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THE NBS TRI-DIRECTIONAL TEST FACILITY

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ABSTRACT

A general description of a unique structural testing apparatus is presented.
The apparatus is called the NBS Tri-directional Test Facility (NBS/TTF). The
NBS/TTF can subject large structural elements to a wide variety of three-
dimensional loadings including both translations and rotations in three orthogonal
directions. The facility is computer based with all aspects of data acquisition,
reduction, and display coordinated and controlled by a minicomputer. The
minicomputer also controls the loading of test specimens as directed by the
operator. The loads are applied by a closed-loop hydraulic system having seven
independently servo-controlled hydraulic actuators. Test specimens having
dimensions as large as 3 m long by 3 m deep by 3.5 m high may be installed and
tested in the facility. Lateral forces of up to ±900 kN may be imposed on
the test specimen in combination with vertical forces of up to ±1800 kN.

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1. INTRODUCTION

In support of the National Bureau of Standards' (NBS) legislated mission to assist in the development of improved design procedures for buildings subject to earthquakes, the NBS Center for Building Technology has constructed a unique structural testing apparatus. The apparatus, referred to as the NBS Tri-directional Test Facility (NBS/TTF), is capable of applying controlled displacements and/or forces in three orthogonal directions simultaneously.

1.1 BACKGROUND

Structures which are subjected to seismic disturbances undergo displacements which include components in three orthogonal directions. As a result, the structural elements which make up the load resisting framework of the structure are also subjected to three-dimensional actions, including both translations and rotations in all three orthogonal directions. However, much of the research on structural component behavior, including ultimate resistances, has been done using two-dimensional representations of the actual imposed conditions. (Such representations generally impose translations and rotations in only two orthogonal directions.) It is necessary to validate the results from such simplified test procedures with data obtained from tests which better represent the three-dimensional nature of the seismic response of structures.

One currently used testing technique is the shake table test. A shake table is a platform on which test specimens are constructed and then vibrated using a movement pattern modeled from some previously recorded seismic event. While shake table tests include dynamic effects (inertial effects and damping) they rarely, if ever, include motions which incorporate translations and rotations in three orthogonal directions.

Another technique currently used in structural testing is the "quasi-static" test. Here, loads are imposed on the test specimen slowly, thereby eliminating dynamic effects. However, a compensating advantage is the ability to closely observe test specimen behavior during the test. The elimination of the dynamic requirements simplifies the application of forces in all three dimensions. For these reasons, the "quasi-static" approach was selected by the NBS researchers as the basis for the development of the NBS/TTF.

1.2 OVERVIEW

The general concept of the NBS/TTF is straightforward, but its actual implementation is complex. At its most basic level the NBS/TTF is an apparatus which controls the actions of two opposite ends of a test specimen. The test specimen is placed between and attached to a pair of loading surfaces (crossheads) as shown in simplified form in figure 1.1. The lower crosshead is attached to a structural tie-down floor and is stationary. The upper crosshead is maintained in position by seven hydraulic actuators. Lateral (horizontal) forces are resisted by vertical buttresses and vertical forces by the tie-down floor. A simplified

depiction of the arrangement is shown in figure 1.2 and the actual NBS/TTF is presented in figure 1.3.

The loading apparatus of the NBS/TTF is composed of a moving (upper) crosshead and a stationary (lower) crosshead. The actions of the seven hydraulic actuators (figure 1.4) directly control all six degrees of freedom (dof) of the upper crosshead. The six dof consist of translations vertically and along each crosshead arm and rotations about each of the translational axes. The upper crosshead can impose any combination of values for the six dof on a test specimen, within the limits of the hydraulic actuator capacities (see section 1.3).

A schematic of the equipment associated with the control system is shown in figure 1.5. The schematic illustrates the primary information necessary to the operation of the control system. The control system equipment is interfaced with the operator by means of computer programs (software) which coordinate the activities of the facility hardware to accomplish the user specified objectives. The NBS/TTF is completely computer based permitting complex tasks to be directed by simple instructions and, thereby, greatly improving the overall efficiency of a test program. The data acquired during a test are stored by the computer for future use. Much of the data reduction and display can be done automatically with little direct operator intervention. The philosophy of the software is to minimize direct user interaction with the NBS/TTF hardware during its operation. The software commands are tailored for convenient use and generally make use of English word commands and worksheet display entry.

1.3 GENERAL CAPABILITIES

The NBS/TTF is contained in a three-story open bay room serviced by two overhead bridge cranes each having a capacity of 90 kN. The room is environmentally controlled, but has direct outside access through an overhead garage-type door, 5 m wide and 4 m high. Normal laboratory facilities are available including compressed air to 850 kPa, hot, cold, and chilled water, and low- and high-pressure steam.

The NBS/TTF can accomodate test specimens which have dimensions less than 3 m long by 3 m deep by 3.5 m high. The vertical height of a test specimen includes any attachments necessary to connect the specimen to the crossheads.

The force and displacement limits are not readily defined since actual test conditions have a significant effect. As a guide, however, the displacement in each of the three translational directions is limited to $\pm$ 50 mm. The force limits are $\pm$ 1800 kN vertical, $\pm$ 900 kN in one lateral direction, and $\pm$ 700 kN in the other lateral direction.

The rate of displacement change is slow (less than 20 mm per second) since the NBS/TTF is designed to test specimens slowly, but with well-defined applied actions. The NBS/TTF as currently configured is not intended for use where fast loading rates or a large number of loading repetitions is required.

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1.4 NBS/TTF COMPONENTS

For purposes of discussion, the NBS/TTF is divided into five major systems.
They include: the reaction system, the loading system, the load distribution
system, the control system hardware, and the control system software. The
remainder of this report is organized on the basis of these systems. A pictorial
description of the construction of the NBS/TTF is presented in an appendix.
The purpose of this report is to provide a general description of the NBS/TTF.
The discussion is devoted to an understanding of the concept, capabilities,
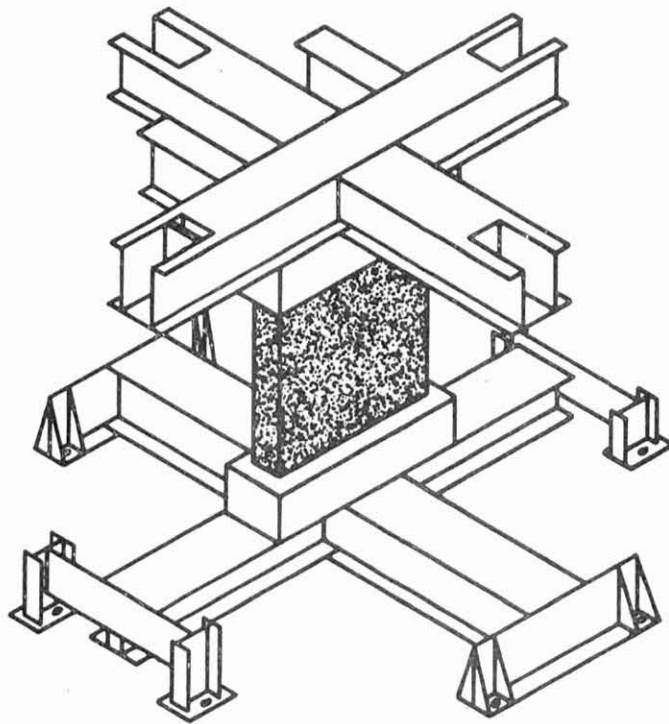and sophistication of the NBS/TTF.

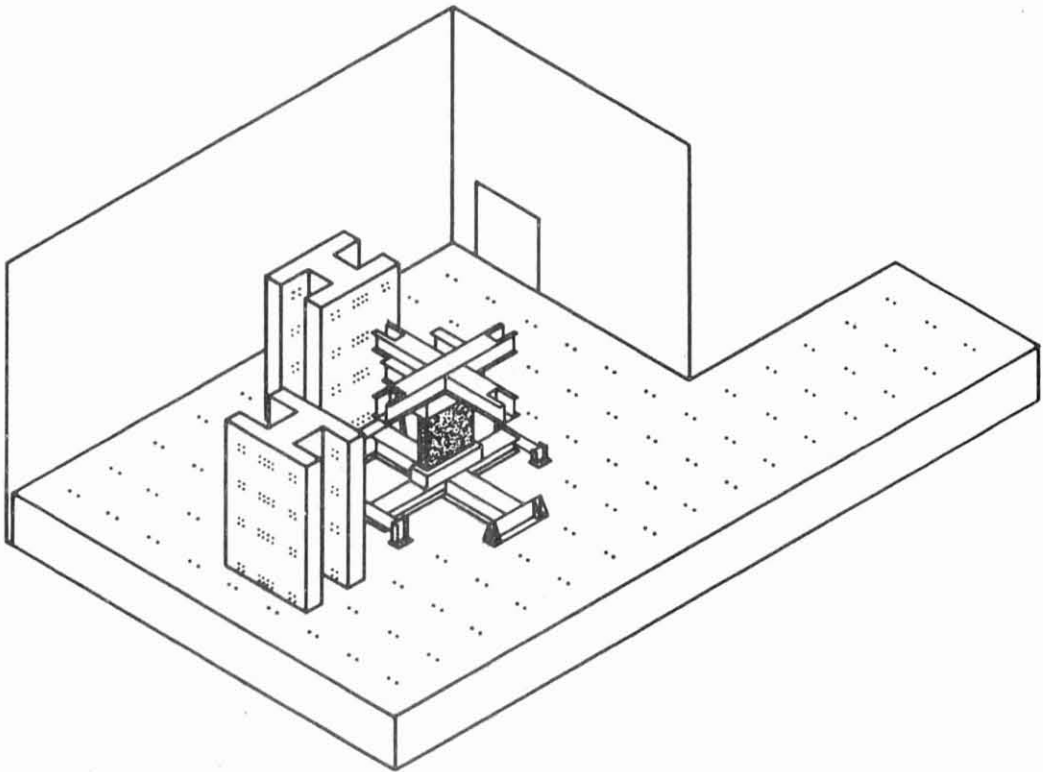Figure 1.1. Crosshead-test specimen arrangement

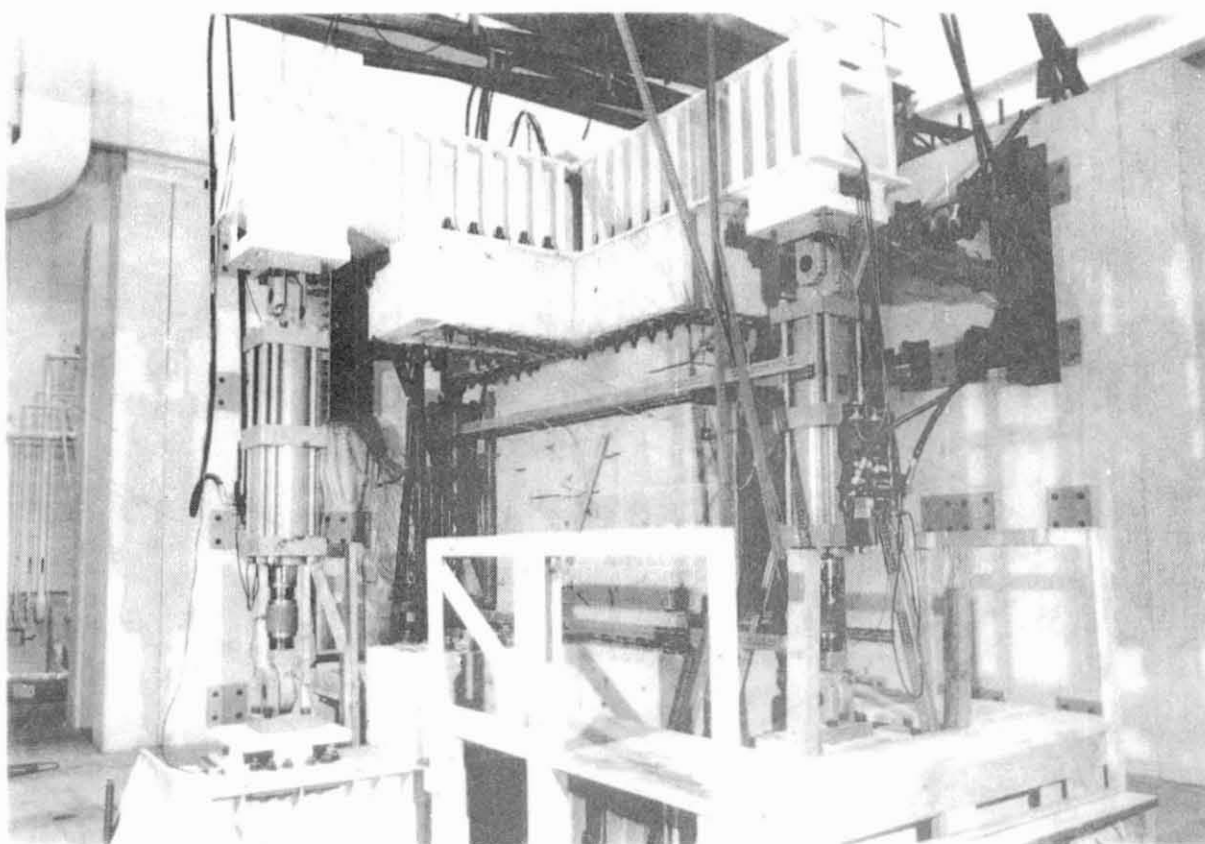Figure 1.2. Simplified sketch of NBS/TFF

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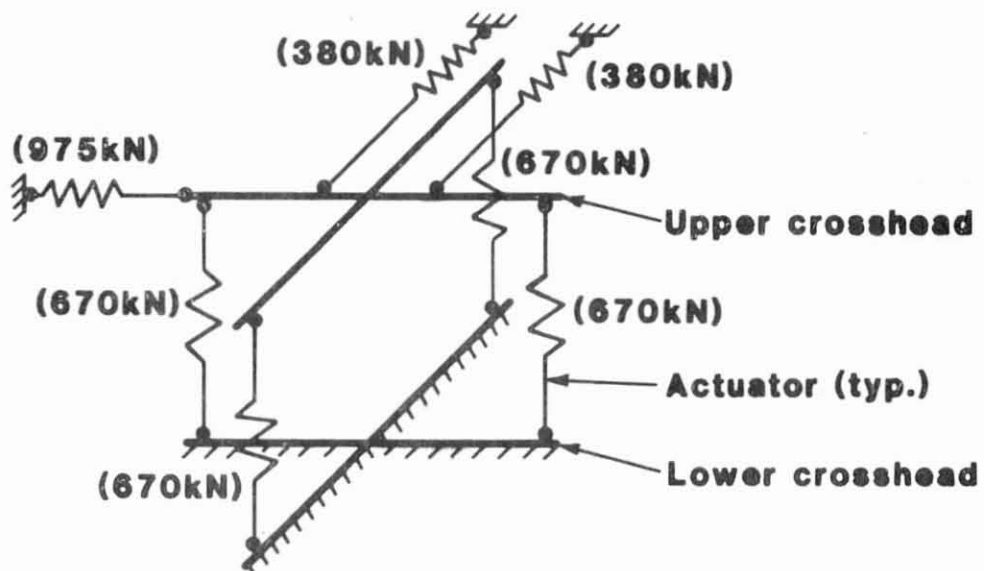Figure 1.3. NBS/TTF

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Figure 1.4. Hydraulic actuator arrangement

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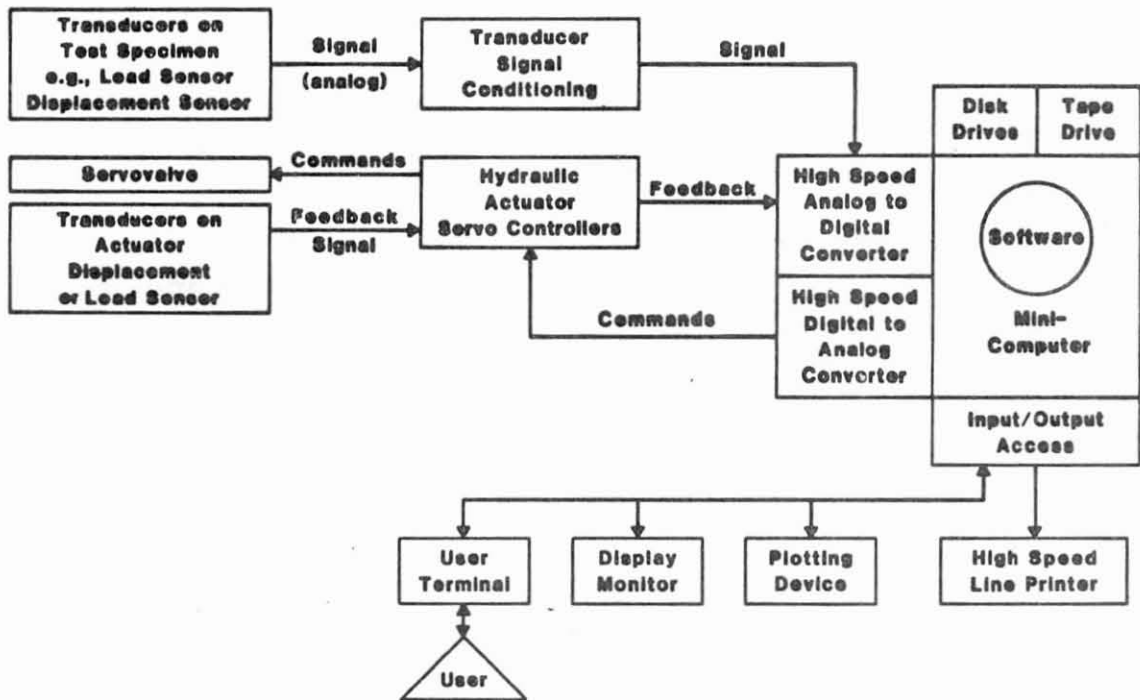**NBS/TTF CONTROL SYSTEM SCHEMATIC.**

Figure 1.5. Control system schematic

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2. REACTION SYSTEM

The reaction system is composed of two parts, a structural tie-down floor and two vertical buttresses (figure 2.1). The structural tie-down floor is a 1.8 m thick heavily reinforced concrete slab. The slab contains an embedded grid of steel beams to resist lateral forces. Anchorage points for connecting test fixtures to the slab are located in a grid 1.5 m on center. The anchorage points (figure 2.2) are flush with the slab surface and have two threaded sleeves which accept threaded high strength steel rods. Each anchorage point (using both sleeves) has a working capacity of 900 kN in both the vertical and horizontal directions. The horizontal resistance is not provided by the threaded rod, but by direct bearing of shear sleeves which are concentric with the threaded rods.

The buttresses are vertical reinforced concrete structures which are post-tensioned both vertically and horizontally (figure 2.3). The orientation of the buttresses with respect to the loading system is shown in figure 1.2. The buttresses are H-shaped in plan view and are 4.9 m tall. There are through holes in each buttress at four heights to permit fastening of attachments. Each buttress has a design lateral load capacity of 1300 kN applied 4.3 m above the slab surface. The capacity is based on a criterion of no vertical tension in the buttress. The moment resistance is principally provided by the twenty-eight vertical post-tensioned rods in each buttress. Each post-tensioned rod is terminated in the tie-down floor with a rock anchor. The rock anchors are made of a length of high strength steel rod embedded in an epoxy material with a coupler at the top to receive the buttress rod. Each rock anchor/buttress rod assembly was proof tested to a load 30 percent greater than its design working load.
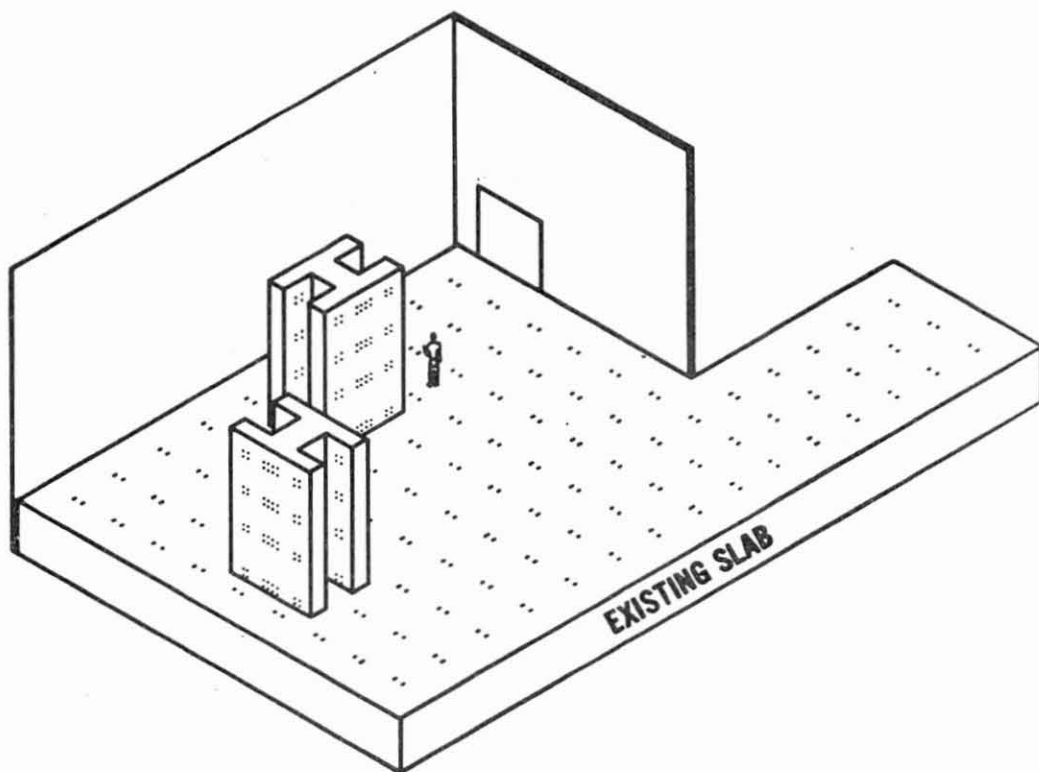
Figure 2.1. Components of reaction system

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Figure 2.2. Floor-slab anchorage detail

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Dimensions are shown in English
units because construction
dimensions were specified in
English units. 1m=3.281 ft.

10'

3'-6" 3'-0" 3'-6"

Vertical threadbar

Horizontal threadbar
at 2'-0" O.C. vertical

Through hole
patterns (typ.)

16'

14'

10'

6'

1'

Floor

Couplers to
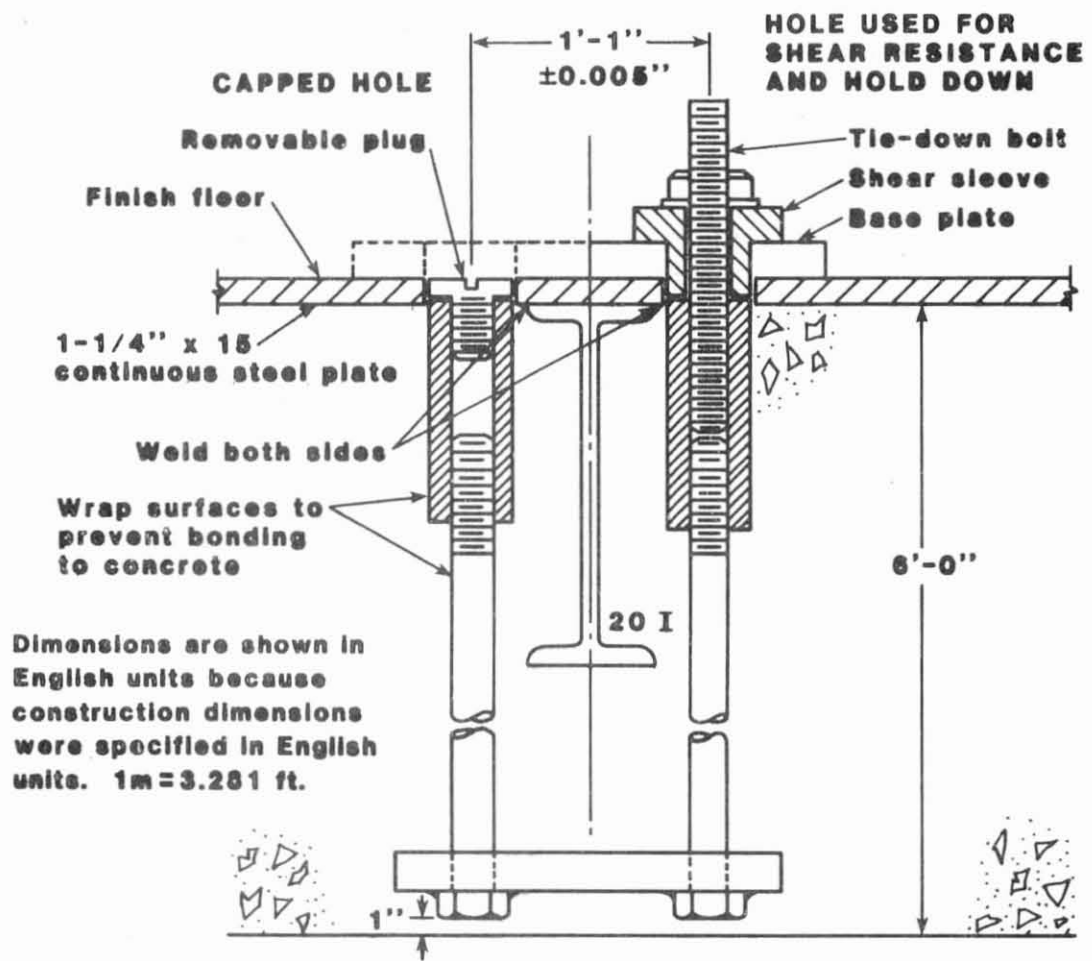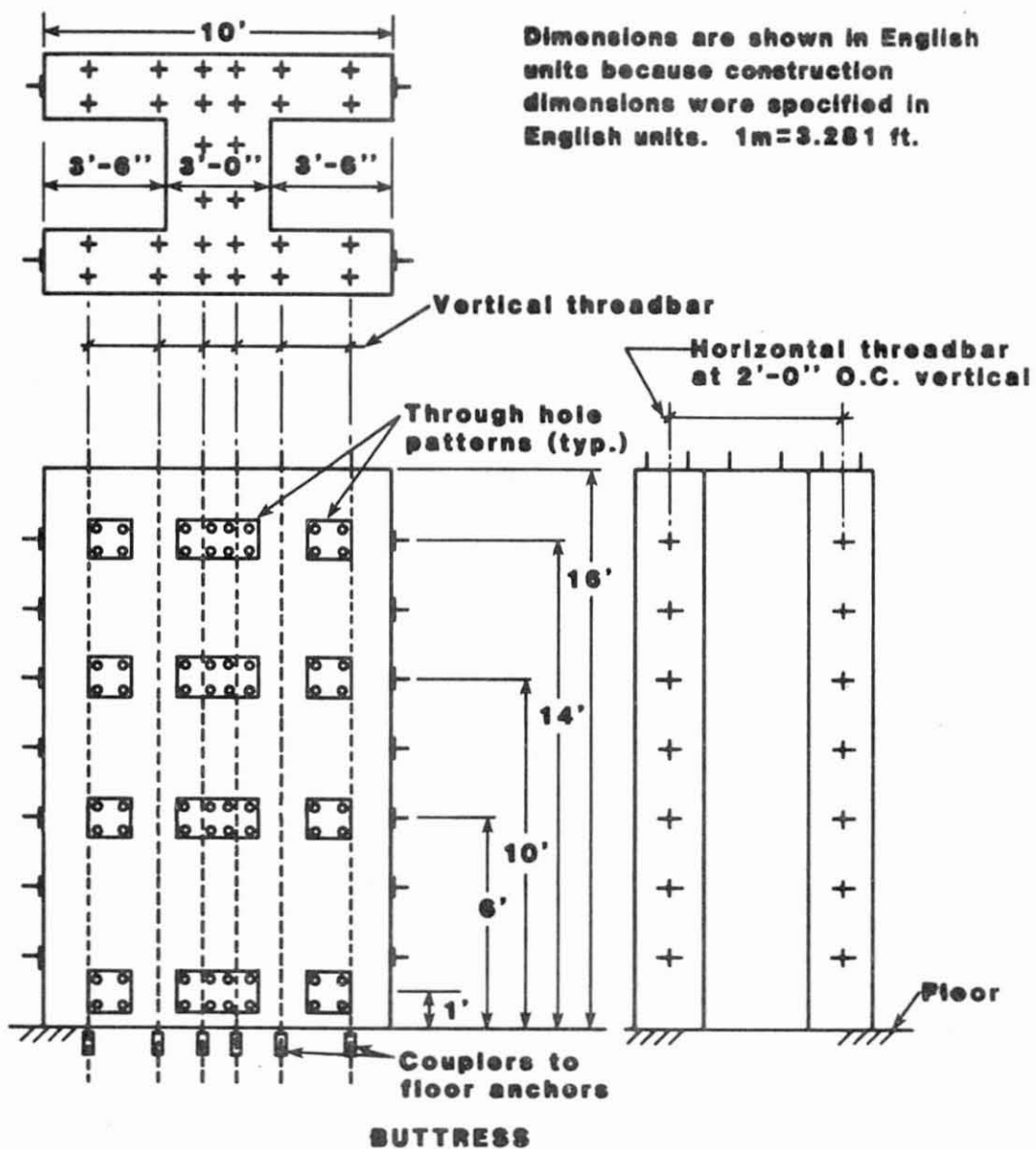floor anchors

BUTTRESS

Figure 2.3. Buttress detail

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3. LOADING SYSTEM

The loading system consists of seven double-ended hydraulic actuators which are part of a general closed-loop, servo-controlled hydraulic system. Support equipment includes a hydraulic power supply (pump), servo-controllers (discussed in section 5.4), and miscellaneous wires, hoses, and other items necessary to interconnect the different parts of the system.

A hydraulic actuator, in its simplest form, is a hydraulic cylinder with a piston which can extend and retract. The movement of the piston is controlled by the volume of oil in the cylinder. A servo-controlled hydraulic actuator has an electrically controlled hydraulic valve to regulate the volume of oil in the cylinder. The hydraulic actuators used in the NBS/TTF have additional components not found on simple hydraulic actuators. A typical hydraulic actuator used in the loading system is shown in figure 3.1 with the major components identified. The major components are the servo valve, service manifold, piston, load transducer (load cell), internally mounted displacement transducer (LVDT-linear variable differential transformer), and swivel end fittings. The servo valve has a flow rating of 3.36 cubic meters per second. The service manifold performs several functions. It filters the oil, controls oil volume fluctuations, permits operation of the actuator in a low-pressure condition and, when needed, prevents the piston from moving even in the absence of an external hydraulic pressure source. The load transducer measures the load applied to the actuator as a result of piston action. The displacement transducer is rigidly mounted inside the body of the actuator and measures the piston movement relative to the actuator body. The swivel end fittings permit relatively unrestrained rotation over an angle of 270 degrees in the plane of the swivel and approximately 10 degrees in the other planes. In short, the swivel can rotate in all three dimensions.

Each of the four vertically installed hydraulic actuators has a total piston movement range of 300 mm. The load capacity of each vertical actuator is 670 kN in either tension or compression. Each of the two horizontal actuators which are parallel to the north-south axis of the NBS/TTF has a stroke of 300 mm and a load capacity of 380 kN in either tension or compression. The single horizontal actuator installed along the east-west axis of the facility has a stroke of 150 mm and a load capacity of 975 kN in either tension or compression.

The hydraulic power supply is a 4.5 cubic meters per second, variable volume pump rated at a pressure of 34 MPa but used at a pressure of 20 MPa.
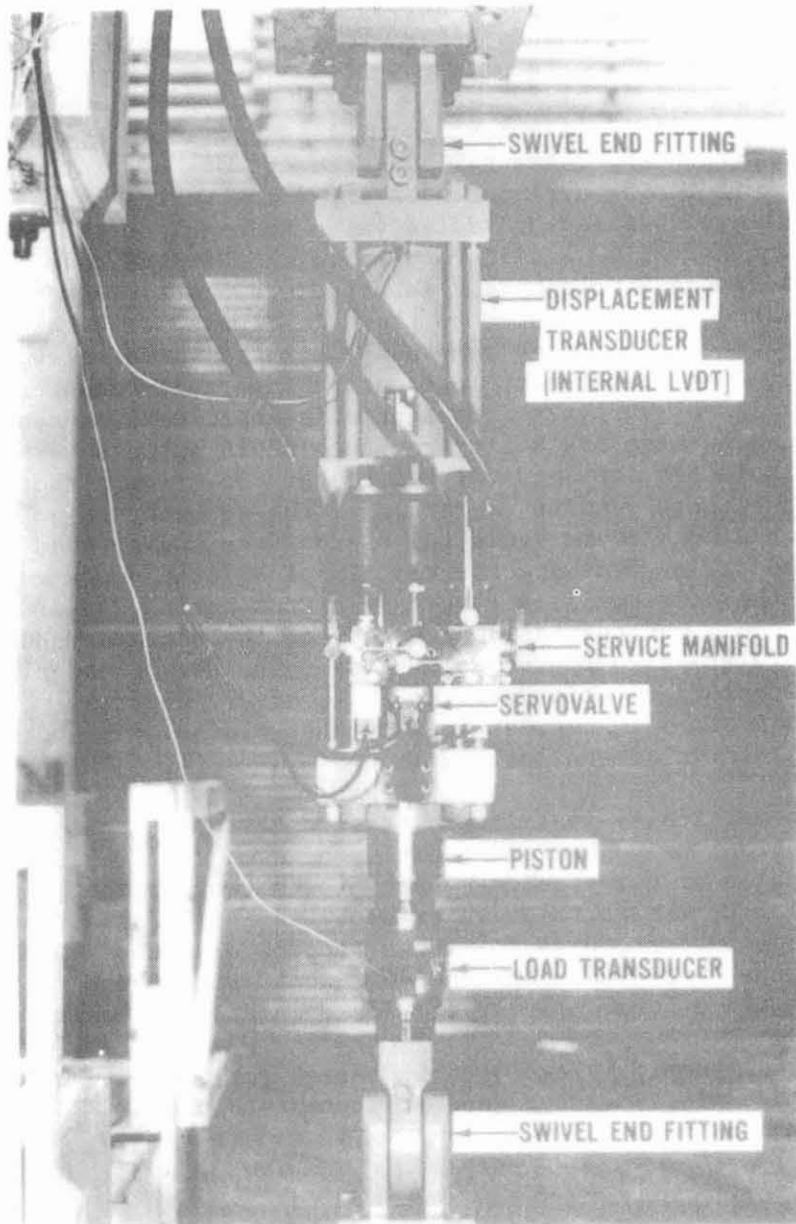
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Figure 3.1. Hydraulic actuator components

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4. LOAD DISTRIBUTION SYSTEM AND ACTUATOR POSITIONING BEAMS

The load distribution system consists of upper and lower steel crossheads. Each crosshead is formed by two approximately 4 m long beams bisecting at a 90 degree angle. Each beam has a cross section in the shape of a flanged box. This shape was made by welding two heavy wide-flange structural shapes (W21 x 132) together along their butted flanges. Each crosshead surface is approximately 635 mm wide and is pierced along its length with holes through which test specimens can be bolted to the crosshead. Each crosshead is heavily stiffened by vertical plates 6 mm thick welded to both the top and bottom flanges and the web of each wide-flange beam. The lower crosshead is bolted to the tie-down floor and held stationary

The horizontal hydraulic actuators are attached to the reinforced concrete buttresses by means of steel positioning beams. A typical beam is shown in figure 4.1. The use of slotted holes and an incremental round hole spacing permits a continuously variable height adjustment. The limits of the adjustment, however, are dictated by the hole pattern of the buttress and are approximately 1.2 m and 4.3 m above the slab surface.
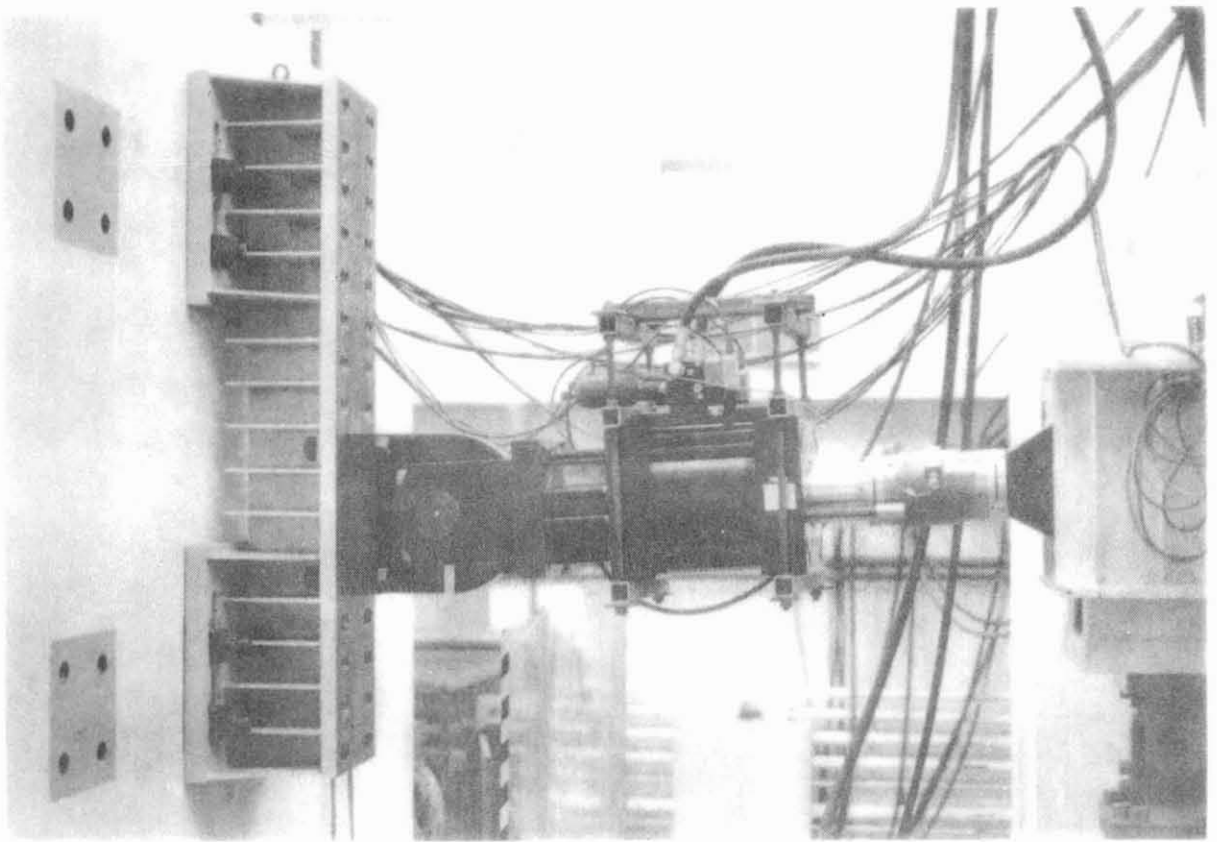
Figure 4.1. Actuator positioning beam

5. CONTROL SYSTEM HARDWARE

The control system coordinates the activities of the NBS/TTF including hydraulic actuator piston movements, test specimen data acquisition, and data display. The control system consists of a minicomputer with the usual peripherals, an analog-to-digital converter, a digital-to-analog converter, seven servo controllers, and computer software. A schematic of the system is shown in figure 1.5. This section discusses the hardware while the next section discusses the computer software.

5.1 MINICOMPUTER AND PERIPHERALS

The minicomputer system is based on a moderately powerful, 16-bit word length, central processing unit (CPU). Enhancements to the CPU include memory management with 18-bit addressing, hardware floating point operations, and hardware integer multiply and divide. The main memory contains 256 kilobytes (kb) of MOS memory which is the maximum possible for 18 bit addressing. Permanent mass storage is provided by three hard media disk drives and one tape drive. There are currently about 18 megabytes (Mb) of disk storage with all but 5 Mb contained in removable media disk drives. The tape drive is an industry compatible nine-track unit supporting both 800 and 1600 bit per inch writing densities. Storage capacity on a tape is affected by several factors but, as a guide, 40 Mb (10 million data points) can be recorded on a single 730-m reel of tape.

The user interface includes several video display terminals, high-speed printing terminals, video graphic devices (including color), a flat-bed digital plotter, and a high-speed (300 line per minute) line printer. The video terminals are used for data display in both tabular and graphical form. The printing terminals are primarily intended as user input devices during a test so that a copy of all user instructions is obtained. The flat-bed plotter is mainly used for post-test data plotting and the line printer is used to obtain a listing of all acquired data immediately after a test.

5.2 ANALOG-TO-DIGITAL CONVERTER (ADC)

The ADC is a high speed multiplexed converter with a sampling rate of 50,000 samples per second. It is connected to the minicomputer by Direct Memory Access such that the total system throughput is equal to the 50 kHz converter sampling rate. The current system has provisions for 192 separate data channels. The ADC has two levels of internal signal amplification (gain) to maximize the conversion resolution. The first gain is determined by interchangeable chips on the circuit boards with each channel being individually adjustable. The second gain is selected by computer instruction and can be set for each channel. The total gain applied to each channel prior to conversion is the product of the two gain levels. The total gain is variable in discrete steps between 1 and 20,000. Active signal filtering is performed on each channel with the cutoff frequency selected by interchangable chips on the circuit boards. The converter has a full-scale range of $\pm$ 10 volts with a digital representation

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provided by a 12-bit word. The resolution (not error) is 1 part in 4096 $(1/2^{12} = 1/4096)$.

5.3 DIGITAL-TO-ANALOG CONVERTER (DAC)

The DAC can be accessed at CPU machine speed, but the rise and settle time is on the order of 5 microseconds. There is a total of eight DAC channels, seven of which connect to the servo-controllers. The DAC has a full-scale range of $\pm$ 10 volts with a resolution of 1/4096.

5.4 SERVO-CONTROLLER

Each hydraulic actuator requires a servo-controller to manipulate the actuator's servo valve. The servo-controller is basically an analog comparator. Its function is to constantly compare an analog command signal with an analog feedback signal and to manipulate the action of the hydraulic actuator's piston such that the difference between the command and feedback signals is zero. The difference between the command and feedback signals is called the error signal. The servo-controller uses the error signal to determine how the servo valve should be directing oil flow. The feedback signal is usually from a load transducer (load control) or a displacement transducer (stroke control). The command signal may be produced internally by the servo-controller and varied manually by the operator at the servo-controller itself or the command signal may be externally generated and varied such as through a DAC. For ease of operation, the servo-controller is calibrated such that the full-scale range of the command signal is equal to the full-scale range of the two feedback transducers. This procedure produces a direct one-to-one correspondence between a given command signal and the resulting feedback signal.

A simple example of servo-controller operation is described below. Assume that stroke (displacement) is the control feedback and the relation between piston movement and feedback voltage is 5 mm per volt with piston extension producing a positive change in voltage. Consider that the actuator's piston is extended 10 mm from its fully retracted position and that this extension corresponds to a feedback signal of +2 volts. If the command signal is set to +2 volts then there is no piston movement. If the command signal is changed to +1 volt then an error signal of -1 volt is produced. The error signal is translated by the servo controller into a current signal to the servo valve which causes oil to flow into and out of the actuator such that the piston retracts 5 mm. There is no further piston movement until the command signal in changed and an error signal generated. Within the load capacity of the actuator the piston will move to satisfy the command signal regardless of the load developed as a result of the movement. The load produced by piston movement is determined by the stiffness of the objects attached to the actuator. If load control is used then the piston moves to whatever position is required (within its stroke limits) to produce the desired load.

6. CONTROL SYSTEM SOFTWARE

All functions associated with hydraulic actuator control and data acquisition, manipulation, and display both during and after a test are computer-based. A large collection of computer software has been developed by NBS researchers to perform the various tasks. In general, all software is user oriented, making it possible for relatively inexperienced operators to use the NBS/TTF. However, the complexity and sophistication of the overall NBS/TTF (both hardware and software) require that a trained and experienced operator must oversee the planning and execution of any test.

6.1 ORGANIZATION

The software which actually supports the performance of a test is all that will be discussed in this report. Post-test data manipulation and display software is of a general nature and not exclusive to the NBS/TTF. It is worthwhile to note, however, that there is extensive software available to support the post-test analysis of data produced by tests in the NBS/TTF.

The software which supports the actual testing of a specimen in the NBS/TTF is called TEX which is an acronym for Test EXecutive. TEX is not a single program, but a collection of separate executable programs (tasks) which operate concurrently in a multi-task environment. The specific needs of a test determine which programs are actually used, but the selection and operation of the various programs is controlled by the software and not by the operator. The use of multi-tasks permits fast response to changing test conditions by enabling the various tasks to be prioritized. The assignment of priorities enables TEX to allocate more computer resources to those tasks which require them and to do it on a real-time basis. There are also pre-test computer programs which support the use of data bases necessary to the execution of TEX. In addition, there is software tailored to the manipulation of the NBS/TFF during test specimen installation.

The functions of TEX can be divided into three main categories: 1) data acquisition and storage, 2) hydraulic actuator control, and 3) data display. In actual practice the functions are not as distinct, but for purposes of the subsequent discussion the division is a convenient classification.

6.2 DATA ACQUISITION AND STORAGE

The function of data acquisition and storage is common to all laboratory testing. TEX requires several separate data acquisition processes, but this discussion is limited to that which pertains to data acquired by user request. The operator predefines the ADC channels which will be sampled during the test but the channel definition may be changed during the test. The same data base can be used for many tests. The operator specifies acquisition rate and can turn the acquisition of data on and off. The acquired data are stored as decimal voltages and the amount of data which can be acquired is limited only by the permanent storage space (disks and tape) available. The user does not have

access to the stored decimal voltage during a test, but to permit data
plotting and display during a test a second form of data storage is provided.
A certain amount of permanent storage is allocated to a data pool. The same
pool is used for each test so the information in the pool exists only during a
test. TEX processes the acquired data on a time available basis to produce
data in engineering units (reduced data) and stores these data in the data pool.
The user may access the data pool to produce graphical or tabular displays of
the acquired information. The data in the pool can be algebraically manipulated
and edited to produce data displays using almost any possible combination of data.

6.3 HYDRAULIC ACTUATOR CONTROL

The computer software which controls the individual hydraulic actuators is
complex, but the use of the software is simple. The operator
need not consider the individual actions of the actuators. Instead, the operator
defines global actions of the upper crosshead. The global actions are defined
in terms of three easily visualized global directions which are north–south,
east–west, and vertical. The lateral directions, north–south and east–west,
are aligned with the two intersecting arms of the crosshead prior to crosshead
movement. Each of the six degrees of freedom of the upper crosshead is defined
by the operator by simply specifying values for the dof in terms of either a
force (moment) or displacement (rotation). The specified value denotes whether
a particular degree of freedom is displacement or load controlled. The method
of control can be changed by simply specifying the desired control value. For
example, the vertical translation degree of freedom may be defined as load
control with the software required to maintain 50 kN of vertical compressive
force on the test specimen. The vertical displacement of the crosshead is then
automatically varied by whatever amount is required to maintain 50 kN. Simul-
taneously, the translation in the north–south direction could be defined as 2
mm in displacement control. The software would then direct the hardware to
move the crosshead 2 mm in the north–south direction while still maintaining 50
kN vertically. The software accounts for the effect of geometry changes caused
by crosshead movement and resolves all actuator piston displacements and imposed
forces into components acting in the global directions.

6.4 DATA DISPLAY

The data display function described in this section is the real–time data
monitor. The display capabilities associated with user specified data acquisition
were discussed in section 6.2. It is important that the operator have certain
test specimen data available on a continuously updated basis. The operator can
more readily verify proper test conduct and alter loading conditions if required.
It would be extremely wasteful of permanent storage space to acquire and store
all of the information needed to produce updated data display. For this reason,
TEX includes a monitor capability which provides a real–time display of user
specified data channels. The data are not stored, but only updated on a video
display terminal. The data displayed by the monitor are reduced data and include
corrections for excitation voltage fluctuations, gage factor, and temperature
effects as specified by the operator. The data channels actually displayed may

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be selected by the operator prior to the test and changed at any time during the test. An alternative to the reduced data format is the display of uncorrected decimal voltage values. This format is useful to verify that transducers are operating properly.

7. REMARKS

The NBS/TTF is an addition to the existing structural testing laboratories and complements the currently available capabilities. The primary enhancement to structural testing provided by the NBS/TTF is its ability to control the movements (translations and rotations) of a test specimen in three orthogonal directions. While the NBS/TTF is primarily devoted to research on improving the resistance of structural elements subjected to earthquake loadings, its usefulness extends into other areas of structural research including the effects of wind loadings on structural elements.

8. ACKNOWLEDGEMENT

APPENDIX: A PICTORIAL DESCRIPTION OF THE CONSTRUCTION OF THE NBS/TTF

Figure A.1.   Laboratory prior to construction

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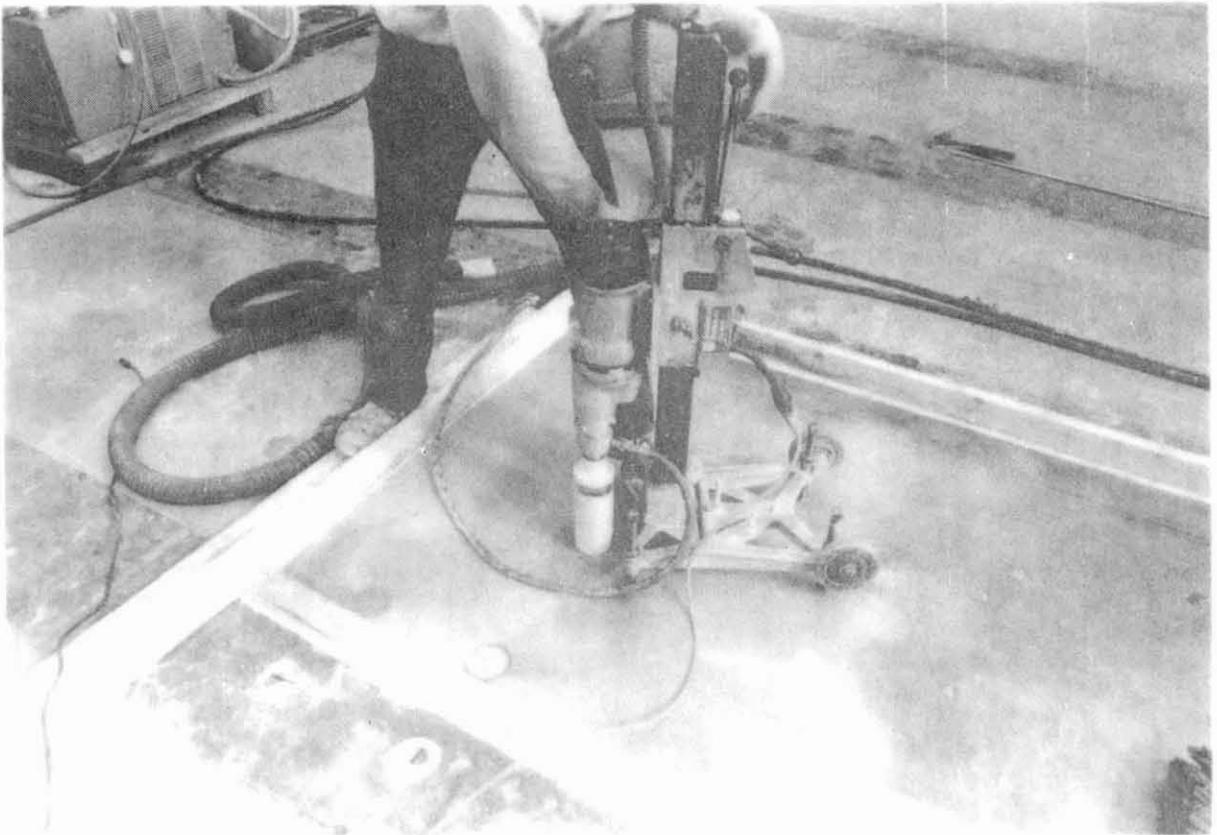
Figure A.2. Drilling holes in tie-down floor for rock anchors

Figure A.3.   Proof-testing an installed rock anchor

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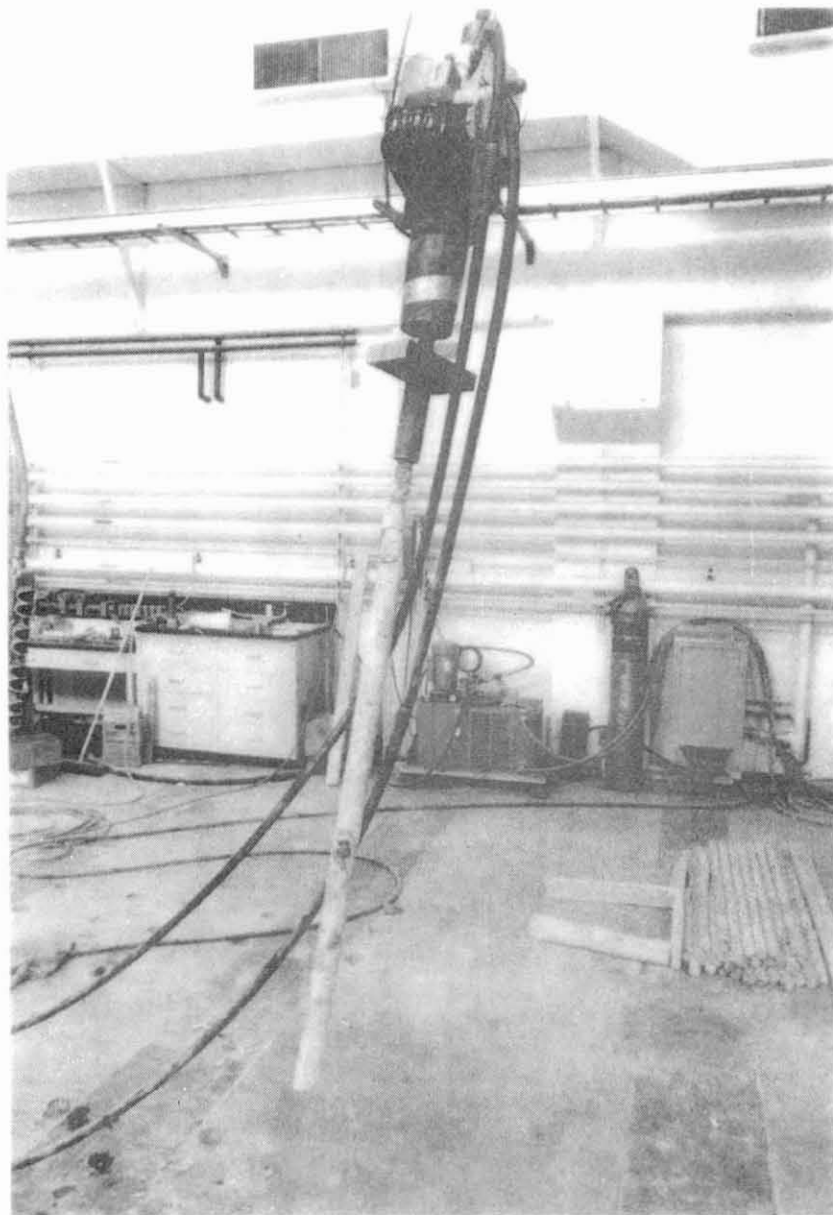
Figure A.4. Rock anchor after removal from tie-down floor

Figure A.5. Roughened outline of buttress cross-section

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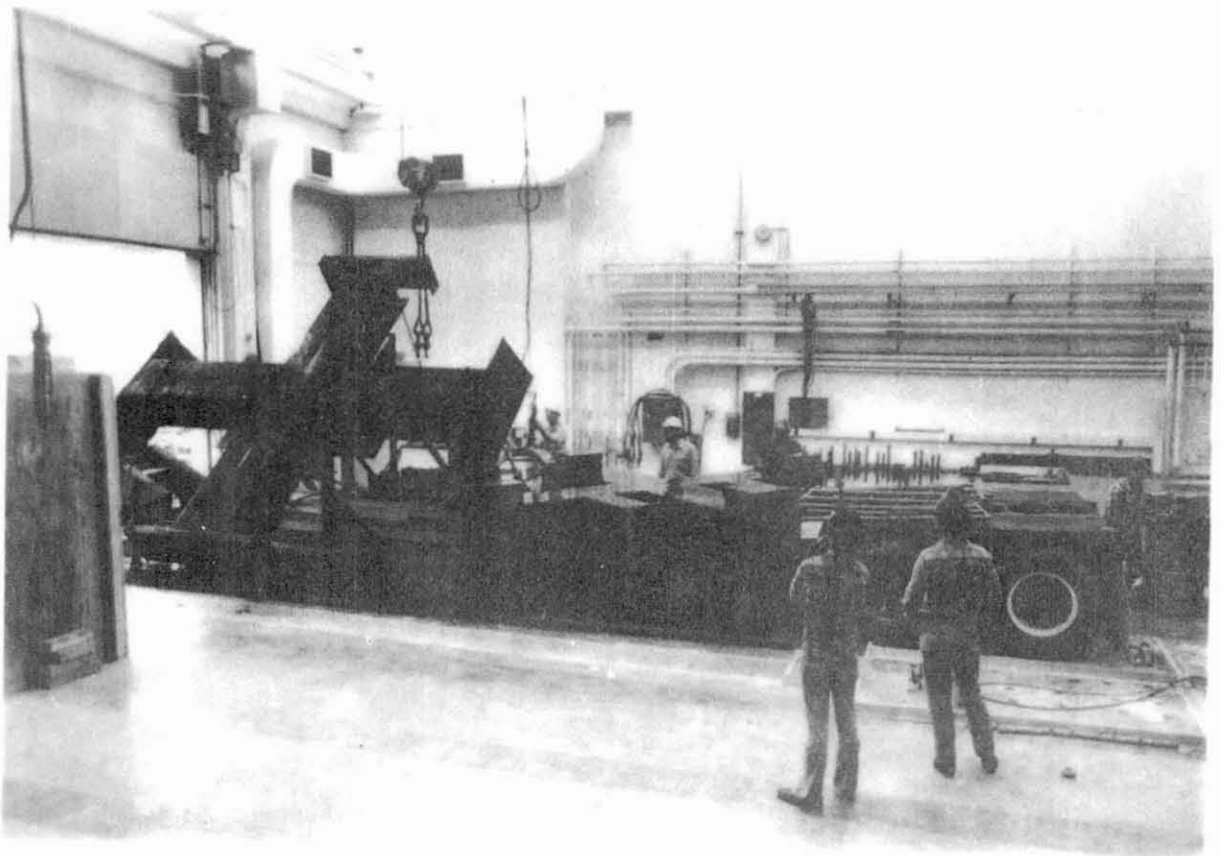
Figure A.6. Arrival of steel crossheads
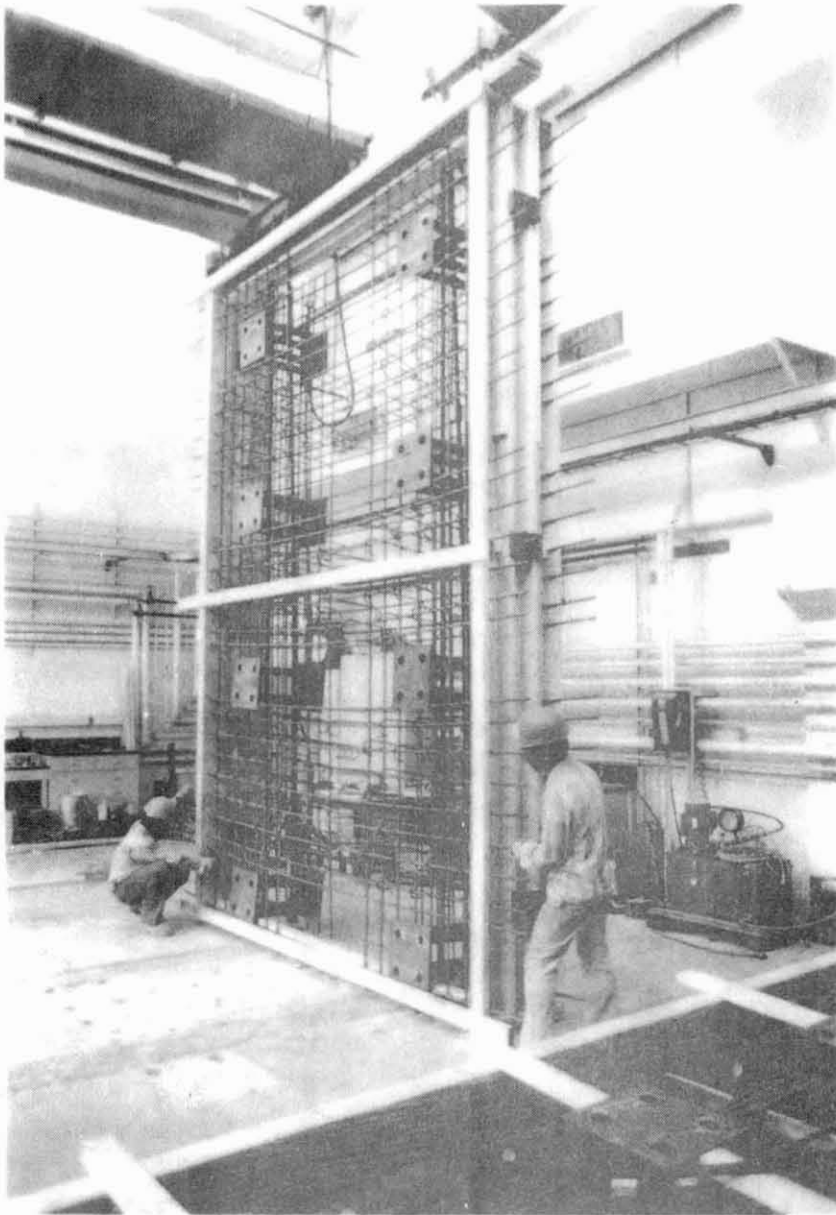
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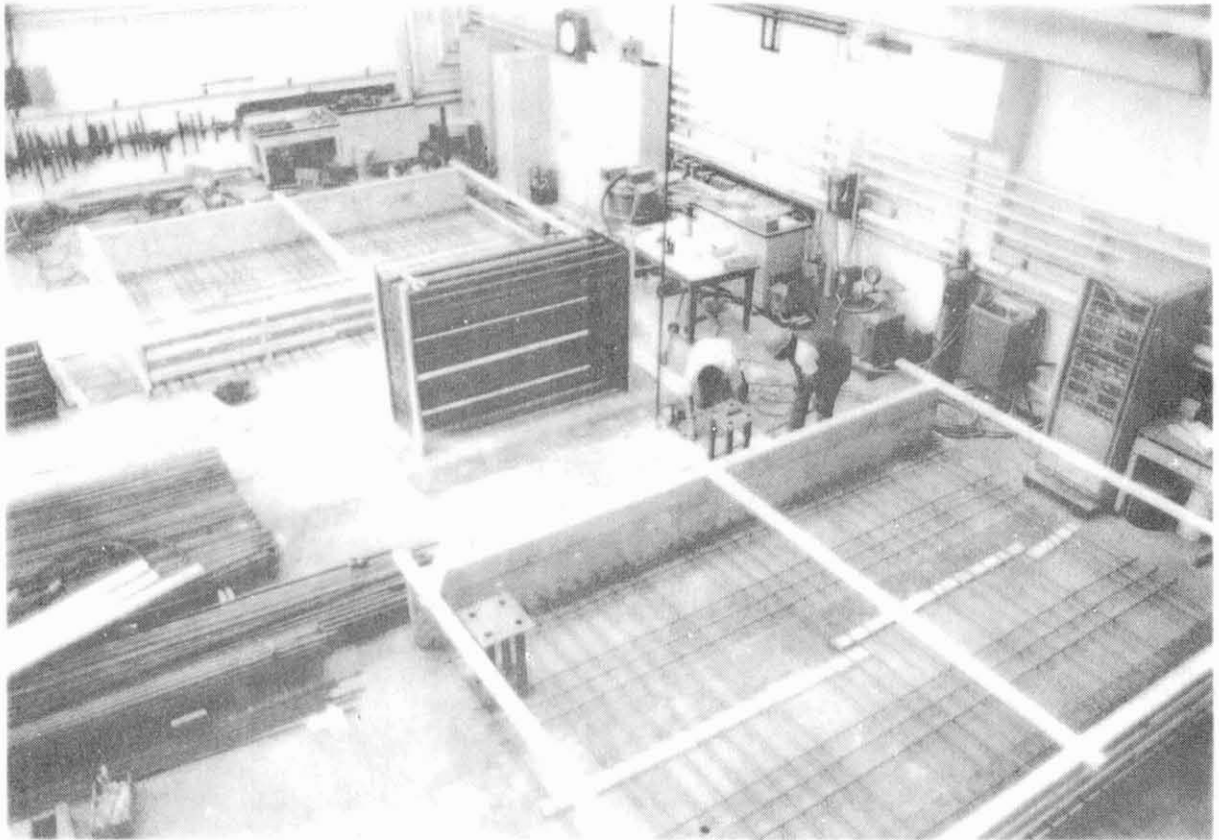
Figure A.7. Fabrication of buttress flange reinforcement

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Figure A.8. Erection of buttress flange

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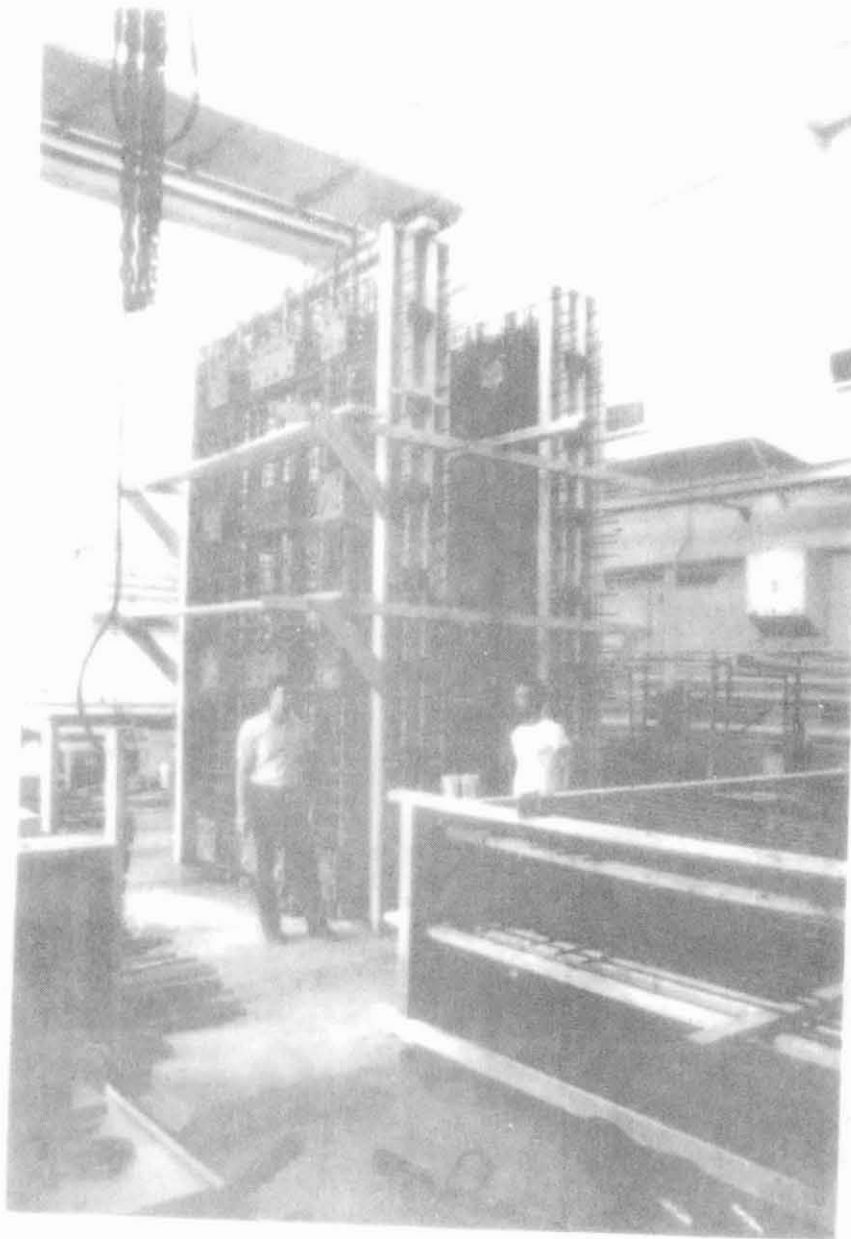
Figure A.9. Buttress reinforcement in place
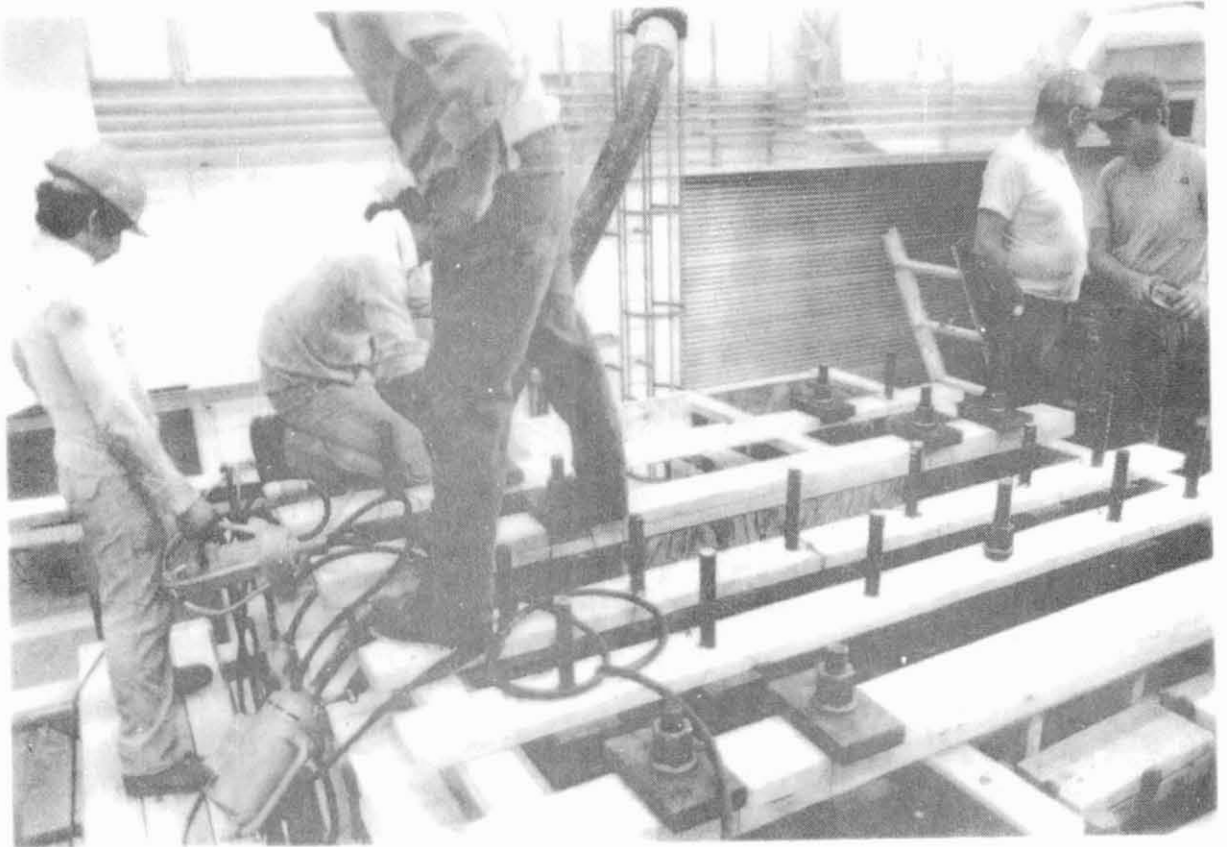
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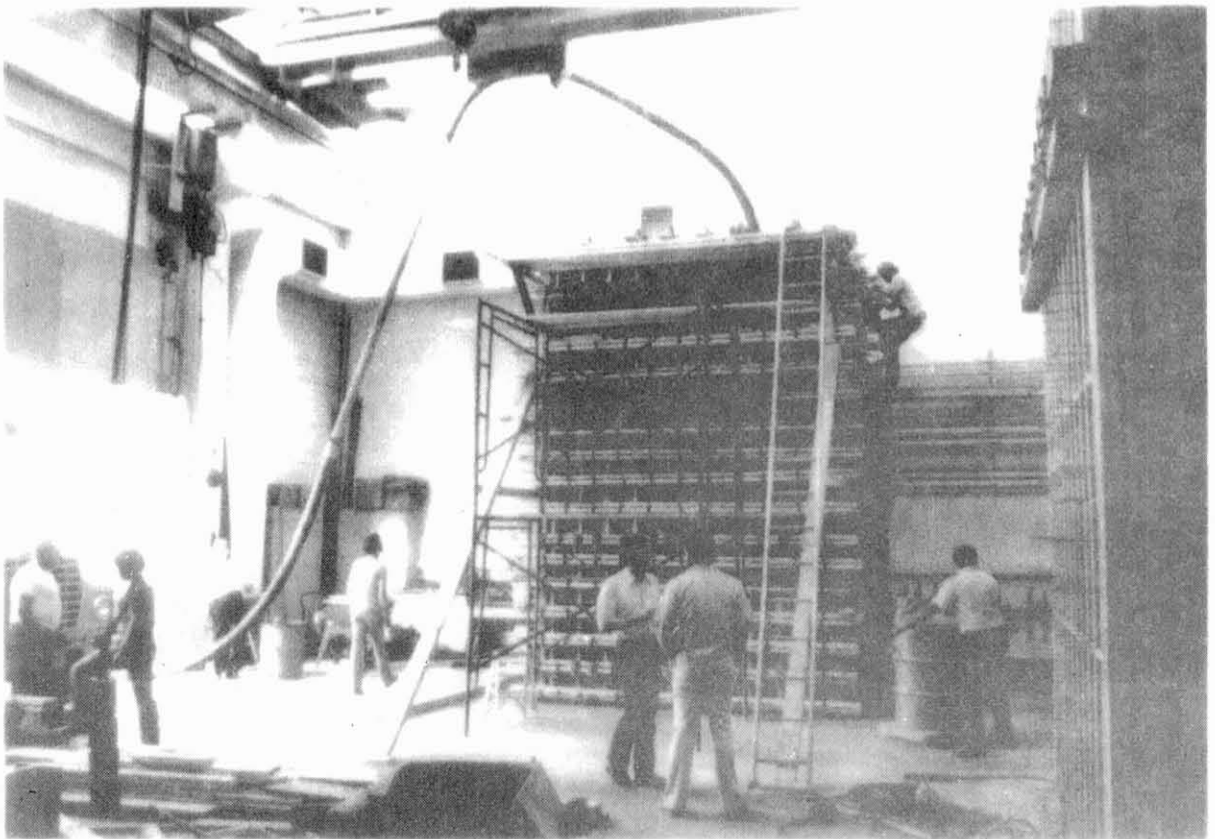
Figure A.10. Pumping of buttress concrete
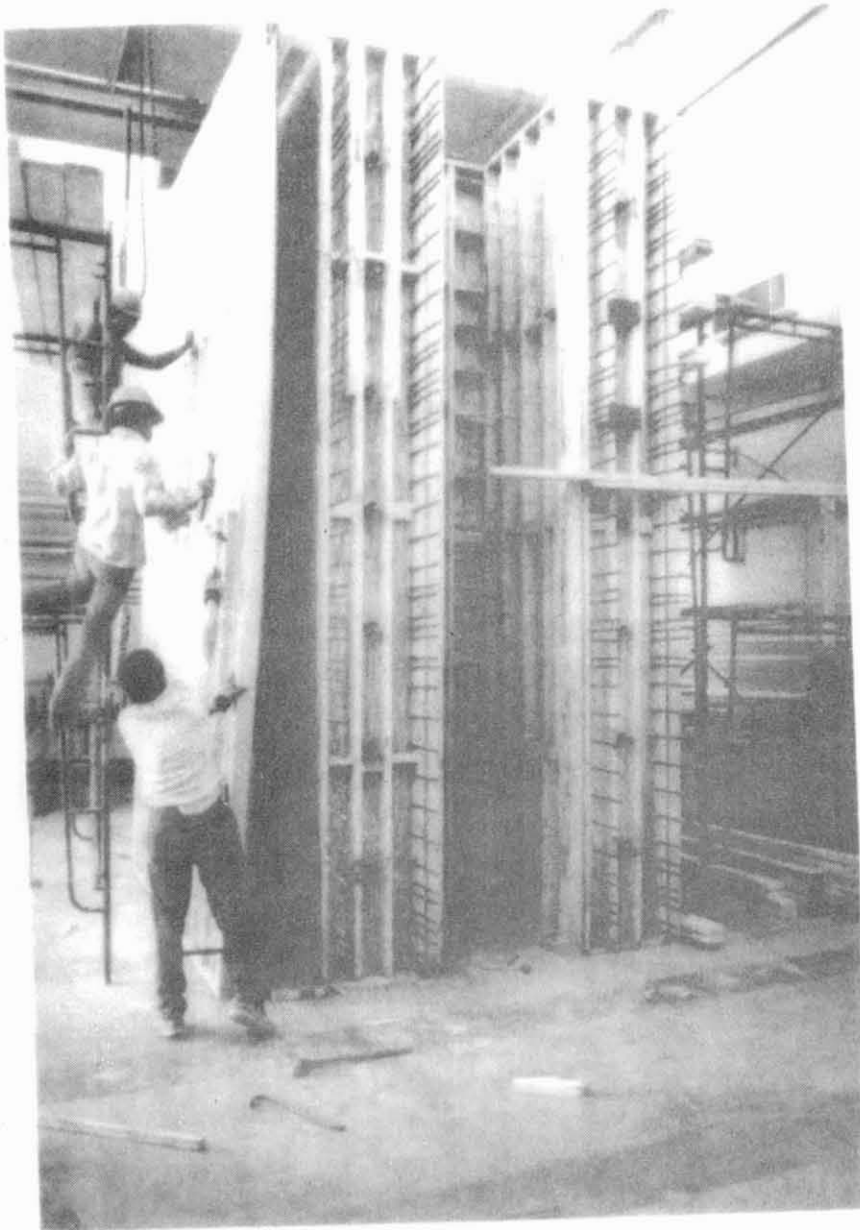
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Figure A.11. Placement of buttress concrete

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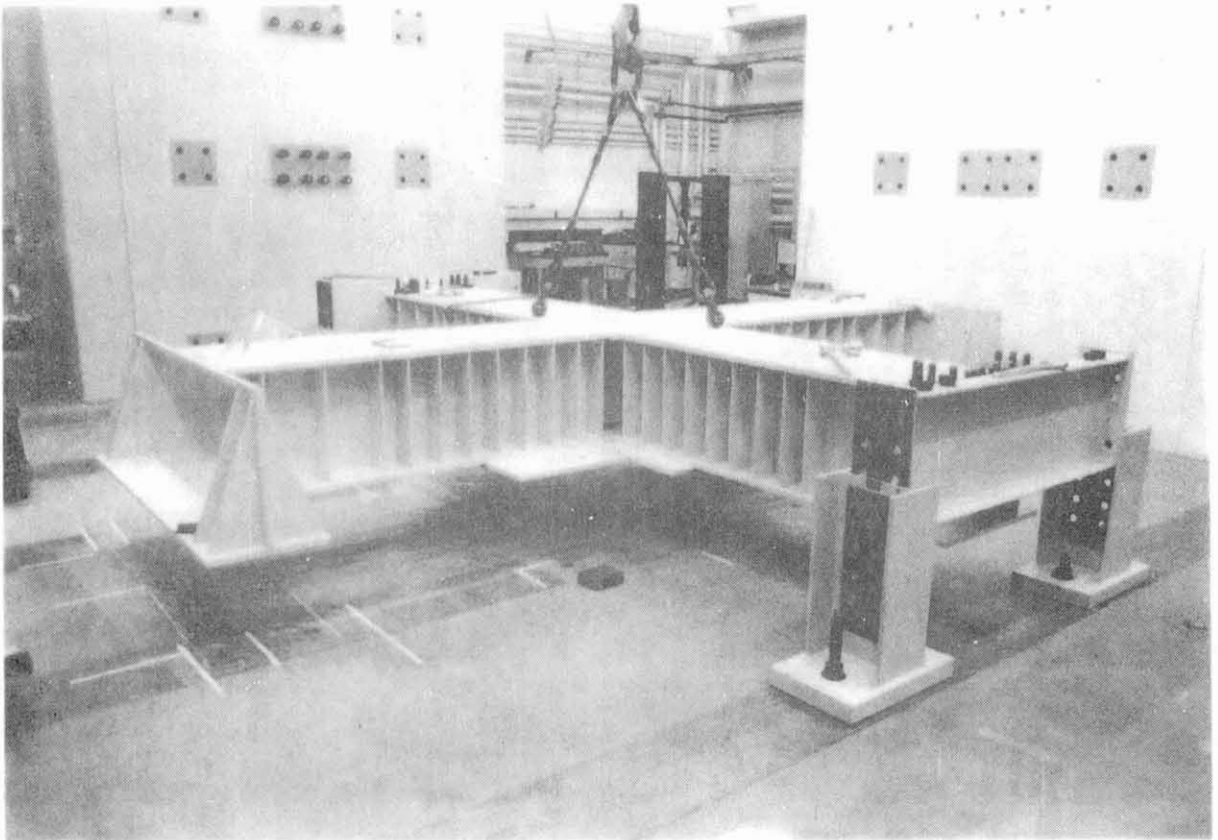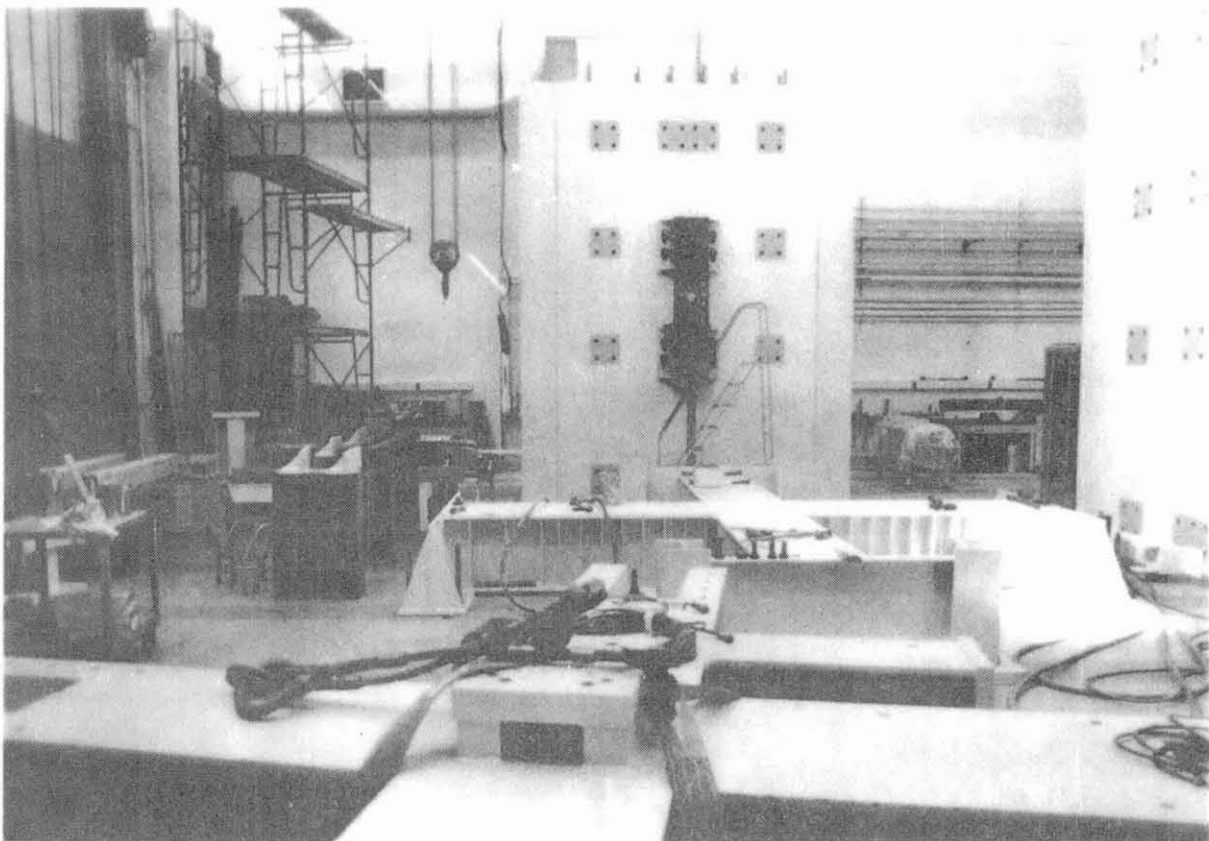Figure A.12. Removal of buttress forms

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Figure A.13.   Installation of lower crosshead

Figure A.14. NBS/TTF nearing completion