 1 Frame Dimensions
and story heights. Load information to be supplied is: load factors to be used in design, uniform dead and live floor loads, spandrel loads on columns, weight of column and fireproofing (assumed), size of concentrated wind loads on each story, and a value for the assumed sway deflection divided by story height. In a 10-story, 3-bay frame with all story dimensions and load intensities the same, this input data amounts to 22 punched cards. When load patterns and geometry are more irregular, proportionally more cards are required as input. Conversely, a 48-story frame with all story loads and heights the same would only require the same 22 punched cards.

The Phase I input data deck is fed into the computer along the Phase I program deck consisting of about 695 cards and the computer calculates the results to be described in the output phase. The calculations are mainly the multiplication of unit loads by tributary areas for each member to be designed. The program includes a function routine to apply the live load reduction provisions of the American Standard Building Code Requirements for Minimum Design Loads in Buildings and Other Structures A58.1--1955. Live load reduction provisions of local building codes could be considered by changing the function routine in the program to suit the particular building code.

A flow chart for Phase I is given in Fig. 2. Following the input and computation steps just described, the output routines are indicated. Almost identical output is produced in two forms: a
Fig. 2 Flow Chart Phase I--Load Tabulation
printed output on paper, and a punched card output to be used as input for Phase II. The information contained in both forms of output includes: frame geometry identical to the input; loads on each column, and uniform loads per foot on each beam. The loads given in the card output are the gravity load values at working level. In the printed output, the values of the ultimate design loads determined by applying the load factors both for gravity load alone (1.70) and for wind plus gravity load (1.30) are presented. In addition the story moments due to the overturning effects of both wind and the P-Δ effect of gravity loads in a displaced position are printed. Figure 3 indicates in symbolic form the load information output by Phase I.

Fig. 3 Sketch Symbolizing Loads Computed and Tabulated in Phase I
2.2 Phase II--Girder Moments and Moment Balance

Phase II of the preliminary design program takes the frame geometry and loading on the structure and prepares listings of the required plastic moments for girders and of controlling values for moment diagrams for girders and columns. In addition it lists the thrusts in each column. All moments and thrusts are tabulated for three load cases: (1) gravity load alone, (2) gravity load plus wind from the left, (3) gravity load plus wind from the right.

The input for Phase II, unless altered by some design options to be described later, is the deck of output cards punched out by Phase I. This data of approximately 144 cards for a 10-story, 3-bay frame would be input with a program deck of approximately 1350 cards. The data would consist of: the original frame geometry dimensions, the working gravity load values of load per foot on the beams, the working gravity load values of thrust on each column, and the sum of the overturning moments due to wind and P-Δ on each story.

Concepts of the theory for preliminary analysis are illustrated in Fig. 4, 5, and 6. Figure 4 shows a free body diagram of columns in a story of height h subjected to a sum of column loads ΣP and a sum of wind shears ΣW. The story is displaced horizontally by an amount assumed to be Δ. The sum of the column end moments ΣM₀ required to resist the overturning moments caused by wind and the gravity loads in the displaced position can be determined from an
equilibrium equation:

\[ \Sigma M_c = - (\Sigma H)h - (\Sigma P)\Delta \]  

(1)

This process is repeated for all stories starting from the top of the frame and working downward. At this stage, the sizes of the individual column end moments are not known, only their total sum. To obtain individual moments to guide the designer, the sum may be divided by the number of column ends, or some other distribution which suits the designer may be selected as an option.

Next the effect of these moments on the end moments of the girders in a floor level may be determined by considering equilibrium of two consecutive stories as shown in Fig. 5. Here the free body sketches of stories n-1 and n are given along with free body sketches of floor level n between them. Since the sum of the moments around each joint must equal zero, an equilibrium equation for the sum of the end moments of the girders can be derived in terms of the sums of column end moments above and below the floor level. It is arbitrarily assumed that half of the sum of column moments in each story is exerted at the top and half at the bottom of each set of columns. This is equivalent to assuming that the columns have inflection points at mid-height. While this assumption is not perfectly accurate, it is suitable to use for a preliminary selection of members because a column in double curvature has nearly the same capacity no matter where the inflection point is located. The sum \( \Sigma M_g \) of the end moments on all girders in the level n may be
Fig. 4 Sum of Column End Moments for Story Equilibrium

Fig. 5 Sum of Girder End Moments for Equilibrium of a Level
obtained from the equilibrium equation based on Fig. 5 as follows:

\[ \Sigma M_g = -\frac{1}{2} \left[ (\Sigma M_c)_{n-1} + (\Sigma M_c)_n \right] \]  

Design of girders to resist these moments plus the moments caused by transverse loads on the girders themselves is based on equations for the moment diagram of the girder shown in Fig. 6. This girder is loaded by the factored gravity load \( F_2w \). The end moments \( M_g \) due to wind plus the \( P \cdot \Delta \) effect are represented by \( M_1 \).
and $M_2$ shown referenced to the intersection of the member centerlines. The joint is assumed to be relatively rigid within the boundaries of the column section, so the plastic behavior is all assumed to take place within the clear span of length $L_g$.

Equations for the statical solution of the member shown in Fig. 6 will result in values of the plastic hinge moment $M_p$ required for a rolled section to serve as a girder to resist the given moments. Values for the end moments $M_1$ and $M_2$ then define the exact shape of the moment diagram for the given transverse load. Moment diagrams for all the girders in a floor level along with the preliminary column moment diagrams serve as the beginning point for an equilibrium process called moment balancing.

Preliminary girder moment diagrams for girders in a typical floor level are shown in Fig. 7 along with column moment diagrams based on Eq. 1. Examination of the sum of moments at each joint reveals that the joints are not in balance even though it is assured by Eq. 1 and 2 that the sums of all moments are sufficient to maintain equilibrium in the story. The left joint is seen to have too much column moment, while the center joint has too little column moment to balance the girder moments. Quite by accident the right joint is in balance. The moment balancing process is an orderly bookkeeping process for altering and recording changes in the column moments at each joint to bring the joints into equilibrium without disturbing story equilibrium.
Fig. 7 Preliminary Moment Diagrams
Prior to Moment Balance

Fig. 8 Preliminary Moment Diagrams
Resulting From Moment Balance
The meaning of the moment balancing process can be illustrated by Fig. 8 which shows by solid lines the final moment diagrams, now in balance, resulting from adjusting column moments from their original arrangement shown by dashed lines. Any increase in a column moment in one story must be accompanied by an equal decrease in moments among other columns in the same story. Examination of the values in Fig. 8 shows that this requirement was met without disturbing either the girder moments or the column moments at any other floor level.

In Fig. 9 is presented a flow chart for Phase II. There are indicated the card input and the computations just described. These are followed by a printer output consisting of the same frame geometry, moments for both beams and columns, and column thrusts. Both moments and thrusts are printed for all of the three loading conditions considered, namely: gravity, wind from the left plus gravity, and wind from the right plus gravity. Figure 10 depicts typical moments for all three cases for a story. Figure 11 depicts the three cases of column thrusts resulting when the wind shears occurring in the girders are added in to those resulting from gravity alone.

The results of the printout of Phase II are adequate to permit the designer to select girder member sizes from the plastic modulus tables of the AISC Manual\textsuperscript{5} and to select beam-column sections for the columns from the $M_{pc}$ tables in Part II of the Design Aids Booklet.\textsuperscript{2} Usual additional checks against local and lateral buck-
PHASE II

CARD INPUT
- Frame Geometry
- Beam Loads (Gravity)
- Column Loads (Gravity)

COMPUTATIONS
Girder Moments & Moment Balance
- Gravity
- Wind From Left
- Wind From Right

PRINTER OUTPUT
- Frame Geometry
- Moments (Beams & Columns)
- Column Thrusts
  - Gravity
  - Wind From Left
  - Wind From Right

Fig. 9 Flow Chart for Phase II—
Girder Moments and Moment Balance
Fig. 10 Three Cases of Final Moments From Moment Balance

Fig. 11 Three Cases of Column Thrusts
ling must be made by observing that member slendernesses are within recommended limits and that support provided by floor system members or other members framing perpendicular into the bent is adequate. With good luck, the members selected from this preliminary design will prove to be just right when the frame is evaluated by some exact analysis method. The sway subassemblage method of analysis to be discussed in Art. 3 is one means of more accurately evaluating the strength and stiffness of a single story.

2.3 Options to Phase II

The output from Phase I and the standard program for Phase II should be adequate as they stand for most typical designs. However, the designer can exercise certain options in setting up the input for Phase II if he believes revised versions of certain procedures will provide him with a better design. Guidance for using such options will probably most often result when a designer has accurate information about the probable real behavior of a given type of structure or when a second preliminary design is being attempted to optimize an earlier one.

The options available to the designer can be generalized as: (1) revised sway moment distributions, (2) revised girder and column depths, (3) use of positive plastic moment factors, and (4) revised joint balancing ratios.

Revised vertical sway moment distribution factors would be inserted into the data when the designer decided to distribute the column moments in some manner other than equally to the tops and
bottoms of columns in a story. Revised horizontal moment factors would distribute the initial column end moments in some manner other than equal to each column. Revised girder sway moment factors would be used to assign the sway moments in the level in a manner other than equally to each girder.

The member size options permit probable real depths to be assumed rather than the column depths of 1 ft. and girder depths one-twentieth of the span which are assumed in the program.

Use of the positive plastic moment factor option allows the designer to determine girder sizes needed to carry the applied forces without forming the second plastic hinge which usually forms to the windward of the center of the girder. This procedure will size the structure to prevent formation of a mechanism at the design ultimate load. It will improve the overall stability of the frame and will decrease working load sway. Use of a factor less than 1.0 initially may eliminate the need to revise a design based on strength of the structure to reduce sway of the structure.

The final option is the use of a revised joint balancing ratio. Ordinarily during the moment balance, equal adjustments are made above and below each joint. Designer preference for a distribution other than equal above and below the joint can be exercised by changing the joint balancing ratio in the input data.
3. **SUBASSEMBLAGE METHOD OF ANALYSIS**

Evaluation of the load versus sway characteristics of a story of a frame already designed can be accomplished by the subassemblage method of analysis.\(^1,6,7\) In this method of analysis, a frame such as shown in Fig. 12 is separated into a typical story such as shown in Fig. 13, and then further separated into typical exterior and interior subassemblages such as shown in Fig. 14. The individual subassemblages are analyzed and then the results are summed for a given story.

![Fig. 13 Typical Story of a Frame](image)

Two stiffness properties are important in the analysis of subassemblages. The first of these is the girder stiffness which tends to resist rotation of the ends of the girder at joints. Figure 15 shows that the change in restraining moment \(\delta M_r\) which occurs at the ends of girders which rotate by equal amounts \(\theta\) is
Fig. 14 Typical Exterior and Interior Subassemblages
given by

$$\delta M_r = 6 \frac{EI \theta}{L}$$

(3)
in terms of the modulus of elasticity $E$, moment of inertia $I$, and girder span $L$. Figure 16 shows that the change in restraining moment for a given rotation is reduced in half when a plastic hinge forms at the lee end. Similar changes in girder restraint as all girders in a story gradually approach moment diagrams such as in Fig. 6 are used to complete the analysis.

The second important stiffness property considered in the analysis is the horizontal shear versus sway characteristic of a given column as it is restrained by beams of different stiffnesses. Figure 17 shows a typical subassemblage design chart for a given axial load ratio and slenderness ratio. The chart contains a family of curves, each for a given stiffness of restraining members presuming those members can retain their original stiffness through infinite rotation. Since the girders are bound to reduce in stiffness as plastic hinges form, cutoff lines for various limiting restraining moments $M'_r$ in terms of the column plastic moment reduced by compression $M'_{pc}$ are shown as lines sloping downward to the right. These curves are the ones used for manual execution of the sway subassemblage method, but a simplification is used for the computer program. This simplification is depicted in Fig. 18 which shows just one of the family of curves as a fine curving line and shows the simplification as a pair of straight lines. Although there is apparently quite a gap between the real curve and the approximation,
\[ \delta M_r = 6 \left( \frac{EI}{L} \right)_{BA} \theta \]

Fig. 15 Girder Stiffness in Elastic Range

\[ \delta M_r = 6 \left( \frac{EI}{L} \right)_{BC} \theta \]

Fig. 16 Girder Stiffness After Formation of One Plastic Hinge

\[ \delta M_r = 3 \left( \frac{EI}{L} \right)_{BC} \theta \]
Axial Load and Stanchiess

Fig. 17 Subassembly Design Chart for a Given

\[ P = 0.50 \text{f}, \quad h = 20 \text{f} \]
Fig. 18 Subassemblage Curve as Approximated by Computer
most solutions fall within the range where the straight line is
the same as the real curve. The major exception occurs when the
column forms a plastic hinge.

The task which the computer must accomplish for each story
is shown in Fig. 19. A graph of column shear $Q$ versus story sway
$\Delta/h$ must be determined for the subassemblage containing each
column. This figure shows the graphs for a story having three
columns. Each graph will be a series of straight lines having one
to four sharp breaks where restraining stiffness acting on the
column changes as plastic hinges form. Since all columns are
assumed to sway equally, the total horizontal shear on the story
can be obtained by adding the shears for all columns $Q_a$, $Q_b$, and $Q_c$
at a given value of sway $\Delta/h$ to obtain the total story shear $Q$.
When this is accomplished for the complete desired range of sway,
the complete graph is obtained.

3.1 **Input--Subassemblage Method of Analysis**

To use the program for subassemblage method of analysis, the
following data must be input: frame geometry, uniform loads on
beams, column thrusts including both gravity and wind, member
properties, and an incremental value of joint rotation which will
be gradually increased until calculations show that enough sway
would have been caused in the story to reach the maximum load and
then deform the frame further.
Fig. 19 Summation of Subassemblage Curves for a Story
The frame geometry input is the same set of centerline dimensions used in the preliminary design. The loads are the loads output by Phase II of the preliminary design.

The large bulk of the input will be one data card of member properties for each member selected in the preliminary design. Here it is possible to take advantage of a standard computer card deck furnished by a steel company containing handbook section properties of all rolled shapes. Figure 20 shows a sketch of a typical card as altered by the authors for use in plastic design. The card provides several section properties of the section which are not used in the program. These have been faded out in the sketch. The program does use the shape size, area, $I_{xx}$, and $r_{xx}$. Added to the card is a value of the plastic modulus $Z_x$ as obtained from a handbook. Use of these cards eliminates the need for typing section properties each time a section is used in design.

![Fig. 20 Sketch of Member Section Property Card](image)
3.2 Flow Charts--Subassemblage Method of Analysis

Figure 21 presents a simplified flow chart for the first portion of the program. Following a record of the data input described above, the flow chart indicates that stiffnesses, moments and rotations existing in the initial state of the frame prior to application of wind loads are calculated. Similarly the limiting values of these functions at which plastic hinges and mechanisms form are calculated. With this data in hand, the program proceeds to increment the joint rotation \( \theta \) as would occur when the structure began to sway due to wind.

Part II of the flow chart is given in Fig. 22. It shows a series of tests for plastic hinges and mechanisms forming in subassemblages. These tests are made after each increment of \( \theta \). If no hinges or mechanisms are formed, the program returns to increment the joint rotation again. When a test shows that a plastic hinge has formed in a girder, the program determines the load and sway at this point and interpolates values linearly between the previous load versus sway point and this point. It then revises the stiffness to reflect the formation of a plastic hinge and proceeds to increment joint rotation if no mechanism has formed. When a test shows that a mechanism has formed in a subassemblage, the load and sway are calculated for subsequent sway from a mechanism equation representing one of the straight lines sloping downward to the right in Fig. 17. At this stage the program returns to the starting point and repeats the calculation for the next subassemblage.
DATA INPUT
- Frame Geometry
- Loads
- Member Properties (Steel Company Deck)
- Incremental Theta

TEST:
NOT LAST SUB.

TEST:
NO MECH.

TEST:
NO GIRDER HINGE

CALCULATE:
- Initial & Limiting
- Stiffnesses
- Moments
- Rotations

INCREMENT JOINT THETA

Fig. 21 Flow Chart--Subassemblage Method of Analysis--Part I
Fig. 22 Flow Chart--Subassemblage Method of Analysis--Part II
CALCULATE:
Initial, etc.

NO

TEST If Last Subassemblage

YES

SUM Q for All Columns
for Each \( \Delta/h \)

PRINTER OUTPUT
Q vs \( \Delta/h \)
Tabulated for Story

Fig. 23 Flow Chart--Subassemblage Method
of Analysis--Part III
When a test shows that the last subassemblage has formed, the program calls for the computer to sum the shear forces $Q$ for all columns for each desired value of $\Delta/h$ up to 0.0250. This is the numerical equivalent of the graphical process shown in Fig. 19. The next step, as shown in Fig. 23 the final part of the flow chart, is to print out a tabulation of total shear on the story versus $\Delta/h$ along with sufficient information about the structure to identify the problem solved.

4. APPLICATIONS OF SMOA PROGRAM

In Fig. 24 is shown a comparison of the load versus sway curve for a typical story as calculated by computer and by hand. The computer plot may be seen to be similar in shape but it slightly overestimates the maximum strength. Figure 25 shows the effect of changing the value of the joint rotation increment $AITH$ used in computing the curve. The curve with $AITH$ equal to 0.00020 radius is the same curve presented in Fig. 24. Decreasing the size of the increment to 0.000020 reduces the height of the apex slightly, bringing the prediction nearer to that obtained manually. This also would cause the program to run longer in the computer. Increasing size of the increment to 0.0020 obviously raises the prediction to an unreasonably unconservative value. Future calculations with this program are being planned with a compromise value of 0.00010 for $AITH$.

The program was also used to study some effects of changing the structural design. In Fig. 26 the effects of changing to the next larger size and the next smaller size of columns are plotted against
Fig. 24 Comparison of Hand and Computer Solution
Fig. 25 Effect of Changing Incremental Theta
Fig. 26 Effect of Changing Column Sizes
Fig. 27 Effect of Changing Girder Sizes
the results of the trial design. It is seen that increasing the column size did not materially improve the design either for ultimate load or for working load sway. All designs exceed the design ultimate load needed indicating that changes might result in some economy. It is probable however that a reduction in member sizes might cause a trend toward unsuitable sway at working load.

The effect of changing girder sizes by one step is shown in Fig. 27. It is apparent that either increases or decreases cause an equivalent change in the strength and stiffness of the whole story.

5. SUMMARY AND CONCLUSIONS

Two workable programs for the preliminary design and analysis of the lateral load versus sway behavior of unbraced frames have been developed. With relatively little effort they should allow the trial design of many frames of alternate design in order to study the effect of a range of major variables.

These two programs give promise of now being able to use the best current knowledge of plastic design in practical designs of multi-story frames. They should contribute to making the plastic design of unbraced frames of practical reality.

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