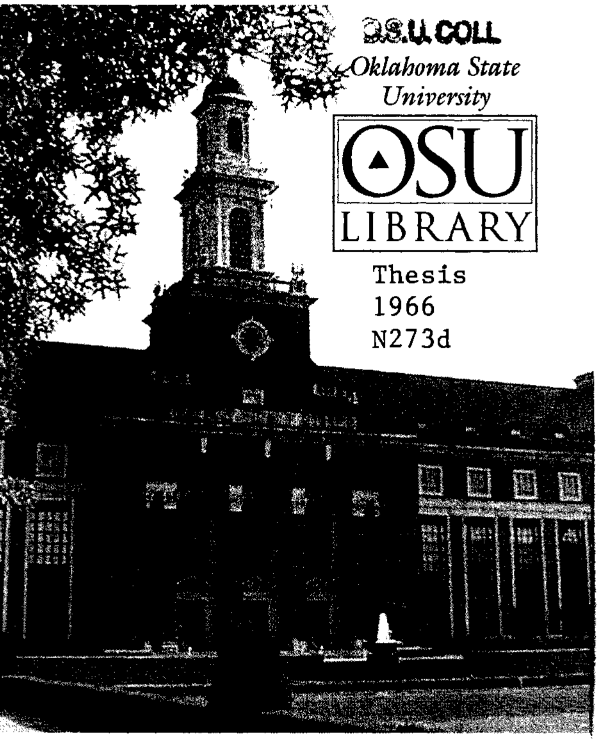

DESIGN OF TALL BUILDINGS BY THE USE OF A SIMULATOR

Seshagiri

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By

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USE OF A SIMULATOR

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CHAPTER I

INTRODUCTION

Growing urbanization and high-density land use have given rise to the increasing trend toward high-rise construction. The tall framed building has now taken its place as one of the most common building types in present-day architecture. The design of such buildings, however, presents problems due to the unweildy amount of computations involved in a thorough analysis of the structure. The substantial number of redundants in multistory structures make them statically indeterminate to a high degree, notwithstanding their basic simplicity of framing. Rigorous treatments such as slope-deflection and energy methods invariably result in a large number of simultaneous equations and their associated large-sized matrices. Even with simplifying assumptions such as lack of torsional restraint, axial or shear deformations etc., these methods are tedious to work with. As a result, complete analyses of multistory bents for worst loading conditions are seldom made. Instead, such approximate methods as the portal and cantilever methods for lateral loads, and modified moment distribution for dead and live loads have been in common use.

The advent of the digital computer has begun to change the picture rapidly because of its capacity to handle a number of simultaneous equations or other types of computations. Consequently, attention has again been directed to adapting the exact methods to machine computation.

Detailed formulations in matrix form which take into account all possible parameter variations, consider the bent as a true space frame, and include the effects of axial and shear deformations etc., are legion in current literature. Such methods require a large memory capacity for the machine, and are practically impossible of hand calculation. Further, in a multistory structure the effect of loading in any story is concentrated within adjacent stories and degenerates in stories away from there. This permits consideration of only a portion of the tall frame of a number of stories without appreciable error for design purposes. Such a treatment may then be possible with the use of smaller capacity computers because of the reduced core storage required, or by hand calculation. By reason of the above statement and also due to the paucity of high-capacity computing equipment such as the IBM 7040 in non-computer-oriented areas such as India, the need is one for a system of analysis which gives reasonable accuracy and yet limits computations to the minimum. Kani (3) presented an iterative technique that is finding growing acceptance because of its ready simulation of sidesway. Bray (4) published an excellent paper, after years of research, in which he showed how a simple electric circuit consisting of resistors simulates slope-deflection equations accurately. Analogs based on other theories have also been proposed variously (6)(7)(8) but because of its relative simplicity, the Bray analog promises to be a most convenient tool for the automatic analysis of the tall building frame. Should an analog that can be built with shelf-stocked components prove satisfactory in analyzing frames with reasonable accuracy and speed, it would then be an economical alternative to the use of computers or hand calculation for this purpose. It is therefore of interest to study how the analog performs in the case of a typical building frame of at least moderate dimensions or portions thereof, and to make comparisons with results obtained by Kani-moment-distribution as well as by the approximate methods now in use. The overall feasibility and usefulness of a simulating device that is simple to construct and operate, as compared to other methods, and with due consideration to the effort involved, cost, speed, etc., are other items of interest in this study.

CHAPTER II

THEORY AND METHOD

2.1 Analog Principles

Before understanding the use of analogies for analysis or other purposes, the basic principle of analogs must be understood, and these may be briefly summarized as follows: In general, if the characteristics of behavior of two or more physical systems can be expressed in identical mathematical form, such systems are said to be analogous to each other. In order for this condition to be satisfied, the physical laws of the systems must be similar in form. In other words, two systems are analogs of each other if their response to similar excitations are similar. Examples of analogies known and used by engineers are legion. Soap films, membranes and conductive sheets are some of the more common analog techniques applied in experimental stress analysis. The purpose of using analogs is to determine or predict the response of a system which cannot be analyzed directly without excessive difficulty or expense. In practical engineering problems, this may be because numerical techniques are involved and laborious, as in the case of the calculation of stresses in elastic bodies and other field problems, or because the prototype system is unwieldy or inaccessible as in the case of stresses in dams.

Basically, an analog is differentiated from a model in the following manner. The word analogy is reserved for situations where the systems are different in kind, as for example, when one is the structural system and the other is the electrical system, and are connected by identity of mathematical relationships of each system. In other words, the equations of the analog must represent those of the prototype, whereas in the model, the physical nature of the behavior is itself directly reproduced, although to a different scale. By reason of this statement, models can be used where the mathematical formulation of the prototype behavior is not available, while an analog can be used only if the laws can actually be determined and matched specifically for both the analog and its prototype. Using this interpretation, then, an analog can be said to be but an indirect way to solve the equations of the prototype.

In passing from the prototype to the use of its analog system, the following procedure is used provided the mathematical formulation of the prototype system is available.

1. Formulation in mathematical form of the analog system in the mode of behavior in which analogy exists.
2. Identification or matching of the analog and prototype expressions.
3. Physical realization of the analog system and its measurement.
4. Deduction of the prototype quantities from the analog data using appropriate scale factors.

It is seen from the above procedure, that the need to actually compute and solve the equations of the prototype is eliminated by the use of the analog. By reason of the above statement, the most useful aspect of analogs can be said to be the possibility of their employment as calculating devices, to 'solve' the equations of the prototype. In the case of multistory frame analysis, then, the analog method at once suggests itself as an eminently useful tool if it can be built and used without special effort or equipment.

2.2 Electrostructural Analogs

Knowledge and use of the existence of analogy between the structural and other physical systems are not new. Simple analog techniques have been used effectively in a variety of distributed field problems involving Laplacian and Poisson-type equations, such as plane stress problems in mechanics (9)(10). Certain shell structures have been conveniently handled by electrical analogs (11).

In the area of framed structures, early work was done by Bush (12) who devised a-c networks for the solution of problems of equilibrium and motion of determinate and redundant frameworks. Currents were used to simulate forces and the similarity between equilibrium of forces and the 'equilibrium' of currents at a junction was utilized. Networks containing 'ideal' transformers were also devised for the slope-deflection equations for a rigid-jointed framework. 'Ideal' transformers appear in all of Bush's circuits. The degree of accuracy with which these can be built and used and the effort involved and other factors make this type of circuitry difficult to realize without at least a moderate knowledge of electrical parts and their construction. More recently, Trudso (13) drew attention to the analogy between certain potential fields and static fields of force and moment in beams and plates. He devised practical electric models of indeterminate beams and their conjugate beams, plates and their conjugate plates, simulating them by using conducting sheets. Leicester (14) extended this to include simple and continuous arch structures by utilizing the similarity between the arch equations and Kirchoff's equations for a resistance strip. He found the analogs considerably time-saving and satisfactory when used with moving-coil meters and high-current capacity resistors. Another interesting paper by E. K. Bridge (15) described a machine for calculating electrically the bending moment and shear effects of varying moving loads on various spans for the British Railways.

Material on direct analog computers in all their aspects are legion. They use high-gain amplifiers as typical components and are particularly effective in solving differential equations and systems with wide variation of parameters and several degrees of freedom. They are efficient in handling such problems as dynamic analyses of tall buildings, and are used widely in the aircraft and missile structural industry for studying wing flutter and other vibrations problems. For using direct analog computers all information is usually expressed in differential equation form. In the case of static analyses of building frames, direct analog computers offer no special advantages, over other analog methods.

2.3 The Ryder Analogy

Recently, F. R. Ryder (7)(16) utilizing the fact that Castigliano's theorem and the principle of least work have their counterparts in electrical networks, developed analogs for a variety of cases, e. g., the two- and three-dimensional truss, two-dimensional rigid frame and truss-frame combinations, and secondary stresses. He constructed an instrument consisting of tapped transformers and adjustable resistors which could be connected to simulate trusses and rigid frames of different combinations. The principle of the Ryder analog may be summarized thus:

> Principle of Least Power - In a circuit consisting of resistors and 'ideal' transformers that is supplied with external alternating currents at a single frequency and phase angle, each internal current is a minimum, subject to the requirements of current-continuity,

which is analogous to

> Principle of Least Work - Each internal force and moment in a structure is a minimum, subject to the requirements of equilibrium.

"Castigliano's theorem" for electric circuits is

> In the circuit mentioned above, if P denotes power dissipated in the circuit, C is a supplied current, V denotes voltage of the point at which C leaves the circuit, then,

$$2V = \frac{2P}{\partial C}$$

which is analogous to "Castigliano's Theorem No. 1"

$$\delta = \frac{\partial W_d}{\partial F}$$

$$\theta = \frac{\partial W_d}{\partial M}$$

where

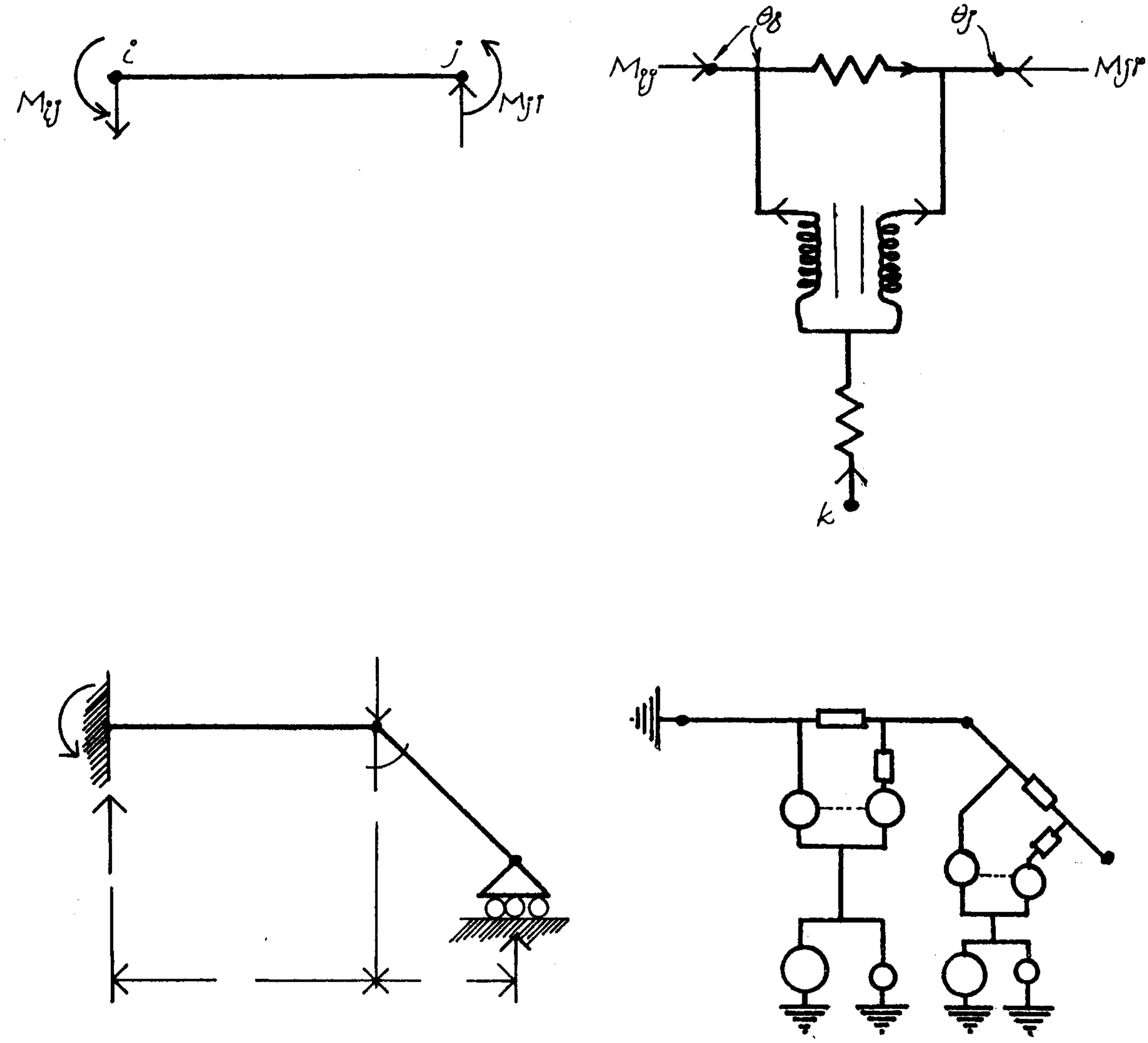


Figure 1 - A Typical Ryder Analog

W_d = the work of deformation,

F = the applied force, and

M = the applied moment.

In the above analogy, the work of deformation corresponds to half of the power dissipated in the circuit, the current corresponds to the applied force or moment, and voltage to deformation.

In spite of the elegance and rigor of the Ryder analog, the circuitry becomes rather complicated, involving transformers etc., because of the use of the power parameter for analogy. The Ryder analogs for the simple cases of a straight beam and a rigid frame are shown in Figure 1 to indicate the nature of the circuitry.

2.4 The Generalized Bray Analog

Bray showed in an excellent paper (4)(5) how the slope-deflection equations of a member were identical to the equations for current in a circuit consisting of three resistors simply connected in π-fashion (also shown to be true in wye-fashion by Sved (6)) satisfying boundary conditions. The circuit was shown to be highly capable for various cases of framed structures including members of any cross-section, rigid and semi-rigid connections, axial loads and plastic hinges. Iyengar and Krishnaswamy (17) showed how the Bray analog simplifies the tedious problem of gridworks. Rawlins extended the Bray analog in an interesting paper (18) to space frames and developed ways in which Bray's π-network could be modified with the use of additional components, to simulate any three-dimensional framework. However, since it is not worthwhile to simulate torsional restraint before estimating the performance of the analog in the planar case, and further because the limited electrical training of architects and structural engineers confines them to the use of only the simplest of circuits and measurement, the Rawlins extension is not considered in this study. Only the Bray analog as it applies to tall building frame analysis will be described here.

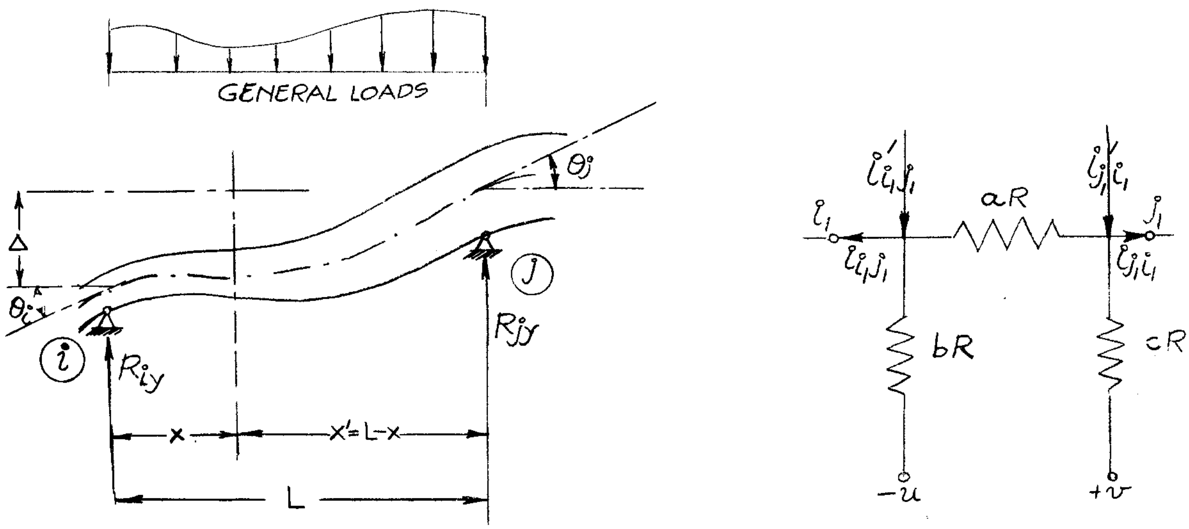


Figure 2 - The Bray Analogy

Consider a free-body of the span ij of a continuous structure of variable cross-section and general system of in-plane loads as shown in Figure 2. The slope deflection equations for the same may be written in general form as follows.

$$M_{ij} = FM_{ij} - \frac{E_{ij}I_o}{L_{ij}} \left(\frac{C_2}{N} \theta_i + \frac{C_1}{N} \theta_j + \frac{C_1 + C_2}{N} \frac{\Delta}{L} \right)$$

$$M_{ji} = FM_{ji} - \frac{E_{ij}I_o}{L_{ij}} \left(\frac{C_1}{N} \theta_i + \frac{C_3}{N} \theta_j + \frac{C_1 + C_3}{N} \frac{\Delta}{L} \right)$$

where

$$C_1 = \frac{I_o}{L^3} \int_i^j \frac{x^2 dx}{I_x}$$

$$C_2 = \frac{I_o}{L^3} \int_i^j \frac{x(L - x)dx}{I_x}$$

$$C_3 = \frac{I_o}{L^3} \int_i^j \frac{(L - x)^2 dx}{I_x}$$

$$N = C_1 C_3 - C_2^2$$

I_o = second moment of inertia of the section at a standard reference point.

Now consider the flow of current through the circuit shown in the right side of the figure. Input currents $i_{i_1 j_1}$ and $i_{j_1 i_1}$ are fed into the circuit at the nodes i_1 and j_1. The branch currents $i_{i_1 j_1}$ and $i_{j_1 i_1}$ are given by

$$i_{i_1 j_1} = i'_{i_1 j_1} - \frac{1}{R}\left[(\frac{1}{a} + \frac{1}{b})V_{i_1} - \frac{1}{a} V_{j_1} - \frac{1}{b} u\right]$$

$$i_{j_1 i_1} = i'_{j_1 i_1} - \frac{1}{R}\left[(\frac{1}{a} + \frac{1}{b})V_{j_1} - \frac{1}{a} V_{i_1} + \frac{1}{b} v\right]$$

The similarity between slope-deflection equations become immediately obvious by the following relationships.

$$a = \frac{2N}{C_1} \qquad b = \frac{2N}{C_2 - C_1} \qquad c = \frac{2N}{C_3 - C_1}$$

$$u = \frac{C_2 + C_1}{C_2 - C_1}\, q\, \frac{\Delta}{L} \qquad v = \frac{C_3 + C_1}{C_3 - C_1} \qquad R = r\, \frac{L_{ij}}{E_{ij} I_o}$$

This identity of relations forms the basis for the generalized Bray analog, which becomes increasingly clear in the case of a straight bar without support displacement governed by the slope-deflection equations

$$M_{ij} = FM_{ij} - \frac{2E_{ij}I_{ij}}{L_{ij}} (2\theta_i + \theta_j)$$

$$M_{ji} = FM_{ji} - \frac{2E_{ij}I_{ij}}{L_{ij}} (2\theta_j + \theta_i)$$

which are identical to the current equations

$$i_{i_1 j_1} = i'_{i_1 j_1} - \frac{1}{R} (2V_{i_1} - V_{j_1})$$

$$i_{j_1 i_1} = i'_{j_1 i_1} - \frac{1}{R} (2V_{j_1} - V_{i_1}) .$$

In this case the voltages u and v are zero.

The analogy is thus defined by these relationships:

$$i_{i_1 j_1} = +p\ M_{ij} \quad i_{j_1 i_1} = -p\ M_{ji} \quad i'_{i_1 j_1} = +p\ FM_{ij} \quad i'_{j_1 i_1} = -p\ FM_{ji}$$

$$V_{i_1} = +q\ \theta_i \quad V_{j_1} = -q\ \theta_j \quad R = \frac{q}{p}\, \frac{L_{ij}}{2E_{ij}I_{ij}} = r\, \frac{L_{ij}}{2E_{ij}I_{ij}}$$

where p, q and r are scale factors which can be varied at will. Physically the following one-to-one correspondence between the bar and the network holds:

Branch Current	=	Fixing End Moment
Feed Current	=	Fixed End Moment
Voltage of junction (above datum or ground)	=	Rotation of corresponding joint
Resistance of each Resistor	=	One-half of flexibility of member $(\frac{L}{2EI})$
Continuity of Currents at a Node	=	Equilibrium of moments at corresponding joint.

2.5 Sign-Convention

On a study of the identity of the relations, it may be noticed that there is a discrepancy in signs. It is observed that negative signs occur in all relations for node j and positive signs in those for node i. Accordingly a quantity called "node-sign", special to the analog, to take care of this discrepancy, is introduced: Alternate nodes take on the same sign, in the analog. In the above case, if i is called positive, then the node j takes on the negative sign, and the next node, if any, becomes positive. Further, the following quantities are called positive: Clockwise moments; anticlockwise rotations; currents entering a node; and voltages above earth potential. Using the "node-signs", the following set of rules have become necessary in order to obtain the correct signs for output values:

Sign of feed current	=	(Node-sign) * (Sign of fixed-end moment)
Sign of fixing end moment	=	(Node-sign) * (Sign of branch-current)

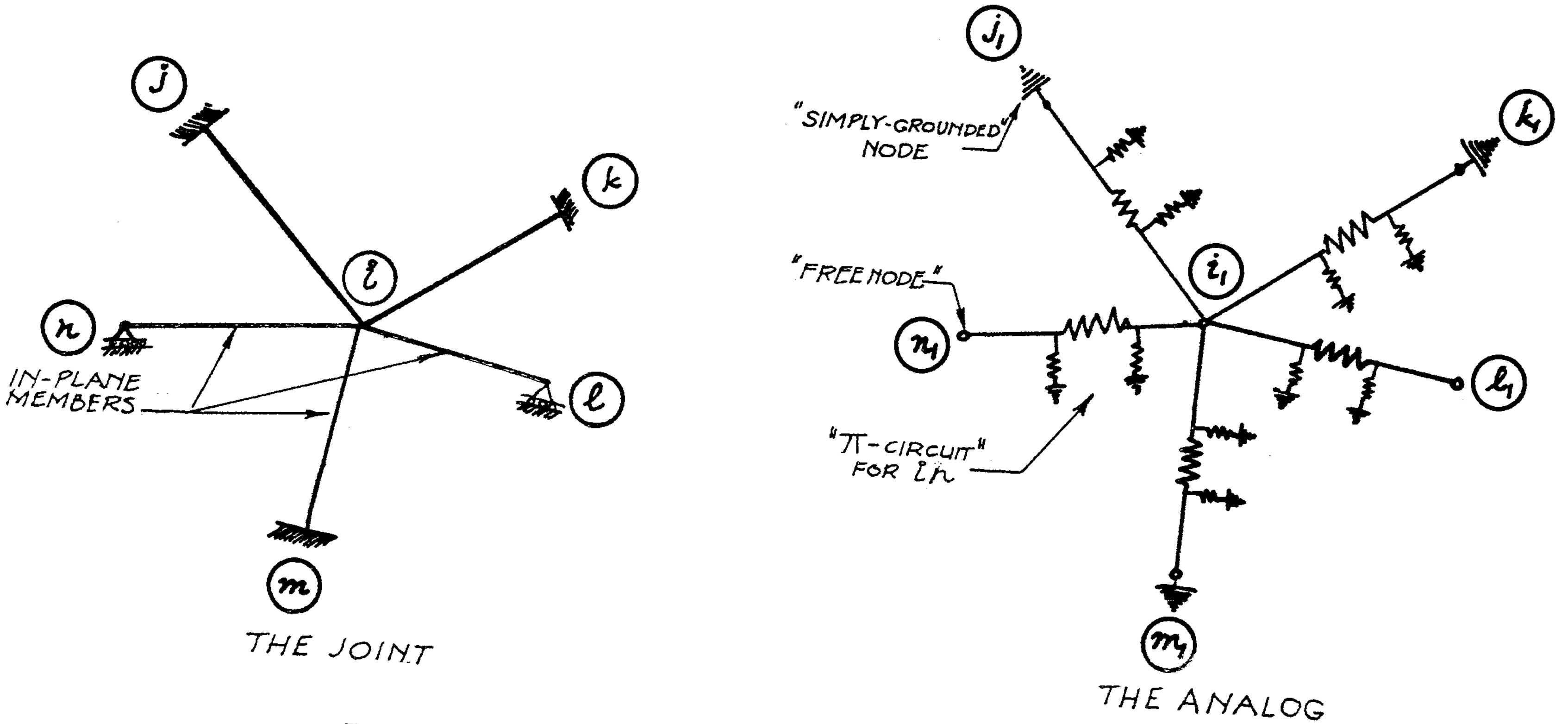


Figure 3 - Node Conditions in the Bray Analog

Sign of Rotation = (Node-sign) * (Sign of node-voltage).

By following the above set of rules and sign convention, it is seen that output values take on the correct signs.

2.6 Support Conditions

The general joint and support conditions in the structure are simulated in the analog in a manner described below. At any hinged joint in the structure, moments are zero and rotations are present. Similarly at any "free-node" in the analog, that is, at any node at which no two π-networks meet, and which is not grounded, the current flowing is zero for reasons of current-continuity, but voltage (or potential difference above ground) is present. And at any fixed joint in the structure, moments are present and rotation is zero, whereas in the analog, at any "simply-grounded" node, or node that is connected to ground, currents flowing are present but voltage above datum or ground is zero. Since, as already noted, currents simulate moments, and node-voltages simulate joint rotations, hinged joints are simulated by free-nodes and fixed joints by "simply-grounded" nodes. Other joints where members are rigidly connected, are simulated by nodes at which the "π's" of the corresponding members are simply connected together as shown in Figure 3.

2.7 Analog-Structure Resemblance

The analogs of a two-span continuous beam and a two-bay two-story framework are shown in Figure 4 to indicate the nature of the circuit and to illustrate the manner in which the joint conditions in

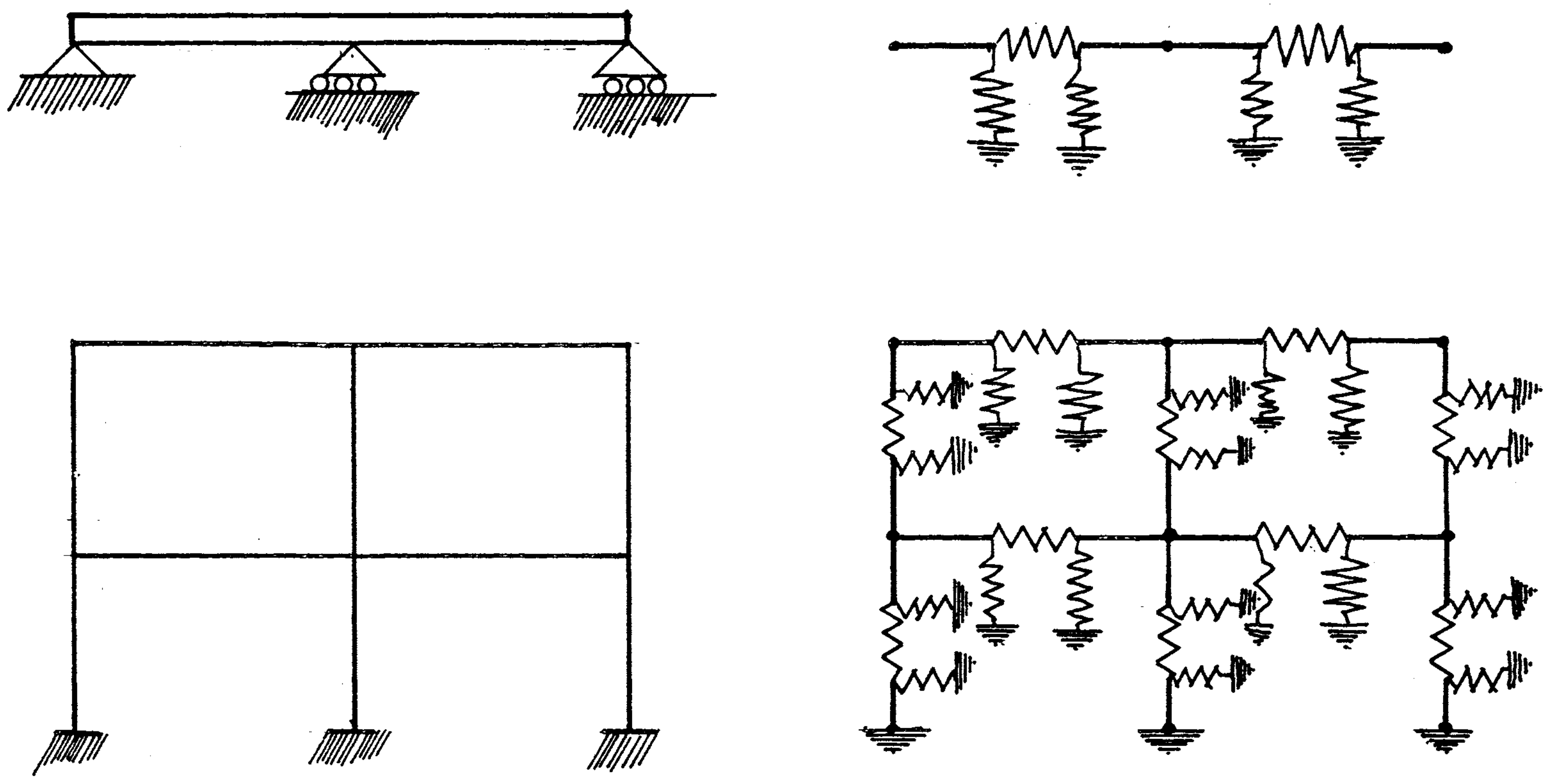


Figure 4 - π-Network Analogs for Typical Cases

the structure are simulated, as explained above. One remarkable feature that is immediately noticeable in the circuits is the direct pictorial resemblance to the configuration of the structure simulated. Each member is represented by a π-network of three resistors which take on values inversely proportional to the stiffness of the member. Such π-networks are connected to other π-networks in the same way pictorially as the members they represent are connected at each joint. Thus, each node simulates a joint. This pictorial resemblance is not affected by the complexity or lack of it in the structure; it actually becomes an advantage in more complex and large structures where a visible orientation is afforded for each part in the structure to its corresponding part in the analog network.

CHAPTER III

DESIGN AND CONSTRUCTION OF SIMULATOR

3.1 Analogy Used in Simulator

The design of the simulator was influenced by considerations of economy and simplicity. In order that it may be used as a rapid design aid by persons without regular electrical training, the instrument must be as non-electrical and free from complicated instrumentation as possible without sacrificing accuracy. Bray's π-network possesses the advantage that it uses no electrical components except resistors to simulate any straight member. Since the circuits used by MacNeal and Ryder employ additional components such as transformers, capacitors, inductors, etc., the construction of an instrument based on their analogs requires a familiarity with electrical circuitry. The minimizing of such equipment required to simulate any given problem would probably give a more accurate performance due to the reduction in losses of efficiency. Further, the π-network simulates slope-deflection equations which are accepted as a rigorous and exact solution for frame analysis. Due to the absence of "ideal" transformers etc., in its circuit, and also due to the fact that the slope-deflection equations are simulated exactly in this analog, the only errors possible in the use of the π-network are the errors in setting the resistances, and in reading the input and output currents. Thus a minimization of errors is seen to occur in the case of the Bray analog, and it can therefore be considered most suitable for the purposes of our method.

3.2 Simulator Components

Initial experiments were conducted with networks for simple continuous beams and small portal frames, using fixed carbon resistors, which possessed a tolerance of ±5.0%. Disadvantages of using such resistors were soon noticeable; their tolerance limits allowed a variation of resistance values, which affected the accuracy with which such values could be set to simulate member-flexibilities. Also, even a small variation of the member sizes changed resistance values correspondingly, and this required a large bank of resistors from which to choose. In the discussion of his paper (5), Bray suggests employing an arrangement of such resistors in parallel to obtain any desired values of resistance. Although this type of arrangement may be satisfactory in the case of relatively small rigid frame problems, the author doubts the efficiency of this arrangement in handling practical building frames of moderate or large size, because of the considerable variation of member properties normally encountered. Continuously variable resistors of some type would probably be better for this purpose. Therefore variable resistors and precision potentiometers as described below were next tried. The potentiometers are compact (2 in. dia.) precision-type, wound with extremely fine windings of a high quality to allow for greater precision in adjustment. They are fitted with eight different nodes to permit greater flexibility in tapping desired resistances;

some of these nodes supply different fixed resistances independent of the setting of the potentiometer; other nodes give different values depending on the setting of the potentiometer. Their linear-taper allows continuous linear variation of resistance, and this eliminates the need for a large stocking of resistors to select and use in parallel. The variable resistors are fairly accurate and are capable of fine adjustment although the extra fineness of the precision potentiometers are absent in them. Such resistors and potentiometers are sold and used commonly as inexpensive controls for television and radio equipment and are readily available at electrical dealers. They can therefore be obtained and used with ease and accuracy even by non-electrical personnel. Other components required to complete the simulator, apart from a power supply and two meters for input and output measurement, are parts of a miscellaneous and non-electrical nature such as a 'Masonite' board with $\frac{1}{8}$" dia. holes punched at 1 in. centers screws, washers, nuts, common connection wiresand a thin strip of shimstock metal, the use of which is described below. The power supply used was 0-30 volts. D. C. continuously-variable transistorized power supply. For the input measurement, a Simpson 270 Series 3 voltohm-milliammeter with a maximum possible error of 1.75% at room temperature in the 0-500 milliammeter range, was used. For the output measurement, a more accurate meter, a Weston D. C. Milliammeter Model 322 with $\pm\frac{1}{2}$% accuracy at 25 degrees C., was available. This meter has 200 graduations on its scale, the full value of which may be set as desired at 0.2, 2.0, 20.0, and 200.0 mA by means of a switch. This enables more refined measurement.

3.3 Node-Connections

A major difficulty in the connection and use of the π-network arises in bringing the meter into the part of the circuit – namely the ends of the π's at which measurement of the currents is desired. This necessitates disconnecting and introducing the meter in series with that part of the circuit. For circuits such as those for continuous beams and portal frames involving a small number of members, this is easily accomplished. In multistory structures, this would be a laborious and time-consuming process. Bray has suggested using switches at all points at which measurements may be desired and introducing the meter into the circuit by means of the switches. In the writer's opinion, such switches become numerous in our case: For example, in the case of a ten-story building, with 140 different member ends, the number of switches required would be 140. It would be simpler and more economical to have some kind of an automatic make-break contact which would accomplish what a switch does. For this purpose, very thin copper strip was first tried in an arrangement shown in Figure 5, in order to make a purely conducting contact. This strip was unsuccessful because of its inelastic behavior; after breaking the contact by the pressure of a probe, the strip stayed in the open position without making contact again. Thin shimstock metal was cut out to the same shape and used, and proved an excellent contact. The resistance of the metal was checked to be zero before its use. In this arrangement, a small strip is cut out to the shape shown in Figure 5 and is held in place firmly by tightening the nut. When a probe is inserted in the small hole opposite to the

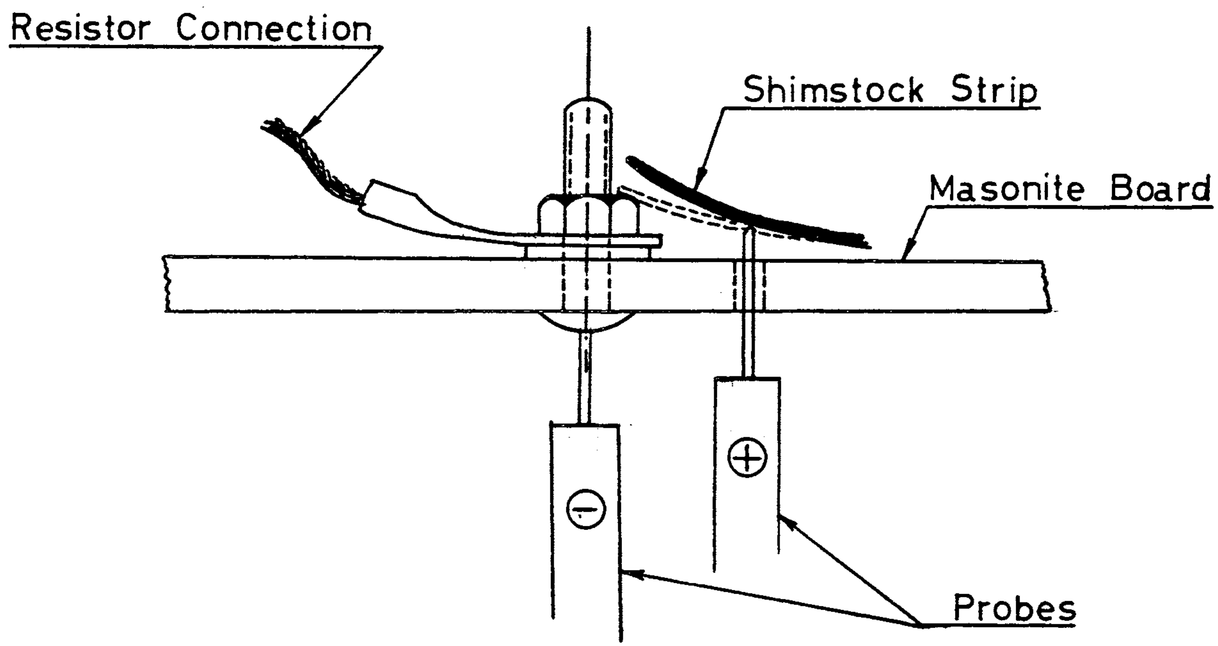


Figure 5 - Detail of Node Connection in the Simulator

concerned strip, and pressed, the contact is broken at the node; and if the probe is taken off the strip snaps back in place thus closing the circuit again. By this arrangement, if one of the probes connected to a meter is used to press the strip, and the other probe connected to the meter touches the node, it is observed that the meter is introduced in series with the strip concerned, just as a switch. In this manner, measurements can be made much faster and the automatic snap-back action of the strip eliminates the need for arrays of switches.

3.4 Design of the Circuit

The application of the Bray analog to the case of multistory frames is straightforward. The "π's" corresponding to the members are built up and connected to each other in the same pictorial fashion as the structure itself, as noted elsewhere. In spite of the simplicity which this type of arrangement suggests, the actual building up and making all the connections, between the "π's" themselves, and to ground at various points, become tedious for a typical building frame. Thus the simulator was sought to be designed such that all connections and the building up of the circuit were made permanently, since these are the same for all rectilinear frameworks. The only changes needed in the simulator before the start of a problem are the settings of the variable resistances to desired values. This necessitates that all connections, nodes, and ends of "π's" be connected and soldered suitably. When the resistors have to be disconnected, for adjustment of resistance, or in order to simulate a smaller structure, such resistor connections are taken off the

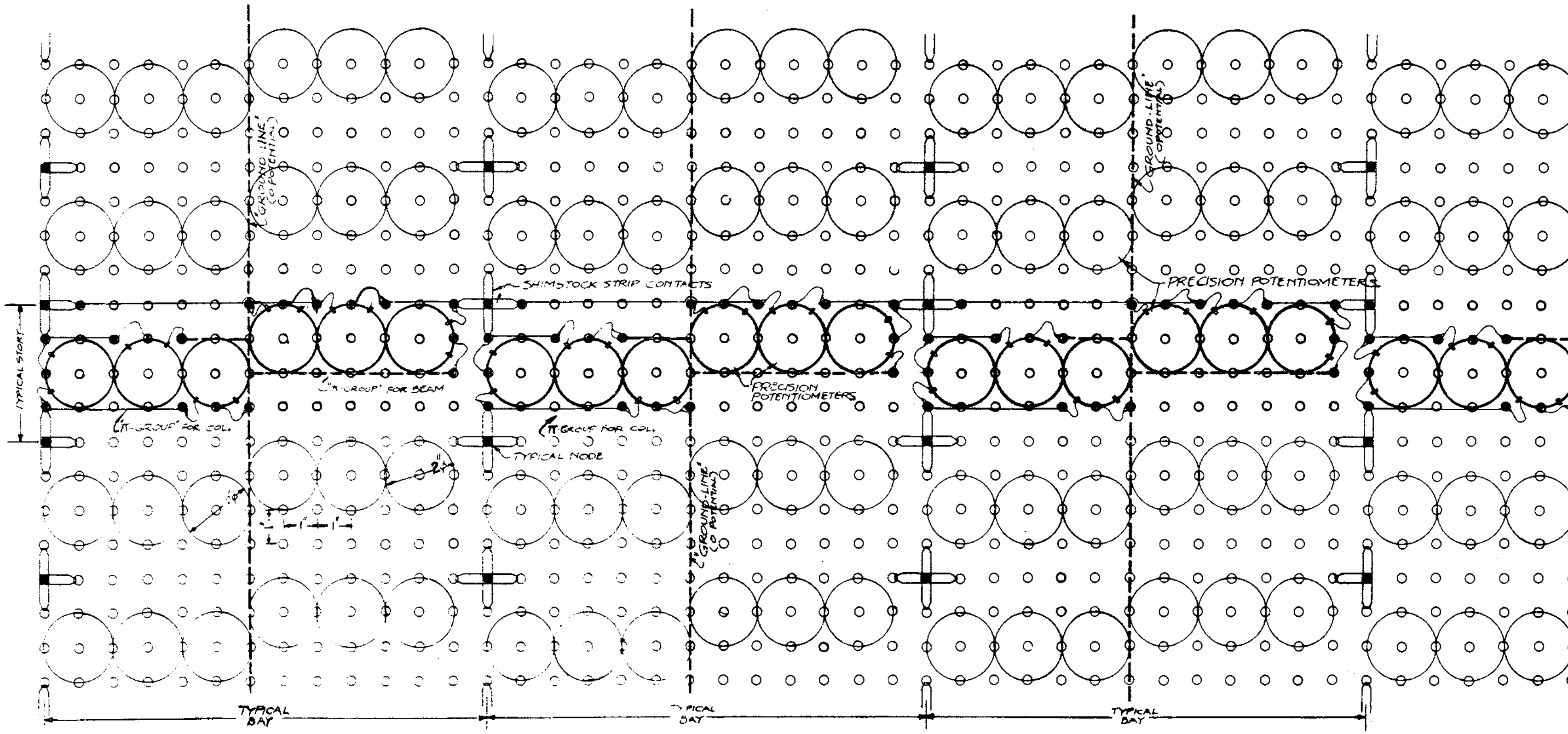


Figure 6 - Design of the Circuit

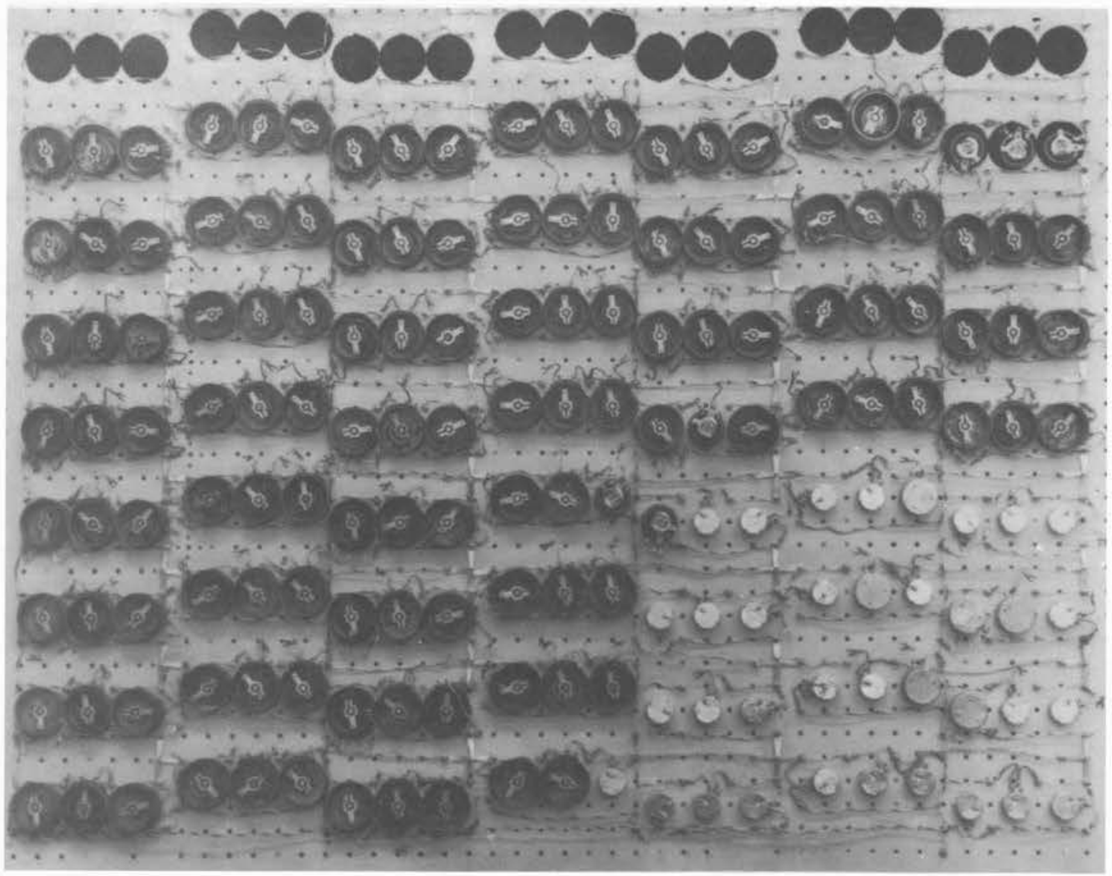


Figure 7 - The Rear View of Simulator

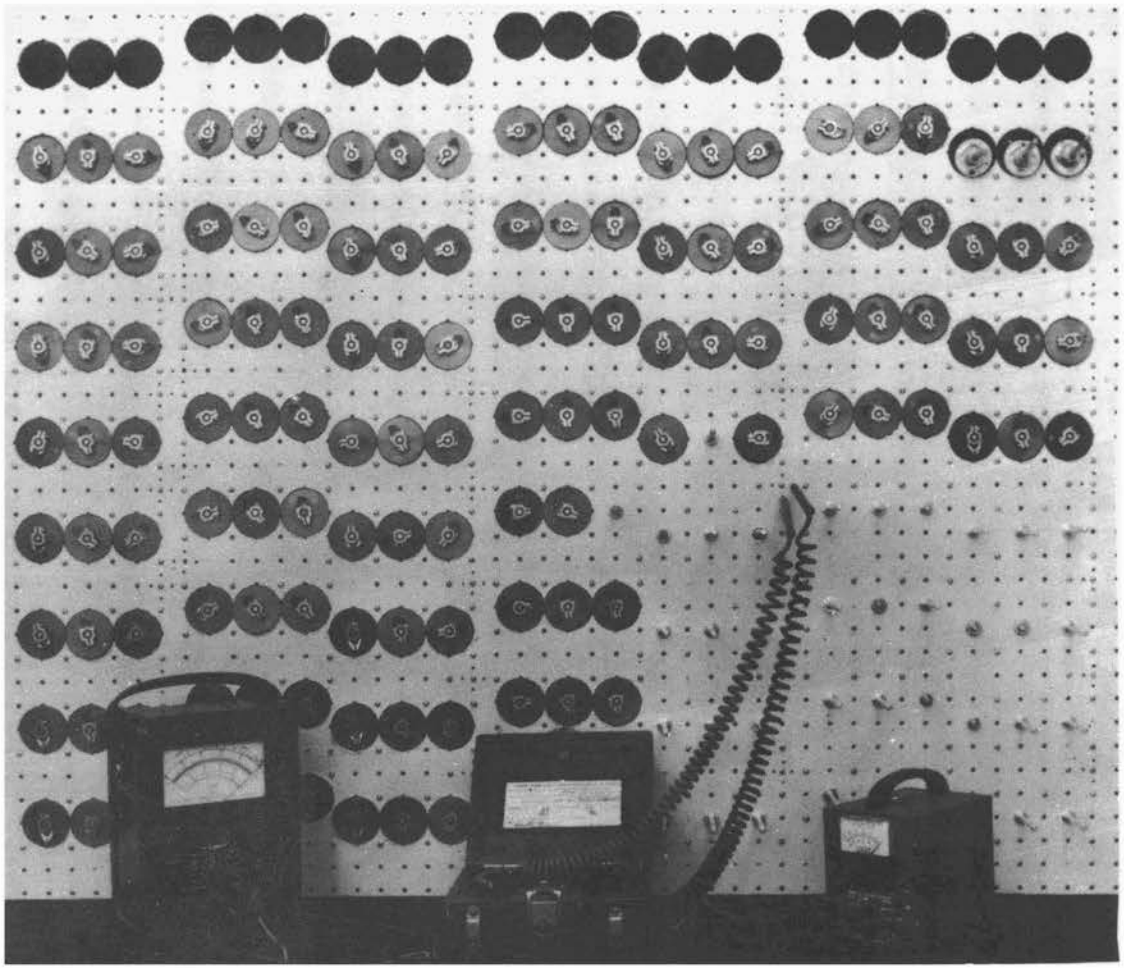


Figure 8 - The Front View of Simulator

connection points by a turn of the nut. In this way, any frame or continuous beam up to the maximum size possible in the instrument can be handled quickly without removing any part from the board.

The arrangement of the resistors corresponding to the members on a tall building frame is shown in Figure 6. The board with in. dia. holes punches at 1 in. centers in both ways, proves most useful for this purpose. These small holes serve to accommodate the screws that act as connection points, and member-to-member junctions. The resistors are mounted on additional holes drilled through the board, 2 in. dia. in size for the potentiometers and $\frac{3}{8}$ in. dia. for the variable resistors. The former are kept in place by plastic cement which glues the resistors firmly to the board.

The very nature of floors being in sequence in multistory buildings, make it possible to line up the "π's" or three-resistor groups of similar members of all floors. In other words, the resistors corresponding to the columns of all floors lined up as columns, and similarly those corresponding to beams lined up as adjacent columns. The resistors corresponding to the columns and beams of any given floor lined up as a single row. Further this facilitated running the vertical "ground-lines" from the bottom to the top story, to which the required ground connections of each "π" are connected. In this manner, a compact arrangement is obtained that is simple and yet retains the pictorial resemblance to the structure.

3.5 Use of Simulator

The use of the simulator to solve for the final end moments in a frame is somewhat similar to the moment distribution process, except that in this case the entire distribution is carried out instantly by electricity. In other words, currents are fed in at the respective nodes in proportion to the fixed end moments at the corresponding points in the structure, and the final values of the end moments are immediately available for measurement. It therefore becomes a problem of making the measurements efficiently and accurately. To feed in the input currents at all the concerned points at the same time requires considerable power supply capacities, especially if a number of floors are loaded. It is proposed to use a small-sized continuously variable 0-30 volt transistorized power supply (that is available in kit form) for this purpose. This alleviates the need for expensive high-capacity power sources and rheostats for control. This supply is connected to the point where input is desired to be made and set to give the desired value. By using this, it is proposed to feed input currents at one point at a time and measure the influence of this at all "π" branches which represent the member-ends of the structure. Since the law of superposition holds for the structure as well as for the analog, the following statement is true in both cases.

$$\overline{M}_{ij} = \sum_{\ell=1}^{\ell\ell} M_{ij}^{\ell}$$

where $\overline{M}_{ij}$ = final end moment at bar ij due to the given loads;

M_{ij}^{ℓ} = moment at bar ij due to moment (f.e.m.) applied at point ℓ;

$\ell\ell$ = number of fixed-end moments caused by the loads considered;

in the analog,

$$i_{i_1 j_1} = \sum_{\ell_1 = 1}^{\ell\ell_1} i^{\ell_1}_{i_1 j_1}$$

where $\overline{i}_{i_1 j_1}$ = final branch current flowing through branch $i_1 j_1$ due to the given feed currents;

$i_{i_1 j_1}$ = branch current flowing through branch $i_{i_1 j_1}$ due to feed current at ℓ_1;

ℓ_1 = point at which current is fed in;

$\ell\ell_1$ = number of feed points.

In this manner, a value may be obtained at each member-end corresponding to each fixed-end moment in each member in the structure. If there are $\ell\ell_1$ such points, there will be $\ell\ell_1$ values which have to be added up to give the final moments. This addition can be performed with ease by the use of a common desk calculator. Thus the effort involved in solving a problem by this method may be summarized in the following steps of procedure.

1. Start. Write the analog bearing pictorial resemblance to the structure.
2. Adopt 'node-signs'.
3. Compute fixed-end moments FM_{ij} for all loaded members.
4. Choose current and resistance scale factors p and r. If joint rotations are desired, compute voltage scale-factor $q = (p \times r)$.
5. Compute, in the general case, the three resistances a.R,, bR and cR required for every member in the

structure. If the members are of uniform section, then,

$$a = B = c$$

and

$$R_{i_1 j_1} = r \cdot \frac{L_{ij}}{2E_{ij} \cdot I_{ij}}$$

Note: If L and I have different units, as when L is in feet and I is in in.^{4}, the scale factor can be suitably selected to take care of this, instead of converting the units each time. Similarly the term 2E does not have to be calculated.

6. Compute feed-currents at all π-ends, proportional to the corresponding fixed-end moments.

   i'_{i_1} = (node-sign of adjoining node) × (p) × (fixed-end moment)

7. Adjust the resistor groups of each member of the structure to their respective values, as obtained in Step 5. Connect the resistors to the corresponding connection points. (For problems in which the structure is smaller than the maximum size of the simulator, i.e. eight stories and three bays, verify that the resistor groups falling outside the range of the given problem, are all disconnected.)

8. Connect the negative lead of the power supply to one of the "ground-lines".

9. Connect the positive end of supply to the positive side of the input-milliammeter; connect the negative side of that meter to the first point at which input is to be made.

10. Turn on the power supply and set it so that the desired

feed current $(i^{!}_{i_1})$ flows through the input meter in the desired direction. (Negative feeds may be made by reversing the leads.)

11. Proceeding from node to node, measure the currents in all branches meeting at the node, by means of the probes connected to the output milliammeter. If joint rotations are desired, record the potential difference $v^{p}_{i_1}$ between the joint and datum, or "ground-lines".

12. Change the feed connection to the next node and adjust the power supply setting to obtain the desired feed current at that node.

13. Go to Step 11.

14. When all feeds and measurements are completed, according to Step 11, add algebraically the values of the current at each branch, due to all the input feeds;

$$\overline{i}_{i_1 j_1} = \sum_{\ell=1}^{\ell\ell_1} i^{\ell}_{i_1 j_1}$$

and, similarly add the node-voltages at the joints due to all inputs;

$$\overline{V}_{i_1} = \sum_{\ell=1}^{\ell\ell_1} v^{\ell}_{i_1}$$

where $v^{\ell}_{i_1}$ = node-voltage at node i_1 due to input fed in point 1.

15. Proceeding from joint to joint, divide $\overline{i}_{i_1 j_1}$ by the current scale factor p, at each branch meeting at the node,

to obtain the final end moments at the concerned bars meeting at the joint.

If joint rotations are desired, divide $\overline{V}_{i_1}$ by the voltage scale factor q to obtain the final rotation of the respective joint.

16. End.

Step 6 may be bypassed if so desired in which case, the node-sign and the appropriate scale factor must be applied after obtaining the output from the simulator, and before calculating the final values. This enables the input of a standard convenient value and sign (positive) for all feed currents, and appropriate scale factors and signs applied to the values measured in the simulator. Such a standard value, e.g. + 100 mA improves the facility with which feed currents may be measured and adjusted, and branch currents recorded. This method involves some additional computation due to the fact that all output values have to be properly adjusted. In the Test Problems described later, this was the method by which inputs are made, and the output values readjusted by means of a desk calculator.

Problems involving lack of symmetry in the structure or loading can be simulated exactly by the analog if proper voltages are made to exist at the ends of the resistors in the π-circuit, as shown earlier in the generalized formulation of the analogy. Although this mode of simulation is exact and straightforward, the application of the proper values for voltage (or potential difference above ground) at the respective points of each π, introduces instrumentation problems. Bray showed in his paper (4) that this can be achieved by a trial-and-error procedure using a modified circuit and additional resistors. For reasons of simplicity of instrumentation and use as already stressed, this modification has not been incorporated in the simulator. Sidesway problems can however be handled in an indirect fashion similar to the moment distribution method: Conveniently chosen values of moments (in proportion to the $\frac{6EI}{L^2}$ values of the cols.) are applied at the ends of the columns and the resulting moments in the structure are recorded. Using these values, equilibrium equations for story shears are written and solved, and the final readjusted moments obtained therefrom.

3.6 Conclusion

To summarize, the π-network analogy due to Bray commends itself as a rapid analyzing tool because of its direct simulation of deformation compatibility; the lack of such instrumentation as 'ideal' transformers etc. makes this analog superior to those based on power-energy relationships. The simulator constructed utilizes the Bray analogy and employs no electrical parts except variable resistors and standard meters for input and output, and a table model power supply. Built with 162 resistors, some of which are precision potentiometers and some variable resistors, the instrument is set up to handle any eight-story portion of a tall building for analyzing that portion of the structure; or it can be used to simulate continuous beams and frames of smaller dimensions. No parts need be mounted on or removed from the board for the simulation of different problems. The only 'programming' needed for any building frame solution is the setting of the potentiometers inversely proportional to the stiffnesses of the members and feeding of currents directly proportional to the fixed-end moments. The influence at any joint within any eight-story portion of a tall building, due to a moment applied at any joint within the same portion of the building, is obtained instantaneously. When a number of members are loaded the fixed-end moments due to those loads are 'applied' one by one and output values obtained in each case. Such values, added up, give the influence at each joint due to all the loads considered. Problems involving sidesway are handled in an indirect manner similar to the moment distribution method.

CHAPTER IV

TEST PROBLEMS, RESULTS AND COMPARISONS

4.1 General

After preliminary problems involving continuous beams and single-story frames using fixed carbon resistors indicated reasonable results, a three-fold program of test problems was envisaged. The objectives of the test program were to obtain, in the case of typical building frames, indications of: The relative advantages and disadvantages of the analog method, as compared to the Kani, Portal and modified moment distribution methods, in the cases of various stories and loadings, with due consideration to the accuracy obtained, effort involved, and other items of interest; the usefulness of the analog method in the case of very tall buildings, considering the degeneration of moment in stories away from the loaded story; the computation involved in satisfying any programmer-specified accuracy parameter. All computations other than those related to the simulator were done by computers. Programs were set up for the Kani and Portal methods, for the IBM 7040 and 1620 respectively. Calculations for the modified moment distribution method were carried out by the program which was already available for the author's use.

4.2 Test Problems

Three series of problems comprised the test program. Two cases of 'trough-loading' which is common in building analyses, were covered by Series A and B. Series C covered wind loads. All three series covered buildings from one to eight stories; in addition to this, Series A included Test Problems IX-A-1 to IX-A-8 with trough loading on one floor at a time, to study the effect on remote stories. Series B included Test Problems IX-B-1 to IX-B-8 with trough loading on one floor at a time, as shown in Figure 10. Similarly Series C covered Test Problems IX-C-2 to IX-C-8 which involved wind load applied to one floor at a time. The various cases studied in Series A, B, and C in the case of an eight-story building are shown in Figures 9, 10, and 11 respectively. In these problems unit values were assumed for all loads except wind loads, which were taken from Sed. 903 of National Building Code (19). All these problems were readily handled by the Kani program and therefore the results of all three series were compared to the Kani results. Wind load cases were solved by the Portal method, and dead and live load cases by modified moment distribution. These cases except wind loads were solved simultaneously with the use of the simulator. The data pertaining to these results are given below.

4.3 Member-Numbering System

For the purposes of identification of members in the tall building frame, the following numbering system is used throughout this study. Floors are numbered in sequence from the bottom.

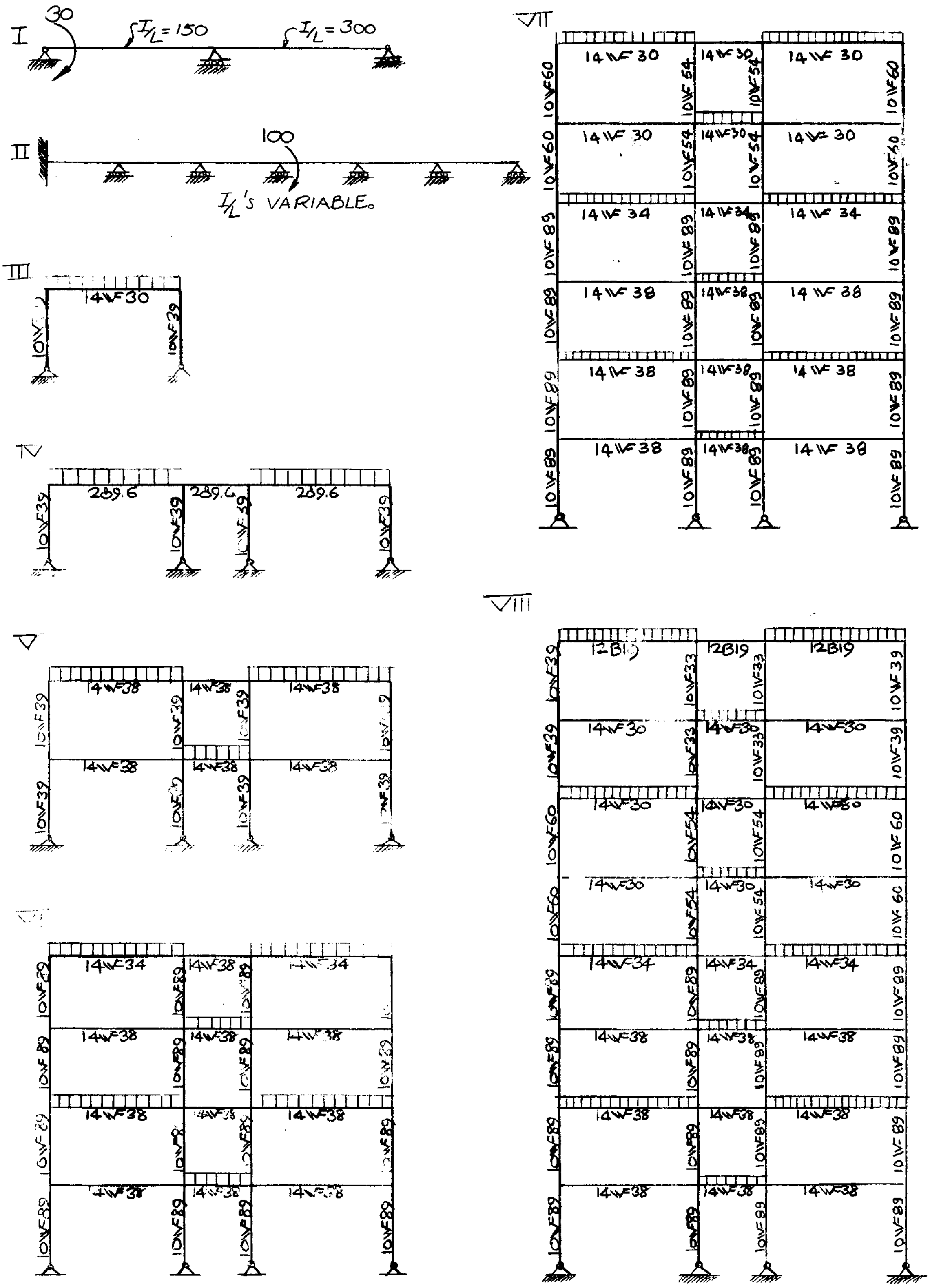


Figure 9 - Test Problems - Series A

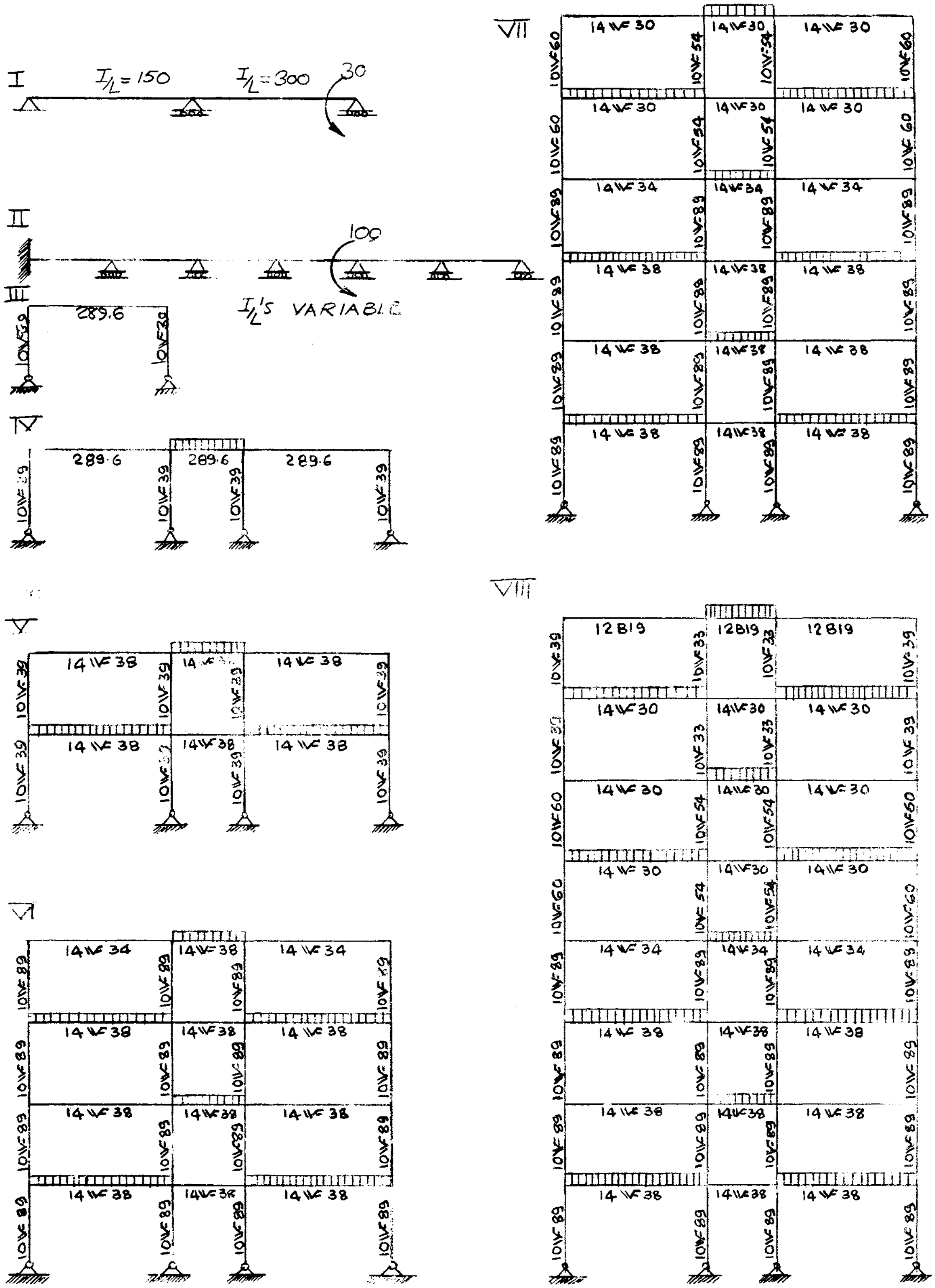


Figure 10 - Test Problems - Series B

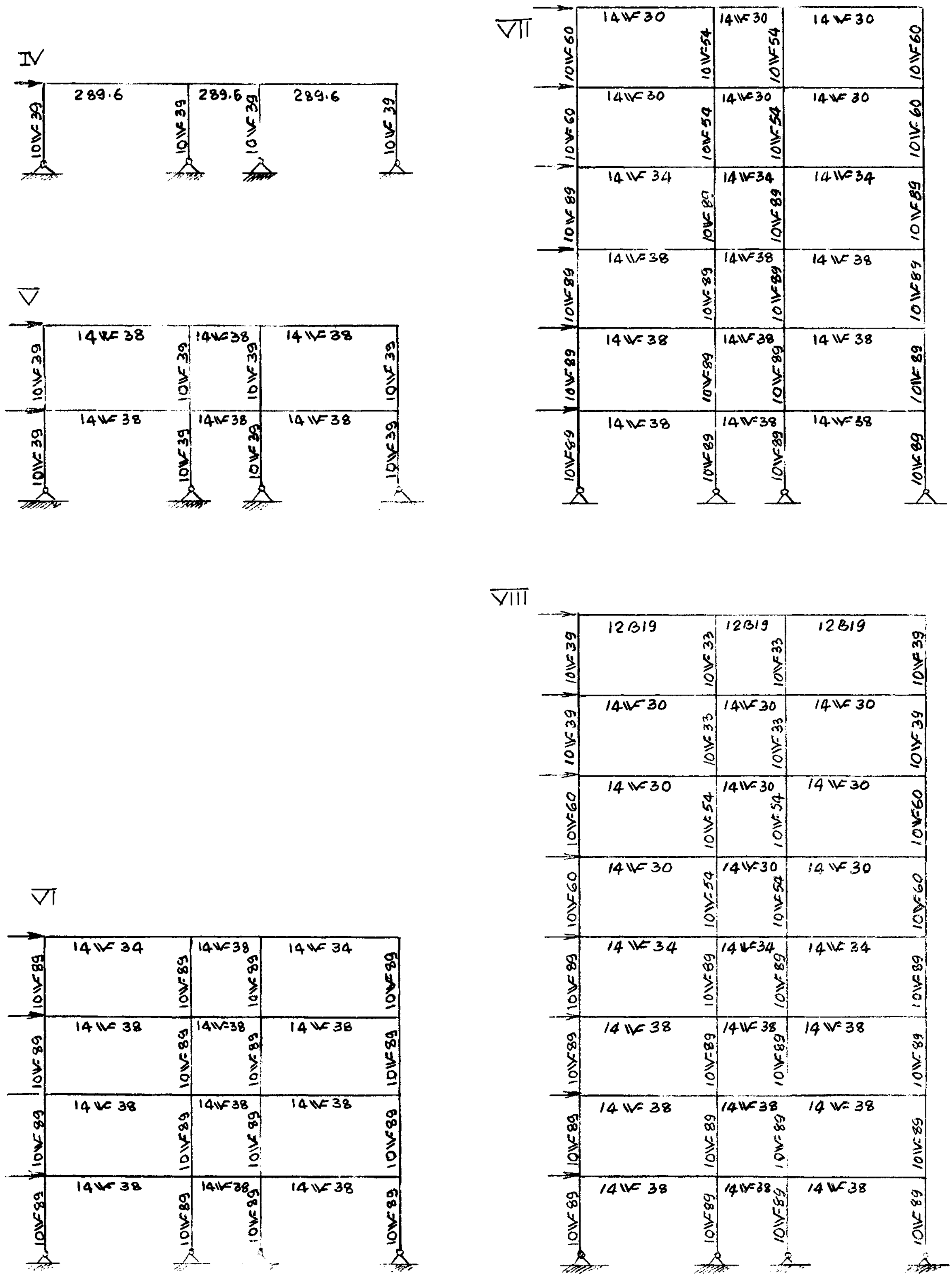


Figure 11 - Test Problems - Series C

Beams, columns and joints in any floor are numbered in sequence from the left. Each beam is designated as in this example: Beam 1-2, the first number indicating the number of story and the second one the number of the beam. Columns are designated e.g. as Col. 4-3, the first one designating the story number, the second one being the number of columns. The bars meeting at any joint are designated as: 1-2-4, the three numbers indicating the story number, joint number and bar number respectively. An illustrative example is shown below:

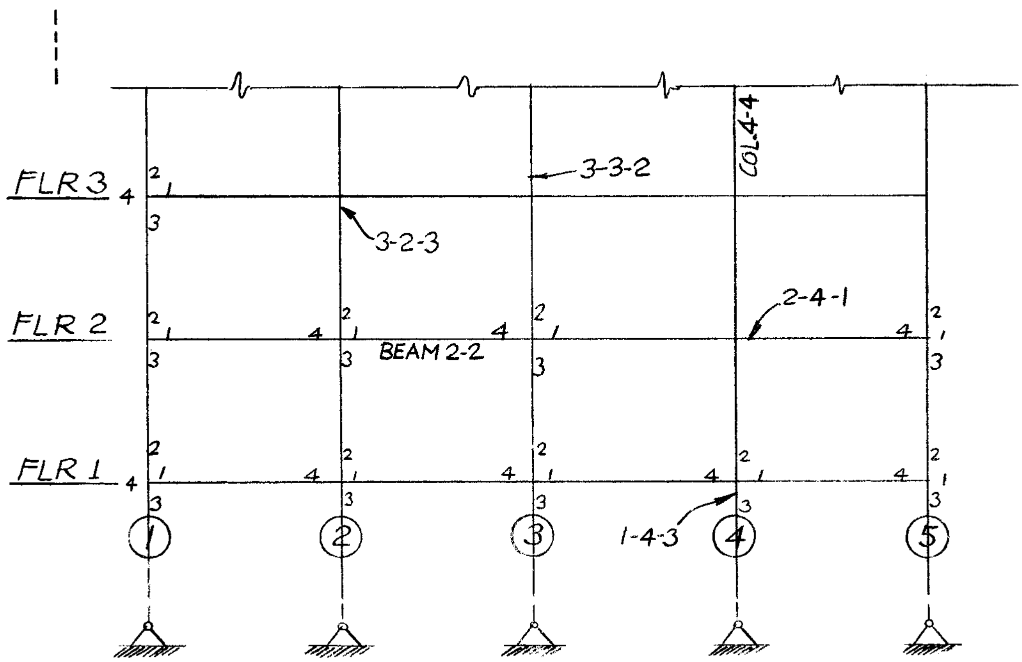


Figure 12 - Member Numbering System

4.4 Analog Results

In using the simulator for the Test Problems described above, it was felt best to use standard input currents of + 100 mA or + 200 mA, and to reduce the output values correspondingly by proper scale factors and signs. Using such a round figure facilitates more accurate setting of the input source. The above values are large enough to produce measurable effects (branch currents) up to about five to six stories in the analogs described herein. Further, the input of such positive round figure currents enables the postponement of input calculations until after all output is recorded. The positive sign eliminates the need for reversing the input circuit at alternate joints because of alternating node-signs. However such values for feed currents do not eliminate but only defer the calculations involving current scale factor; these calculations which are mainly multiplication and addition, although performed with the use of a desk calculator, proved somewhat cumbersome in the case of taller buildings because of the number of inputs and outputs involved.

It was observed that because of the accuracy with which input and output must be made, the operations involved are best performed by two persons: One person to make the input at the right location and to use the probes to obtain the output desired; the second person to take the output readings. If only one person is available for this, the operation of making the input and measuring output becomes not only tedious and time-consuming but also liable to manual error.

The programming and running of a two-span continuous beam problem on the simulator is shown on the following page to indicate the effort involved.

The accuracy obtained and the amount of effort involved in this case appear impressive; all the measurements needed were to read the input and the output currents. The output current,

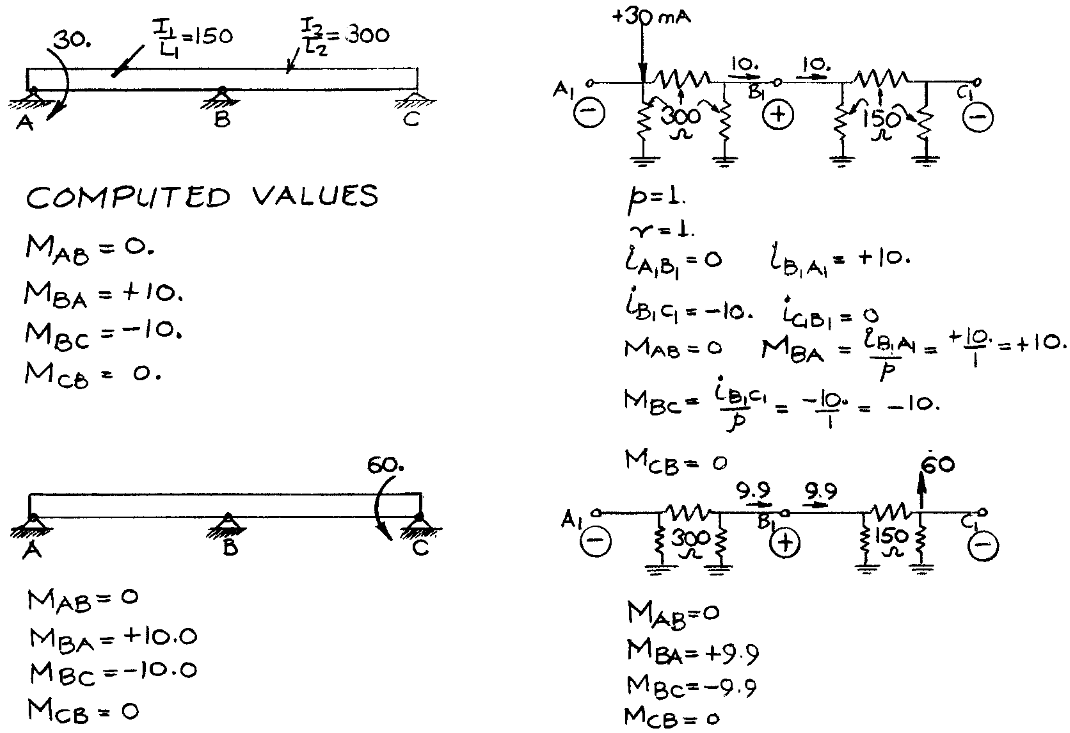
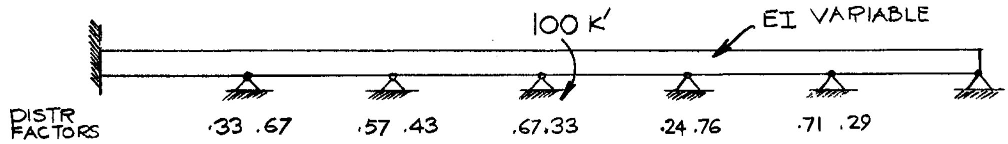


Figure 13 - Test Problems I-A, I-B

multiplied by the proper scale factor and sign, gives the value of the moment desired. However for problems involving more members and applied moments the effort involved and therefore the time, proportionately increased. It was observed that during such running time for a problem, when the power supply is kept on, it shows a tendency to creep up or down according as the setting of the supply knob was turned up or down to the desired value. This creep effect, or the change in the output of the power source, was of the order of 10-15% soon after the setting. In the author's opinion, this may have been the cause of the loss of accuracy noticed in certain measurements in more involved problems. One such problem is given below:



MOMENTS

COMPUTED	1.617	3.223	19.335	67.45	12.75	1.902	0.
ANALOG	1.75	3.6	19.00	60.00	14.00	1.85	0.

UNITS - KIP-FT.

Figure 14 - Test Problems II-A

Attempts to correct or determine this creep loss exactly were unsuccessful and steps had to be taken to prevent it completely during the execution time in any problem. Because of this necessity to prevent the creep of the power source and the consequent loss of accuracy it is seen best to keep the feed current under constant observation and adjust the setting of the power supply accordingly. This was done during the execution time of the following problems.

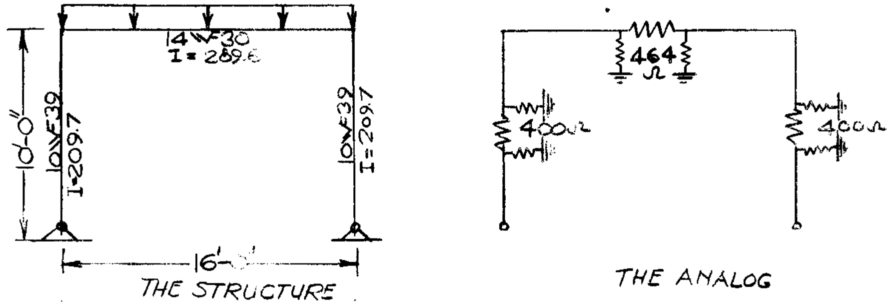


Figure 15 - Test Problems III-A

$$R_{col\ 1-1} = \frac{r}{2E} \cdot \frac{10}{209.7} \ ;$$

$$R_{col\ 1-2} = \frac{r}{2E} \cdot \frac{10}{209.7} \ ;$$

$$R_{beam\ 1-1} = \frac{r}{2E} \cdot \frac{16}{289.6}$$

Choosing a convenient value for R for cols. 1-1 and 1-2, such as 400 ohms;

$$R_{cols\ 1-1\ \&\ 1-2} = \frac{r}{2E} \cdot \frac{16}{209.7} = 400 \ .$$

$$r = 400 \cdot 2E \cdot \frac{209.7}{2 \cdot 10} = 8388 \, .$$

$$R_{beam\ 1-1} = \frac{r}{2E} \cdot \frac{16}{289.6} = 463.43$$

$$FM_{1-1-1} = -\frac{1 \times 16^2}{12} = -21.333$$

$$FM_{1-2-4} = +\frac{1 \times 16^2}{12} = 21.333$$

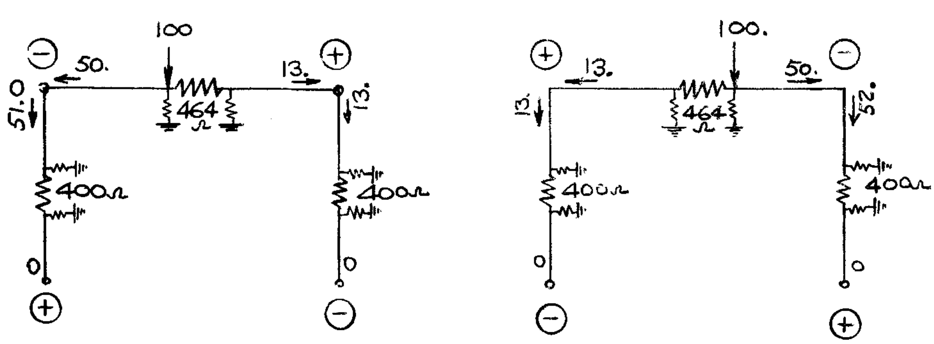


Figure 16 - Analog for Problem III-A

It is observed that the input of +100. mA at the two nodes (corresponding to joints at which fixed-end moments are applied) produces the above flow pattern for currents in the π-branches. These values of branch currents are recorded in an output record, in a format that is suitable for tall building problems.

OUTPUT AT			INPUT AT			
FLR	JT	BAR	(1) 1-1-1	(2) 1-2-4	(1)+(2)	FINAL MOMENTS
1	1	1	-50.00	+13.00	63.00	-13.65
		2	0.00	0.00	0.00	0.00
		3	+51.00	-13.00	-64.00	13.86
		4	0.00	0.00	0.00	0.00
	2	1	0.00	0.00	0.00	0.00
		2	0.00	0.00	0.00	0.00
		3	-13.00	-52.00	-65.00	-14.08
		4	-13.00	-50.00	+50.00	13.65

It may be observed that there is a slight apparent discrepancy in the continuity of currents at the joints at which input is made, in the first case $i_{i_1 j_1} = -1.0$ and -2.0 in the second case. This is obviously due to the creep of the power supply from a desired value of 100 mA to 101 mA in the first case and 102 mA in the second case.

For each problem, a value would be obtained at each member-end corresponding to excitation at each member-end in the structure. As a result, complete output values for the Problems V to VIII series are too numerous to be reproduced here. Therefore only

TABLE I. OUTPUT FOR TEST PROBLEMS IV-A, B

OUTPUT AT FLR	JT	BAR	1-1-1	1-2-4	1-2-1	1-3-4	1-3-1	1-4-4
1	1	1	12.17	+1.83	-0.42	-.08	+.31	+.09
		2	0	0	0	0	0	0
		3	-12.17	-1.83	+0.42	+.08	-.31	-.09
		4	0	0	0	0	0	0
	2	1	-1.86	-8.96	-3.10	-.64	+2.56	+.58
		2	0	0	0	0	0	0
		3	-1.77	-8.11	+2.03	+.32	-1.28	-.29
		4	+3.84	17.07	+1.07	-.30	+1.22	-.29
	3	1	-.34	-1.22	+.30	+1.07	+17.07	+3.73
		2	0	0	0	0	0	0
		3	-.34	-1.28	+.32	+2.03	-8.11	-1.71
		4	+.68	+2.56	-.64	-3.10	-8.96	-1.71
	4	1	0	0	0	0	0	0
		2	0	0	0	0	0	0
		3	-.09	-.31	+.08	+.45	-1.83	-12.18
		4	+.09	-.08	+.31	+.45	+1.83	+12.17

TABLE II. FINAL MOMENTS AND COMPARISONS FOR TEST PROBLEMS IV-A, B

Test Problem IV-A

FLR	JT	BAR 1 Analog	BAR 1 Kani	BAR 1 Mod. Mom. D.	BAR 1 % Analog/Kani	BAR 2 Analog	BAR 2 Kani	BAR 2 Mod. Mom. D.	BAR 2 % Analog/Kani	BAR 3 Analog	BAR 3 Kani	BAR 3 Mod. Mom. D.	BAR 3 % Analog/Kani	BAR 4 Analog	BAR 4 Kani	BAR 4 Mod. Mom. D.	BAR 4 % Analog/Kani
1	1	14.140	13.768	13.768	104.5	0	0	0	-	14.40	13.768	13.768	104.5	0	0	0	-
	2	7.68	8.635	8.635	89.0	0	0	0	-	11.45	10.004	10.004	114.4	19.24	18.640	18.640	103.2
	3	19.24	18.640	18.640	103.2	0	0	0	-	11.45	10.004	10.004	114.4	7.68	8.635	8.635	89.0
	4	0	0	0	0	0	0	0	-	14.40	13.768	13.768	104.5	14.40	13.768	13.768	104.5

Test Problem IV-B

FLR	JT	BAR 1 Analog	BAR 1 Kani	BAR 1 Mod. Mom. D.	BAR 1 % Analog/Kani	BAR 2 Analog	BAR 2 Kani	BAR 2 Mod. Mom. D.	BAR 2 % Analog/Kani	BAR 3 Analog	BAR 3 Kani	BAR 3 Mod. Mom. D.	BAR 3 % Analog/Kani	BAR 4 Analog	BAR 4 Kani	BAR 4 Mod. Mom. D.	BAR 4 % Analog/Kani
1	1	.50	.47	.47	106.3	0	0	0	-	.5	.47	.47	106.3	0	0	0	-
	2	3.74	3.581	3.581	104.4	0	0	0	-	2.35	2.031	2.031	115.7	1.370	1.550	1.550	88.4
	3	1.37	1.550	1.550	88.4	0	0	0	-	2.35	2.031	2.031	115.7	3.74	3.581	3.581	104.4
	4	0	0	0	-	0	0	0	-	.5	.47	.47	106.3	.5	.47	.47	106.3

TABLE III. TYPICAL SIMULATOR OUTPUT RECORD FOR

TEST PROBLEMS VII-A, B (6 Stories Trough Loading)

OUTPUT AT				INPUT AT *						
FLR	JT	BAR		5-1-1	5-2-4	5-2-1	5-3-4	5-3-1	5-4-4	
4	1	1	...	+1.440	-.261	+.065	+.013	-.054	-.019	...
		2	...	-3.520	-.159	+.040	-.003	+.014	+.008	...
		3	...	+2.101	+.421	-.105	-.010	+.041	+.010	...
		4	...	0	0	0	0	0	0	...
	2	1	...	+.410	+.768	-.192	-.039	-.158	-.134	...
		2	...	-.080	-2.400	+.600	+.080	-.320	-.012	...
		3	...	+.533	+1.077	-.270	-.084	+.336	+.100	...
		4	...	+.859	+.586	-.146	-.036	+.143	+.046	...
	3	1	...	+.046	+.143	-.036	-.146	+.586	-.859	...
		2	...	-.012	-.320	+.080	+.600	-2.400	-.080	...
		3	...	+.100	+.336	-.084	-.270	+1.077	+.533	...
		4	...	-.134	-.158	-.039	-.192	+.768	+.410	...
	4	1	...	0	0	0	0	0	0	...
		2	...	+.008	+.014	-.003	+.040	-.159	-3.520	...
		3	...	+.010	+.041	-.010	-.105	+.421	+2.101	...
		4	...	-.019	-.054	+.013	+.065	-.261	+1.440	...
3	1	1	...	+.200	+.008	-.002	+.002	-.010	-.005	...
		2	...	-.672	-.113	+.028	+.001	-.006	0	...
		3	...	+.470	+.107	-.029	-.004	+.018	+.005	...
		4	...	0	0	0	0	0	0	...
	2	1	...	+.100	+.149	-.037	+.002	-.008	-.023	...
		2	...	-.158	-.394	+.098	+.025	-.100	-.023	...
		3	...	+.109	+.180	-.045	-.019	+.077	+.030	...
		4	...	-.053	+.066	-.017	-.008	+.034	+.016	...
	3	1	...	+.016	+.034	-.008	-.017	+.066	-.053	...
		2	...	-.023	-.100	+.025	+.098	-.394	-.158	...
		3	...	+.030	+.077	-.019	-.045	+.180	+.109	...
		4	...	-.023	-.008	+.002	-.037	+.149	+.100	...
	4	1	...	0	0	0	0	0	0	...
		2	...	0	-.006	+.001	+.028	-.113	-.672	...
		3	...	+.005	+.018	-.004	-.027	+.107	+.470	...
		4	...	-.005	-.010	+.002	-.002	+.008	+.200	...

* Input values proportional to fixed-end moments at corresponding member-ends.

TABLE IV. TYPICAL SIMULATOR OUTPUT RECORD FOR

TEST PROBLEMS VIII-A, B (8 Stories Trough Loading)

OUTPUT AT*				INPUT AT**						
FLR	JT	BAR		5-1-1	5-2-4	5-2-1	5-3-4	5-3-1	5-4-4	
6	1	1	...	+1.216	-.108	+.027	+.013	-.052	-.014	...
		2	...	+1.344	+.190	-.048	-.010	+.041	+.008	...
		3	...	-2.560	-.092	+.023	-.003	+.012	+.007	...
		4	...	0	0	0	0	0	0	...
	2	1	...	+.351	+1.000	-.250	-.047	-.186	-.096	...
		2	...	+.164	+.533	-.133	-.044	+.177	+.040	...
		3	...	-.067	-2.069	+.517	+.044	-.176	+.012	...
		4	...	-.447	+.511	-.128	-.047	+.187	+.045	...
	3	1	...	+.045	+.187	-.047	-.128	+.411	-.447	...
		2	...	+.040	+.177	-.044	-.133	+.533	+.164	...
		3	...	+.012	-.176	+.044	+.517	-2.069	-.067	...
		4	...	-.096	-.186	+.047	-.250	+1.000	+.351	...
	4	1	...	0	0	0	0	0	0	...
		2	...	+.008	+.041	-.010	-.048	+.190	+1.344	...
		3	...	+.007	+.012	-.003	+.023	-.092	-2.560	...
		4	...	-.014	-.052	+.013	+.027	-.108	+1.216	...
5	1	1	...	-16.427	-1.371	+.343	+.053	-.213	-.030	...
		2	...	+7.253	+.597	-.149	-.024	+.096	+.012	...
		3	...	+9.173	+.773	-.193	-.029	+.118	+.018	...
		4	...	0	0	0	0	0	0	...
	2	1	...	+.875	+6.827	+3.733	+.541	-2.165	-.320	...
		2	...	+.613	+5.547	-1.413	-.221	+.885	+.107	...
		3	...	+.613	+5.547	-1.440	-.250	+1.000	+.133	...
		4	...	-2.133	-18.133	-.853	-.144	+.576	+.078	...
	3	1	...	+.078	+.576	-.144	-.853	-18.133	-2.133	...
		2	...	+0.107	+.885	-.221	-1.413	+5.547	+.613	...
		3	...	+.133	+1.000	-.250	-1.440	+5.547	+.613	...
		4	...	-.320	-2.165	+.541	+3.733	+6.827	+.875	...
	4	1	...	0	0	0	0	0	0	...
		2	...	+.012	+.096	-.024	-.149	+.597	+7.253	...
		3	...	+.018	+.118	-.029	-.193	+.773	+9.173	...
		4	...	-.030	-.213	+.053	+.343	-1.371	-16.427	

* All output values in mA.

** All input values proportional to fixed-end moments of respective members.

TABLE V. FINAL MOMENTS AND COMPARISON FOR TEST PROBLEM VIII-A (8 Stories, Trough Loading)

OUTPUT* AT FLR	JT	INPUT AT BAR 1 Analog	1 Kani	1 Mod. Mom. D.	1 % Analog / Kani	2 Analog	2 Kani	2 Mod. Mom. D.	2 % Analog / Kani	3 Analog	3 Kani	3 Mod. Mom. D.	3 % Analog / Kani	4 Analog	4 Kani	4 Mod. Mom. D.	4 % Analog / Kani
8	1	16.861	16.970	17.545	99.36	0	0	0	-	16.861	16.970	17.545	99.36	0	0	0	-
	2	6.863	6.668	6.030	102.6	0	0	0	-	12.249	11.847	12.674	103.4	19.115	18.514	18.705	103.2
	3	10.115	18.514	18.705	103.4	0	0	0	-	12.249	11.847	12.674	103.4	6.863	6.668	6.030	102.6
	4	0	0	0	-	0	0	0	-	16.861	16.970	17.545	99.36	16.861	16.970	17.545	99.36
7	1	3.143	2.680	.48	117.3	4.138	4.161	3.853	99.44	1.435	1.481	.24	96.9	0	0	0	-
	2	0.768	0.743	3.85	103.4	2.155	2.673	1.293	80.62	1.288	1.312	1.29	98.0	2.327	2.103	1.26	110.6
	3	2.627	2.103	1.81	110.6	2.155	2.673	1.293	80.62	1.202	1.312	1.18	91.61	0.768	.743	4.19	103.4
	4	0	0	0	-	4.138	4.161	3.853	99.44	1.435	1.481	.29	96.9	3.143	2.680	.60	117.3
6	1	17.013	17.140	18.050	99.25	5.739	5.685	6.840	100.95	11.165	11.455	11.211	97.47	0	0	0	-
	2	6.503	6.401	5.242	101.45	3.965	3.877	4.949	102.27	8.234	8.351	8.852	98.60	18.483	18.629	19.044	99.22
	3	18.483	18.629	19.043	99.22	3.881	3.877	4.949	100.10	8.234	8.351	8.852	98.60	6.503	6.401	5.242	101.45
	4	0	0	0	-	5.739	5.685	6.840	100.95	11.165	11.455	11.211	97.47	17.013	17.140	18.050	99.25
5	1	1.357	1.266	.39	107.18	2.056	1.849	.19	111.2	0.744	0.582	.19	127.8	0	0	0	-
	2	2.184	2.419	4.33	90.28	0.427	0.483	1.69	88.3	1.326	1.349	1.69	98.30	1.497	1.553	.94	96.39
	3	1.555	1.553	.94	100.12	0.427	0.483	1.69	88.3	1.326	1.349	1.69	98.30	2.184	2.419	4.33	90.28
	4	0	0	0	-	2.056	1.849	.19	111.2	0.744	0.582	.19	127.8	1.357	1.266	.39	107.18
4	1	19.686	18.15	18.80	108.46	7.075	6.593	7.292	107.3	12.649	11.557	11.508	109.45	0	0	0	-
	2	4.963	4.956	7.29	100.14	4.601	4.685	5.667	98.2	8.973	9.568	10.056	93.78	18.905	19.208	19.652	98.42
	3	18.864	19.208	11.508	98.2	4.601	4.685	5.667	98.2	8.973	9.568	10.056	93.78	4.961	4.956	3.930	100.10
	4	0	0	0	-	7.075	6.593	7.292	107.3	12.649	11.557	11.508	109.45	19.686	18.150	18.800	108.46
3	1	1.322	1.219	.34	108.4	1.402	1.385	.16	101.2	0.178	0.166	.169	107.21	0	0	0	-
	2	2.292	2.571	4.51	89.15	0.125	0.117	1.8	108.00	1.316	1.225	1.86	107.4	1.757	1.462	.79	120.1
	3	1.757	1.462	.78	120.1	0.125	0.117	1.8	108.00	1.316	1.225	1.86	107.4	2.296	2.571	4.51	89.30
	4	0	0	0	-	1.402	1.385	.78	101.2	0.178	0.166	.169	107.21	1.322	1.219	.33	108.4
2	1	16.433	18.499	18.93	88.83	8.055	8.453	9.47	95.29	8.223	10.046	9.47	81.85	0	0	0	-
	2	4.400	4.437	3.60	99.17	6.748	6.883	8.11	98.04	6.190	8.103	8.11	76.39	19.700	19.423	19.83	101.4
	3	19.700	19.423	19.83	101.4	6.748	6.883	8.11	98.04	6.190	8.103	8.11	76.39	4.400	4.437	3.60	99.17
	4	0	0	0	-	8.055	8.453	9.47	95.29	8.223	10.046	9.47	81.85	16.433	18.499	18.93	88.83
1	1	0.359	0.347	.34	103.45	2.581	3.019	.17	85.46	2.229	2.672	.17	83.42	0	0	0	-
	2	3.837	3.654	4.51	104.83	1.142	1.215	1.86	94.00	3.691	3.782	1.86	97.60	1.124	1.086	.79	103.50
	3	1.124	1.086	.79	103.50	1.142	1.215	1.86	94.00	3.691	3.782	1.86	97.60	3.837	3.654	4.51	104.83
	4	0	0	0	-	2.581	3.019	.17	85.46	2.229	2.672	.17	83.42	0.359	0.347	.34	103.45

*Signs are omitted in this table for convenience.

TABLE VI. TYPICAL RESPONSE TO EXCITATIONS IN REMOTE STORIES

OUTPUT AT				INPUT AT*					
FLR	JT	BAR		1-1-1	1-2-4	1-2-1	1-3-4	1-3-1	1-4-4
6	1	1	...	+.003	0	0	0	0	0
		2	...	0	0	0	0	0	0
		3	...	-.003	0	0	0	0	0
		4	...	0	0	0	0	0	0
	2	1	...	+.001	0	0	0	0	0
		2	...	0	0	0	0	0	0
		3	...	-.001	0	0	0	0	0
		4	...	-.001	0	0	0	0	0
	3	1	...	0	0	0	0	0	-.001
		2	...	0	0	0	0	0	0
		3	...	0	0	0	0	0	-.001
		4	...	0	0	0	0	0	+.001
	4	1	...	0	0	0	0	0	0
		2	...	0	0	0	0	0	0
		3	...	0	0	0	0	0	-.003
		4	...	0	0	0	0	0	+.003
5	1	1	...	+.007	0	0	0	0	0
		2	...	+.016	+.003	-.001	0	0	0
		3	...	-.020	-.003	+.001	0	+.001	0
		4	...	0	0	0	0	-.001	0
	2	1	...	+.004	+.003	-.001	0	0	-.001
		2	...	+.004	+.003	-.001	0	+.002	+.002
		3	...	-.005	-.007	+.002	-.001	-.004	-.001
		4	...	+.001	+.001	0	0	+.001	+.001
	3	1	...	+.001	+.001	0	0	+.001	+.001
		2	...	+.002	+.002	0	-.001	+.003	+.004
		3	...	-.001	-.004	-.001	+.002	-.007	-.005
		4	...	-.001	+.001	0	-.001	+.003	+.004
	4	1	...	0	0	0	0	0	0
		2	...	0	+.001	0	-.001	+.003	+.016
		3	...	0	-.001	0	+.001	-.003	-.020
		4	...	0	0	0	0	0	+.007

* Input values proportional to fixed-end moments of respective members.

TABLE VII. TYPICAL RESPONSE TO EXCITATIONS IN REMOTE STORIES

OUTPUT AT				INPUT AT						
FLR	JT	BAR		6-1-1	6-2-4	6-2-1	6-3-4	6-3-1	6-4-4	
2	1	1	...	-.021	-.003	0	0	0	0	...
		2	...	+.050	+.011	-.003	0	+.002	+.001	...
		3	...	-.029	-.008	+.002	0	-.002	-.001	...
		4	...	0	0	0	0	0	0	...
	2	1	...	-.007	-.004	+.001	0	+.001	+.001	...
		2	...	+.014	+.014	-.003	-.002	+.008	+.003	...
		3	...	-.009	-.008	+.002	+.001	-.005	-.003	...
		4	...	+.002	-.002	+0	0	-.002	-.001	...
	3	1	...	-.001	-.002	+0	0	-.002	+.002	...
		2	...	+.003	+.008	-.002	-.003	+.014	+.014	...
		3	...	-.003	-.005	+.001	+.002	-.008	-.009	...
		4	...	+.001	+.001	-0	+.001	-.004	-.007	...
	4	1	...	0	0	0	0	0	0	...
		2	...	+.001	+.002	-0	-.003	+.011	+.050	...
		3	...	-.001	-.002	+0	+.002	-.008	-.029	...
		4	...	0	0	0	0	-.003	-.021	...
1	1	1	...	-.003	0	0	0	0	0	...
		2	...	+.008	+.002	-0	0	+.001	0	...
		3	...	-.006	-.002	+0	0	-.001	0	...
		4	...	0	0	0	0	0	0	...
	2	1	...	-.001	0	0	0	0	0	...
		2	...	+.002	+.002	-0	0	+.002	+.001	...
		3	...	-.002	-.001	+0	0	-.001	-.001	...
		4	...	0	-.001	+0	0	0	0	...
	3	1	...	0	0	0	0	-.001	0	...
		2	...	+.001	+.002	-0	0	+.002	+.002	...
		3	...	-.001	-.001	+0	0	-.001	-.002	...
		4	...	0	0	0	0	0	-.001	...
	4	1	...	0	0	0	0	0	0	...
		2	...	0	+.001	-0	0	+.002	+.008	...
		3	...	0	-.001	+0	0	-.002	-.006	...
		4	...	0	0	0	0	0	-.003	...

TEST PROBLEM IX-A-1. 8 STORIES, 3 BAYS.

FINAL END MOMENTS BY KANI MOMENT DISTRIBUTION.

FLR	JOINT	BAR 1	BAR 2	BAR 3	BAR 4
8	1	-17.128	0.000	17.128	0.000
8	2	-6.351	-0.000	-12.322	18.673
8	3	-18.673	0.000	12.322	6.351
8	4	-0.000	-0.000	-17.128	17.128
7	1	-2.202	5.706	-3.503	-0.000
7	2	2.175	-4.621	1.917	0.530
7	3	-0.530	4.621	-1.917	-2.175
7	4	0.000	-5.706	3.503	2.202
6	1	0.388	-1.289	0.901	0.000
6	2	-0.290	0.753	-0.440	-0.023
6	3	0.023	-0.753	0.440	0.290
6	4	-0.000	1.289	-0.901	-0.388
5	1	-0.087	0.286	-0.200	-0.000
5	2	0.058	-0.147	0.090	-0.000
5	3	0.000	0.147	-0.090	-0.058
5	4	0.000	-0.286	0.200	0.087
4	1	0.018	-0.071	0.053	0.000
4	2	-0.011	0.033	-0.024	0.001
4	3	-0.001	-0.033	0.024	0.011
4	4	-0.000	0.071	-0.053	-0.018
3	1	-0.005	0.017	-0.012	-0.000
3	2	0.003	-0.008	0.005	-0.000
3	3	0.000	0.008	-0.005	-0.003
3	4	0.000	-0.017	0.012	0.005
2	1	0.001	-0.004	0.003	0.000
2	2	-0.001	0.002	-0.001	0.000
2	3	-0.000	-0.002	0.001	0.001
2	4	-0.000	0.004	-0.003	-0.001
1	1	-0.000	0.001	-0.001	-0.000
1	2	0.000	-0.000	0.000	-0.000
1	3	0.000	0.000	-0.000	-0.000
1	4	0.000	-0.001	0.001	0.000

ACCURACY DESIRED AT LEAST= 0.00001
17DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ANALYSIS COMPLETE.

TEST PROBLEM IX-A-5. 8 STORIES, 3 BAYS.

FINAL END MOMENTS BY KANI MOMENT DISTRIBUTION.

FLR	JOINT	BAR 1	BAR 2	BAR 3	BAR 4
8	1	0.007	0.000	-0.007	0.000
8	2	-0.004	-0.000	0.004	0.000
8	3	-0.000	0.000	-0.004	0.004
8	4	-0.000	-0.000	0.007	-0.007
7	1	-0.038	-0.048	0.086	-0.000
7	2	0.026	0.021	-0.048	0.001
7	3	-0.001	-0.021	0.048	-0.026
7	4	0.000	0.048	-0.086	0.038
6	1	0.175	0.262	-0.437	0.000
6	2	-0.154	-0.133	0.316	-0.028
6	3	0.028	0.133	-0.316	0.154
6	4	-0.000	-0.262	0.437	-0.175
5	1	-0.622	-1.592	2.214	-0.000
5	2	0.684	1.024	-1.909	0.201
5	3	-0.201	-1.024	1.909	-0.684
5	4	0.000	1.592	-2.214	0.622
4	1	-18.468	7.175	11.293	0.000
4	2	-4.249	-5.550	-9.779	19.579
4	3	-19.579	5.550	9.779	4.249
4	4	-0.000	-7.175	-11.293	18.468
3	1	-0.824	3.435	-2.612	-0.000
3	2	0.971	-3.250	1.963	0.316
3	3	-0.316	3.250	-1.963	-0.971
3	4	0.000	-3.435	2.612	0.824
2	1	0.200	-0.801	0.601	0.000
2	2	-0.198	0.648	-0.401	-0.048
2	3	0.048	-0.648	0.401	0.198
2	4	-0.000	0.801	-0.601	-0.200
1	1	-0.045	0.191	-0.146	-0.000
1	2	0.039	-0.134	0.088	0.007
1	3	-0.007	0.134	-0.088	-0.039
1	4	0.000	-0.191	0.146	0.045

ACCURACY DESIRED AT LEAST= 0.00001
19DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ANALYSIS COMPLETE.

TEST PROBLEM IX-A-8. 8 STORIES, 3 BAYS.

FINAL END MOMENTS BY KANI MOMENT DISTRIBUTION.

FLR	JOINT	BAR 1	BAR 2	BAR 3	BAR 4
8	1	-0.000	-0.000	0.000	-0.000
8	2	0.000	0.000	-0.000	-0.000
8	3	0.000	-0.000	0.000	-0.000
8	4	0.000	0.000	-0.000	0.000
7	1	0.000	0.001	-0.001	0.000
7	2	-0.000	-0.000	0.000	0.000
7	3	-0.000	0.000	-0.000	0.000
7	4	-0.000	-0.001	0.001	-0.000
6	1	-0.002	-0.003	0.005	-0.000
6	2	0.001	0.001	-0.003	0.000
6	3	-0.000	-0.001	0.003	-0.001
6	4	0.000	0.003	-0.005	0.002
5	1	0.008	0.018	-0.026	0.000
5	2	-0.006	-0.009	0.015	-0.001
5	3	0.001	0.009	-0.015	0.006
5	4	-0.000	-0.018	0.026	-0.008
4	1	-0.039	-0.082	0.121	-0.000
4	2	0.035	0.045	-0.086	0.006
4	3	-0.006	-0.045	0.086	-0.035
4	4	0.000	0.082	-0.121	0.039
3	1	0.159	0.460	-0.619	0.000
3	2	-0.156	-0.306	0.499	-0.037
3	3	0.037	0.306	-0.499	0.156
3	4	-0.000	-0.460	0.619	-0.159
2	1	-0.645	-2.036	2.681	-0.000
2	2	0.755	1.525	-2.524	0.244
2	3	-0.244	-1.525	2.524	-0.755
2	4	0.000	2.036	-2.681	0.645
1	1	-18.783	8.816	9.967	0.000
1	2	-3.751	-7.597	-8.448	19.795
1	3	-19.795	7.597	8.448	3.750
1	4	-0.000	-8.816	-9.967	18.783

ACCURACY DESIRED AT LEAST= 0.00001
18DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ANALYSIS COMPLETE.

typical parts of the output records are shown to indicate the nature and magnitude of the operation. One such part, taken from Problems VIII (eight stories, three bays, trough loading) is given in Table 4.

Final values were computed for all the problems from the simulator output in the manner described previously. A typical final-moments record for the case of Problem VIII-A (eight stories, three bays) is given in Table 5. The final tables for all the problems of the project are too numerous to be reproduced here. The table gives, for each bar meeting at each joint in the structure, the values for final end moments obtained by the simulator, the Kani and the modified moment distribution methods. Also given for each such bar is the percentage of analog values expressed as percentage of the corresponding Kani values.

A study of the table indicates the simulator values to be in agreement with the Kani values within ten per cent throughout except for infrequent cases where this range exceeds 10-15%. One remarkable feature of the output values obtained is the fairly frequent occurrence of accuracies within 99-100%, accompanied by many values in the order of 3-5% and some in the 7-9%. The values obtained beyond the 10% range are probably due to manual errors rather than instrumental errors, because of the relative infrequency of such values and the fact that the electrical parts used are precision instruments may be expected to offer constant performance during the execution of a problem.

The disagreement of the modified moment distribution values and the Kani results are clearly noticeable especially in all the column moments, and in the case of beam moments in the middle bay of the structure. This tendency continues throughout the test problems, and is explained by the fact that only a two-story tier of the building is considered at a time in the modified moment distribution method, assuming the columns to be fixed at the far ends, and no carry-over of moments occurs to the adjoining stories.

The general characteristics observed in Table 5 for Problem VIII-A are indicated in all the problems studied, for the A and B series. It is the author's opinion that, provided some practice is acquired in the accurate operation of the instrument, and in setting the resistances manual errors can be eliminated to a large degree, in which case accuracies well within 90-100% can be expected with confidence.

4.5 Comparison of the Portal and Kani Values

Wind loads cases were studied in the Series C problems as shown in Figure 11, by the Portal and Kani methods. Typical values obtained by the methods are shown below for comparison purposes.

FLR	JOINT	BAR 1	2	3	4
6	1	2285.332	0.000	-2285.332	0.000
6	2	2962.501	0.000	-4845.792	1883.291
6	3	1883.291	0.000	-4845.792	2962.501
6	4	0.000	0.000	-2285.332	2285.332
5	1	6038.652	381.227	-6419.879	0.000
5	2	8631.195	-3250.102	-10558.218	5177.124
5	3	5177.124	-3250.102	-10558.218	8631.195
5	4	0.000	381.227	-6419.879	6038.652
4	1	11085.508	-4070.452	-7015.059	0.000
4	2	16795.141	-8951.448	-17585.233	9741.539
4	3	9741.539	-8951.448	-17585.233	16795.141
4	4	0.000	-4070.452	-7015.059	11085.508
3	1	15446.071	-4787.475	-10658.600	0.000
3	2	24333.531	-15612.230	-22527.724	13806.418
3	3	13806.418	-15612.230	-22527.724	24333.531
3	4	0.000	-4787.475	-10658.600	15446.071
2	1	19865.351	-7077.379	-12787.976	0.000
2	2	31769.503	-19736.292	-29908.269	17875.051
2	3	17875.051	-19736.292	-29908.269	31769.503
2	4	0.000	-7077.379	-12787.976	19865.350
1	1	27601.428	-5755.930	-21845.505	0.000
1	2	40721.266	-26547.814	-38154.489	23981.031
1	3	23981.031	-26547.814	-38154.489	40721.266
1	4	0.000	-5755.930	-21845.505	27601.428

ACCURACY DESIRED AT LEAST= 0.01000
35DISTRIBUTION CYCLES WERE REQUIRED TO 38TAIN THIS

UNITS--MOMENTS IN KIP-FT.

	GIRDER MOMENTS			COLUMN MOMENTS			
FLR	AB	BC	CD	A	B	C	D
6	2.50	1.25	2.50	2.50	3.75	3.75	2.50
5	9.00	4.50	9.00	6.50	9.75	9.75	6.50
4	17.00	8.50	17.00	10.50	15.75	15.75	10.50
3	24.00	12.00	24.00	13.50	20.25	20.25	13.50
2	30.00	15.00	30.00	16.50	24.75	24.75	16.50
1	36.00	18.00	36.00	19.50	29.25	29.25	19.50

Disagreement between the methods is observed in almost all the cases studied, and the errors are seen to be much more serious than those of the modified moment distribution method. Errors in the range of 25% are commonly noticeable; those in the order of 50% are not uncommon. The greatest errors are seen to occur in the moments in the middle bay girders where the values are in disagreement by amounts exceeding 80-100%. This is explained by the fact that the middle bay girder on account of its shorter length in our case than the end bay girders, takes on a considerably greater stiffness value and this causes a larger share of the moment at a joint to be distributed to the middle bay girder. The Portal method, on the other hand, does not take member stiffnesses into account, and hence this error takes on serious proportions in cases where some members possess substantially higher stiffnesses relative to other members in the structure.

4.6 Comparison of Time, Effort and Speed

The effort involved in the simulation of a typical eight-story problem is as follows: The number of branch currents measured or 'probed' for each input = 108; the number of inputs made utilizing symmetry of structure = 12. Hence a total of twelve sets of 108 readings are required. For each such set the time taken was observed on the average to be approximately sixty minutes. For problems involving smaller structures the time interval is proportionately reduced. Additional to this is the programming effort necessary before the start of a problem, namely the calculation and setting of the variable resistors; this may be compared to that of preparation of data for digital computers. The actual execution time in the digital machine for any given problem, being of small magnitudes, cannot be compared to other methods in this respect. However in order to obtain the number of cycles of iteration required in the Kani method, to satisfy arbitrary accuracy parameters, instructions are set up in the program to accept such an accuracy parameter for each problem, to keep a record of the number of distribution cycles performed to obtain this specified accuracy and to print that information with the output. Examples of such listings in typical cases are given below.

```
ACCURACY DESIRED AT LEAST= 0.00001
  15DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ACCURACY DESIRED AT LEAST= 0.00001
  10DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ACCURACY DESIRED AT LEAST= 0.00001
  12DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ACCURACY DESIRED AT LEAST= 0.00001
  21DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ACCURACY DESIRED AT LEAST= 0.00001
  22DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS
```

It may be noted that the number of cycles were of the order of 10 - 20 in the case of the dead and live loads of unit magnitude in the A and B Series. In the C series concerning wind loads in pounds per square foot according to N.B.C. (19), the number of cycles required increased considerably for the same accuracy condition; the problems ran for abnormal amounts of time without ever reaching that accuracy; hence the accuracy specified was reduced to 0.01 and the following values were obtained.

```
ACCURACY DESIRED AT LEAST= 0.01000
  33DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ACCURACY DESIRED AT LEAST= 0.01000
  37DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS

ACCURACY DESIRED AT LEAST= 0.01000
  33DISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS
```

CHAPTER V

SUMMARY AND CONCLUSIONS

5.1 Summary

Analog methods based on power-energy relations or the simulation of deformation compatibility conditions by means of the voltage relationships for a π or wye circuit, are available for the analysis of framed structures. Of these the latter method offers the advantages of simplicity of instrumentation and consequent minimization of experimental errors. A simulating instrument based on this type of analogy can be constructed with ease using such common parts as meters for reading the input and output currents, variable resistors and potentiometers. The circuit designed is based on a modular system and is capable of continuation and extension along the same lines to any desired size. The connections at the joints are simulated electrically by thin shimstock metal strips which act as flexible make-break contacts. The readings obtained indicate throughout that the exact current continuity conditions at the nodes to be achieved by this arrangement. By the use of two probes, one of which is used to depress the desired strip and the other to contact the node concerned, branch currents can be measured instantaneously. Thus in a structure or portion of a frame up to eight stories tall and three bays wide, the moment in any member due to the loads in any other member is obtained instantaneously, the process of distribution throughout the structure being completed by electricity instantaneously. By reason of this statement the simulator can also be termed as an instant automatic moment distributor.

The building up of the circuit which involves such common parts as resistors, 'Masonite' board, screws, nuts, etc., and common wire, compares quite favorably in terms of the effort involved, cost, and speed with the instrumentation required in other experimental analysis methods.

5.2 Efficiency of Simulator

The accuracies obtained in the case of a typical building frame problems studied ranged from less than 1% in some cases to those in the order of 3-6% and 7-10% in a number of cases, and over 10% in infrequent instances. Because of the general consistency in the accuracies obtained throughout the study, the advantage of using such parts as continuously variable precision potentiometers which are produced in controlled processes, is observed. This forms a better arrangement than Bray's arrangement of using several fixed resistors in parallel to obtain a certain resistance, in terms of flexibility of use, simplicity of construction and economy. This also compares favorably with the large part of hand-built instrumentation used in expreimental methods such as models. The accuracy of the instrument lies in most cases between modified moment distribution and Kani methods, for buildings several stories tall.

The effort involved in hand calculation by any method is considerably reduced by the use of the instrument, and is converted from numerical computations to one of measurement of currents in branches of a circuit that bears direct pictorial resemblance to the configuration of the structure. Thus the need for rechecking of the numerical computations is eliminated by the analog. In the author's opinion, manual errors can be avoided to a great extent with a little practice in the operation of the simulator, for which no special training or electrical background is required.

5.3 Comparison with Machine Computation

The simulator thus can effectively serve as a rapid aid in the design office, and can be used by architects and engineers with no training in electrical measurements. The programming involved and the ease with which the parts can be assembled compare favorably with the use of data processing facilities. In underdeveloped areas such as India, where a paucity of high-speed digital equipment exists, the simulator provides an excellent and economical alternative to hand calculation methods.

However in areas where ample electronic data processing facilities are available, the computer proves a considerably better method because of the extreme accuracies obtainable, and the speed, efficiency and flexibility with which such computation is possible. Modern computing equipment have already reached a state of considerable sophistication. The present progress in digital computing systems, it may be safely predicted, would before long make the computer a more inexpensive and commonly available tool. In that case, machine computation is superior to any other computing method for tall building analysis and design. The program set up for Kani moment distribution in this project proves superior to some other methods, because of the relatively small core storage locations required and the speed of the solution. Further, the flexibility of the program can be increased with the revision of a few statements, to include any general condition in structure or loading, provided axial loads and torsional restraint are not considered. For this reason, machine computation proves somewhat superior to the use of the simulator as a valid research tool.

5.4 Usefulness as a Teaching Aid

The direct pictorial resemblance of the π-group arrangement to the building frame members and the similarity of the current distribution to the distribution of moments in the structure, makes this instrument a useful teaching aid. The flow of currents through the network through parts of low resistance is identical to the 'flow' of moments in a building frame through the relatively stiffer members. This similarity serves as a physical demonstration of the moment distribution processes and can therefore be used in the teaching of a first course in indeterminate structures. Because of the saving in computation time itself, the simulator can be used for student projects in courses on the design of tall buildings.

5.5 Suggestions for Further Study

For the problems in this study building frames of typical proportions and sizes were assumed and the simulator set up for these values. Analysis was performed by inducing simulated moments at various parts of the structure and recording their influences at every joint. However, by reason of the fact that all distribution is completed instantly by electricity and no "cycles of distribution" are involved as in hand calculation methods, the following approach to the use of the simulator suggests itself. By changing the stiffness of a member the resulting changes in the moments can be recorded rapidly in the simulator; thus several changes in stiffness values of members and the resulting changes in the distribution of the moments may be simulated by turning the knobs to the desired values and recording the new values for branch currents. By means of such changing and experimentation with member properties optimum sizes may be obtained for any member for any given conditions. If the potentiometers are calibrated inversely with chosen scale factors to read relative stiffness values the stiffness variation mentioned above may be simulated very rapidly. A study of the feasibility of this approach of using the simulator as working tool for optimum design, would be of interest.

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APPENDIX

PROGRAMS FOR MACHINE COMPUTATION

All the computations involved in this study other than those related to the simulator were done by computers. Programs were set up by the author for the Kani and Portal methods on the high-speed IBM 7040-32K machines respectively. These programs are complete only in the sense they generate instructions for the operations for the method as used in this study. The base condition was assumed hinged, which is the common case in multistory buildings. More complete generalization of the structure and loading is possible by the revision of a few statements.

A machine listing of the program is given in the following page, followed by auxiliary information and input format. A listing of the 'Portal method' program and input information for it are also given.

```
N SESHAGIRI ARCHENGR THESIS           FORTRAN SOURCE LIST
 ISN        SOURCE STATEMENT

   0 $IBFTC KANI          NODECK
     C
     C       'KANI MOMENT DISTRIBUTION' FOR TALL BUILDINGS.
     C
     C       MAXIMUM LIMIT  --  100 STORIES,  10 BAYS.
     C       DEAD, LIVE AND WIND LOADS OR ANY COMBINATION THEREOF.
     C       LANGUAGE -- FORTRAN IV                      MACHINE -- IBM 7040-32K
     C
   1         DIMENSION GL(12,101),WMG(12,101),HT(101),WM(12,101),SUMKC(12,101)
   2         DIMENSION SUMKG(12,101),DF1(12,101),DF2(12,101),DF3(12,101)
   3         DIMENSION DF4(12,101),CORF(12,101),SIGK(101),FEM1(12,101)
   4         DIMENSION FEM2(12,101),Q(101),SWAY(12,101),SUMBM(101),BM1(12,101)
   5         DIMENSION BM2(12,101),BM3(12,101),BM4(12,101),A(12,101)
   6         DIMENSION W(101),X(12,101),ID(12)
     C
   7 100     FORMAT(2I4,F7.3,F8.5)
  10 101     FORMAT(F6.2,F8.2)
  11 102     FORMAT(9F8.2)
  12 103     FORMAT(20X,46HFINAL END MOMENTS BY KANI MOMENT DISTRIBUTION./)
  13 104     FORMAT(20X,3HFLR,2X,5HJOINT,23X,3HBAR)
  14 105     FORMAT(39X,1H1,9X,1H2,9X,1H3,9X,1H4/)
  15 106     FORMAT(20X,I3,4X,I3,4F10.3)
  16 107     FORMAT(/20X,26HACCURACY DESIRED AT LEAST=,F8.5)
  17 108     FORMAT(20X,I4,48HDISTRIBUTION CYCLES WERE REQUIRED TO OBTAIN THIS)
  20 200     FORMAT(1H1,7X,12A6//)
  21 201     FORMAT(12A6)
  22 202     FORMAT(///20X,18HANALYSIS COMPLETE.)
     C
  23 1       READ(5,201)ID
  25         READ(5,100)N,M,BAY,ACCRCY
  30         IF(N.EQ.0)CALL EXIT
  33         N=N+1
  34         DO 109 I=2,N
  35 109     READ(5,102)(GL(J,I),WMG(J,I),J=2,M)
  43         DO 110 I=2,N
  44 110     READ(5,102)(X(J,I),J=2,M)
  52         M=M+1
  53         READ(5,101)(HT(I),W(I),I=2,N)
  60         DO 111 I=2,N
  61 111     READ(5,102)(WM(J,I),J=2,M)
     C
     C       PRELIMINARY CALCULATIONS
     C
  67         DO 6 I=2,N
  70         DO 2 J=2,M
  71         IF(J.EQ.2)SIGK(I)=WM(J,I)/HT(I)
  74         IF(J.GT.2)SIGK(I)=SIGK(I)+(WM(J,I)/HT(I))
  77 2       CONTINUE
 101         DO 6 J=2,M
 102         IF(I.EQ.2)WM(J,I-1)=0.
 105         IF(I.EQ.2)HT(I-1)=1.
 110         IF(J.EQ.2)WMG(J-1,I)=0.
 113         IF(J.EQ.2)GL(J-1,I)=1.
 116         IF(J.EQ.2)X(J-1,I)=0.
 121         IF(J.EQ.M)WMG(J,I)=0.
```

```
N SESHAGIRI ARCHENGR THESIS              FORTRAN SOURCE LIST KANI
ISN        SOURCE STATEMENT

124        IF(J.EQ.M)GL(J,I)=1.
127        IF(J.EQ.M)X(J,I)=0.
132        SUMKC(J,I)=WM(J,I)/HT(I)+WM(J,I-1)/HT(I-1)
133        SUMKG(J,I)=WMG(J,I)/GL(J,I)+WMG(J-1,I)/GL(J-1,I)
134        DF1(J,I)=-.5*(WMG(J,I)/GL(J,I))/(SUMKC(J,I)+SUMKG(J,I))
135        DF2(J,I)=-.5*(WM(J,I-1)/HT(I-1))/(SUMKC(J,I)+SUMKG(J,I))
136        DF3(J,I)=-.5*(WM(J,I)/HT(I))/(SUMKC(J,I)+SUMKG(J,I))
137        DF4(J,I)=-.5*(WMG(J-1,I)/GL(J-1,I))/(SUMKC(J,I)+SUMKG(J,I))
140        CORF(J,I)=-1.5*(WM(J,I)/HT(I))/SIGK(I)
141        IF(I.EQ.N)CORF(J,I)=CORF(J,I)*2./1.5
144        IF(I-2)3,3,4
145 3      SWAY(J,I-1)=0.
146        Q(I)=(HT(I)/2.)*BAY*W(I)
147        GO TO 5
150 4      Q(I)=Q(I-1)+(((HT(I)+HT(I-1))/2.)*BAY*W(I))
151 5      SWAY(J,I)=Q(I)*(HT(I)/3.)*CORF(J,I)
152        FEM1(J,I)=-X(J,I)*GL(J,I)**2/12.
153 6      FEM2(J,I)=X(J-1,I)*GL(J-1,I)**2/12.
156        DO 7 I=1,N
157        DO 7 J=1,M
160        X(J,I)=SWAY(J,I)
161        BM1(J,I)=0.
162        BM2(J,I)=0.
163        BM3(J,I)=0.
164 7      BM4(J,I)=0.
    C
    C      DISTRIBUTION
    C
167        NCYCLS=0
170 8      NCYCLS=NCYCLS+1
171        DO 18 I=2,N
172 9      DO 17 J=2,M
173        A(J,I)=X(J,I)+X(J,I-1)+FEM1(J,I)+FEM2(J,I)
174        IF(I-N)10,13,13
175 10     IF(J-M)11,12,12
176 11     A(J,I)=BM1(J-1,I)+BM2(J,I+1)+BM3(J,I-1)+BM4(J+1,I)+A(J,I)
177        GO TO 16
200 12     A(J,I)=BM1(J-1,I)+BM2(J,I+1)+BM3(J,I-1)+A(J,I)
201        GO TO 16
202 13     IF(J-M)14,15,15
203 14     A(J,I)=BM1(J-1,I)+BM3(J,I-1)+BM4(J+1,I)+A(J,I)
204        GO TO 16
205 15     A(J,I)=BM1(J-1,I)+BM3(J,I-1)+A(J,I)
206 16     CONTINUE
207        BM1(J,I)=A(J,I)*DF1(J,I)
210        BM2(J,I)=A(J,I)*DF2(J,I)
211        BM3(J,I)=A(J,I)*DF3(J,I)
212 17     BM4(J,I)=A(J,I)*DF4(J,I)
214 18     CONTINUE
216        DO 21 I=2,N
217        DO 20 J=2,M
220        IF(I.EQ.N)GO TO 19
223        IF(J.EQ.2)SUMBM(I)=BM3(J,I)+BM2(J,I+1)
226        IF(J.GT.2)SUMBM(I)=BM3(J,I)+BM2(J,I+1)+SUMBM(I)
231        GO TO 20
```

```
N SESHAGIRI ARCHENGR THESIS              FORTRAN SOURCE LIST KANI
 ISN        SOURCE STATEMENT

 232 19     IF(J.EQ.2)SUMBM(I)=BM3(J,I)
 235        IF(J.GT.2)SUMBM(I)=BM3(J,I)+SUMBM(I)
 240 20     CONTINUE
 242        DO 21 J=2,M
 243 21     X(J,I)=CORF(J,I)*SUMBM(I)+SWAY(J,I)
     C
     C      CALCULATION OF FINAL MOMENTS
     C
 246        DO 22 I=2,N
 247        DO 22 J=2,M
 250        IF(J.LT.M)SM1=2.*BM1(J,I)+BM4(J+1,I)+FEM1(J,I)
 253        IF(J.EQ.M)SM1=2.*BM1(J,I)+FEM1(J,I)
 256        SM2=2.*BM2(J,I)+BM3(J,I-1)+X(J,I-1)
 257        SM4=2.*BM4(J,I)+BM1(J-1,I)+FEM2(J,I)
 260        IF(I.LT.N)SM3=2.*BM3(J,I)+BM2(J,I+1)+X(J,I)
 263        IF(I.EQ.N)SM3=2.*BM3(J,I)+X(J,I)
     C
     C      ACCURACY CHECK
     C
 266        SUMMOM=SM1+SM2+SM3+SM4
 267        SUMMOM=ABS(SUMMOM)
 270        IF(SUMMOM.GT.ACCRCY)GO TO 8
 273 22     CONTINUE
 276        WRITE(6,200)ID
 277        WRITE(6,103)
 300        WRITE(6,104)
 301        WRITE(6,105)
 302        DO 23 I=2,N
 303        DO 23 J=2,M
 304        IF(J.LT.M)DF1(J,I)=2.*BM1(J,I)+BM4(J+1,I)+FEM1(J,I)
 307        IF(J.EQ.M)DF1(J,I)=2.*BM1(J,I)+FEM1(J,I)
 312        DF2(J,I)=2.*BM2(J,I)+BM3(J,I-1)+X(J,I-1)
 313        DF4(J,I)=2.*BM4(J,I)+BM1(J-1,I)+FEM2(J,I)
 314        IF(I.LT.N)DF3(J,I)=2.*BM3(J,I)+BM2(J,I+1)+X(J,I)
 317        IF(I.EQ.N)DF3(J,I)=2.*BM3(J,I)+X(J,I)
 322        K=N-I+1
 323        L=J-1
 324 23     WRITE(6,106)K,L,DF1(J,I),DF2(J,I),DF3(J,I),DF4(J,I)
 327        WRITE(6,107)ACCRCY
 330        WRITE(6,108)NCYCLS
 331        WRITE(6,202)
 332        GO TO 1
 333        END
```

The input for the program would be in punched cards as follows:

Cards	Information Punched	Col. Nos.	Dec. in Col. Nos.
1st card	Title of Problem of any identifying information (or blank if desired).	1-72	-
2nd card	No. of stories in bldg.		
	if single-digit	4	-
	if double-digit	3-4	--
	No. of cols.	8	--
	Bay width in lateral direction (or spacing of wind bents)	10-15	12
	Accuracy desired	17-23	18
3rd card	Length of first beam (from left) in top floor	4-9	6
	m. i. of __ do	11-17	14
	length 2nd beam in top floor	20-25	22
	m. i. of 2nd	27-32	30
	. . .		
	. . .		
	. . .		
Next card	__ do __ for all floors from top	as above	4-8-2
Next card	Distr. load on beams of top floor, from left to right	2-16; 18-24; 26-32;	14; 22; 30
	-do- for all flrs. from top	etc. as above	etc. as above
Next card	Ht. of top story	2-6	4
	Wind Pressure (per sq. ft.) at top story	8-14	12
	— do — for all stories	as above	as above
Next card	M. I. of cols. of top floor from left to right	2-16; 18-24; 26-32; etc.	14; 22; 30 etc.

Next card must be first card of following problem if any or blank; last card must be blank.

```
C   N SESHAGIRI    ARCHENGR THESIS
C
C                         PROGRAM II
C
C     'THE PORTAL METHOD'  FOR TALL BUILDINGS.
C
C     MAXIMUM LIMIT  --  20 STORIES.
C     LANGUAGE  --  FORTRAN II                  MACHINE  --  IBM 1620-20K
C
      DIMENSION W(20),SUMPX(20),HT(20)
      DIMENSION HA(20),HB(20),HC(20),HD(20),BMAP(20),BMAQ(20),BMBP(20)
      DIMENSION BMBQ(20),BMCP(20),BMCQ(20),BMDP(20),BMDQ(20),VA(20)
      DIMENSION VB(20),VC(20),BMAB(20),BMBC(20),BMCD(20),PX(20),PYB(20)
      DIMENSION PXAB(20),PXBC(20),PXCD(20),PYA(20),PYD(20),PYC(20),L(20)
C
5     FORMAT(I5,5F10.3,I5)
10    FORMAT(2F10.2)
15    FORMAT(3HFLR,6X,2HAB,6X,2HBC,6X,2HCD,7X,1HA,7X,1HB,7X,1HC,7X,1HD)
18    FORMAT(49HUNITS--MOMENTS IN KIP-FT. SHEARS AND THRUSTS IN K,3HIPS)
20    FORMAT(8X,14HGIRDER MOMENTS,14X,14HCOLUMN MOMENTS)
25    FORMAT(I3,7F8.2)
30    FORMAT(8X,13HGIRDER SHEARS,15X,13HCOLUMN SHEARS)
35    FORMAT(8X,14HGIRDER THRUSTS,14X,14HCOLUMN THRUSTS)
C
40    BMAP(1)=0.0
      BMBP(1)=0.0
      BMCP(1)=0.0
      BMDP(1)=0.0
      READ 5,N,AB,BC,CD,BAY,HTP,M
      DO 75 I=1,N
      IF(M)45,45,50
45    READ 10,PX(I),HT(I)
      IF(I-1)60,60,65
50    READ 10,W(I),HT(I)
      IF(I-1)55,55,62
55    PX(I)=(BAY*((HT(I)/2.0)+HTP)*W(I))/1000.0
60    SUMPX(I)=PX(I)
      GO TO 70
62    PX(I)=(BAY*((HT(I)+HT(I-1))/2.0)*W(I))/1000.0
65    SUMPX(I)=PX(I)+SUMPX(I-1)
70    HA(I)=SUMPX(I)*(AB/2.0)/(AB+BC+CD)
      HB(I)=SUMPX(I)*((AB+BC)/2.0)/(AB+BC+CD)
      HC(I)=SUMPX(I)*((BC+CD)/2.0)/(AB+BC+CD)
      HD(I)=SUMPX(I)*(CD/2.0)/(AB+BC+CD)
      BMAQ(I)=(HT(I)/2.0)*HA(I)
      BMBQ(I)=(HT(I)/2.0)*HB(I)
      BMCQ(I)=(HT(I)/2.0)*HC(I)
      BMDQ(I)=(HT(I)/2.0)*HD(I)
75    CONTINUE
      DO 100 I=2,N
      BMAP(I)=BMAQ(I-1)
      BMBP(I)=BMBQ(I-1)
      BMCP(I)=BMCQ(I-1)
      BMDP(I)=BMDQ(I-1)
```

```
100   CONTINUE
      DO 150 I=1,N
      PYB(I)=0.0
      PYC(I)=0.0
      BMAB(I)=BMAQ(I)+BMAP(I)
      BMBC(I)=BMBQ(I)+BMBP(I)-BMAB(I)
      BMCD(I)=BMDQ(I)+BMDP(I)
      VA(I)=BMAB(I)*2.0/AB
      VB(I)=BMBC(I)*2.0/BC
      VC(I)=BMCD(I)*2.0/CD
      IF(I-1)125,125,140
125   HA(I-1)=0.0
      HB(I-1)=0.0
      HC(I-1)=0.0
      HD(I-1)=0.0
      PYA(I-1)=0.0
      PYD(I-1)=0.0
140   PXAB(I)=PX(I)+HA(I-1)-HA(I)
      PXBC(I)=PXAB(I)+HB(I-1)-HB(I)
      PXCD(I)=HD(I)-HD(I-1)
      PYA(I)=PYA(I-1)+VA(I)
      PYD(I)=PYD(I-1)+VC(I)
      L(I)=N-(I-1)
150   CONTINUE
      PUNCH 18
      PUNCH 20
      PUNCH 15
      DO 200 I=1,N
200   PUNCH 25,L(I),BMAB(I),BMBC(I),BMCD(I),BMAQ(I),BMBQ(I),BMCQ(I),
     1BMDQ(I)
      PUNCH 30
      PUNCH 15
      DO 250 I=1,N
250   PUNCH 25,L(I),VA(I),VB(I),VC(I),HA(I),HB(I),HC(I),HD(I)
      PUNCH 35
      PUNCH 15
      DO 300 I=1,N
300   PUNCH 25,L(I),PXAB(I),PXBC(I),PXCD(I),PYA(I),PYB(I),PYC(I),PYD(I)
      GO TO 40
      END
```

The input data for Program II may be punched without regard to format statements, if compilation is performed with PDQ FORTRAN COMPILER, and FREE-FORM subroutines used during the execution phase. Hence, the following information is given without details of format.

1st card	Number of stories (fixed-point number) Widths of bays from left (infloating point form) Spacing of wind bents in the lateral direction Height of parapet wall (0 if none; fixed point) Indicator (1 for wind loads; 0 for earthquake loads)
Next card	Wind pressure (psf) at top story Height of top story
Next card	__ do __ for all stories from top

. . .
. . .
. . .

```
    N SESHAGIRI ARCHENGR THESIS                       IBLDR -- JOB   THESIS


                        M E M O R Y   M A P

SYSTEM, INCLUDING IOCS                                00000 THRU  12273

FILE BLOCK ORIGIN                                     12302

    NUMBER OF FILES -       2

    1.   S.FBIN                      12302
    2.   S.FBOU                      12325

OBJECT PROGRAM                                        12350 THRU  75426

    1.   DECK 'KANI  '  *            12350
    2.   SUBR 'INSYFB'               72222
    3.   SUBR 'OUSYFB'               72261
    4.   SUBR 'POSTX '               72312
    5.   SUBR 'CNSTNT'  *            72425
    6.   SUBR 'F05   '               72435
    7.   SUBR 'F06   '               72436
    8.   SUBR 'IOS   '               72437
    9.   SUBR 'RWD   '               72714
   10.   SUBR 'ACV   '               73374
   11.   SUBR 'FCV   '               73424
   12.   SUBR 'HCV   '               73516
   13.   SUBR 'ICV   '               73621
   14.   SUBR 'XCV   '               73641
   15.   SUBR 'INTJ  '               73662
   16.   SUBR 'FFC   '               74176
   17.   SUBR 'SLI   '               74604
   18.   SUBR 'SLO   '               74631
   19.   SUBR 'FPT   '               74656
   20.   SUBR 'XEM   '  *            75214
   21.   SUBR 'XIT   '               75425

   (* - INSERTIONS OR DELETIONS MADE IN THIS DECK)

INPUT - OUTPUT BUFFERS                                77067 THRU  77776

UNUSED CORE                                           75427 THRU  77062

 OBJECT PROGRAM IS BEING ENTERED INTO STORAGE.
```

N SESHAGIRI ARCHENGR THESIS

OKLAHOMA STATE UNIVERSITY COMPUTING CENTER
IBM 7040 COMPUTER SYSTEM

TIME ANALYSIS FOR RUN 8-KANI
PROJECT NUMBER 2505-40005
JOB START 6.87
JOB STOP 6.97
TIME USED 0.10

TIME BY SYSTEM SEGMENT

SYSTEM SEGMENT	TIME IN HOURS
EXECUTION	0.08
SYSTEM LOADER	0.01
FORTRAN COMPILE	0.02

INPUT/OUTPUT SUMMARY

DEVICE	RECORDS READ	RECORDS WRITTEN
SYSTEM LIBRARY	174	
SYSTEM INPUT	1258	
SYSTEM OUTPUT		1820
SYSTEM PUNCH		0
UTILITY UNITS	239	272

4 UTILITY UNITS USED

EXECUTION COMPLETE

VITA

Natesan Seshagiri

Candidate for the Degree of

Master of Architectural Engineering

Thesis: DESIGN OF TALL BUILDINGS BY THE USE OF A SIMULATOR

Major Field: Architectural Engineering

Biographical:

Personal Data: Born in Madras, India, February 24, 1944, the son of Mr. and Mrs. R. Natesan.

Education: Graduated from P.S. High School, Madras, India, in June 1957; attended the University of Mysore, India, during 1957-58; received the degree of Bachelor of Engineering from the University of Madras, India, in June 1963. Completed the requirements for the degree of Master of Architectural Engineering at Oklahoma State University in May 1966.

Professional Experience: Employed as Junior Engineer in the Highways Department, (Investigation Division) Government of Madras, India, from July 1963 to January 1964. Worked as Junior Executive at Gannon, Dunkerley and Co., Madras, India, from January 1964 to September 1964. Worked during summer 1965 in Mid-America Engineers, Inc., Chicago, Illinois.

Organizations: Member of Prestressed Concrete Institute; Member of Chi Epsilon, national honor fraternity for civil and architectural engineers.