NATIONAL CENTER FOR EARTHQUAKE
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REINFORCED CONCRETE FRAME COMPONENT TESTING FACILITY — DESIGN, CONSTRUCTION, INSTRUMENTATION AND OPERATION

by

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PREFACE

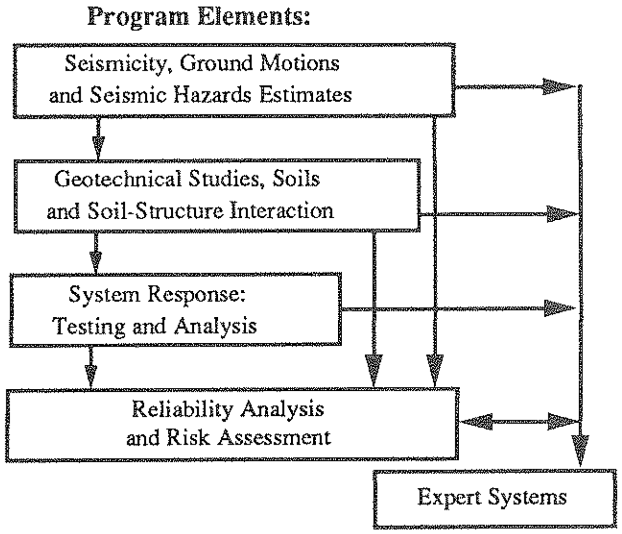
The National Center for Earthquake Engineering Research (NCEER) is devoted to the expansion and dissemination of knowledge about earthquakes, the improvement of earthquake-resistant design, and the implementation of seismic hazard mitigation procedures to minimize loss of lives and property. The emphasis is on structures and lifelines that are found in zones of moderate to high seismicity throughout the United States.

NCEER's research is being carried out in an integrated and coordinated manner following a structured program. The current research program comprises four main areas:

- Existing and New Structures
- Secondary and Protective Systems
- Lifeline Systems
- Disaster Research and Planning

This technical report pertains to Program 1, Existing and New Structures, and more specifically to system response investigations.

The long term goal of research in Existing and New Structures is to develop seismic hazard mitigation procedures through rational probabilistic risk assessment for damage or collapse of structures, mainly existing buildings, in regions of moderate to high seismicity. The work relies on improved definitions of seismicity and site response, experimental and analytical evaluations of systems response, and more accurate assessment of risk factors. This technology will be incorporated in expert systems tools and improved code formats for existing and new structures. Methods of retrofit will also be developed. When this work is completed, it should be possible to characterize and quantify societal impact of seismic risk in various geographical regions and large municipalities. Toward this goal, the program has been divided into five components, as shown in the figure below:



Tasks:

Earthquake Hazards Estimates,
Ground Motion Estimates,
New Ground Motion Instrumentation,
Earthquake & Ground Motion Data Base.

Site Response Estimates,
Large Ground Deformation Estimates,
Soil-Structure Interaction.

Typical Structures and Critical Structural Components:
Testing and Analysis;
Modern Analytical Tools.

Vulnerability Analysis,
Reliability Analysis,
Risk Assessment,
Code Upgrading.

Architectural and Structural Design,
Evaluation of Existing Buildings.

System response investigations constitute one of the important areas of research in Existing and New Structures. Current research activities include the following:

1. Testing and analysis of lightly reinforced concrete structures, and other structural components common in the eastern United States such as semi-rigid connections and flexible diaphragms.
2. Development of modern, dynamic analysis tools.
3. Investigation of innovative computing techniques that include the use of interactive computer graphics, advanced engineering workstations and supercomputing.

The ultimate goal of projects in this area is to provide an estimate of the seismic hazard of existing buildings which were not designed for earthquakes and to provide information on typical weak structural systems, such as lightly reinforced concrete elements and steel frames with semi-rigid connections. An additional goal of these projects is the development of modern analytical tools for the nonlinear dynamic analysis of complex structures.

The testing of lightly reinforced concrete elements and frames is pursued at several institutions using various model sizes and loading methods. A large loading frame was built at Cornell University which enables the testing of full-scale frame components (joints) with large column loads and cyclic moments. The design and construction of this facility, as well as the associated software and electronics for loading and data acquisition, are described in this report.

ABSTRACT

This report describes the capabilities and operation of a test system which has been constructed to test lightly reinforced concrete columns and beam-column joint details. The test system can be used to load interior and exterior beam-column connection assemblies in a manner causing combined axial force and reversing double curvature in the columns. Testing is done primarily in two dimensions, considering the interaction between beams and columns along the same frame. Some three-dimensional effects such as confinement by transverse beams and slabs may also be included.

The test system was built to study essentially full-scale components at force levels comparable to those in an actual structure. Forces are applied to a specimen in a quasi-static manner by three servo-controlled hydraulic actuators. A single 400 kip capacity actuator is used to apply the column axial force, and two 110 kip capacity actuators are used to apply the beam forces. Each actuator is operated independently in closed-loop displacement mode.

A computer program was written to control the force application and data acquisition tasks during an experiment. This software allows a test to be made according to either a force or displacement history. Various levels of operator intervention provide the operator the ability to alter the test plan, influence the speed of execution, or manipulate the graphical output on the microcomputer monitor during the course of an experiment.

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SECTION 1
INTRODUCTION

1.1 Purpose

This report describes the capabilities and operation of a test system constructed to study the behavior of full-scale lightly reinforced concrete columns and beam-column joint details under reversing cyclic loadings similar to those produced by seismic action. The test frame described in this report is located in the George Winter Laboratory for Structural Engineering Research at Cornell University.

The purpose of this report is to serve as a reference document for studies made using this test system, so that interested readers and potential users may obtain detailed information about the system.

1.2 Background

As stated above, the test system was constructed to study lightly reinforced concrete construction. The focus of the study is the many thousands of multistory reinforced concrete buildings constructed over the last 40 years in the Eastern and Central United States for which the designs have been dominated by gravity load effects. The lateral load resistance of many of these structures is considered suspect, particularly for moderate to severe seismic loading. In order to assess the vulnerability to damage of these buildings to various intensities of earthquakes, the cyclic behavior of lightly reinforced components must be better understood.

A review of all editions of the ACI 318 Building Code [1] and related detailing manuals [2] published since the late 1940 's identified two details that may be critical to building performance in an earthquake. These details are:

1. lightly-confined column bar splices located just above floor level; and,
2. bottom beam reinforcement that is not continuous through the beam-column joint.

The test system described in this report, though designed to test these details, is not limited to studies of lightly reinforced concrete. An attempt was made to design a system with the ability to accommodate various specimen sizes and geometries.

1.3 Scope

Section 2 of this report presents the design criteria established in the planning stages of development that the test system had to satisfy, and therefore provides an overview of its capabilities and operation. Section 3 describes in detail the force and reaction system, and Section 4 describes the control system hardware and software.

SECTION 2

DESIGN CRITERIA

2.1 Introduction

Specimen loading criteria for the test system were established in the planning stage of development. Some of the more important criteria are explained in this section, providing an overview of the general capabilities of the test system.

2.2 Full-Scale Components

To accurately study column splice behavior, the experiments were to be conducted at essentially full scale. Present small-scale modelling techniques cannot adequately represent the complex force transfer along a lapped splice, or the deterioration of this force transfer as the load on the splice is cycled. Because full-scale specimens were to be tested, the loading would have to be applied in a quasi-static manner to isolated structure components.

2.3 Specimen Configuration and Loading Arrangement

The two basic specimen configurations selected for study are shown in Figure 2.1. Figure 2.1 (a) represents an interior beam-column connection, and Figure 2.1 (b) an exterior connection. Both specimen configurations were to be loaded in a manner causing combined axial force and reversing double curvature in the column, as shown in Figures 2.1 (c) through (f). The specimen configuration and loading arrangement were chosen to model the loading and deformation in a real structure in sidesway. The ends of the top and bottom column stubs represent inflection points which often occur (initially) about midheight of a column as a building displaces laterally.

The column axial force shown acting in Figures 2.1 (c) through (f) represents the gravity force which acts during a seismic event. In addition to this axial force, it may be useful in some tests to apply gravity forces to the beam stubs of a specimen. This offers several important advantages. First, the beam-column joint will be subjected to more realistic confining forces. Second, the behavior of specimens with discontinuous bottom beam reinforcement can be more realistically studied, as the forces from seismic action will act together with those due to gravity. Third, the bottom column

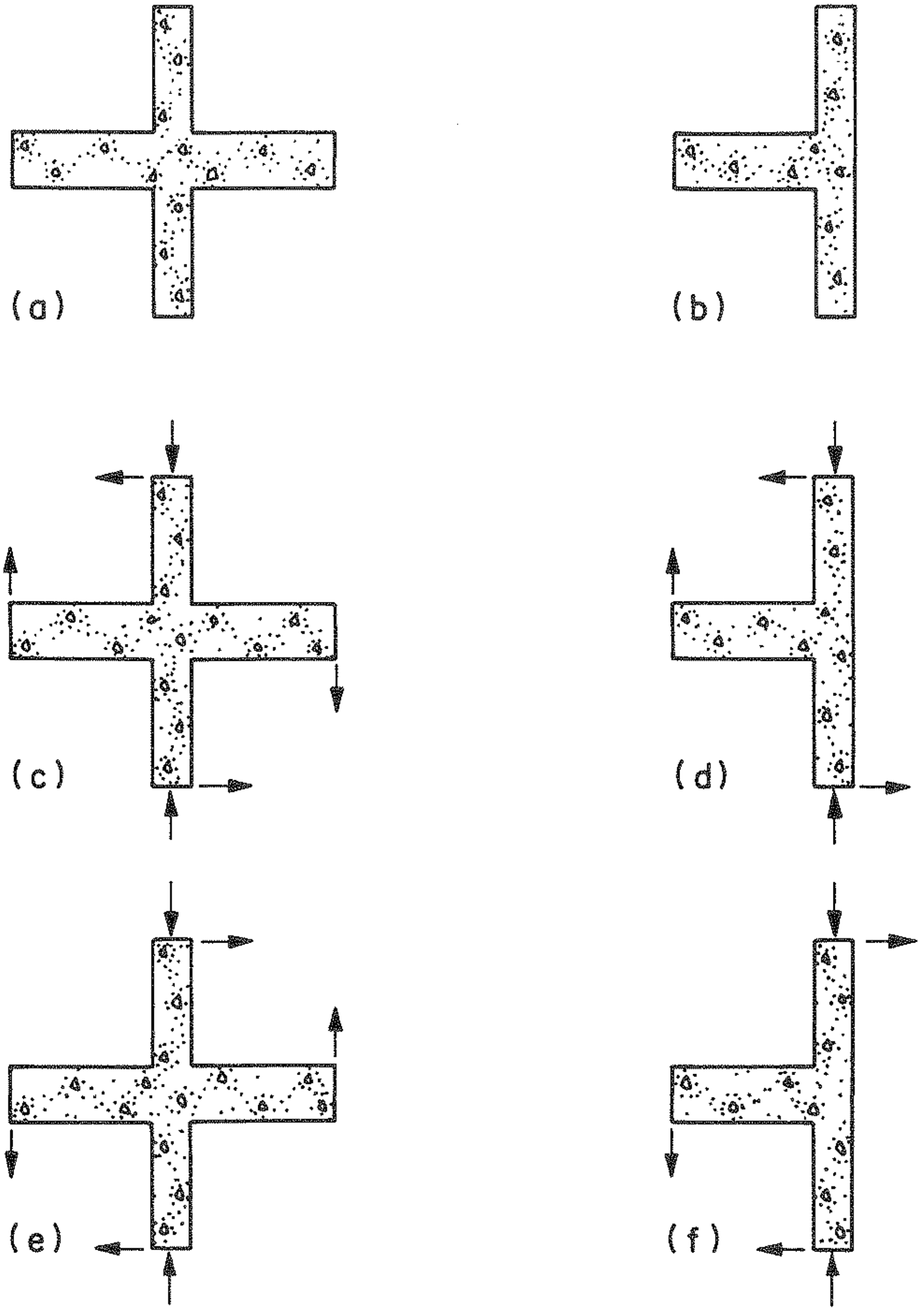


Figure 2.1 Basic specimen configurations: a) interior column; b) exterior column; and, c) through f) loading to cause combined axial force and reversing double curvature

stub will be subjected to a larger axial force as compared to the top column stub, as would be the case in an actual structure. Figure 2.2 shows the result of applying gravity beam forces in addition to the column axial force prior to applying cyclic lateral load. The forces acting in this figure represent the conditions prior to the seismic event. Note that shear is present in the exterior column specimen as a result.

For simplicity, the testing was to be confined to two dimensions, considering only the interaction between beams and columns along the same frame. However, provision was made to include some three-dimensional effects such as the confinement offered by transverse elements such as beams and slabs. Figures 2.3 (a) and (b) are isometric drawings of specimens which include these features.

Not all columns in a structure have inflection points located near column midheight. Therefore, within the specimen configurations just described, a wide range of specimen sizes had to be allowed for. Total column height and the relative heights of the top and bottom column stubs can be varied over a wide range, to provide the required ratio of shear to moment (V/M) that a particular test may demand. As will be explained further in Section 3, the points of load application on the beam stubs can also be varied to provide the required V/M ratio.

Though not essential, it was desirable to load the specimens with the columns oriented vertically in a manner which would provide a clear view of all sides of the column and beam-column joint during a test.

2.4 Computer-Based Control

Many of the tasks during an experiment were to be computer-controlled. Thus a computer program (control program) had to be written. This program was designed to provide flexibility in the testing plan and also provide various levels of operator intervention during a test. An overview of the control program is postponed until Section 4, as the discussion of the force and reaction system in Section 3 needs to be presented first.

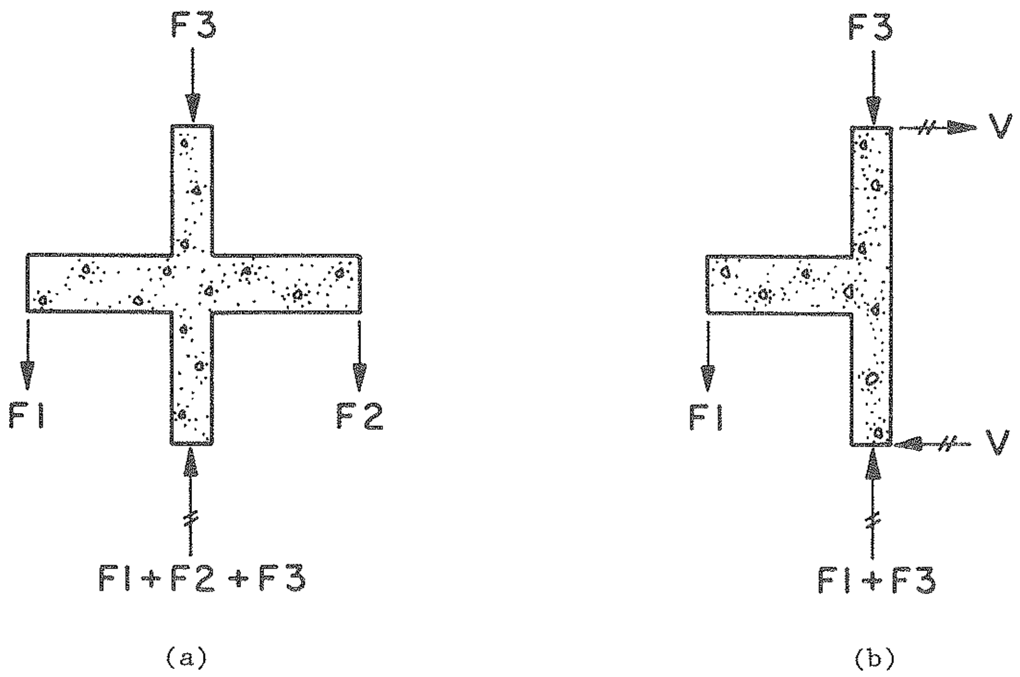


Figure 2.2 Gravity forces applied to: a) interior column; and, b) exterior column

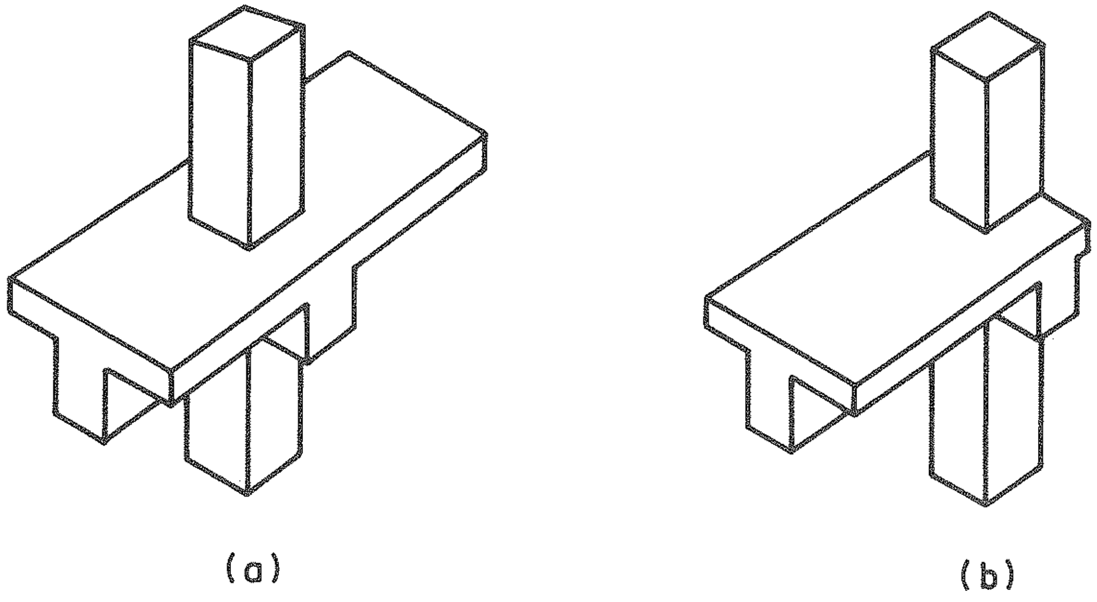


Figure 2.3 Specimens that include transverse beams and slabs: a) interior column; and, b) exterior column

2.5 Compatibility with Existing Laboratory Facilities

Lastly, the design of the test frame had to be compatible with the existing laboratory facilities, particularly the locations of reaction anchors in the laboratory floor and strong columns in the laboratory walls.

SECTION 3
FORCE AND REACTION SYSTEM

3.1 Introduction

Figure 3.1 is a photograph of the testing frame, with an interior column specimen positioned in the frame ready for testing. The testing frame and peripheral equipment occupy about 500 square feet of floor area in a 4-story high test bay. This area of the laboratory is serviced by a 10-ton capacity overhead bridge crane.

Two elevations of the frame are illustrated in Figures 3.2 (a) and (b). The following discussion of the loading and reaction system will refer to the components labelled in this figure. The discussion is presented for the case of an interior column specimen. The discussion for an exterior column specimen would be similar and is not presented here.

3.2 Force and Reaction System Idealization

The configuration and operation of the entire test system can be explained with the idealization of the force and reaction system shown in Figure 3.3. In this figure, actuators are represented as variable length elements, and the top and bottom reaction arms as stiff links. Open circles between elements represent pinned connections. Both ends of the column actuator are shown pinned, as are both ends of the link supporting the lower column stub, and both ends of each reaction arm.

As the beam actuators apply forces to the specimen in opposite directions, forces of equal magnitude and opposite direction (horizontal force equilibrium) will be generated in the reaction arms, regardless of the relative lengths of the column stubs. It is clear from this figure that both the lower end of the column actuator and the upper end of the link supporting the lower column will displace as required to ensure that all shear is transferred to the reaction arms.

Finally, because the upper reaction arm is pinned at both ends it can undergo small rotation required as the specimen column changes length during a test.

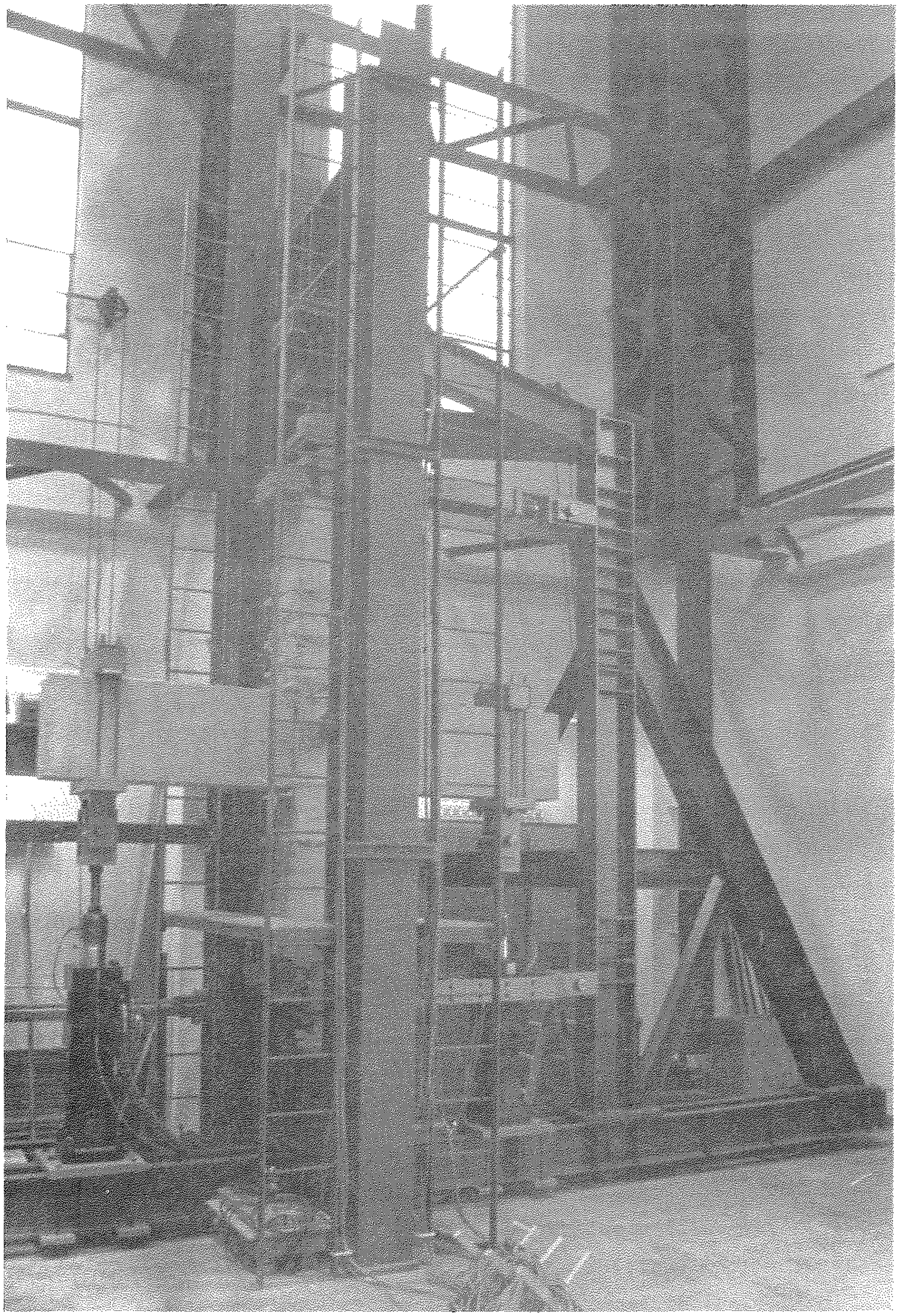


Figure 3.1 Photograph of the testing frame with an interior column specimen in the frame ready for testing

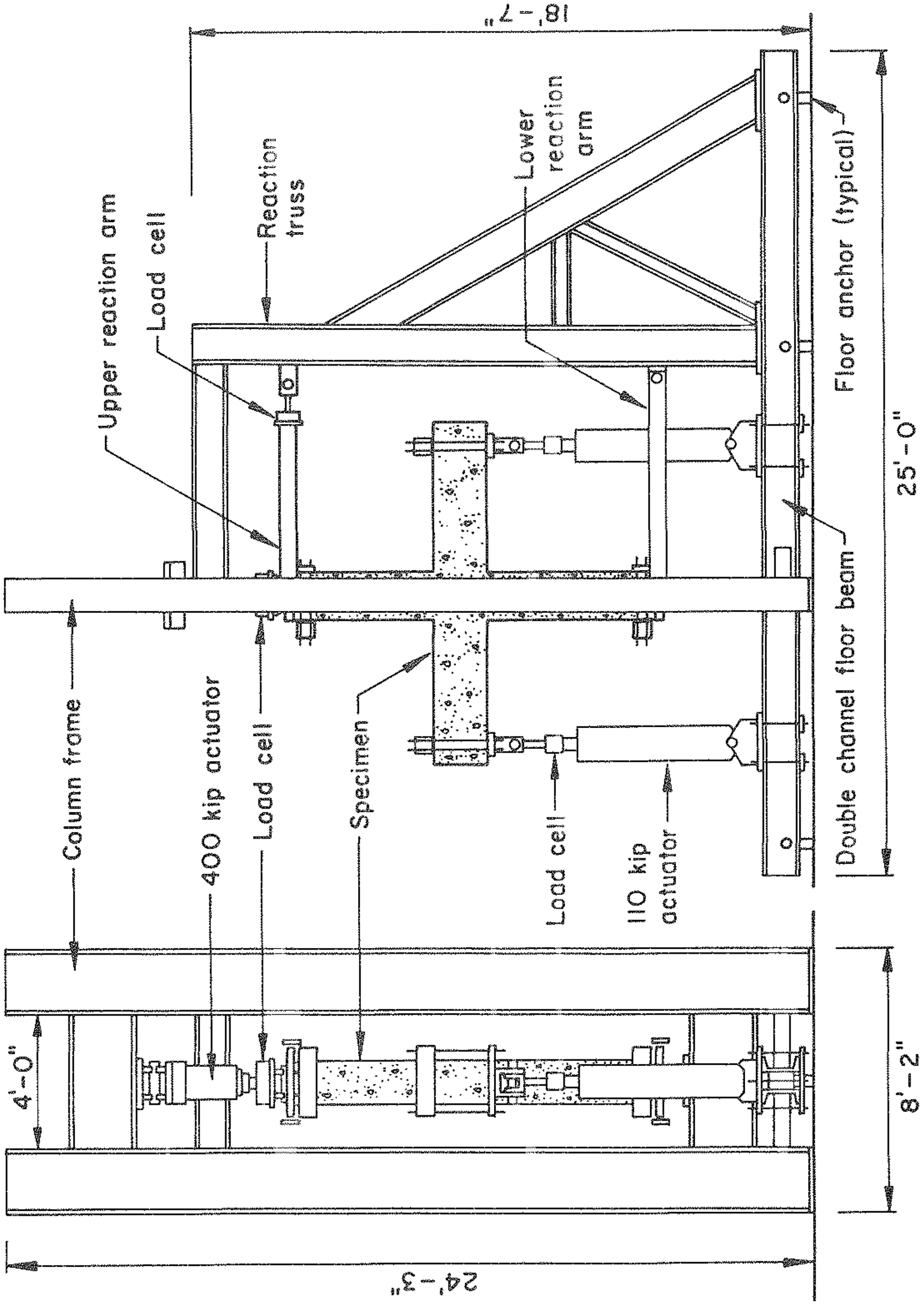


Figure 3.2 Two elevation views of the testing frame

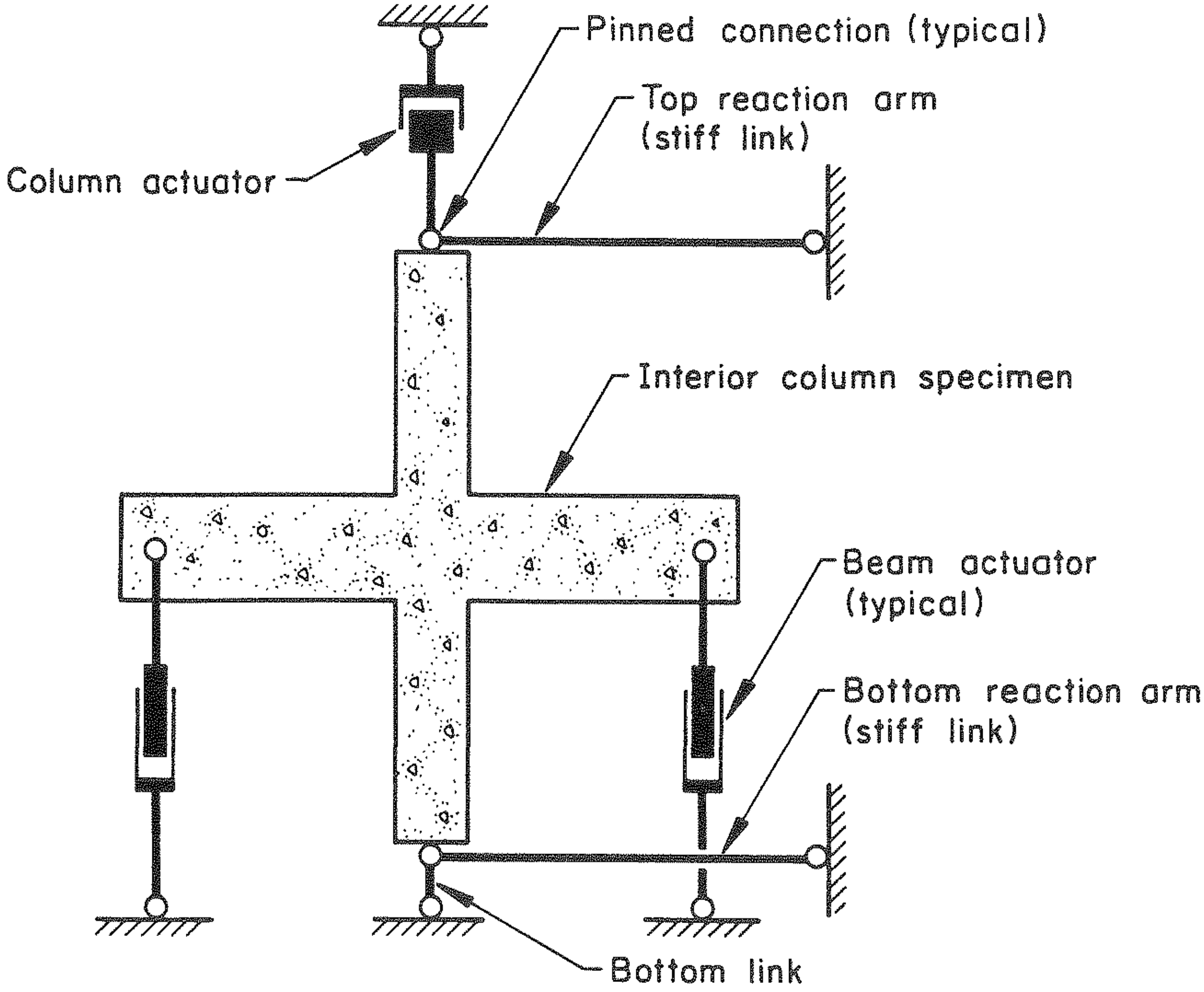


Figure 3.3 Idealization of the force and reaction system

3.3 Column Axial Force

Axial force is applied to the specimen column with a hydraulic actuator suspended from the top girder of the column frame. This servo-controlled, double-ended actuator has a 400 kip capacity and 4 inch (in.) stroke. During an experiment, the actuator is operated in closed-loop displacement control. Displacement increments as small as 0.0010 in. can be applied to the specimen with the hardware assembled for this system. Control system hardware is discussed in Section 4.

The axial force applied by the column actuator reacts against the top and bottom girders of the column testing frame in a self-equilibrating manner; thus no external anchorage is required for this force.

The top and bottom girders in the column frame are designed to resist a force of 400 kips. In addition, the location of each girder can be repositioned to any height in the column frame in three inch increments to provide various column shear spans as discussed in Section 2.3.

Large steel sections (W24x162) were used to construct the column frame to provide adequate stiffness of the frame relative to the stiffness of the specimen.

3.4 Beam Forces

Forces are applied to the specimen beam stubs by two 6 in. stroke, double-ended, 110 kip capacity hydraulic actuators. Each servo-controlled actuator is operated independently in closed-loop displacement control, and can apply a displacement increment as small as 0.0015 inch.

The beam actuators react against a floor beam constructed of two steel channel sections. Each actuator clamps to the floor beam and can be positioned over a wide range along its length to provide the required V/M ratio in each beam stub. Forces in the floor beam are transferred into 4 reaction anchors in the laboratory floor.

Figure 3.4 shows the hardware that attaches each beam actuator to a beam stub. This hardware was designed to provide a pinned connection to the specimen.

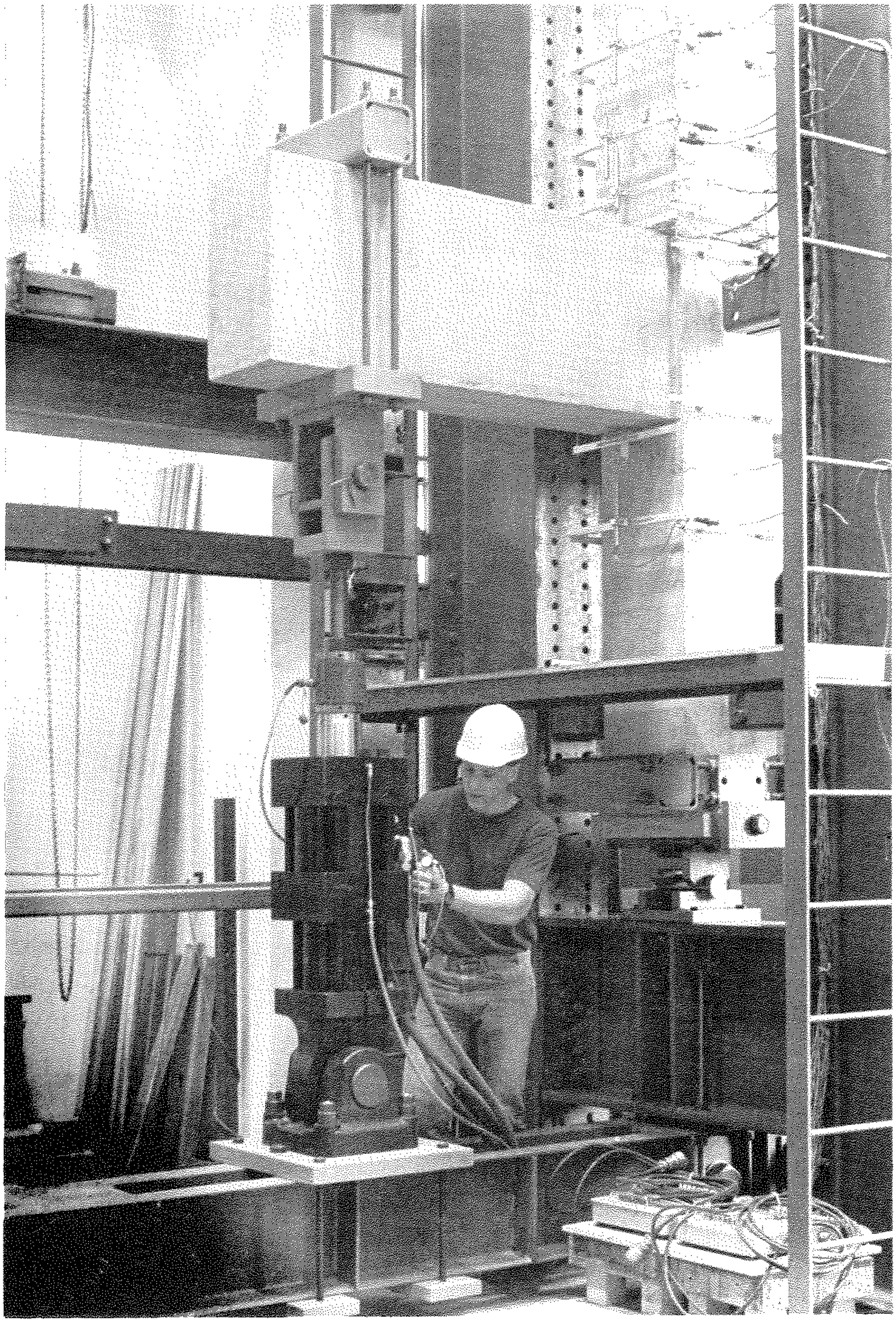


Figure 3.4 Typical beam actuator

Figure 3.4 also shows the pinned support at the base of each actuator, and how the actuator is clamped to the floor beam.

3.5 Column Shear Forces

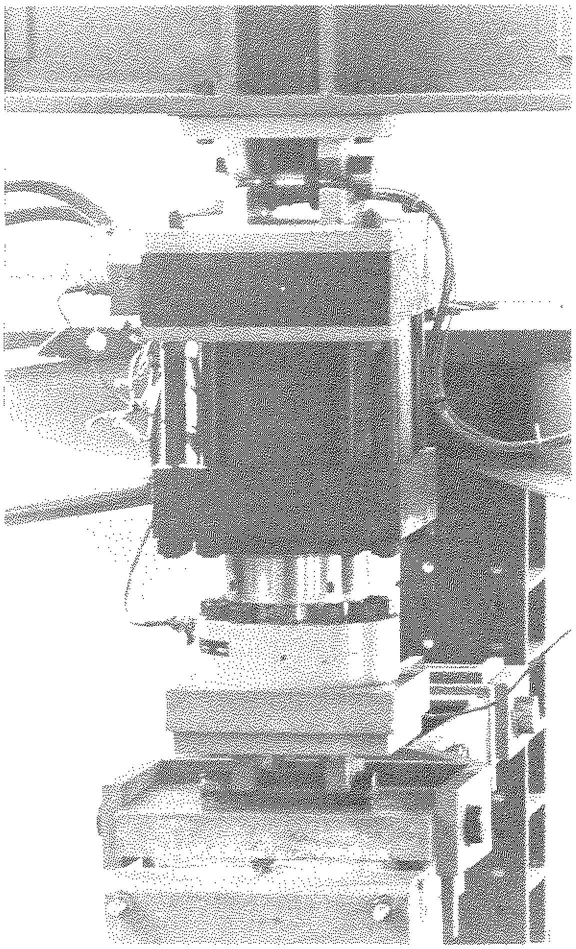
The shear forces in the top and bottom column stubs are reaction forces caused by unequal beam stub forces (for equal beam shear spans). From equilibrium it is seen that the column shear forces are equal in magnitude and opposite in direction. The column shear forces are transferred from the specimen to the reaction truss by the top and bottom reaction arms. Note that the lower reaction arm is a small frame that straddles the beam actuator in its path.

Each reaction arm is designed to resist a 100 kip force in tension or compression. Again, to allow for a range of column heights, each reaction arm can be repositioned in 3 inch increments along most of the height of the reaction truss. The reaction truss is designed to resist two oppositely directed, 100 kip forces acting anywhere along its height. The connections between the reaction arms and the truss were detailed to behave as a pinned supports.

3.6 Column Support Details

As stated in Section 2.3, the column stub ends represent inflection points in an actual structure in sidesway, and are points of zero moment. Therefore, the top and bottom column supports had to be detailed to provide zero moment resistance.

To obtain this condition at the top column stub, machined bearing surfaces were provided at both ends of the column actuator. These bearing surfaces allow both ends of the actuator to rotate about an axis perpendicular to the plane containing the two primary directions of testing. Figure 3.5 (a) shows the actuator support details. Because the actuator is free to rotate about both ends, it acts as a link which can undergo a small translation at its lower end to ensure that all the column shear in the top column stub is transferred to the top reaction arm. Figure 3.5 (b) shows a similar link system employed at the bottom column stub, using a short steel link with machined bearing surfaces at each end. The top of this link can undergo a



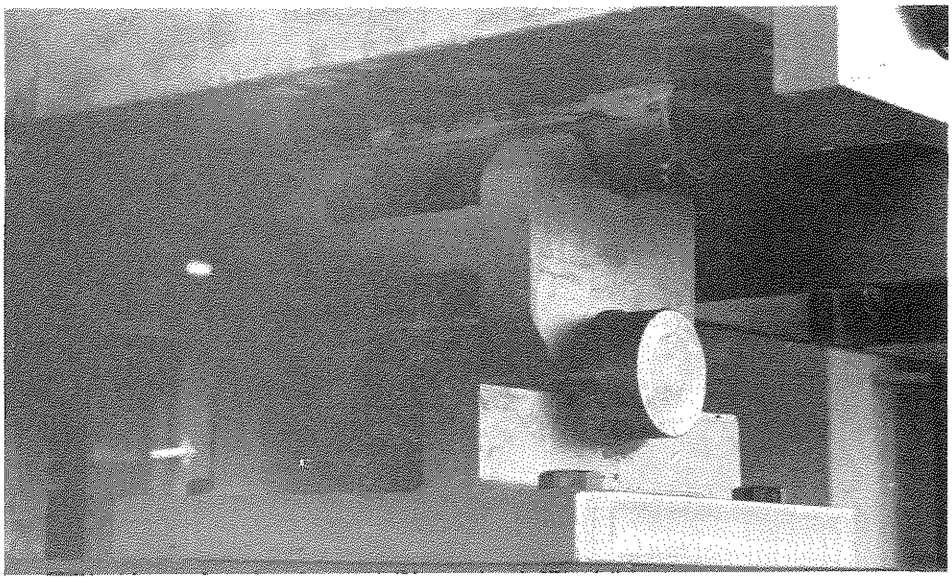


Figure 3.5 a) Column actuator support details; and, b) lower column link support

small translation to ensure the shear force in the bottom column stub is resisted by the bottom reaction arm.

3.7 Force Measurement

Force transducers are used to measure the force applied to a specimen by each of the three actuators. To check the assumption that all column shear is transferred to the reaction arms as described previously, a fourth load cell is positioned in the upper reaction arm to measure the top column shear force directly.

Results from an actual test reveal that most of the column shear force is resisted by the reaction arms. Figure 3.6 is a plot of the shear force measured in the upper reaction arm, versus the shear force computed from equilibrium using the measured forces in the two beam actuators. Superposed on the figure is a line with unit slope and zero intercept, which corresponds to perfect agreement between the measured and computed quantities. Figure 3.6 shows good agreement between the two values. Clearly, how well these two values agree can be influenced by many factors, for example how well the bearing surfaces are lubricated, and the magnitude of the column axial force (normal force on the bearing surfaces).

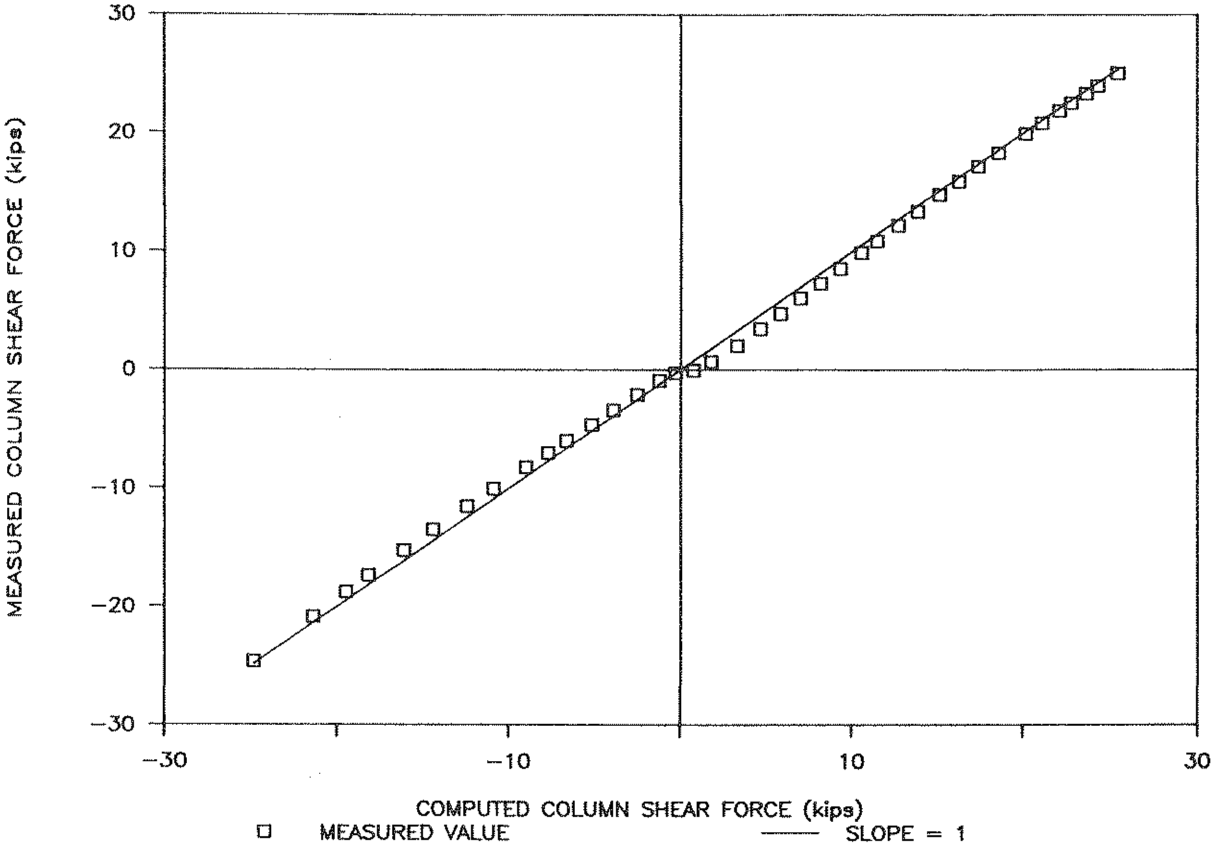


Figure 3.6 Measured column shear force versus predicted column shear force

SECTION 4
TEST CONTROL SYSTEM

4.1 Introduction

The test control system consists of the electronic hardware and software used to perform the force application and data acquisition tasks during an experiment. Force application tasks involve coordinating the movement of the three independently operating hydraulic actuators. Data acquisition tasks include sampling transducers, using these measured values in decision-making algorithms that coordinate actuator movements, and storing these values for post-test analysis.

In this report the discussion of the control system is presented in two parts. The operation of the control system software, written in the BASIC computer language, is explained first in Section 4.2, providing a complete description of how a typical test is performed. The control system hardware is discussed in Section 4.3. In a few instances, terminology which may be unfamiliar to some readers is necessarily used in Section 4.2. A reader who encounters unfamiliar terms will likely find an explanation in Section 4.3.

4.2 Control System Software

4.2.1 General Approach to Test Control

In most quasi-static tests, a predetermined test plan (usually a displacement or force history) specifies the loading to be applied to a specimen. Consider, for example, a test made using a predetermined displacement history. This displacement history specifies the number of cycles or repetitions at a given displacement value. The value or level of displacement is often expressed as a percentage of the yield displacement of the member.

The test system described in this report can use either the displacement or force history approach to experiment control. In the displacement history mode the rotation of one or more member cross-sections serves as the control parameter. Options in the control program allow a test to be controlled by either one or two independent control parameters, or the combined values of these parameters (for example combined top and bottom column rotation). Force control is usually in terms of the values of the forces in the two beam actuators.

The cyclic loading part of all tests performed to date have been made in displacement control using two independent control parameters, namely the top and bottom column rotations adjacent to the beam-column joint. To simplify the discussion in Section 4.2.2, the control program is described for this case. A test controlled in terms of forces would be similar and is not described here.

4.2.2 Overview of Control Program

Figure 4.1 shows an overview of the organization of the control program. The program can be divided into 5 parts, each of which is described in detail in Sections 4.2.2.1 through 4.2.2.5. Part 1 of the program is concerned primarily with verifying the operation of many of the hardware components in the test system, and applying hydraulic pressure to the actuators. Gravity forces are applied to a specimen in part 2. In part 3, an initial low-level cycle of load is applied for the purpose of experimentally determining the initial stiffness of a specimen. Together, parts 1, 2 and 3 comprise the preliminary steps in a test. The remainder of the cyclic loading is controlled by part 4 of the program. Accordingly, this is where most of the actual testing occurs. Part 5 of the program is used to remove all forces from a specimen at the conclusion of a test.

As discussed in Section 4.2.1, the cyclic loading part of a test will be described for the case of a test made using the displacement history approach. For all tests (whether displacement or force control), parts 2, 3 and 5 provide control based solely on the state of forces acting on a specimen. This is explained further in the sections that follow.

A discussion of some forms of operator interaction with the program is necessarily presented in Sections 4.2.2.1 through 4.2.2.5. However, most of this discussion is postponed until Section 4.2.3, so that an understanding of the basic structure of the control program may be obtained first.

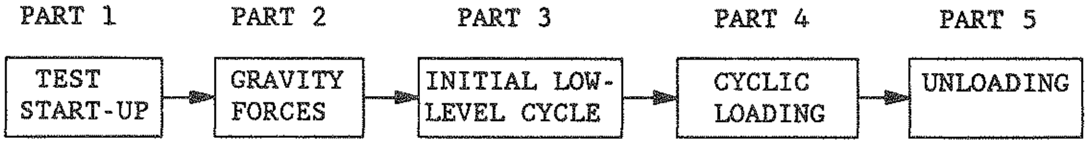


Figure 4.1 Organization of the control program

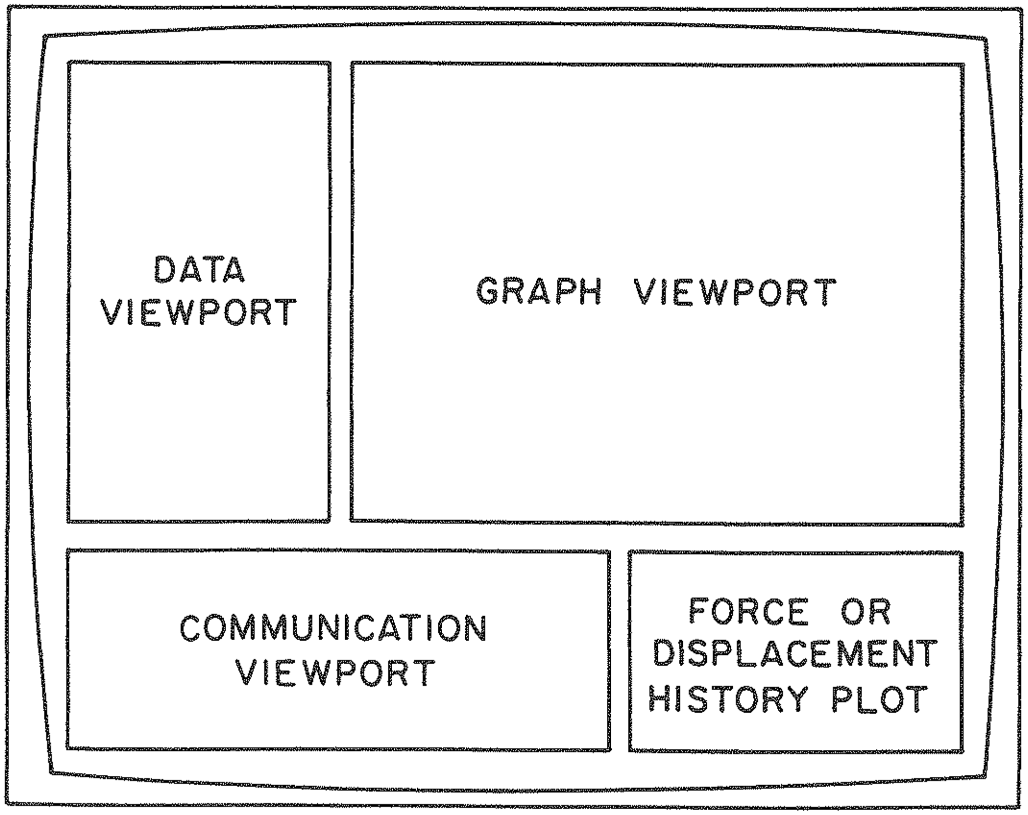


Figure 4.2 Organization of the display on the microcomputer monitor

4.2.2.1 Test Set-up

This part of the control program performs those tasks required before hydraulic pressure can be applied to the system. First, the program provides the operator an opportunity to verify that all instrumentation is being read correctly, and to verify that input parameters particular to the current test are correct.

Second, a description of the current test is input. This description is then included in all printed data and data written to disk.

The final task in the start-up phase is to send an initial command signal to each actuator equal to its initial feedback signal so that all actuators will remain at rest when hydraulic pressure is applied. The feedback signal from each actuator is obtained from a display on the controller console, and entered as a response to prompts from the control program. Then the program prompts the operator to apply hydraulic power to the actuators.

4.2.2.2 Gravity Forces

As discussed earlier in Section 2.3, this test system can subject interior and exterior column specimens to combined gravity forces and reversing double curvature. Figure 2.1 shows qualitatively the forces and reactions acting on specimens under this type of loading. The purpose of this part of the control program is to apply the gravity forces which act on a specimen during a seismic event.

The gravity forces are applied to a specimen in an incremental manner, with a fraction of both the column force and beam forces applied in each increment. The number of increments to use, and hence the fraction of load applied in each increment, is specified by the operator in response to a prompt from the program. Gravity forces are applied in such a manner to cause the horizontal column reactions to remain close to zero force (for an interior column specimen) independent of the deformation of the specimen.

Figure 4.2 shows the organization of the display on the microcomputer monitor during this part of the test. This format is used throughout the test. The upper left portion of the display (data viewport) shows force and displacement values relevant to the current phase of the test, and additional information to describe the test status. The upper right portion of the display (graph viewport) is used to plot various graphs during test execution. The lower right portion of the display shows a plot of the rotation history to be applied to the specimen, and the lower left portion (communication viewport) is reserved for interaction with the control program.

At the conclusion of the automated procedure that applies the gravity forces, a menu appears in the communication viewport that gives the operator the ability to move each actuator individually. This allows minor changes to be made in the forces acting on a specimen to make the actual force values equal to the desired gravity force values. Once the operator is satisfied with the force levels, the menu is exited and all force and displacement values are recorded as the reference values to which subsequent behavior can be compared.

Figure 2.2 introduces some terminology which will be used in later discussions. For the case of an interior column specimen, the actuators acting on the left and right beam stubs will be referred to as actuators 1 and 2 respectively. The column actuator will be referred to as actuator 3. The sign convention where tension forces are positive and compression forces are negative is used.

4.2.2.3 Initial Low-Level Cycle

In the third phase of a test, a single low-level cycle of load is applied to a specimen for the purpose of predicting the "yield" rotations of the upper and lower columns. These yield rotations are then used as the control parameters during the cyclic loading portion of the test to follow.

Defining a "yield" rotation value for a reinforced concrete member is difficult because of the nonlinear behavior of the concrete in compression, and cracking in the member. For these tests, yield rotations are computed as defined in Figure 4.3. The initial flexural stiffness of the upper and lower columns are each extrapolated to their nominal flexural strengths (including the interaction with axial force). The corresponding rotations are taken as the yield rotations. Similar approaches have been used by other researchers.

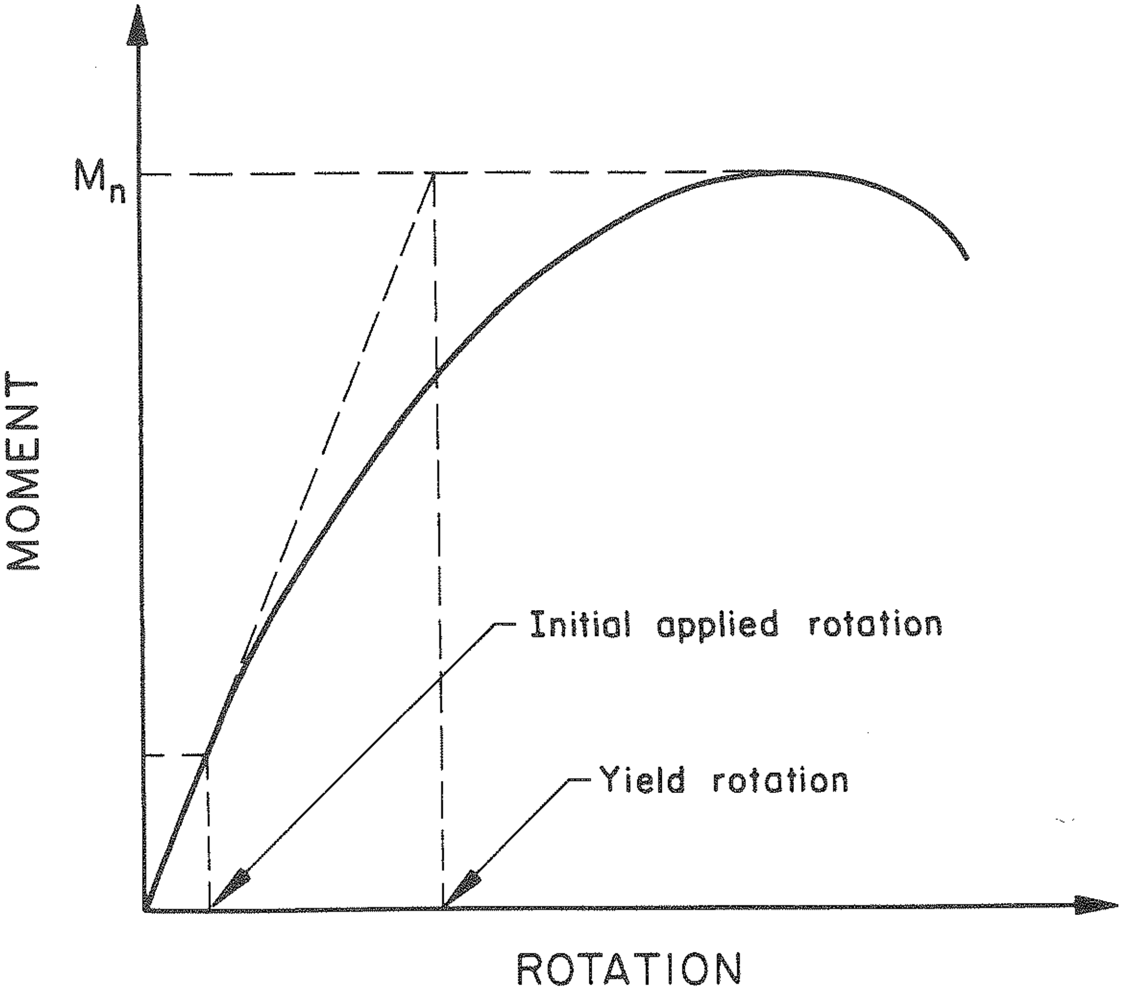


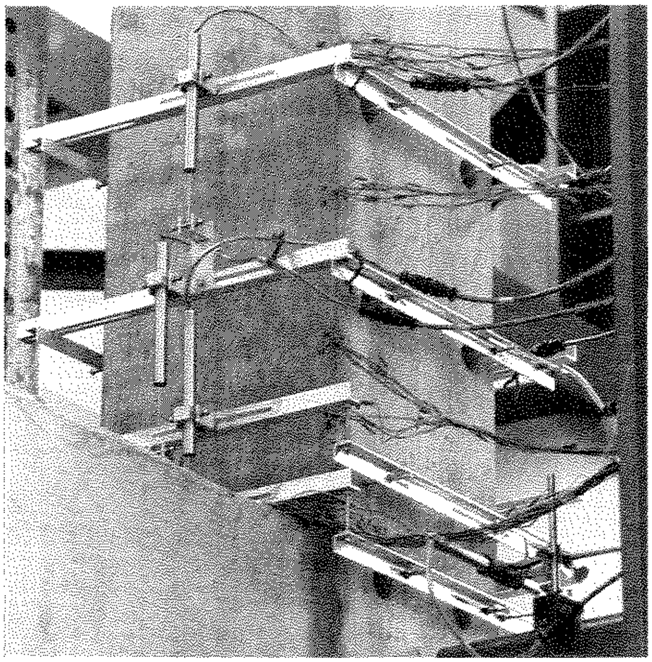
Figure 4.3 Definition of yield rotation

The low-level cycle of loading is applied under force control, with the value of the bending moment (shear force) in the top column at the beam-column joint used as the control parameter. Note that each actuator is still operated under independent closed-loop displacement control. Force control here refers to the external open-loop involving control transducers and programmed decisions in the microcomputer. The maximum moment applied to the column is specified in an input data file prepared for each specimen before a test. Typically it is about 25 percent of the nominal flexural strength of the member.

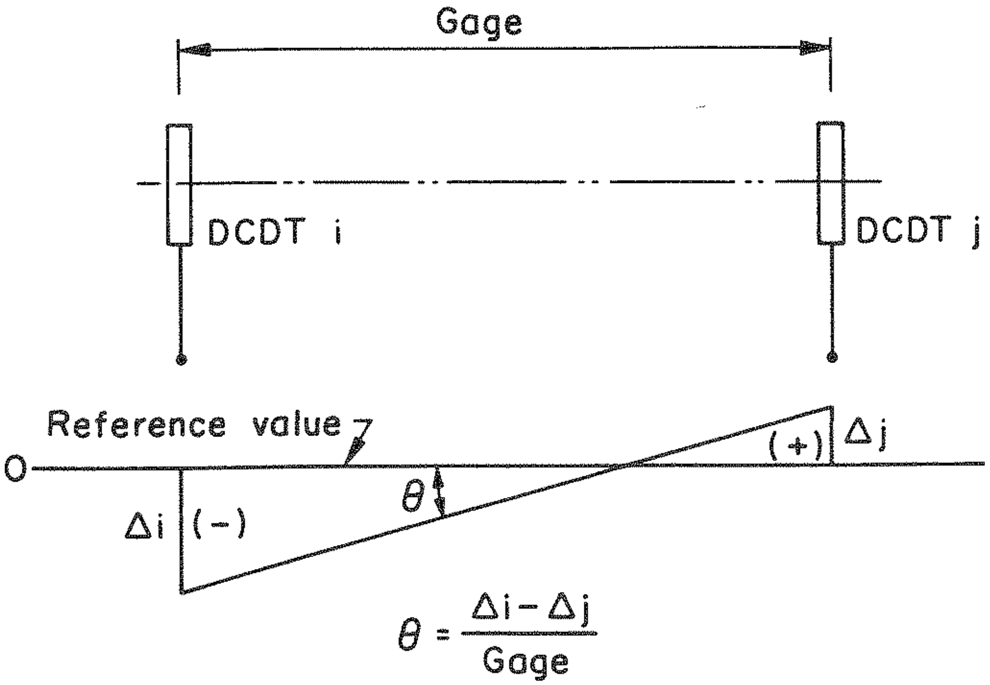
Figure 4.4 (a) is a photograph of the instrumentation used to obtain column rotations. Rotation values are computed from displacement measurements made with direct current powered linear variable differential transformers (DCDT) positioned on opposite faces of a column. The DCDTs are attached to aluminum collars which are bolted to threaded rods cast into the specimen. Figure 4.4 (b) explains how the rotations are computed from the displacement changes relative to the reference values obtained immediately after the gravity forces were applied to the specimen. Note that when the reference values were recorded, the columns were defined to have zero rotation.

During this low-level cycle, records of moment-rotation data are compiled separately for the top and bottom columns. A separate least-squares linear regression analysis is used to obtain the best-fit lines to each set of data, which are then used to predict the yield rotations as described in Figure 4.3. The results of these regression analyses and predicted yield rotations are displayed in the communication viewport.

The sign convention is as follows: Tension (+) in the top reaction arm is defined to cause positive shear in the top column stub. The accompanying compression (-) in the bottom reaction arm is defined to cause negative shear in the bottom column stub. In addition, there is a positive and negative <u>direction</u> of loading. The positive direction of loading causes an algebraic increase in the shear and rotation in the top column stub, and an algebraic decrease in the shear and rotation in the bottom column stub. Similarly, the negative direction of loading causes an algebraic decrease in the shear and



(a)



$$\theta = \frac{\Delta i - \Delta j}{Gage}$$

(b)

Figure 4.4 a) Photograph of the instrumentation used to obtain column rotations; and, b) computation of rotations from displacement measurements rotation in the top column stub, and an algebraic increase in the shear and rotation in the bottom column stub.

During the low-level load cycle, the graphics viewport is used to plot the moment-rotation response of the top and bottom columns using the sign convention described above.

4.2.2.4 Cyclic Loading

This part of the program controls an experiment during most of the actual testing. Prior to entering this part of the program, sustained forces representing gravity loads were applied to a specimen, and a low-level cycle of lateral load was applied to predict the column yield rotations. Now the specimen is to be loaded according to a predetermined rotation history, expressed in terms of the yield rotations. The basic approach here is to manipulate the beam actuator strokes in a manner causing the columns to deform to the rotations specified by the current step in the rotation history.

To understand how this is accomplished, consider as an example the rotation history in Figure 4.5. The maximum rotation to be applied in any step, $\bar{\theta}$, is given by

$$\bar{\theta} = \alpha * \theta_Y \tag{4.1}$$

where θ_Y is the yield rotation and α is the rotation amplitude for the given step.

Next suppose that the test is currently in step number 9. From Figure 4.5, α equals 0.75. Further, to simplify the following discussion, consider for the present only the behavior of the top column. Then a portion of the moment-rotation response at this step in the test might appear as in Figure 4.6. Shown in this figure are θ_Y and $\bar{\theta}$ for step number 9. To obtain a accurate record of the moment-rotation response, it is desirable to save data at intermediate points between the two maximum rotations in steps 8 and 9. Accordingly, point A in Figure 4.6 represents the last intermediate point at which data was saved. The next intermediate point at which data will be saved

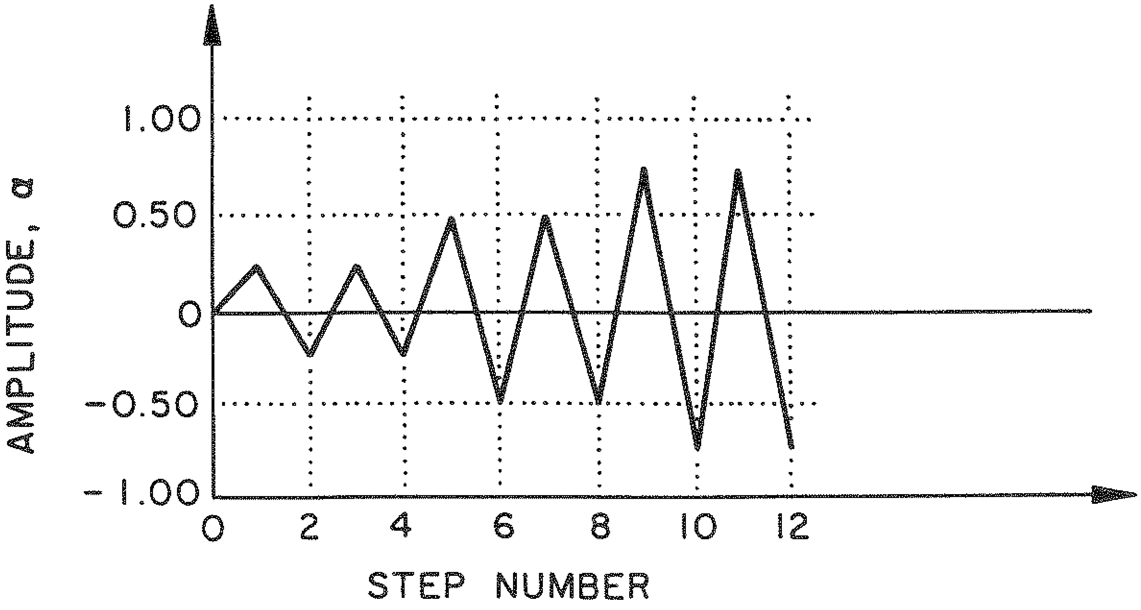


Figure 4.5 Example rotation history

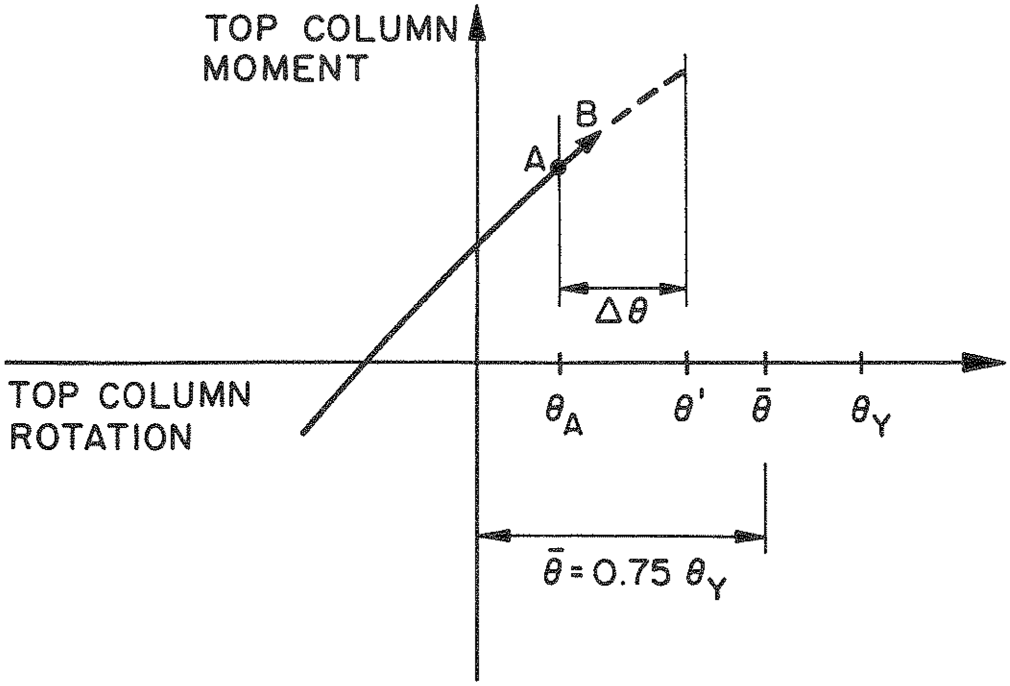


Figure 4.6 Example portion of moment rotation response

occurs at θ', where

$$\theta' = \theta_A + \Delta\theta \tag{4.2}$$

The value of the rotation increment $\Delta\theta$ is specified by the operator. During the execution of the program, the control transducers are sampled and the current values of the top column moment and rotation are computed. The result might be that the current state of the specimen is represented by point B in Figure 4.6. Because the current column rotation is less than the next intermediate target rotation θ', the decision is made to apply more load to the specimen. After applying this additional load, the control transducers are sampled again, and the top column moment and rotation are recomputed. This iterative process will continue until sufficient load has been applied to cause the top column rotation to reach θ', at which point the decision will be made to save data. After saving data, a new intermediate target rotation θ' is calculated using Eqn. 4.2, and substituting θ_B in for θ_A. Finally, the iteration to reach this new rotation value begins.

The value of θ' will continue to increase in this manner until θ' equals $\bar{\theta}$. When this happens, loading will proceed in the opposite direction towards a new $\bar{\theta}$ value specified by the amplitude of the next step in the rotation history. From Figure 4.5 the next amplitude is -0.75.

In this example, the top column rotation and moment are increasing in step number 9. According to the sign convention discussed at the end of Section 4.2.2.3, this is the positive direction of loading. Loading the specimen in the positive direction can be accomplished by either retracting actuator 1 or extending actuator 2 (or both). Retracting actuator 1 and holding the stroke of actuator 2 fixed will cause a net increase in the summation of forces applied by actuators 1 and 2. Similarly, extending actuator 2 and holding actuator 1 fixed will cause a net decrease in this summation of forces. The current version of the control program is written to keep the axial forces in the top and bottom column stubs equal to the gravity force values during a test. Therefore, the summation of the forces applied by the beam actuators must remain constant during a test. As a result, which beam actuator is called on to displace depends in part on whether the current summation of forces applied by these actuators is greater or less than the gravity force sum. For example, if the present force sum is less than the sustained force sum, actuator 1 will be retracted. It is also clear at this point that to maintain the axial force constant in the top column stub, its value must be checked in each iteration and any adjustments made as needed.

A version of the control program is being written which will provide an axial force level that varies in proportion to the bending moment in the column during cycling. This is to simulate the variations in axial force that occur as an entire structure undergoes sidesway.

To summarize, three conditions must be satisfied before data can be saved:

1. The current value of the control rotation has to equal θ' (within a specified tolerance);
2. the column actuator force has to be within a specified tolerance of its gravity force value; and,
3. the summation of forces in the two beam actuators has to be within a specified tolerance of the summation of gravity forces.

Further, three factors are considered when deciding which actuator is to be displaced in each iteration through the program:

1. The direction of loading (whether rotation is to increase or decrease);
2. the current force values; and,
3. the gravity force values.

The discussion above was presented for the case of just one control displacement parameter, namely the top column rotation. The program execution for the case of two (or more) control parameters is similar. The value of each parameter is checked in each iteration through the program loop and compared to an intermediate value (similar to θ') to determine if data is to be saved.

The iterative process of applying load and saving data is done with minimum operator intervention. When a point is reached in a test where data is to be saved, the operator is asked for a command to save data and continue execution of the test. The operator may also specify a limit on how many uninterrupted iterations may be performed by the program. If this limit is reached before data is to be saved, the operator is asked for a command to continue execution. This is done to provide a safer test, as the test is thus not able to run indefinitely without operator intervention. Generally, the limit on the number of uninterrupted iterations is set higher than the number ordinarily required to reach the point where data can be saved, so that the test will usually continue to run until data is to be saved. The value of this limit can be changed during test execution.

The information displayed in the data viewport of the monitor during this part of a test includes:

1. Current forces in actuators 1, 2, and 3 and the column shear force;
2. the current step number in the rotation history;
3. bending moments in the top and bottom column stubs at the beam column joint;
4. yield rotation θ_Y, maximum rotation for the current step number $\bar{\theta}$, current intermediate target rotation θ', and actual rotation θ for the top and bottom columns stubs;
5. a counter that increments by 1 with each iteration of the control loop.

The graph viewport during this part of the test is used to plot the moment-rotation responses of the top and bottom column stubs.

4.2.2.5 Unloading

This part of the program is used to remove all forces from a specimen at the conclusion of a test. Forces are removed in an incremental manner, with a fraction of the column force and beam forces removed in each increment. As when the gravity forces were first applied, the fraction of force removed in each increment depends upon the number of increments selected by the operator.

4.2.3 Operator Interaction

Section 4.2.2 described the basic structure and operation of the control program. Some forms of operator interaction were mentioned there. This section briefly describes some additional ways the operator can interact with the program to alter the test plan, influence the speed of execution, influence the amount of data saved, and modify the display shown on the monitor during the execution of a test.

Most of the forms of interaction outlined above are initiated from a menu which is accessed by depressing a function key on the keypad of the microcomputer. Some forms of interaction arise during normal program execution, and others are initiated by depressing separate function keys.

4.2.3.1 Test Plan

There are two ways to modify the rotation history during the execution of a test. First, the operator may change (through the menu) the amplitude of the <u>current</u> step at any point during execution. Second, at the end of each step in the rotation history and before loading begins in the opposite direction, the operator is given the opportunity to change the amplitude of the <u>next</u> step.

A situation may arise where a test may have to be terminated before the entire rotation history has been applied to a specimen. This may occur because the specimen has failed and continued testing is no longer meaningful. In this situation, the operator may access (through the menu) the unloading part of the control program at any point in the execution of the test.

4.2.3.2 Execution Speed

There are several parameters that in combination affect the execution speed of a test. One of these parameters is the displacement increment applied by each actuator. The value of this parameter can be changed through the menu during the execution of a test. As stated in Section 3.4, each beam actuator can apply a displacement increment as small as 0.0015 inches. In an actual test a much larger displacement increment (usually between 0.006 and 0.015 in.) is used to speed up execution. As a point in the program is reached where data is to be saved, smaller displacement increments (0.0015 in.) are automatically used. This is necessary because of the two conditions that must be satisfied by the forces on a specimen before data can be saved (see Section 4.2.2.4). If smaller increments were not used, the system would have a difficult time trying to simultaneously satisfy these force requirements. After data is saved, the larger displacement increments previously in use are automatically used once again.

Larger displacement increments are used as a test progresses. This is because as a test progresses a specimen becomes damaged. A damaged specimen has less stiffness, so a given displacement increment will cause a relatively smaller change in force as compared to an undamaged (stiffer) specimen.

4.2.3.3 Data Storage

Many portions of the moment-rotation curves can be represented well by straight lines. Accordingly, fewer data points need to be saved along these portions to accurately record the response. During test execution, the operator may change the value of $\Delta\theta$, thereby affecting how often data is saved. This also has some impact on the speed of execution, as the test is momentarily halted each time data is to be saved while the program waits for a command from the operator to continue.

Data can also be saved at any point in a test, regardless of the force values, by pressing a designated function key.

4.2.3.4 Monitor Display

During most of the test, the graphics viewport is used to plot the moment-rotation hysteresis curves of the top and bottom column stubs. The control program provides some ability to modify how this output is displayed. First, either the top or bottom column responses can be displayed separately, or both can be displayed together. Second, the scales of both the moment and rotation axes can be changed. This becomes useful as the specimen is cycled to higher rotation amplitudes. Finally, it is possible to display only a selected range of results. This becomes useful especially after many cycles of load have been applied and it becomes difficult to see the response from any particular cycle.

4.3 Control System Hardware

Figure 4.7 is a schematic drawing of the control system hardware assembled for this test system. The basic components are:

1. Microcomputer (80286 processor, 10 MHz)
2. Analog to Digital Converter
3. Digital to Analog Converters
4. Servo-controllers
5. Servovalves
6. Transducers
7. Signal Conditioning

Power supplies are omitted from this figure for clarity, and manufacturer's identification of the more significant hardware is included for completeness. The following discussion explains the exchange of information between components and how the information is used by each component.

Three functionally distinct types of transducers are used:

1. control transducers
2. data only transducers
3. feedback transducers

The function of each transducer is indicated in parentheses in Figure 4.7. Control transducers may also act as data only transducers. The use of each type of transducer will become apparent in the discussion that follows.

Hardware component blocks labelled "force transducer (control)" and "displacement transducer (control)" provide information to the microcomputer about the current force and deformation state of a specimen. Analog signals (voltages) obtained from these control instruments are converted to digital signals by the analog to digital converter (ADC) before being sent to the microcomputer. Signals from the force transducers are very small, and must be balanced and amplified (with signal-conditioning) before they are sent to the ADC.

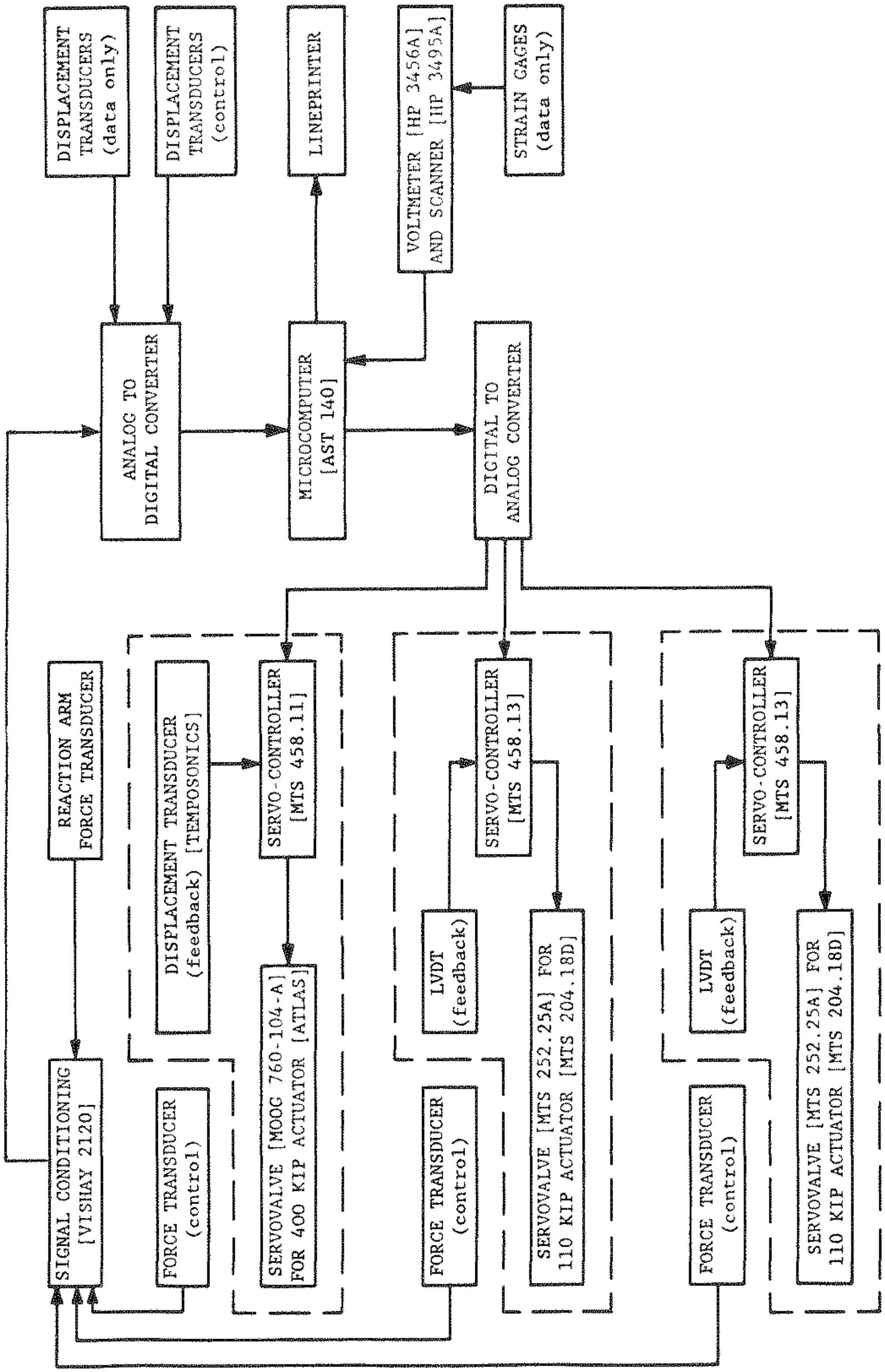


Figure 4.7 Control system hardware

Data from the control transducers are used in decision-making algorithms which direct action during a test, specifically whether to read and save all transducer data (control and data only transducers) or whether to continue to load the specimen without saving data. If all transducers are to be read and their values stored, the appropriate commands are issued by the microcomputer. Commands to sample strain gages (if present) are issued to a voltmeter and scanner via a general purpose interface bus (GPIB) in the microcomputer. All data are written to a hard disk in the microcomputer, and selected results are sent to a line printer.

If, instead, the specimen is to be loaded further before saving data, current force and displacement values are used to compute new strokes (piston positions) for each actuator. These new strokes are then issued by the microcomputer as commands to each controller. Each command is first converted to an analog signal by a digital to analog converter (DAC).

In addition to a command signal, each controller receives a feedback signal from a (feedback) displacement transducer in its corresponding actuator. This feedback signal is a measurement of the current stroke position of an actuator. Each controller then computes an error signal, which is the difference between the command (desired stroke) and feedback (present stroke) signals, and sends this error signal to the servovalve. The servovalve then adjusts the flow of hydraulic oil in the actuator to reduce the error signal to zero, thereby implementing the new desired stroke.

Once the stroke command signals are issued, each controller-feedback transducer-servovalve operates in a closed-loop mode to achieve and maintain this stroke until a new command is received. Thus there are three independently operating closed-loop systems, enclosed by dashed lines in Figure 4.7. An external loop which includes the control transducers and microcomputer controls the test in an open-loop with various levels of interaction by the operator.

Up to 16 channels of control and data only transducers can be measured with the present ADC. Samples can be taken at a one microsecond interval, allowing multiple samples to be taken and averaged each time data is read. Additional transducers can be scanned through the GPIB. However, sampling through the GPIB is comparatively slow (about 3 channels per second).

SECTION 5

SUMMARY

5.1 Summary

This report describes the capabilities and operation of a test system which has been constructed to test lightly reinforced concrete columns and beam-column joint details. The test system can be used to load interior or exterior beam-column connection assemblies in a manner causing combined axial force and reversing double curvature in the columns. Testing is done primarily in two dimensions with the ability to include a limited number of three-dimensional effects such as confinement offered by transverse beam stubs or a floor slab.

The test system was built to test essentially full-scale components at force levels comparable to those in an actual structure. As discussed in Section 3, forces are applied to a specimen in a quasi-static manner by three servo-controlled hydraulic actuators. Each actuator is operated independently in closed-loop displacement mode. The test frame hardware can apply a column axial force up to 400 kips and beam actuator forces up to 110 kips.

The control system software and hardware used to perform the force application and data acquisition tasks is described in Section 4. The control system software, discussed in Section 4.2, allows tests to be made according to either a force or displacement history. Various levels of operator intervention are provided throughout a test, providing the operator with an opportunity to alter the test plan, influence the speed of execution, or manipulate the information displayed on the monitor of the microcomputer.

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