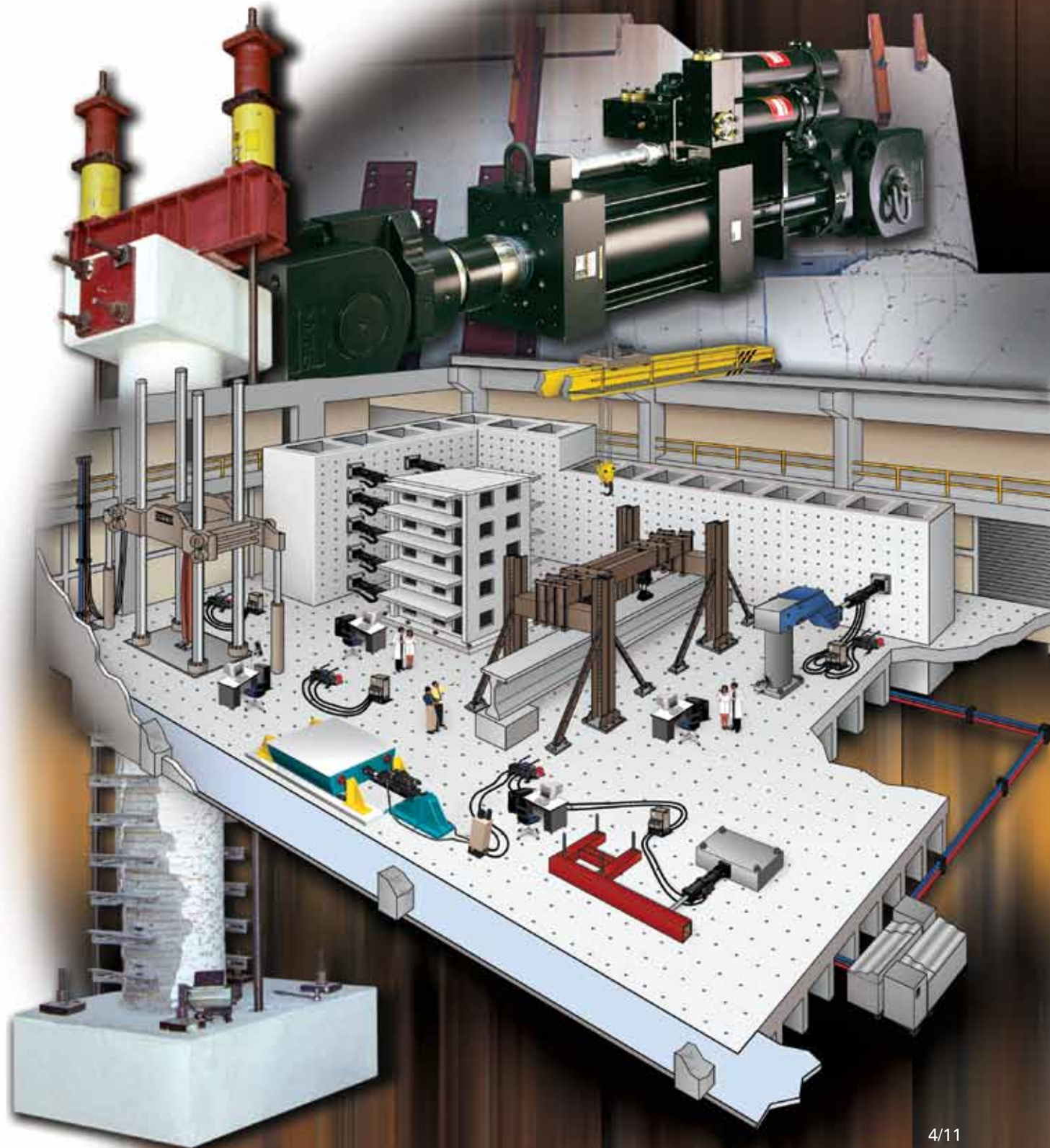


# Civil, Structural and Architectural Engineering Testing Capabilities



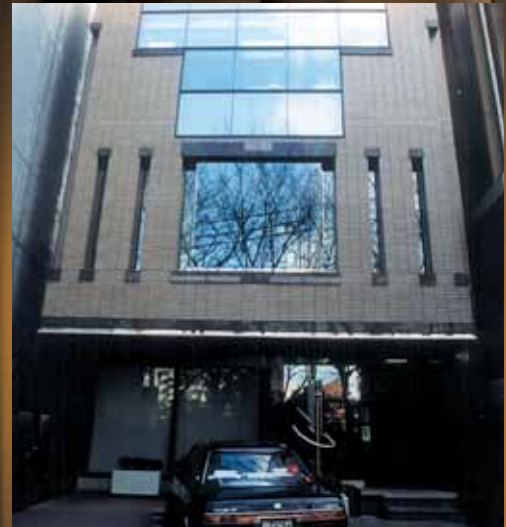




**MTS Systems Corporation**  
**Minneapolis, Minnesota U.S.A.**



**MTS Systems GmbH**  
**Berlin, Germany**



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**Tokyo, Japan**

### **MTS Systems Corporation**

MTS provides researchers with testing solutions they use to evaluate mechanical properties, strength, and durability of materials and structures.

Consistently meeting customer expectations is our definition of total quality. We use our world-wide corporate resources to continuously improve the products, services and support we offer our customers.

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## General Overview

**M**TS Systems Corporation offers a wide range of products and services to support all aspects of Civil, Structural and Architectural Engineering throughout the world. In addition to traditional items such as actuators, servo hydraulic controllers, and hydraulic performance packages, MTS also offers other services such as building design consulting, structural testing training, long term maintenance and calibration con-

tracts, etc. We have engineered our products, software and services to specifically address structural testing customer requirements. The following pages present an overview of MTS products and capabilities and are meant to be in introduction to MTS solutions to Civil, Structural, and Architectural testing applications.





# Structural Testing Requirements

The previous artist sketch of a Structural Testing Laboratory illustrates some of the areas where MTS can provide technical solutions and supporting services. In addition to structural components, servo-hydraulic controls and hydraulic distribution networks, MTS also manufactures various types of general purpose static and fatigue testing systems for other areas of a research or testing laboratory. Additional capabilities at MTS include Rock and Concrete Mechanics and High Force Testing of high strength materials.

For Structural Testing, the majority of applications fall into one of the below categories:

## **Quasi-Static and Low Performance Dynamic Testing**

- ▶ Step-by-step or static deflection testing.
- ▶ Pseudodynamic testing.  
(Displacement histories imposed by solving equations of motion while increasing the time domain of a seismic event to allow quasi-static test steps.)

*Tests can vary from static to low performance dynamic testing to 4 hertz.*



*Quasi-Static Testing of a Bridge Structure*

## **Dynamic Testing**

- ▶ Cyclic Loading.
- ▶ Impulse Loading.
- ▶ Complex Wave-shape definition.
- ▶ Block Loading.
- ▶ File Playback of loading records such as bridge loading or seismic events.

*Tests can vary from low performance to high frequency applications. (0 - 50 hertz)*

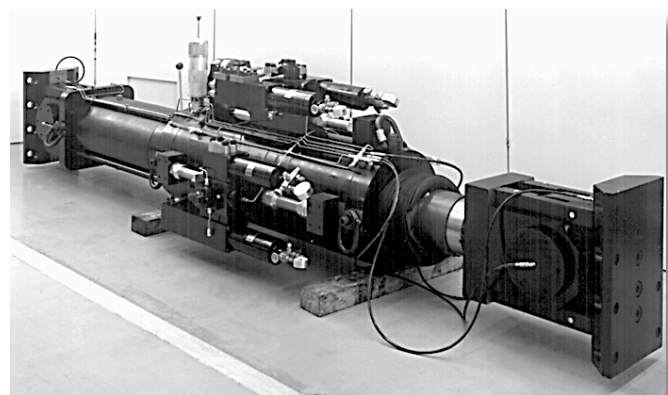


*Dynamic Testing of a Column Support*

## **High Flow/High Performance Testing**

- ▶ High flow dynamic performance for simulation of real time seismic events of high capacity actuators. (High flow servovalves rated from 5,000 LPM to 40,000 LPM)
- ▶ Real time Pseudodynamic testing.

*Tests are extremely demanding and require state-of-the-art testing equipment and facilities.*



*High Performance Actuator (3) 1500 LPM Servovalves*

## Actuator Offerings

The following information is presented to illustrate the types of equipment that MTS may recommend for each of the above categories depending on customer requirements.

### ***Actuator Types:***

For Dynamic, Pseudodynamic and High Performance Testing, MTS recommends the 244 Actuator Series.

These actuators are a double ended, equal area design and are recommended for almost any applications requiring high accuracy and high performance testing. They are well suited for all types of testing (from static to dynamic) and are known for their excellent fatigue reliability, accuracy and repeatability. These actuators are the most versatile and by far the most popular solution for all forms of servo hydraulic testing.



*The above illustration shows a typical 244 style actuator with a MTS 249 backlash free swivel head and swivel base.*

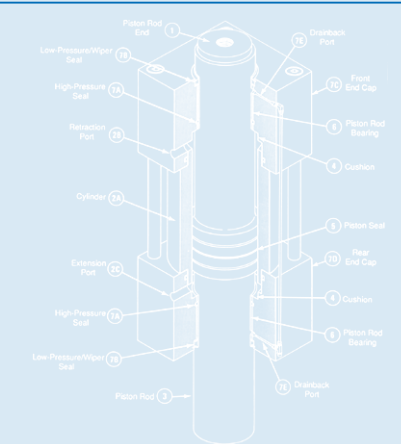
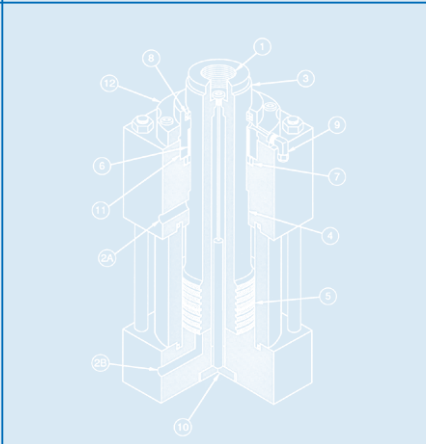
For Quasi-Static, Pseudodynamic and Low Frequency Testing, MTS may suggest the 243 Actuator Series depending on testing needs and budgets.

These single ended actuators are economically designed for high force compression loading with reduced tension loading and are well suited for low dynamic performance requirements. They can be purchased with either a MTS 249 backlash free swivel joint or MTS 243 pivot end depending on the intended applications.



*This illustration shows a MTS 243 style actuator assembly with a MTS 249 backlash free swivel head and swivel base.*

## Summary of Actuator Types

<u>Actuator Features</u>	<u>244 Series Actuators</u>	<u>243 Series Actuators</u>
Force Capacities Available (Other custom sizes available)	15 kN to 2,000 kN (3,300 lbs to 440,000 lbs)	30 kN to 2,700 kN (6,600 lbs to 600,000 lbs)
Standard Stroke Units	150 mm, 250 mm and 500 mm (6 inches, 10 inches, and 20 inches)	250 mm, 500 mm and 1000 mm (10 inches, 20 inches, and 40 inches)
Optional Lengths	Available	Available
Stroke Transducer	LVDT	Temposonics II™
Double Ended Design	Standard on all units	Optional Feature
Single Ended Design	Not Available	Standard on all units
Piston Rod Bearing	Direct bond, high capacity polymer material.	High capacity non-metallic material
Hydraulic Cushions	Optional	(not available)
Resistance to Side Load	High resistance due to double ended design and long wheel base to react side load.	Acceptable tolerance to side load, but has limited wheel base due to single ended piston design.
Mounting Configurations	MTS 249 Swivel Head and Swivel Base are commonly provided for backlash free testing capabilities. Lower cost pedestal base or clevis pin mounting is also available. These are usually steel castings with spherical bearings.	MTS 243 Pivot Head and Pivot Base without backlash adjustments are typically provided. Optionally, MTS 249 Swivel Head and Swivel Base with backlash adjustment or Pedestal Base mounting configurations are available. These are usually welded plates with spherical bearings with less rotation.
252 and 256 Style Servovalves	Available	252 series normally provided
		
	<i>MTS 244 Actuator Sectional View</i>	<i>MTS 243 Actuator Sectional View</i>

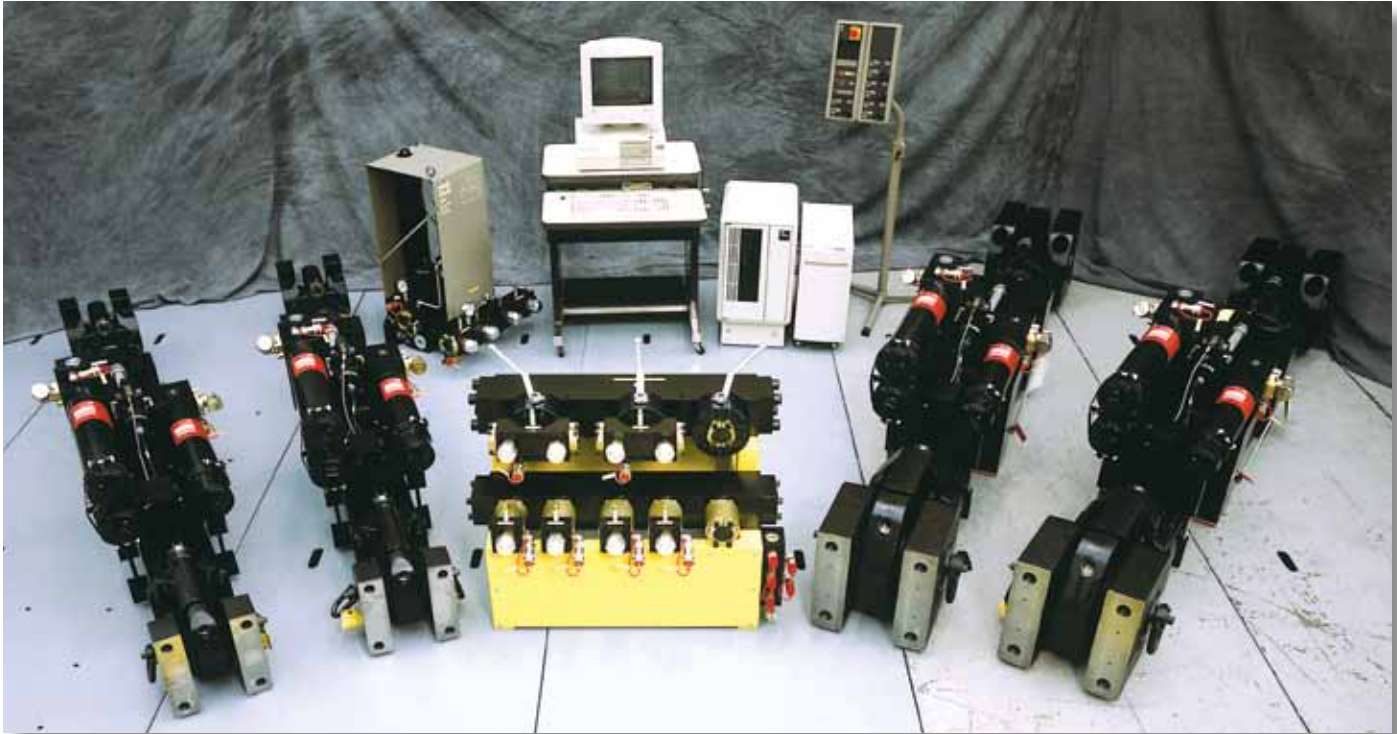


## Actuator Examples

The following photographs are included to illustrate the types of equipment and the quality of the product that MTS provides to our customers.

This photograph is representative of a typical structural testing laboratory. It shows:

- ▶ 2 sets of MTS 244.51, 100 ton actuators
- ▶ 2 sets of MTS 244.41, 50 ton actuators
- ▶ MTS 4 channel TestStar™ Control Electronics
- ▶ Hydraulic distribution manifolds and valving



*4 Channel System*

Photograph of (2) 25 ton High Performance Actuators

- ▶ MTS 244.31 dynamic actuators
- ▶ Additional accumulators for high performance fatigue testing
- ▶ +/- 100 cm/sec (+/- 40 in/sec) velocity



*25 ton High Performance Systems*

View of 50 ton structural actuators

- ▶ MTS 244.41, 50 ton dynamic actuators
- ▶ MTS 249 Swivel Heads and Swivel Bases
- ▶ MTS 256 series 3 stage servovalve for dynamic performance
- ▶ +/- 300 mm (+/- 12 inch) stroke capability



*50 ton Structural Actuators*





View of a 200 ton structural actuator

- ▶ MTS 210 series, 200 ton dynamic actuator
- ▶ MTS 249 Swivel Head and Swivel Base
- ▶ MTS 256 series 3 stage servovalve for dynamic performance
- ▶ +/- 150 mm (+/- 6 inch) stroke capability
- ▶ +/- 1 cm/sec (2.5 inch/sec) velocity



View of Structural System for Static Testing

- ▶ MTS 243.70 static actuators
- ▶ MTS 249.51 Swivel Heads and Swivel Bases
- ▶ MTS FlexTest II™ Digital Control Platform
- ▶ MTS 293 Hydraulic Service Manifolds

# High Force Load Frame Offerings

MTS Systems Corporation is a recognized quality supplier of High Force Testing Systems throughout the world. We have applied our expertise in designing servo controlled testing systems to develop various types of high force testing capabilities. The following materials are presented to illustrate MTS capabilities in this area and to stimulate additional ideas about your testing needs.

## Overview

In Civil Engineering applications, you may be interested in testing a wide variety of specimens, components or full scale test articles that requires a precise application of high force loads or displacements. Many tests are conducted for verification of critical designs which are directly or indirectly related to the safety and health and well being of people.

Test applications may vary from simple concrete and reinforcing steel material qualifications to full scale design verifications. With over 30 years of experience, we can recommend various configurations to most any test requirements and can deliver proven solutions in a timely manner.

## Product Offerings

MTS recommends two types of testing solutions depending on your applications.

- ▶ For laboratories primarily concerned with material verification and smaller components, a free standing, self supporting load frame concept is usually the most cost effective approach.
- ▶ For laboratories primarily concerned with large scale and component testing, a frame with an extended baseplate or one fully integrated into a strong floor is usually recommended.

We can provide either solution for most any force rating to meet your testing requirements and will explain the differences between these offerings.

## MTS 311 Series High Force Load Frames

This type of testing system is usually referred to as a universal testing machine. It is a free standing, self reacting design and may not require any special pit or custom foundations to support the loading profiles for most testing programs (i.e. the test specimen is contained within the load frame test space). For Civil

Engineering applications, MTS recommends a cross-head mounted actuator concept to simplify test set up and to reduce fixturing costs for large specimen testing. While this approach is slightly more expensive, the overall benefit to the customer is reduced fixturing costs and ease of test set up for various testing programs. This optional configuration should strongly be considered for most Civil Engineering applications.



*2,500 kN Universal Testing System  
with Crosshead Mounted Actuator.*

The following typical size frames are available from MTS. In addition, custom configurations can always be recommended for your application.

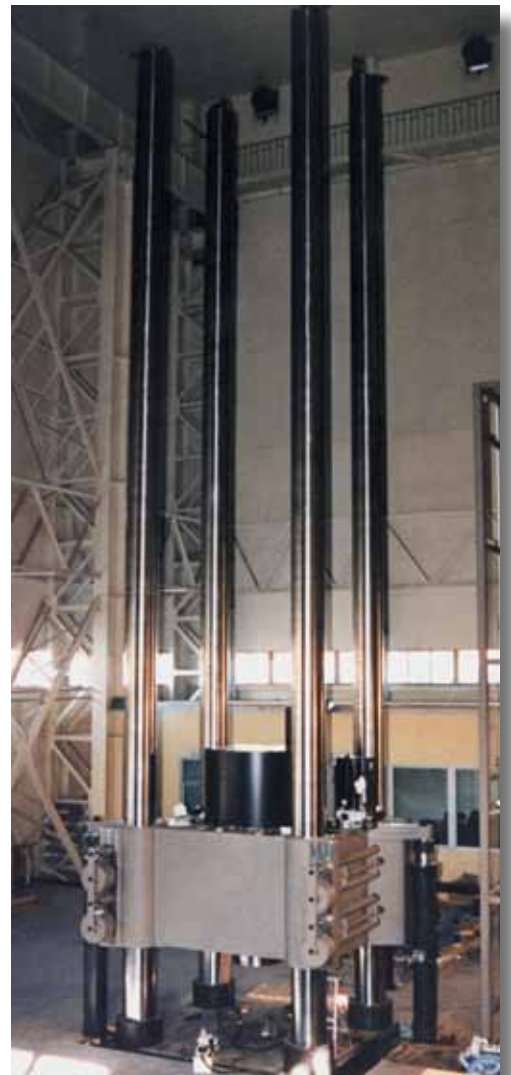
<b>Model</b>	<b>Force Capacity</b>	
311.31	1,000 kN	(100 ton)
311.41	2,500 kN	(250 tons)
311.51	5,000 kN	(500 tons)
311.71	10,000 kN	(1,000 tons)
311.72	15,000 kN	(1,500 tons)
311.81	20,000 kN	(2,000 tons)
311.91	30,000 kN	(3,000 tons)



*10,000 kN High Frequency Dynamic Testing System.*

Depending on the performance requirements, the servo control and hydraulic distribution system can be customized to meet the dynamic requirements. While many traditional high force tests are performed in a static or low frequency manner due to the large oil flow requirements, there is a significant effort to evaluate high force structures at higher frequencies and larger amplitudes due to the types of damage experienced in the Kobe earthquake in January, 1995. Current research under consideration includes velocity performance to 1 and 2 meters/second for up to 10 cycles at amplitudes up to 300 mm or larger and loads from 200 to 500 tons for some structures. These types of performance levels on civil engineering structures have never been investigated to date, so this should be a new and challenging area of future research around the world.

*20,000 kN  
High Force  
Testing  
System*





### **MTS 311S Extended Base Frame Concept**

For full scale or near full scale applications in Civil Engineering testing such as long supporting beams or highway bridge components, research is performed on very long specimens in a 3 or 4 point bending manner. While the basic mechanics of the load frame and dynamic performance are similar to the conventional 311 series, the primary difference between these two systems is the extended baseplate.

#### **► Self Reacting Base Structure**

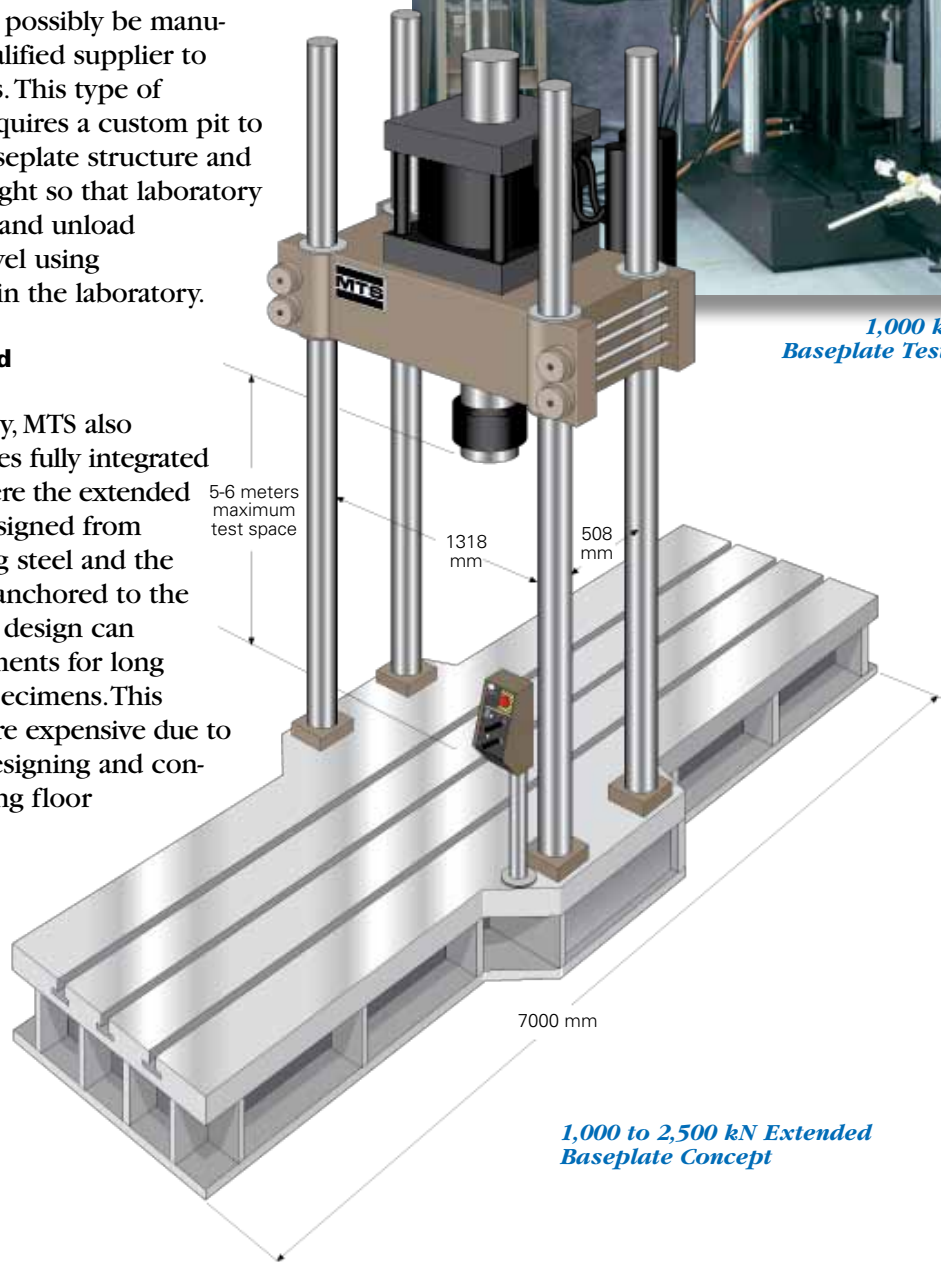
Depending on the force and moment levels, it is possible to make an extended baseplate from either a solid, cast or a steel weldment to react the bending moment. This extended base structure is usually massive and can possibly be manufactured locally by a qualified supplier to reduce the project costs. This type of configuration usually requires a custom pit to mount the extended baseplate structure and to minimize the test height so that laboratory personnel can still load and unload specimens at ground level using conventional tools within the laboratory.

#### **► Strong Floor Integrated Structure**

To expand this capability, MTS also designs and manufactures fully integrated baseplate structures where the extended baseplate test area is designed from concrete and reinforcing steel and the load frame baseplate is anchored to the concrete structure. This design can react high bending moments for long span or full scale test specimens. This concept however, is more expensive due to the additional cost of designing and constructing a complex strong floor reaction mass.

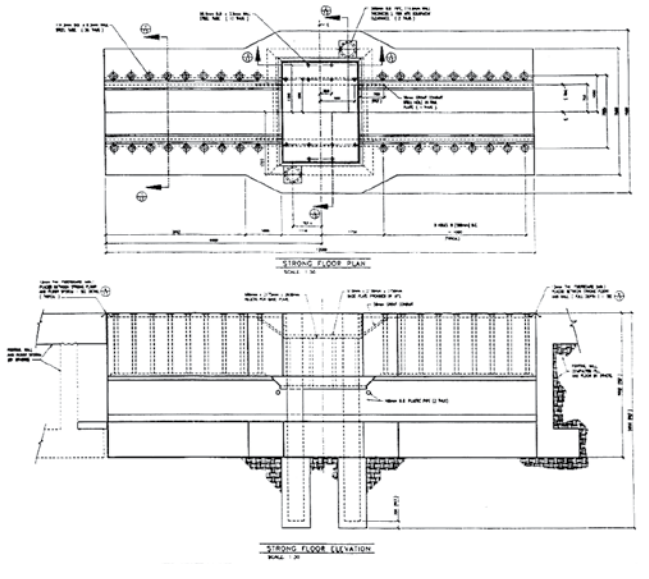


*1,000 kN T-Slotted  
Baseplate Testing System*



*1,000 to 2,500 kN Extended  
Baseplate Concept*

This brief overview shows typical capabilities that MTS Systems Corporation can offer in the area of High Force Testing. In addition to the testing systems described, MTS can also design and manufacture custom solutions to meet your demanding testing requirements for static, dynamic or high performance applications.



*Top and Section View of Strong Floor Integrated Concept*



*15,000 kN Strong Floor Integrated Design with Work Platform.*

# Servocontroller Offerings

## **Servohydraulic Controls and Automation**

MTS offers several controls platforms to provide a wide range of testing solutions. Every offering utilizes advanced electronic designs to guarantee the best testing results possible. The recommended solution for your particular application depends on many factors including testing requirements, the number of actuator channels or independent stations desired, long term laboratory planning goals, the level of automation and data acquisition needed, budget, etc. All of these factors and more are considered when MTS makes our suggestion on a hardware configuration.

## **MTS FlexTest™ SE Controller**

The FlexTest SE Basic digital controller is the most cost-effective choice for performing single-channel, single-station strength or fatigue tests components for which a simple command and a single result are all that is required. Featuring up to 3 digital universal conditioners (DUCs) and a single 2- or 3-stage valve driver, the FlexTest SE Basic model delivers real-time closed-loop control, including transducer conditioning and function generation, to support monotonic, cyclic, or simple block cyclic testing commands without computer supervision. FlexTest SE Basic model capabilities include:

- ▶ Bumpless start
- ▶ Hydraulics-on mode-switching
- ▶ Auto-zeroing
- ▶ Auto-tuning
- ▶ Saving and restoring PID settings
- ▶ On-line scope to observe signals
- ▶ Digital display of measurements
- ▶ Full-range calibrations
- ▶ Integrates with third party data acquisition and program generation

## **Automation Options**

The FlexTest SE Basic model can be outfitted from the factory or in the field with a dedicated PC running MTS 793 Software to deliver automated operation.

## **Portability and Convenience**

Lightweight FlexTest SE controllers are designed for portability, featuring a multiposition handle to facilitate easy transport to other test locations.



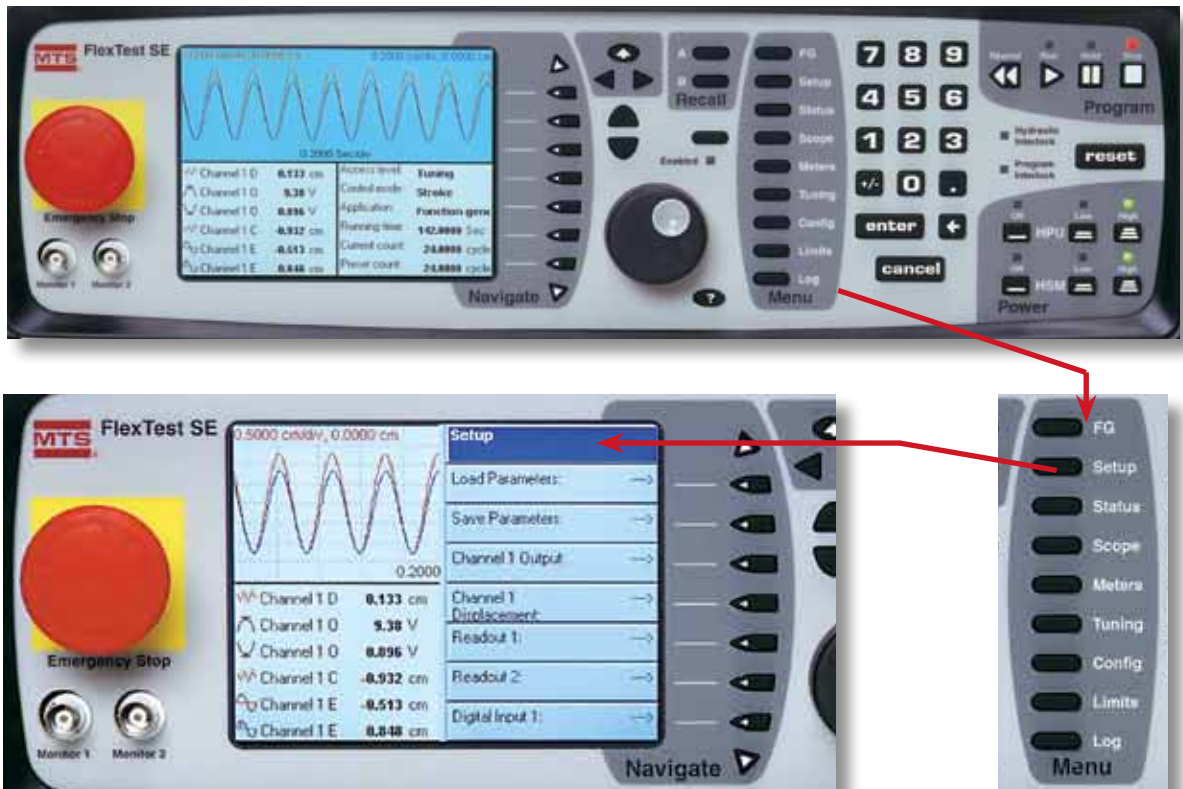
*FlexTest SE controller*



## Integral Front Panel Controls

The front panels of all FlexTest SE controllers feature integrated system controls designed to facilitate easy test setup and monitoring. This intuitive front panel combines a sharp, multi-color display with easy-to-read graphics and an array of controls including dedicated, direct-access menu keys, a keypad, HPS, HSM, program

run-stop-hold, E-stop, and a rotary adjustment knob. For the stand-alone FlexTest SE Basic, the front panel serves as the controller's main user interface. For the PC-dependent Plus and 2-Channel models, the front panel supplements the PC interface and eliminates the need for a Remote Station Control (RSC) pendant.



## Direct-Access Keys

With dedicated, direct access menu keys you have instant access to your main test control functions for setting up and running tests. Whether used as a stand-alone or with a PC, it is easy to set up and run tests. You'll spend less time setting up tests and more time testing.

## Premier Display

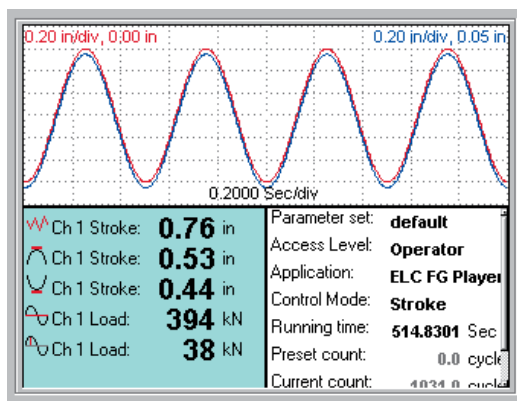
Sharp and bright graphics feature very wide viewing angles. The display is easy to see and read in all lab lighting conditions.

## Optional On-Line Scope

The optional scope features a quarter, half, or full screen view and multiple trace colors to make it easier to distinguish between signals.

## Meter Displays

- Real-time calibrated measurements and readings shown in user's choice of engineering units or volts
- Select small or large digits
- Supports up to six meters
- Select more or fewer significant digits to display for each meter
- Display timed, min-max, amplitude-mean, or peak-valley data
- Select command, compensated command, any output, any input, error, frequency, etc.



## MTS FlexTest™ GT Controller

The FlexTest™ GT control system includes the digital FlexTest™ GT Controller and a PC with FlexTest™ GT software working together as a tightly integrated system. A 100Mbit Ethernet connection links the PC and the controller, providing fast, reliable communications and data transfer. Closed-loop control is completely managed by the digital controller, which contains signal conditioning and data acquisition modules.

The FlexTest™ GT control system is a powerful and flexible system. It supports up to 8 control channels and up to 8 independent stations (tests) with no configuration constraints. A 16 channel version of FlexTest IIm™ is also available for more complicated testing requirements.

Like other MTS control and analysis products, the FlexTest™ GT controller employs the Windows XP operating system. It's easy to integrate the FlexTest™ GT control system into your organization's computer networks, and to share data with other networked equipment.

The FlexTest™ GT multi-tasking operating system allows defining new tests and analyzing results of prior and current tests while other tests are still in progress.

### Multiple PC Option

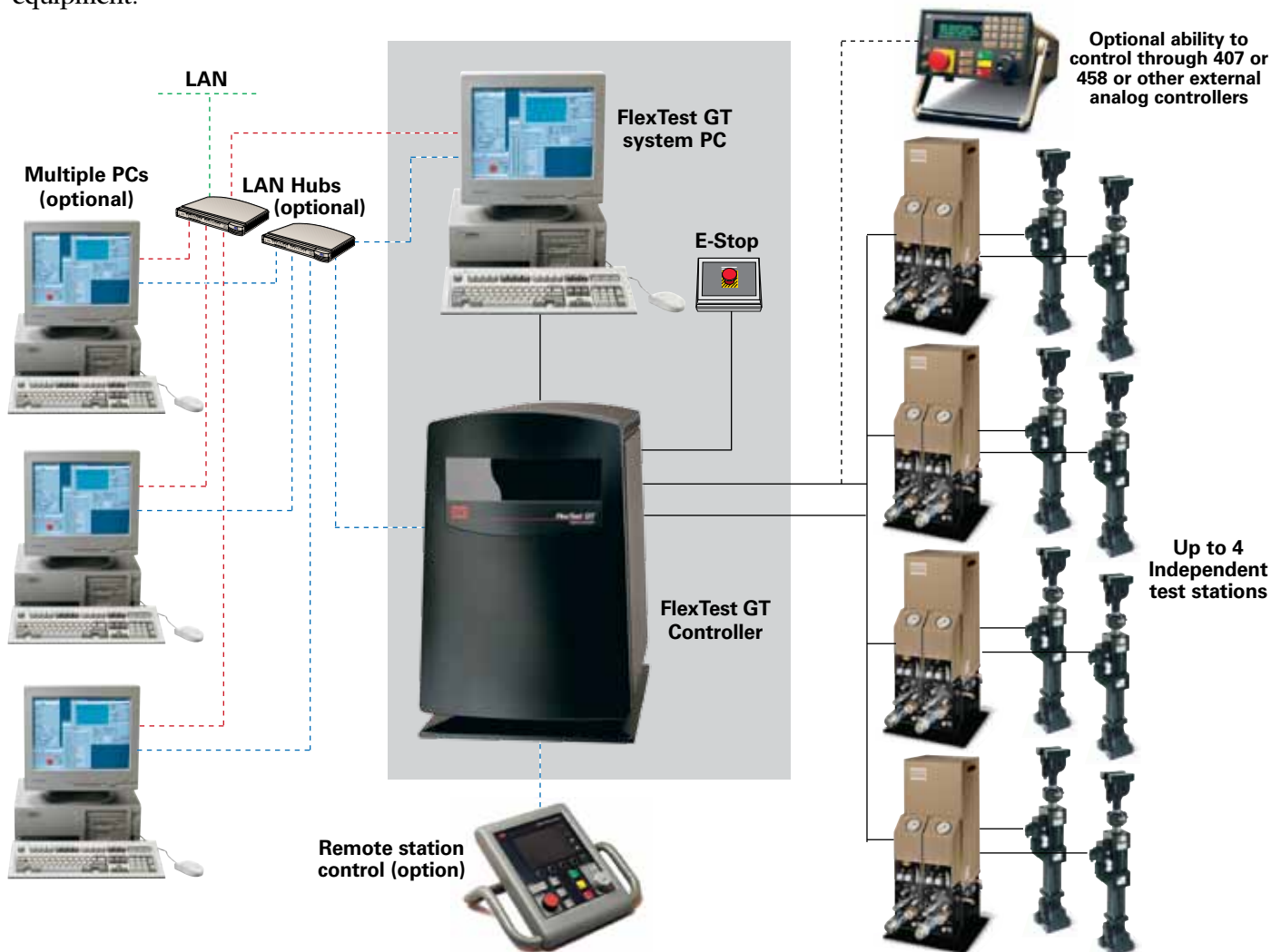
Additional PCs can be optionally provided, so multiple operators and remote test locations can be accommodated in multi-station applications.

### Remote Station Control Option

Remote Station Control with programmable display is available to simplify specimen loading, test setup in remote test location.

### Calculated Channel Option

Calculated channels is one of the new powerful features of FlexTest GT, it allows researchers to define calculations from input signals. Calculations are easy to define. Available mathematical functions include: +, -, x, /, cos, exp, ln, log, power, sin, tan, and time. It is possible to use one defined calculation in another calculation.



### **MTS TestWatch™ Option**

TestWatch™ is a new capability developed by MTS Systems Corporation. This remote monitoring software package allows you to visit your laboratory from any remote computer with dial-up connection capabilities and a Web Browser. Once connected to your network or directly to the host computer, TestWatch™ allows you to check the status of your test systems' hydraulic and program states, signal values, cycle counts, interlocks and data files. TestWatch™ software is designed to work with FlexTest™ controller.

This new testing solution is ideal for laboratories conducting long duration or overnight tests where operators would like to check on the status of the test conditions without making a special trip to the laboratory. In addition to access from home or the road, test status can be queried from other office locations within the laboratory facility allowing both the operators and program managers to watch the test progress.



*MTS TestWatch™ Software Capability*

### **Digital Transducer Options for FlexTest™ IIm**

FlexTest™ IIm allows digital transducers to be directly integrated into the servocontrol loop. This added feature enhances test applications that require high resolution displacement control or data acquisition. An example of a such a test is in the area of earthquake and seismic evaluation using the Pseudodynamic Testing method. The use of high resolution displacement information in the numerical integration algorithm helps to reduce any undesirable error propagation effects improving the results of the simulation.

MTS can provide various optional interface electronics with compatibility to MTS Tempsonics® III transducers or Heidenhein® transducers. The MTS Tempsonics® transducers utilize a magnetostrictive technology and can be purchased in various housing styles including a captive slide housing for robust testing applications. The resolution specification for the Tempsonics® transducer is 0.005 mm (0.0002 inches) which can be achieved in a structural testing environment.



*Tempsonics® Digital Displacement Transducers*



# Structural Testing Software

For Structural testing applications, MTS has developed several specific software capabilities that will allow highly specialized testing for your laboratory. An overview of some of our specific capabilities is listed below:

## Static Software

This software will allow ramp, hold and combinations of ramp and hold for static testing. It will control up to 4 actuators for TestStar II™ and up to 8 actuators for FlexTest IIm™ and each actuator ramp rate is automatically calculated so that all actuator channels will reach the defined target end level at the same time. The software

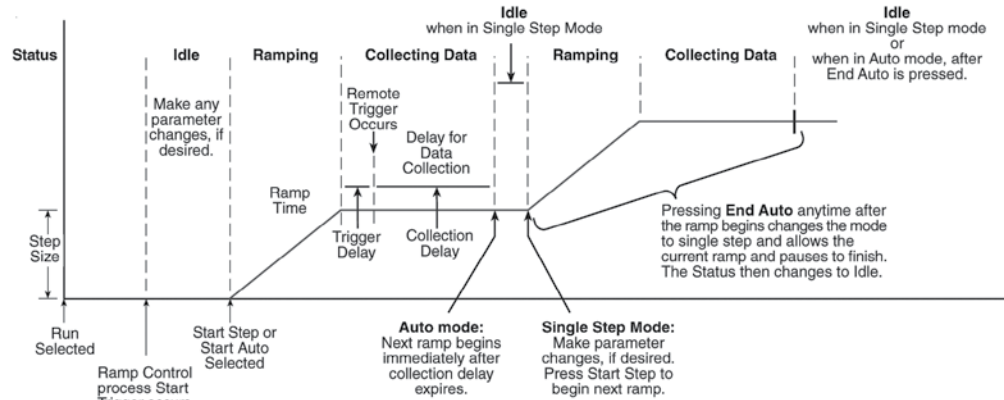
also provides triggering to non-MTS data acquisition systems using an external trigger input. All critical test information is stored in a data file including all end levels, acquired data, test comments, etc. This information can be appended on a restart condition so that a common file is established for a single test specimen.

The “Static Deflection” software allows loads or deflections to be incrementally applied to the specimen in a ramp and hold manner with data acquisition triggering. As the test is running, the operator determines what the next incremental step will be and changes the test parameters accordingly for the next incremental step. A similar test sequence is applied until test failure criteria is satisfied. The above sketch illustrates the general needs for such a test.

To simplify this testing methodology, MTS has created a testing “Process” under the general application program. This “Process” includes a run-time control editing template with the ability to stop and restart the test at any time or to change the control mode of the actuator from load to displacement as required. While the incremental ramps are applied, ultimate target values are monitored to put the test into hold should they be reached. The template also features a manual mode for individual operator input or an automatic mode to allow repeat steps without manual intervention. To allow static data acquisition of non-MTS supplied devices such as data

loggers, there is a programmable trigger available during each hold cycle for data collection. Additionally, a trigger pulse can be executed at any time to initiate a single scan data collection on those same devices.

To help record potential test conditions as they



occur or changes to specific end levels, ramp rates or target values, a comment section allows manual entry of “text” which is stored to the data file on each ramp/hold update. See the example template for an idea of the simple operator interface for “Static Deflection” testing.

To assist the researcher in understanding how well the test is proceeding and to help determine the next step conditions, up to 4 real time plots can be displayed simultaneously. These plots are active throughout the “Static Deflection” step process.

# Pseudodynamic Testing

## Pseudodynamic Test Method

To survive from severe earthquakes without collapse, structures are usually designed to deform inelastically. Critical structural component with good energy dissipation is crucial for seismic performance.

Evaluation of seismic performance is difficult by analytical method due to the complex inelastic behavior exhibited by most structures and components under seismic loading conditions. Experimental testing is commonly used for evaluating the inelastic seismic performance of structures.

The pseudodynamic test method is an experimental technique for evaluating the seismic performance of structural models in a laboratory by means of on-line computer control simulation. Using the right test equipment, it is reliable, economic and efficient method for evaluation of large scale structure that are too large or too heavy to be tested by shaking table.

The pseudodynamic test method(1) combines well-established analytical techniques in structural dynamics with experimental testing. A test structure must be first idealized as a discrete-parameter system, so that the equations of motion for the system can be represented by second-order ordinary differential equations. Based on analytically prescribed inertial and viscous damping characteristics of the system, as well as on structural restoring forces directly measured during the test, the governing equation of motion for the test specimen can be solved by a step-by-step numerical integration method. The displacement response computed, based on a specific earthquake excitation record, is then imposed on the test structure by means of electro-hydraulic actuators. Thus, the quasi-statically imposed displacements of the test structure will resemble those that would be developed if the structure were test dynamically.

Reference:

1. Pui-Shum B. Shing, Stephen A. Mahin "Pseudodynamic test method for seismic performance evaluation: theory and implementation." 1984

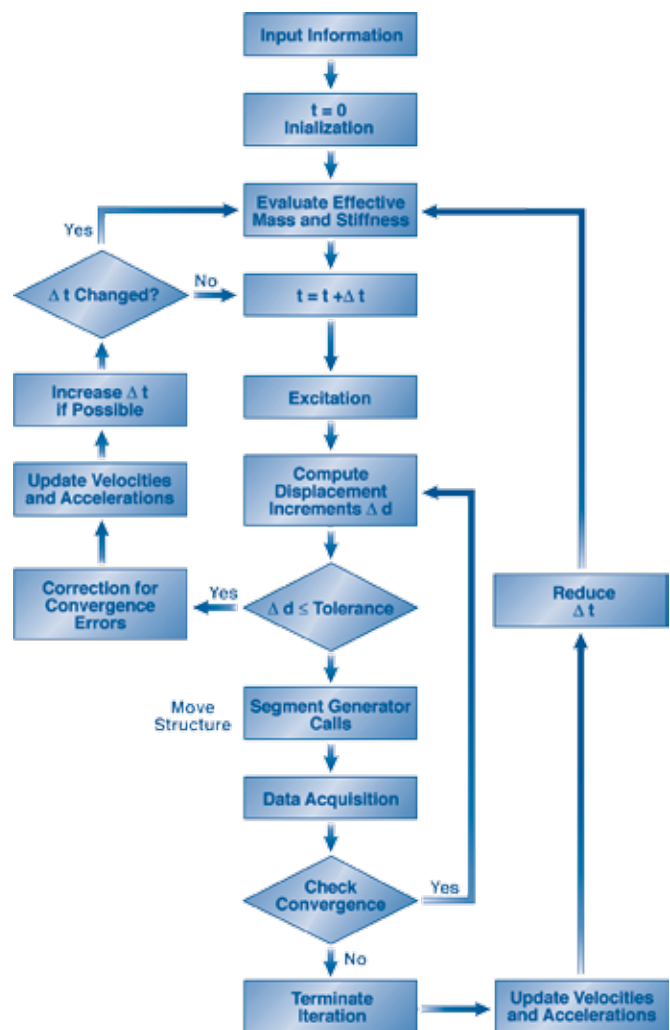
## Pseudodynamic Software

MTS has developed a Pseudodynamic Program in cooperation with the University of Colorado under the direction of Dr. Benson Shing. Dr. Shing is a recognized expert in this area of research. The program utilizes the Alpha method of Hilber, Hughes and Taylor for time

integration. A variable time stepping strategy has also been incorporated to assure robust convergence for structures with severe strain softening behavior.

Some of the key features of the program include:

- Advanced algorithms employed for numerical integration.
- Program is written in C++ and includes the source code to allow customer changes or modifications.
- Real time graphics to monitor the test as it develops.
- Ability to re-create earthquake ground records or to use sinusoidal inputs.
- The ability to put a test in hold and restart as desired.
- Test output file stored in comma delimited format for future analysis by spreadsheet software such as Excel®.



Flowchart of Test Sequence

An overview of the program is included below:

### **Introduction**

The pseudodynamic testing program is written using Borland C++ for Windows NT. The program includes source code if the customer desires to make changes and the program is written such that the numerical integration methods are subroutines to allow program changes in a more straight forward manner.

### **Graphics**

Up to four graphics windows can be opened at the same time, and each window can display up to two curves. Windows can be resized and replaced any time during a test. The user will be prompted to enter the numbers of those channels whose readings are to be displayed in the graphs and to define the axes during data input. After each converged step, readings from the selected channels are plotted.

### **Test Execution**

The user is prompted to enter:

- a. The specimen characteristics, i.e. the number of degrees of freedom, the initial stiffness [kN/mm], mass [ $10^6$  kg] and damping matrices [kN sec/mm]. For example, a mass of 10000 kg should be entered as 0.01.
- b. The integration parameters, namely, the value of time interval [sec], the minimal time interval for variable time steps [sec], the parameter QL for the divergence check [rad/sec], the convergence tolerance for each DOF [mm], and the total time span for dynamic simulation [sec].
- c. The excitation type and the characteristics of the excitation. For sinusoidal functions, one needs to specify the amplitude [mm/sec], frequency [rad/sec], and duration of the excitation [sec]. For earthquake ground motions, one needs to specify the name of the file in which the record is stored, the number of data points in the record, the time interval with which the data is recorded [sec], and the amplification factor for the ground motion. A ground motion data file contains two columns. First for digitized ground acceleration readings and second for the number of the reading.
- d. The initial conditions, which can be one of the following:
  - The 'zero' starting position, which refers to zero initial displacements and velocities.
  - The 'non-zero' starting position, for which the program asks the user to enter the values

of initial displacements [mm] and velocities [mm/sec]. When the test starts, the program sends commands to the actuators so that the initial displacements are imposed on the structure.

- Restarting a test, which will be explained later in the section.
- e. The information related to the control or data acquisition channels. The user has to specify the control channel for each degree of freedom. Since the displacement and restoring force for each DOF are needed by the program for computation, the channels acquiring these readings need to be specified. Internally, the controllers assume SI units, so measured forces and displacements are in [kN] and [mm]. The maximum actuator velocity has to be specified [mm/s]. The actuator which has the largest displacement increment will assume the maximum velocity. The velocities of the other actuators are adjusted accordingly so that they will reach the targeted displacements at the same moment. The user also needs to specify if an external data acquisition system will be used and how long the program needs to wait for that acquisition system to perform the required operation [sec].
  - f. The name for the output file. The length of the name is limited to seven characters. The name entered will be used for four files that are created during the test. These files will have different extensions.
    - The "Zero" file contains the zero (offset) readings of all channels. The extension for this file is "zer".
    - The "Output" data file contains readings from all channels acquired during the test, as well as the velocity, acceleration, and the corrected displacement and restoring force for each DOF at the end of a time step. Data is written in columns so that readings from one channel are grouped in one column. The first column contains the time and the subsequent columns contain the measured data. These are followed by the columns containing the corrected displacement and restoring force, and the computed acceleration and velocity for each DOF. The data is identified by column headers. The extension for this file is "out".
    - The "Error" file contains the time, the number of iterations and the convergence errors at each step. The extension for this file is "err".
    - The "Input" file is created during the interactive input, and is used to repeat the same test without going through the interactive input again, as well as to run a new test. The extension for this file is "inp".



- g. The plotting information. The user is prompted to enter the number of plots, the channel numbers whose readings are to be plotted and to define the axes.

When all the information is entered and the graphic windows are opened, the test can start. A test can be started only when the text input window is closed.

### **Interrupting a Test**

The user can stop a test any time. Pressing the Hold button during a test will hold the actuators and the test will pause. Execution is resumed by pressing the Run/Resume button.

### **Interrupting a Test**

A prematurely terminated test can be restarted by the restart option when the program is called. The user will be urged to enter the new output file name, the initial displacements, velocities, accelerations, and restoring forces (these are the values at the last time step stored in the output file of an interrupted run). The user will then be prompted to enter the time of the last time step completed in the interrupted run and the name of the zero file for the interrupted run. The actuators will impose the specified displacements on the specimen. The channel readings are stored in the new output file. The restart option can not be used if the test had a non-zero starting position.

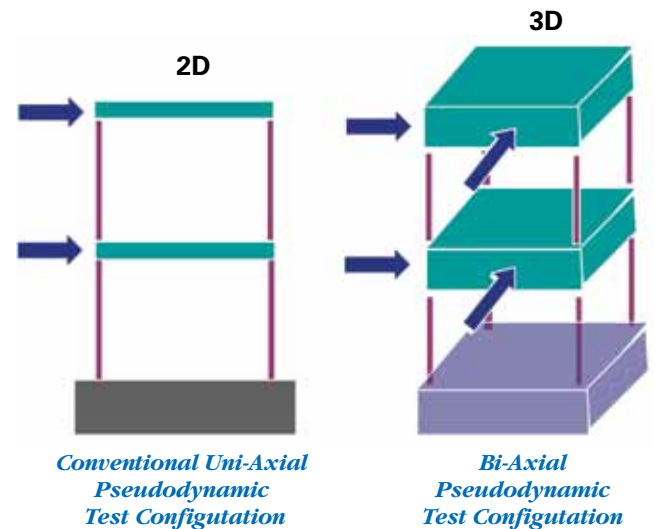
### **Data Reduction**

Output files are written in a format which can be used by Microsoft Excel. A comma is used as the column delimiter.

### **Bi-Axial Pseudodynamic Software**

Currently, MTS is in the process of documenting Bi-Axial Pseudodynamic Testing Capabilities. Under a cooperative program with the National Center for Research in Earthquake Engineering in Taiwan, the conventional pseudodynamic program that MTS has distributed in the past has been expanded to include Bi-Axial testing which allows for multi-axis testing configuration in orthogonal directions. This capability will again allow users the flexibility to enter in new areas of research by considering multi-axis loading conditions. The program is again written in C++ and the source code will be provided so that users can make changes as required for their specific testing programs.

**Why is Bi-Axial Pseudodynamic Testing Required?**  
Looking at the below diagram, typical loading directions are shown for the respective testing applications. The current Pseudodynamic program allows testing in 2D geometry which can be used for simplified testing capabilities in one direction of ground motion. Fundamental research is possible using such methods. An extension now to 3D geometry was the next step to developing a closer approximation to real physical structures. With 3D modeling capabilities, X-Y seismic effects can be analyzed on specimens such as building floor/column structures or building/wall element structures. In bridge research, rigid decks on flexible pier columns can be more accurately modeled also.



MTS recently began promoting the Bi-Axial Pseudodynamic Applications and there is worldwide interest in this technique.

The Bi-axial Pseudodynamic technique is proposed for the testing of structures under two lateral perpendicular seismic excitations in this study. This technique consists of two major features. One is to manipulate large rigid body translations and rotation precisely, and the other is to update the restoring forces and torque experienced by the rigid specimen with respect to its moved configuration. These two features are achieved through a well-formulated scheme for configuration mapping, which takes into consideration the analytical geometrical relationships among the rigid specimen, the actuators and the reaction frames. The rigid body motion of the specimen can therefore be determined accurately from actuator lengths, and vice versa. As a consequence, the geometrically induced nonlinearity due to large rigid body motion in such

kind of testing can be fully eliminated. Verification tests of: (1) a symmetric specimen under uni-axial seismic excitation; (2) a mass-eccentric and stiffness-symmetric specimen under bi-axial seismic excitation have both been conducted. Satisfactory experimental results fully support the feasibility of the proposed Bi-axial Pseudodynamic technique as a powerful vehicle for future research on seismic performances of large scale three-dimensional structures.



A recent paper was presented at the 2000 World Conference on Earthquake Engineering in New Zealand that discusses the Bi-Axial capabilities and the testing program that was completed for Bi-Axial Pseudodynamic Capabilities at NCEE.

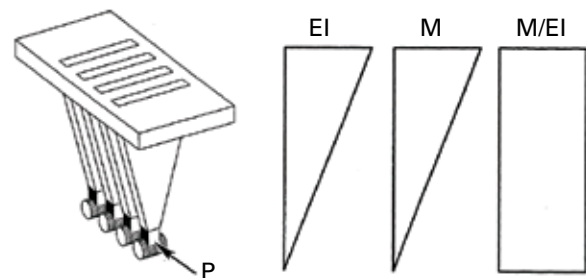
### **Substructure Pseudodynamic Software Package**

Substructuring technique of Pseudodynamic test combines a physical test assembly with an analytical sub-assembly to simulate the seismic response of the complete system. The technique is primarily used for economic reason to test only a portion of a complete structure and model the remaining part analytically.

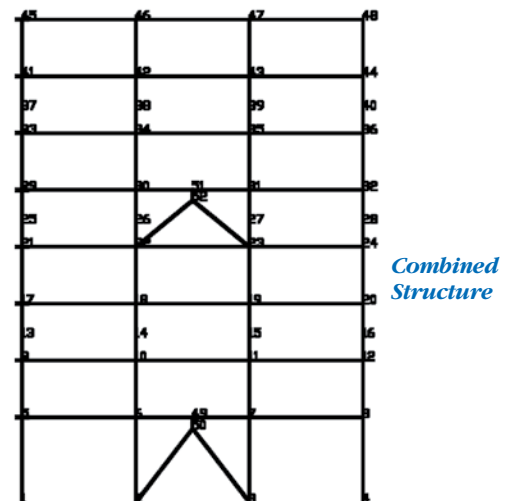
In the substructure technique, the displacements that are imposed on the test structure, would be obtained by solving the equation of motion of the combined system, where the restoring force characteristics of the portion that is not subjected to experimental testing, are provided by mathematical models.



*Substructure Pseudodynamic Test of TADAS device at NCEE*



*Triangular Plate added Damping and Stiffness TADAS device*



*Combined Structure*



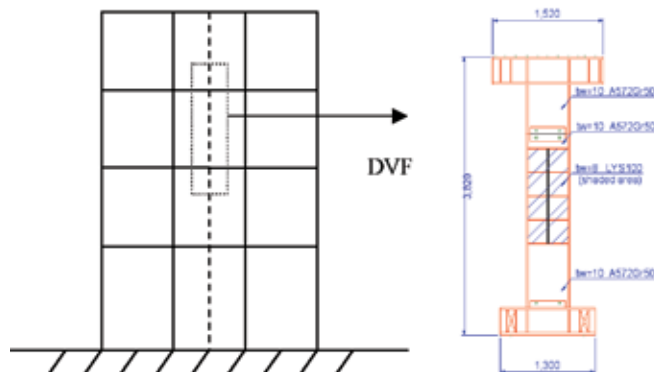
Application includes evaluation of effects of supporting soil and foundation by modeling the soil structure while the structural specimen (such as bridge column) is physically tested. Study of dynamics response of components or equipment mounted on structures can also be benefited with the substructuring method.

Drain 2D+ program, the modeling software, is a non-linear 2D finite element analysis program. It applies Bilinear Model to simulate nonlinear behavior of structural elements. The program is modified to work with MTS pseudodynamic program and control electronic for substructuring pseudodynamic test.

Under a cooperative program with the National Center for Research in Earthquake Engineering (NCREE) in Taiwan, MTS will soon be offering a software package for the substructure pseudodynamic test.



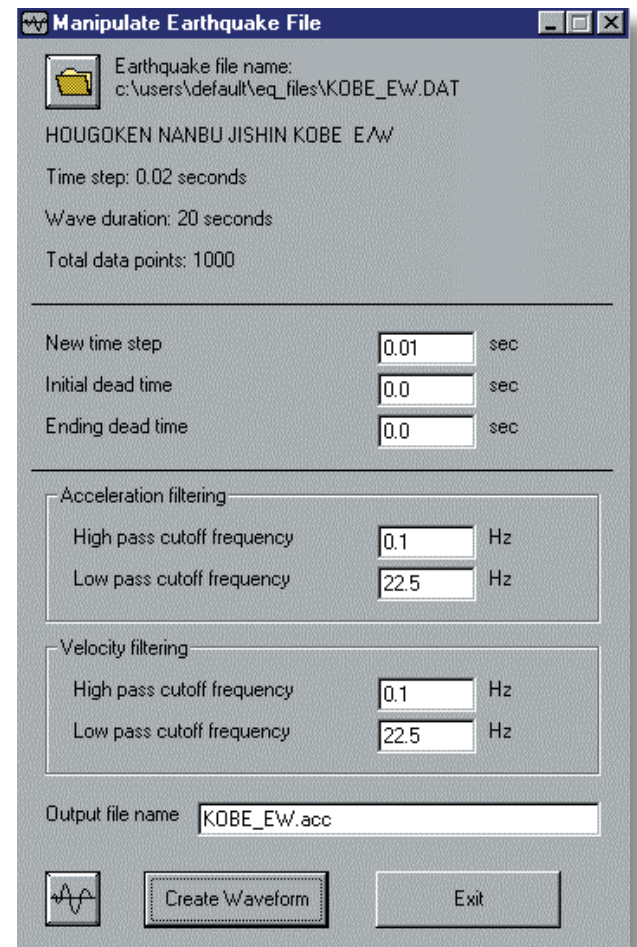
*Substructural Pseudodynamic Test of DVF at NCREE*



*MRF with Ductile Vierendeel Frame (DVF)*

## **Waveform Generation Software**

MTS offers a software package capable of generating waveforms for testing structural components for seismic studies. The Waveform Generation software provides two main capabilities. The first is the ability to generate data points based on user inputs for sine, square or random waveshapes and the second is to manipulate existing earthquake acceleration files using interpolation, filtering and integration to achieve the desired displacement drive file.



*Example of Input Window for Sine Sweep File creation*

## **Data Point Generation**

Data points are generated using a designated time step and number of channels. With user specified parameters, a sine sweep, cyclic waveform or random waveform can be generated.

- ▶ The sine sweep is defined using a start frequency, ending frequency, sweep rate (linear or log), and an initial dead time. This function also allows the amplitude to be proportional to the frequency.
- ▶ The cyclic waveform is defined using a dwell frequency, number of cycles and an initial dead time.



The waveform can be repeated multiple times with a defined dead time between each pass.

- ▶ The random waveform is defined using frequency amplitude pairs. The spectral shape from the frequency-amplitude pairs is used to shape the random white noise.

### Earthquake Acceleration File Conditioning

Using a supplied earthquake acceleration file, the user first can define a new time step, initial dead time and ending dead time if desired. Next, the high pass and low pass cutoff frequencies are defined. After any adjustments for a new time step, initial dead time and ending dead time, the acceleration file is filtered and integrated to produce the velocity values. Finally the velocity values are filtered and integrated to produce displacement values. The velocity and displacement values are written to separate files.

Note, the waveform generation software requires a commercially available software package from Exceed Software for complete functionality.

### Dynamic and General Purpose Software

MTS includes, a flexible general purpose control and function generation software package with our digital control systems. For FlexTest™, up to 16 channels of control are possible. All load and stroke data can be acquired and saved to a data file for future evaluation. In addition, an oscilloscope and real time plotting packages are included to allow presentation of data as it is acquired. All load and stroke data can simultaneously be sent to a static or dynamic 3rd party data acquisition system so that a common file can be established on the high channel count DAQ package. In addition to traditional waveshapes such as Haversine, Ramp and Step functions, an assortment of other processes are available to allow custom waveshapes of combined loading patterns of most any configuration. The software also includes a File Playback capability that allows ASCII Text files to be played back as the function generation signal for re-creation of such complex waveshapes as seismic records. The same software package also fully integrates MTS data acquisition commands, Digital I/O commands, Analog I/O command, etc all from the same Test Generation Window.

The screenshot shows the 'Sine Waveforms' window with the following settings:

- Sine option:** ☒ Sine sweep, ☐ Sine dwell, ☐ Sine beat
- Initial frequency:** 0.2 Hz
- Final frequency:** 2.2 Hz
- Sweep rate:** 8.0 Hz/min
- Frequency to define amplitude:** 0.2 Hz
- Dead time between passes:** 0.0 sec
- Number of passes:** 1
- Initial dead time:** 0.0 sec
- Sweep type:** ☒ Linear, ☐ Log
- Amplitude proportion:** ☒ constant, ☐ 1/f, ☐ 1/f<sup>2</sup>
- Channel 1:** Phase (deg) 0.0, Amplitude 4.87, DC Offset 0.0
- Channel 2:** Phase (deg) 0.0, Amplitude 2.33, DC Offset 0.0
- Filtering and integration passes:** ☒ None, ☐ 1, ☐ 2
- Output file name:** sweep1.drv
- Buttons:** Create Waveform, Exit

Example of Input Window for Earthquake File Manipulation

# SilentFlo Hydraulic Power Unit

MTS has designed and manufactured hydraulic power units for thirty years. In that time we have gained a reputation for incredible durability, quality and performance. It is from that foundation that we are pleased to introduce the next generation of MTS power units, namely the SilentFlo line. The SilentFlo line carries a range of flow rates from 7 gpm(26 lpm) to 180 gpm (675lpm).

The SilentFlo line is so quiet and so clean you can put it directly in your laboratory rather than in a noisy, dirty pump room. MTS has developed a new design that reduces the noise level to 70 db(A) fully compensated and eliminated oil leaks. How did we do it? By using a special liquid cooled motor immersed in the oil reservoir, by mounting other key components within the oil reservoir, and by packaging the integrated system in a carefully designed enclosure with sound-absorbing materials and treatments.

## **Some of the SilentFlo Advantages:**

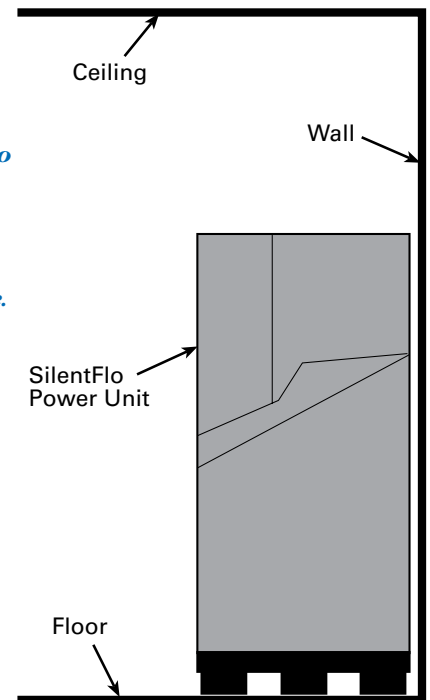
### **Pump Room Is Not Required.**

The SilentFlo units can be placed almost anywhere inside a building, eliminating the need for a costly pump room.



*The SilentFlo Hydraulic Power Units Flow rates from 30 to 180 gallons/minute(114 to 684 lpm) at 3000 psi\**

*The "WallHugger" design allows you to place the SilentFlo power unit directly against the back wall, thus saving valuable floorspace.*



### **Less Costly Floor Space**

The SilentFlo units can be placed close to the wall where is typically not as valuable as open, unrestricted space.

### **Reduced Hard Line Cost**

When you can strategically locate your power unit, you may significantly reduce hard line/distribution costs.

### **Eliminate Ventilation Cost**

The SilentFlo gives off almost no heat to the room in which it is located. Due to extensive insulation, heat is contained. Since no ventilation is necessary to cool the liquid cooled motor, expensive ventilation fans and ducting are not necessary.

### **Facility Flexibility**

The SilentFlo offers customers long range flexibility. With previous systems, once a hydraulic system is put in place it is generally fixed for the next 20-30 years. The cost of pump rooms, hardline distribution systems and ventilation systems makes relocation a very costly exercise. To relocate a SilentFlo unit all you need to do is provide electrical power and cooling water.

### **Built-In Electrical Disconnect**

The SilentFlo units have the main power disconnect built into the main electrical panel. You only need to have power run to the electrical box.

# Specifications

	<b>505.30 60 Hz</b>	<b>505.30 50 Hz</b>	<b>505.60 60 Hz</b>	<b>505.60 50 Hz</b>	<b>505.90 60 Hz</b>	<b>505.90 50 Hz</b>
Operating Pressure	210bar/3000 psi	210bar/3000 psi	210bar/3000 psi	210bar/3000 psi	210bar/3000 psi	210bar/3000 psi
Flow Rates per minute	113L/30gpm	100L/26gpm	227L/60gpm	200L/53.2gpm	340.5L/90gpm	300L/80gpm
Reservoir capacity(max)	341L/90Gal	341L/90Gal	950L/250.1Gal	950L/250.1Gal	950L/250.1Gal	950L/250.1Gal
Standard (return) filtration	3 micron	3 micron	3 micron	3 micron	3 micron	3 micron
Noise level (1m/3ft)*****	63 db(A)	63 db(A)	68 db(A)	68 db(A)	68 db(A)	68 db(A)
Width	86.4cm /34 in	86.4cm /34 in	104cm / 41 in	104cm / 41 in	104cm / 41 in	104cm / 41 in
Height	137cm / 54in	137cm / 54in	199.5cm / 78.5in	199.5cm / 78.5in	199.5cm / 78.5in	199.5cm / 78.5in
Length	157.5cm / 62in	157.5cm / 62in	287cm / 113in	287cm / 113in	287cm / 113in	287cm / 113in
Weight with max oil	863Kg/1,900lbs	863Kg/1,900lbs	1,907Kg/4,200lbs	1,907Kg/4,200lbs	2,134Kg/4,700lbs	2,134Kg/4,700lbs
Max. ambient oper. Temp.	40C/104F	40C/104F	40C/104F	40C/104F	40C/104F	40C/104F
Min. ambient oper. Temp.	5C/40F	5C/40F	5C/40F	5C/40F	5C/40F	5C/40F

	<b>505.120 60 Hz</b>	<b>505.120 50 Hz</b>	<b>505.150 60 Hz</b>	<b>505.150 50 Hz</b>	<b>505.180 60 Hz</b>	<b>505.180 50 Hz</b>
Operating Pressure	210bar/3000 psi	210bar/3000 psi	210bar/3000 psi	210bar/3000 psi	210bar/3000 psi	210bar/3000 psi
Flow Rates per minute	454L/120gpm	400L/106.4gpm	567.5L/150gpm	500L/133gpm	681L/180gpm	600L/160gpm
Reservoir capacity(max)	1,893L/500Gal	1,893L/500Gal	1,893L/500Gal	1,893L/500Gal	1,893L/500Gal	1,893L/500Gal
Standard (return) filtration	3 micron	3 micron	3 micron	3 micron	3 micron	3 micron
Noise level (1m/3ft)*****	68 db(A)	68 db(A)	69 db(A)	69 db(A)	70 db(A)	70 db(A)
Width	104cm / 41 in	104cm / 41 in	104cm / 41 in	104cm / 41 in	104cm / 41 in	104cm / 41 in
Height	199.5cm / 78.5in	199.5cm / 78.5in	199.5cm / 78.5in	199.5cm / 78.5in	199.5cm / 78.5in	199.5cm / 78.5in
Length	457cm / 180in	457cm / 180in	457cm / 180in	457cm / 180in	457cm / 180in	457cm / 180in
Weight with max oil	2,338Kg/5,150lbs	2,338Kg/5,150lbs	2,542Kg/5,600lbs	2,542Kg/5,600lbs	2,747Kg/6,050lbs	2,747Kg/6,050lbs
Max. ambient oper. Temp.	40C/104F	40C/104F	40C/104F	40C/104F	40C/104F	40C/104F
Min. ambient oper. Temp.	5C/40F	5C/40F	5C/40F	5C/40F	5C/40F	5C/40F

\*\*\*\*\*Sound pressure level (db(A)) is expressed as a free filed value. Readings may vary with the acoustic environment.



# Hydraulic Hardline and Distribution Capabilities

MTS can offer 30 years of experience as a supplier of hydraulic equipment to conceptualize, engineer, fabricate and install complete hydraulic distribution systems. With our large installed base of servohydraulic equipment, MTS has developed in-house expertise to design hardline systems ranging from very simple piping to very complicated networking distributions.

For a typical Structural Testing laboratory, the hydraulic requirements can vary considerably, but are usually on the order of 300 LPM to 1200 LPM of flow depending on the size and the charter of the laboratory. The types of testing programs will greatly influence the sizing of the distribution network.

MTS tries to work closely with our customers during the conceptual stage to determine both the immediate needs and the potential future requirements. We typically make our final recommendation based on performance requirements, anticipated needs and current budgets.

Items that are considered when designing a hardline system:

- ▶ Facility issues.
- ▶ Total length of the main circuit and any branch lines.
- ▶ Pressure drops that will occur reducing performance levels.
- ▶ Stainless steel tubing or piping routing to compliment the design of the building.

- ▶ Hydraulic outlet requirements.
- ▶ Hydraulic accumulation requirements.
- ▶ Hydraulic power supply location and electric sizing.
- ▶ Hydraulic oil cooling requirements and sizing for either air/oil or water cooling systems if required by the customer.
- ▶ Hydraulic cleanliness of the oil system for maximum performance.

For flows up to 600 LPM, MTS normally recommends 2 inch (50 mm) stainless steel tubing. We typically engineer the system, manufacture most major lengths of piping and complex shapes and then perform the final checkout at the Minneapolis factory. In many cases, the systems are pre-cleaned and flushed and verified for complete operation before being shipped for on-site installation.

Standard stainless steel tubing sizes are 0.75 inch, 1 inch, 1.25 inch, 1.5 inch and 2.0 inch and are determined by MTS to give optimum price/performance both now and in the future.

For flows in excess of 600 LPM, MTS recommends steel piping that is carefully sized around minimum oil velocity to prevent cavitation. Our standard steel pipe sizes are 2.5 inch, 3.0 inch, 6.0 inch and custom sizes depending on flow requirements. The following chart is representative of the tubing or pipe size that MTS may likely recommend.



*The following photographs show examples of completed hardline systems as manufactured and pressure tested at the factory. These piping systems are easily installed at the customer site and allow quick installation.*

**Hardline Piping System**





*Hardline Systems*



## Reaction Floor, Reaction Walls and Portal Frames

Depending on the testing requirements of the laboratory, the facility needs will vary from laboratory to laboratory. Most large scale structural testing facilities will consist of some type of strong floor and strong wall reaction mass with a variety of portal frame components to act as secondary reaction frames for custom test configurations. The size and shape of these facilities are typically determined by the testing charter of the laboratory. For smaller scale structural testing laboratories a lower capacity strong floor or reaction bedplate is often used with portable reaction walls anchored to the bedplate.

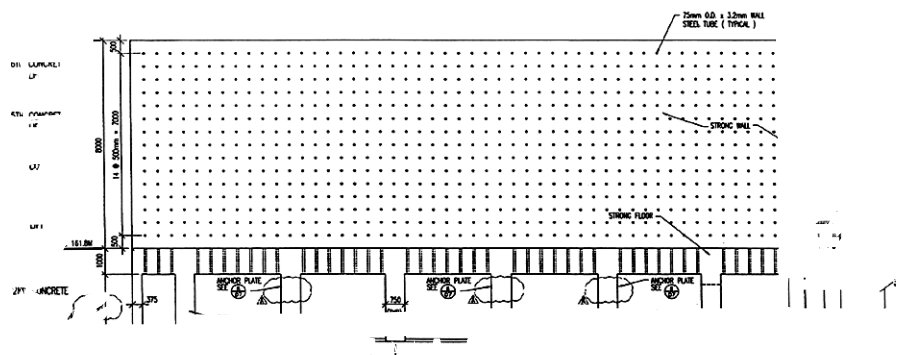
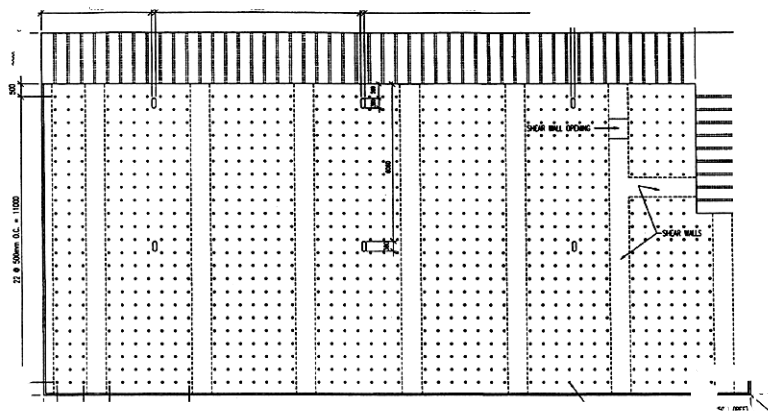
MTS can assist you in various ways during the planning stages of a new facility or modifications to an existing building depending on the level of support that you require. We can provide simple recommendations based on our experience and the success of other laboratories doing similar types of tests or we can perform design contract studies to help conceptualize the entire project. In addition to early planning or design contract studies, MTS can provide the detailed design and documentation by a registered architectural engineering firm familiar with these types of facilities so that you can have the building constructed with your local contractor. We can assist you throughout the project from the beginning to the end.

MTS can provide services and equipment to support either approach. To give a brief overview of the different types of facilities the following information is provided.

### Large Scale Testing Laboratory

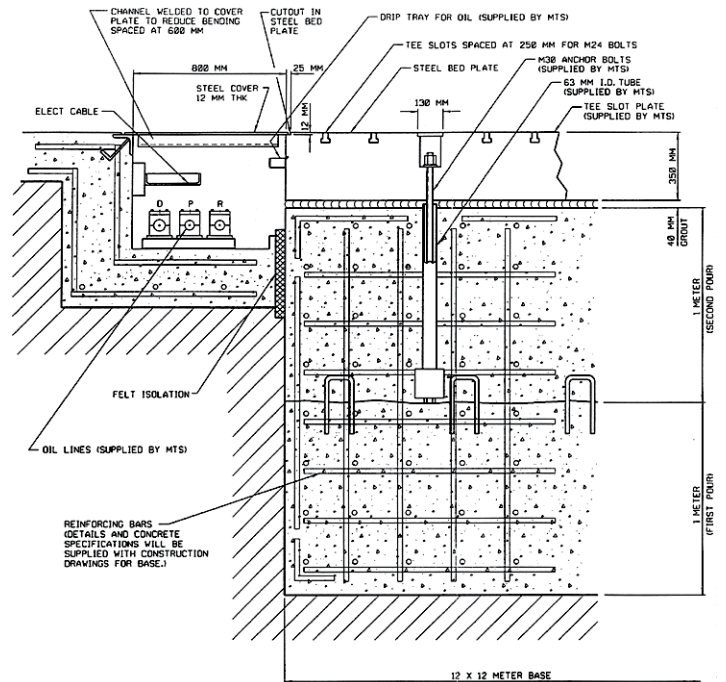
To simulate failures of full scale structures or large components as applied to Civil and Architectural Engineering applications a flexible testing laboratory is required. Such a facility usually consists of a large building designed to react high force loads for both

static and dynamic testing. The building usually consists of a strong floor and strong wall reaction mass designed as an integrated structure. The strong floor is usually fabricated from reinforced concrete and is constructed as a box beam design to allow access to both the top and bottom work surface of the floor. The floor and wall usually include an anchoring system which allows concentrated loads ranging from 100 to 150 tons per anchor point. The grid is typically on a 0.5 meter or 1.0 meter spacing to allow flexibility in designing fixturing and specimens. The floor is usually between 1 and 2 meters thick to react these types of loads. The strong wall can be a similar design, but is typically a solid reaction mass and is often post tensioned to prevent small scale cracking and to allow higher moment design loads. The following illustration is representative of the design of such a facility. MTS provided the detailed design through ESI, a local architectural firm, for the design of the strong floor and strong wall for the project illustrated.



### **Smaller Scale Testing Laboratory**

For laboratories that do not require full scale testing capabilities or for those that require a higher precision work surface compared to a concrete floor, a steel bedplate design is available. While such a solution still requires building integration planning, the building interface issues are more straight forward. This type of solution may not be a lower cost when compared to concrete construction, depending on the size of the work area. This solution is more typical for a component testing laboratory. The working loads for smaller components are usually from 10 to 50 tons per actuator and flexibility is gained with a T-slotted bedplate construction to simplify fixturing. Portable strong walls are also fabricated from cast or welded reaction structures which can be bolted to the bedplate as required. Portal frames are also used with this type of solution to provide a primary reaction element to react loads into the bedplate. The example drawing shows the type of foundation required for a large bedplate that was approximately 12 meters x 12 meters in size. The foundation consisted of a 2 meter thick reinforced concrete mass in which the bedplate was anchored. As can be seen from the sketch, the hydraulic distribution system was carefully integrated in trenches along the outside edges of the bedplate.



*Example of foundation required for a large bedplate*



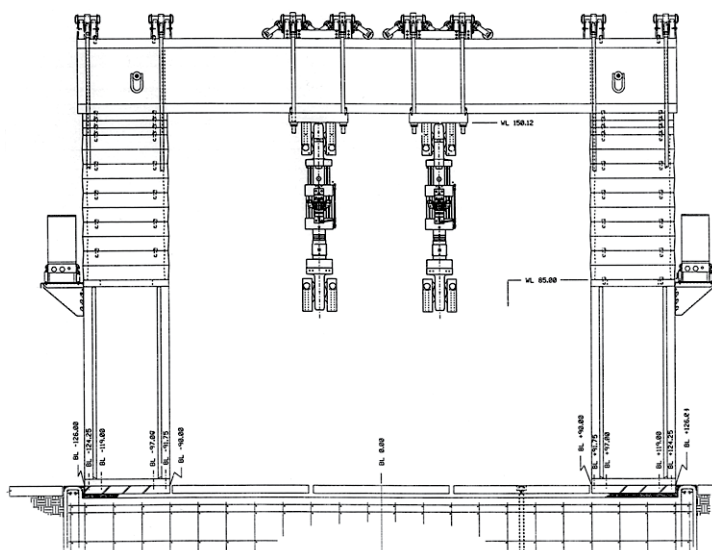
*Integrated 12 x 12 meter bedplate with portable reaction*

## Portal Load Frames

MTS can provide two types of portal frames depending on your testing requirements. We manufacture a high stiffness design used for high performance dynamic testing and a conventional universal style that can be flexibly constructed for most any configuration.

## High Stiffness Design

The portal frame shown in this photograph is rated for either two 50 ton actuators equally spaced across the span or one 150 ton actuator spaced at the center of the span. The maximum frame deflection at 150 tons is approximately 1.5 mm. This frame is ideal for higher frequency testing applications. The frame can support up to 30 tons side load at a height up to 2 meters. The horizontal test space is approximately 3.5 meters and the vertical test space can be adjusted according to test requirements within the operating range. All adjustments are performed manually and an overhead crane is required to lift the horizontal girder into the proper position.



### Portal Frame Assembly

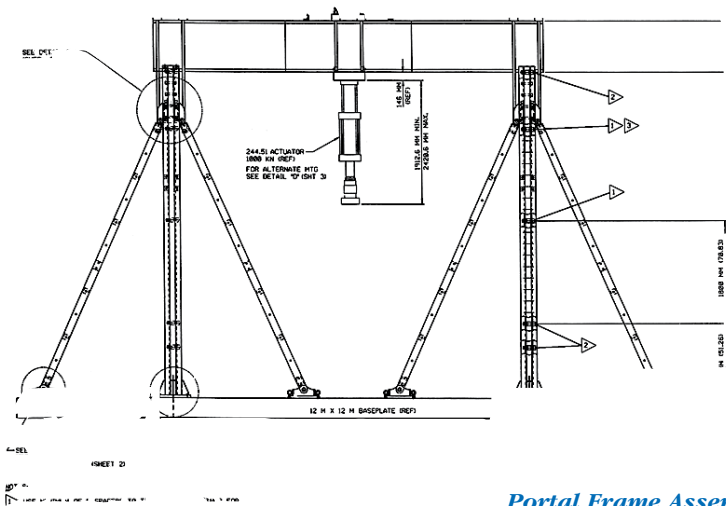


### High Stiffness Portal Frame



## Universal Portal Frame Design

This type of portal frame is based on the more traditional I beam and girder approach. Various sections can be added and moved around to allow actuators to be placed where they are needed for custom test set-ups. The standard MTS design is rated for 200 tons maximum load when configured with a double top girder. The maximum span in this configuration is 6.3 meters. The lateral span is 4.2 meters and the maximum vertical clearance is 5.7 meters. This frame is primarily designed for static testing, but can be used for low level dynamic testing with reduced loads. The maximum frame deflection at 200 tons is 5 mm when using a double girder. If desired, each end portal can be used as an individual reaction frame where the end portals are rated at 100 tons with a maximum deflection of approximately 1.8 mm.

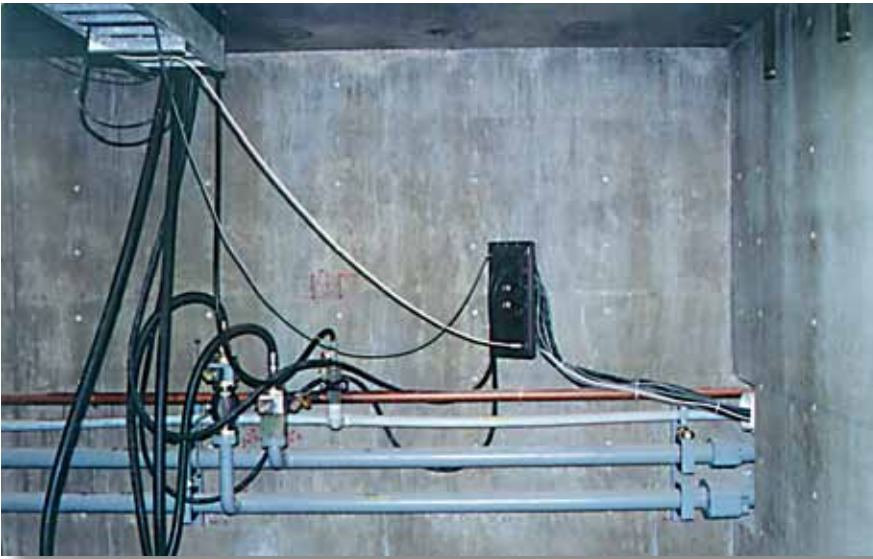


*Portal Frame Assembly*



*Universal Portal Frame*

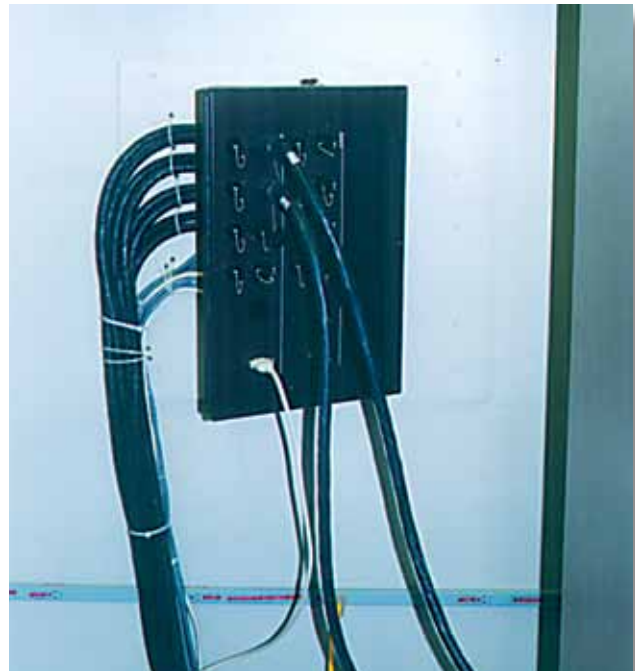
## Supercable Concept



- Strong floor junction box location
- Basement cell location
- Cables from junction box to control room are permanently installed
- Cables from actuator area are dropped from the test floor through access holes and connection to junction box



- View of basement cell area between two shear walls
- Note cable trays permanently installed in the basement to route cables to the control room
- Note tie rod anchor points securing foundation mass block for single bent test program
- Note location of supercable junction box on far wall
- Note hydraulic hardline distribution in each shear wall area



- Control room junction box
- 4 channels of actuator control can be routed to various test cell areas of the strong floor area

# Training and Maintenance

## **Training**

To capitalize on your investment in structural testing equipment, it is important to realize immediate productivity gains through the use of your equipment and personnel. To assist in this process, MTS offers various levels of training support for your staff. Our goal is to train your staff in the use of the testing equipment and the long term maintenance of that equipment. MTS offers optional:

- ▶ Factory Class Room Training Courses on Operation and Maintenance.
- ▶ Hands-On Factory Training Consulting.
- ▶ Additional On-Site Training After Installation is Completed.
- ▶ Coordination of Training at Institutions related to the Construction Industry on Testing Methodology.

## **Maintenance Contracts**

In any productive testing environment, one very important aspect is to keep the testing equipment operational at all times and to keep that equipment calibrated according to the established national standards.

MTS offers various levels of support to achieve these goals. First, MTS is an ISO certified corporation and manufactures our equipment to the highest quality

standards. For the situations that do involve replacement of a component or electronics due to an unexpected failure under normal use, MTS includes a 12 month warranty on all testing systems.

When the testing equipment is first supplied, all transducers are calibrated to NIST traceable standards. MTS recommends that the hardware be re-calibrated according to established industry standards. In most contract testing laboratories, annual re-calibration is typically required for all transducers.

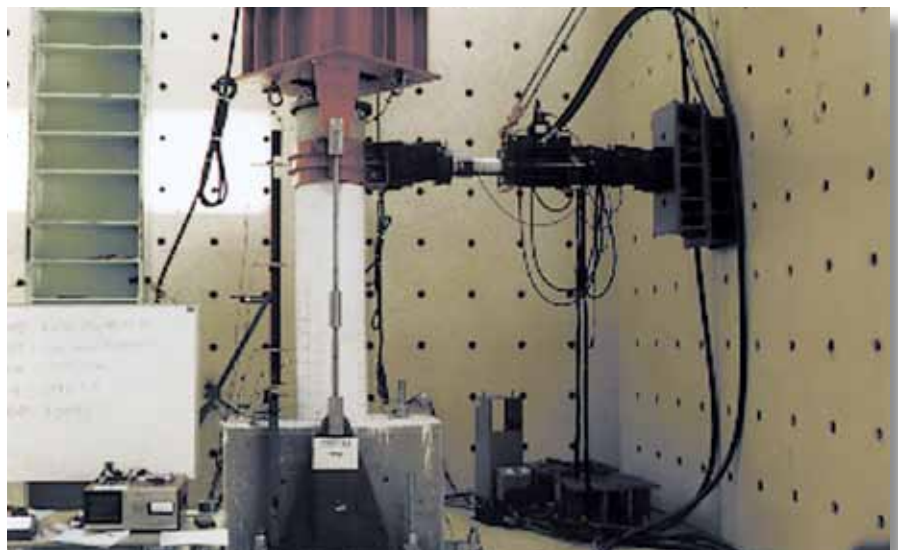
In addition to good maintenance practices and following scheduled procedures, it is also recommended that laboratories involved in critical testing programs consider placing Long Term Maintenance Contracts with MTS. Each contract is customized for your specific needs and is typically designed to supply both emergency services and preventative maintenance services and expendables. MTS can customize a specific plan to address your needs. These plans are usually designed around an annual operating budget for the laboratory and can be expanded as required by each customer.



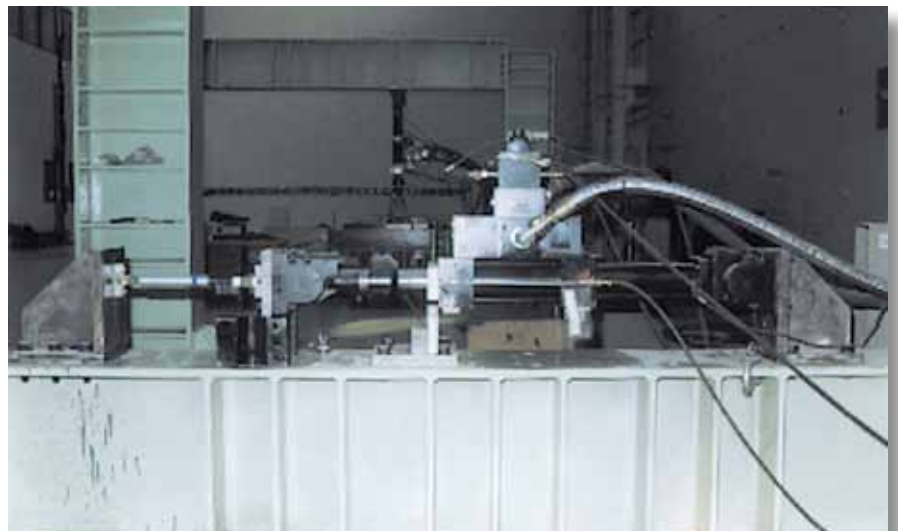


# **Structural Testing Applications**

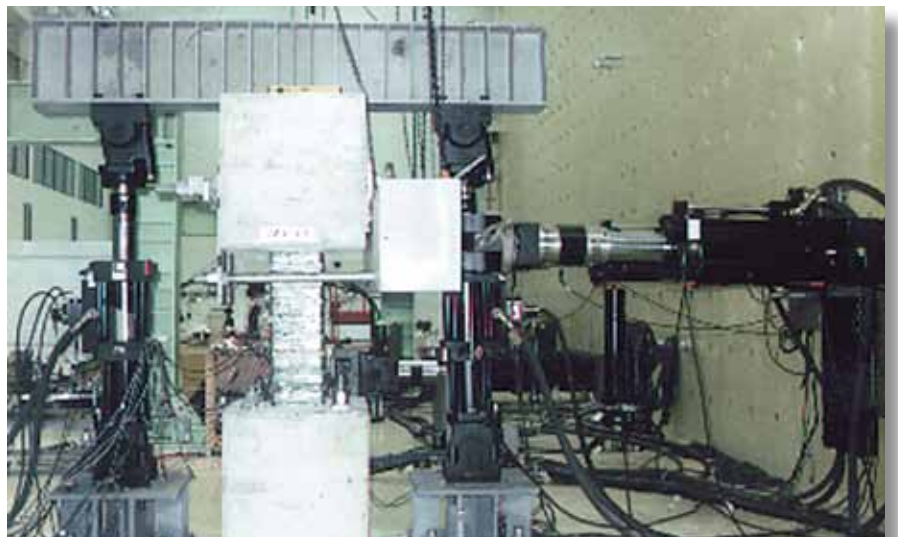
- Seismic performance test on concrete bridge piers retrofitted by fiber glass

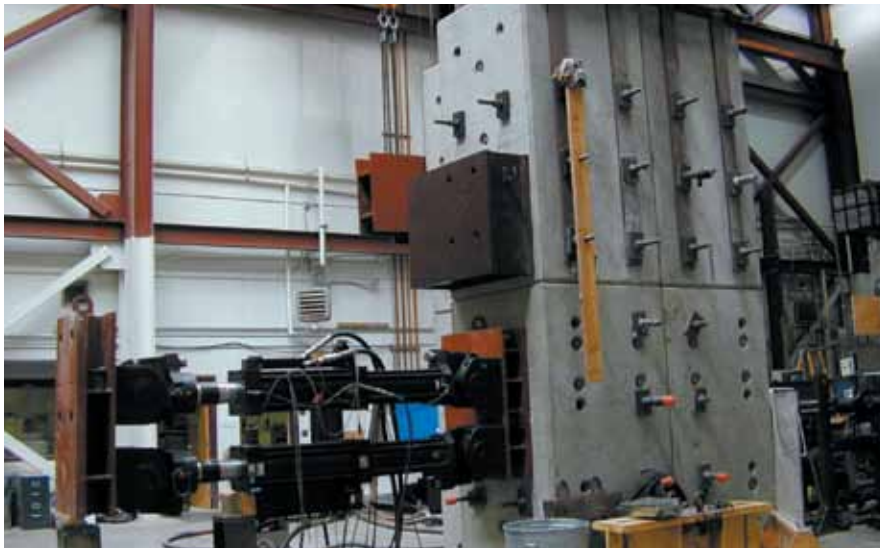


- Cyclic loading test on evaluating the energy dissipation capacity of viscous damper, varying the cyclic loading frequency



- Quasi-static test for evaluating the shear strength of building columns without exerting bending moment

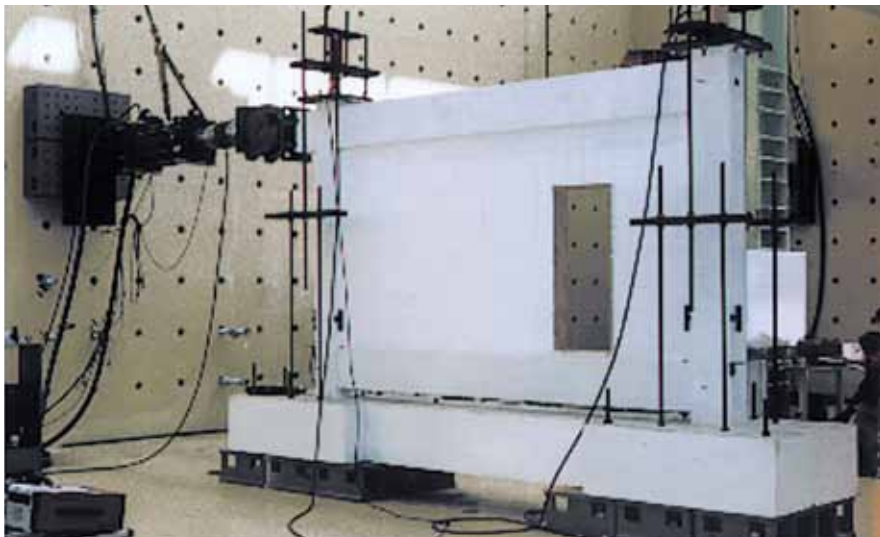




- Reinforced Concrete Block Assembly for Vertical Reaction at University of Nevada - Reno



- Seismic performance test on concrete shear wall system



- Seismic performance test on concrete frame and masonry wall with the opening

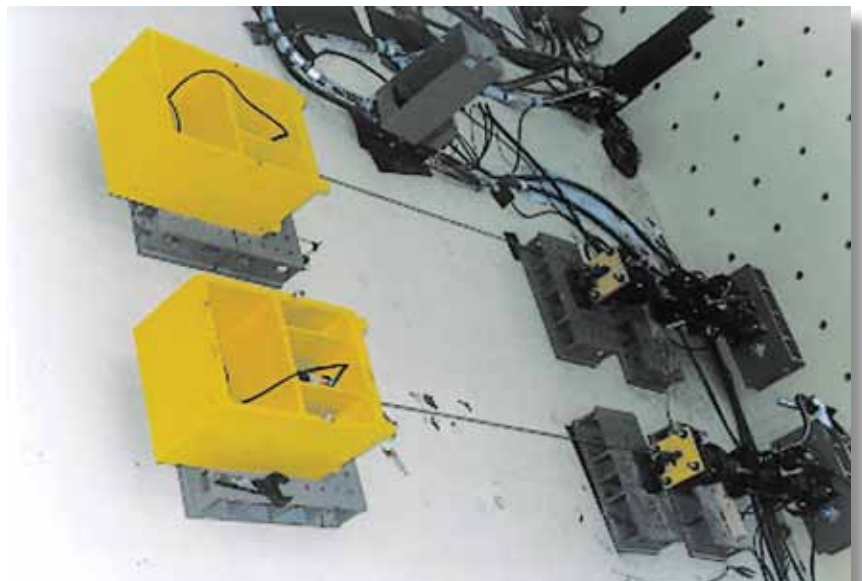




- Two Level, 4 channels  
Dynamic Testing at University  
of California, San Diego



- Fatigue strength test on  
bridge expansion joint



- Fatigue strength test on  
vertical hanger cables of  
suspension bridges



- Real Time Pseudodynamic Testing at National Center for Research on Earthquake Engineering, Taiwan



- Close Up View of Viscous Damper Specimen

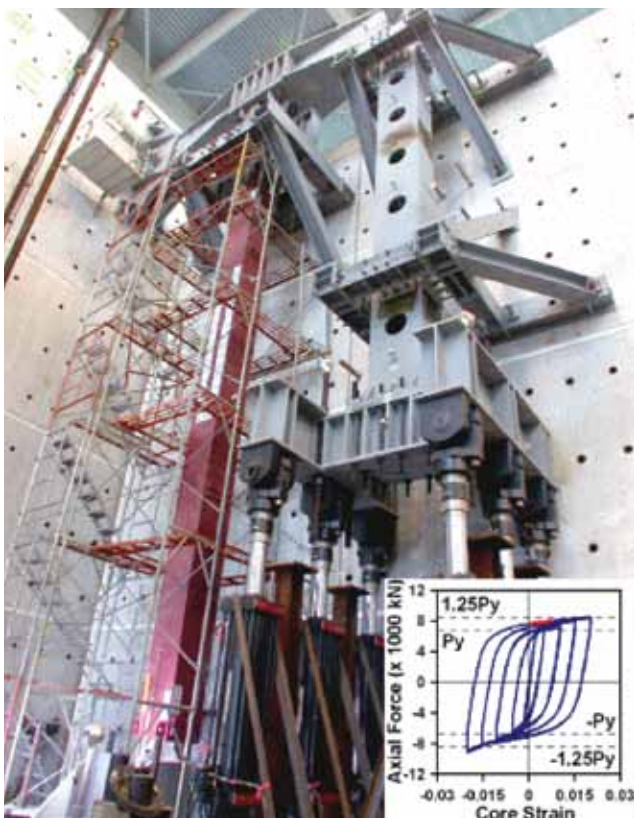


- Close Up View of Rubber Bearing





- Performance evaluation of a Full Scale 3-story 3-Bay Reinforced Concrete and Steel (RCS) Frame at NCREE, Taiwan



- Cyclic test of a 10m Buckling Restraint Brace at NCREE, Taiwan



- Testing of Reinforced Concrete and Steel (RCS) Component



*The following photographs were all taken at the University of California, San Diego, Charles Lee Powel Structural Testing Laboratory during May 1996.*

## Single Column Bent



- Lateral load through MTS horizontal actuator with 48 inch stroke capabilities
- Vertical pre-load through static cylinders and tie rods



- Column under static loading
- Approximate 15 inch deflection

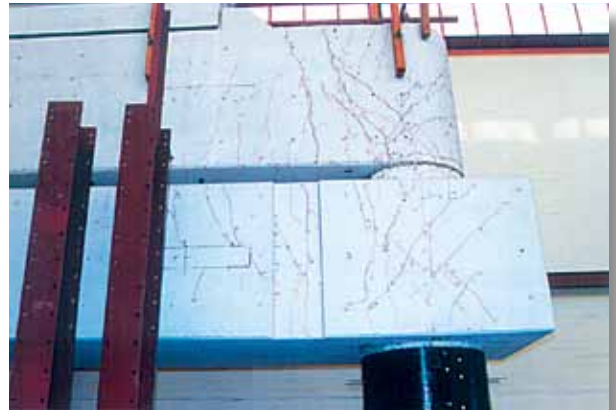


- Close up view of damaged area
- Deflection measurement transducers for lateral displacement and for rotational measurement

## Two Column Bent, Retrofit Program



- Full scale testing of columns, cap beam, link beam and foundation
- Structure loaded through horizontal actuator located between the strong wall and the specimen
- Carbon fiber wrapped column reinforcement techniques



- Crack development markings of initial cap beam (top section)
- Crack development markings of link beam (lower section) which was added for additional lateral stiffness after cap beam studies were completed



- Close up view of maximum
- Illustration of damaged rebar sections which were literally separated into two separate pieces at various locations
- Close up view of carbon fiber wrapped column



## Single Column Bent with Deck Structure

- Preparation for future testing program
- 4/10 scale testing of highway road structure
- Prestressed joint design



- End view showing future location of actuator assembly (one at each end of structure)
- Additional actuators to be placed at vertical positions to generate a moment into the column assembly



- Top view of structure showing load spreader plates where future actuators would be loaded from the bottom





## Glass Fiber Composite Road Deck Structure



- 3 point bend testing evaluation
- Structure loaded through vertical mounted actuator



- Underside of deck surface showing displacement measurement



- Close up view showing both vertical stroke measurement and angle inclinometer

## Building Joint Study



- Dynamic loading of beam ends
- Two actuators used at end flanges in a vertical manner



- Close up view showing damaged area

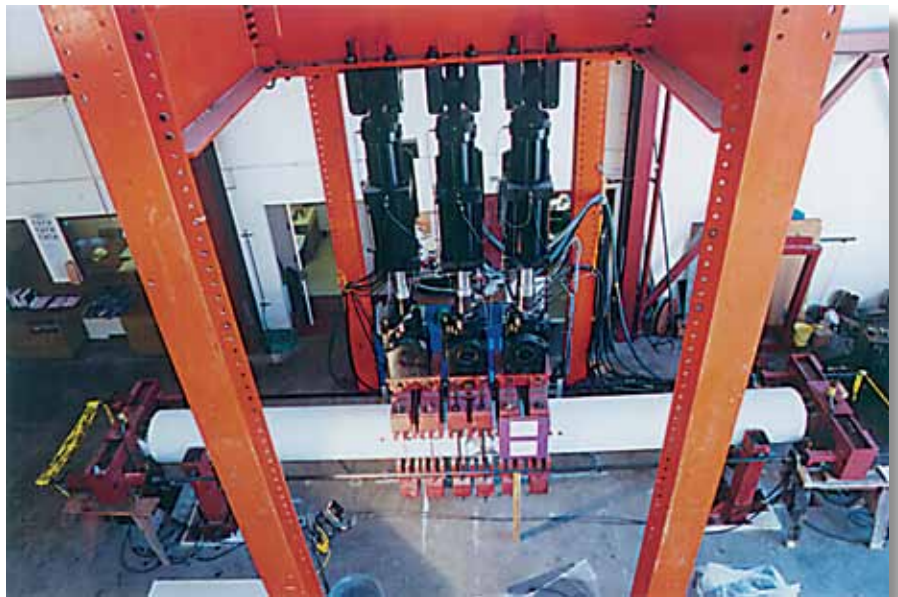


- Steel beam specimen preparation area

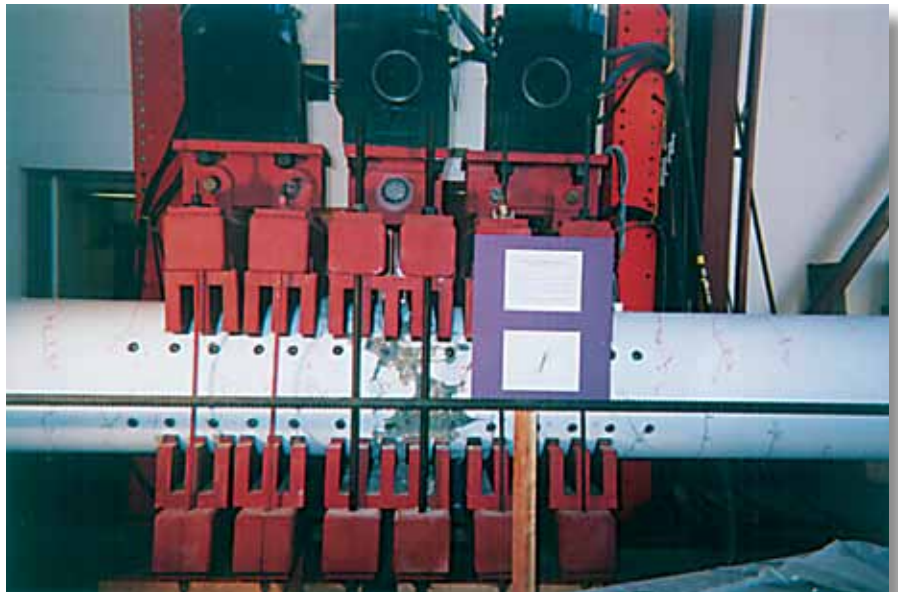


## Concrete Piling Testing Program

- Specimens tested in horizontal configuration
- Pile pre-loaded by static cylinders and tie rods
- Maximum moment area of soil location simulated by vertical actuators



- Close up view of damaged section
- Custom fixturing to simulate distributed loading on concrete surfaces



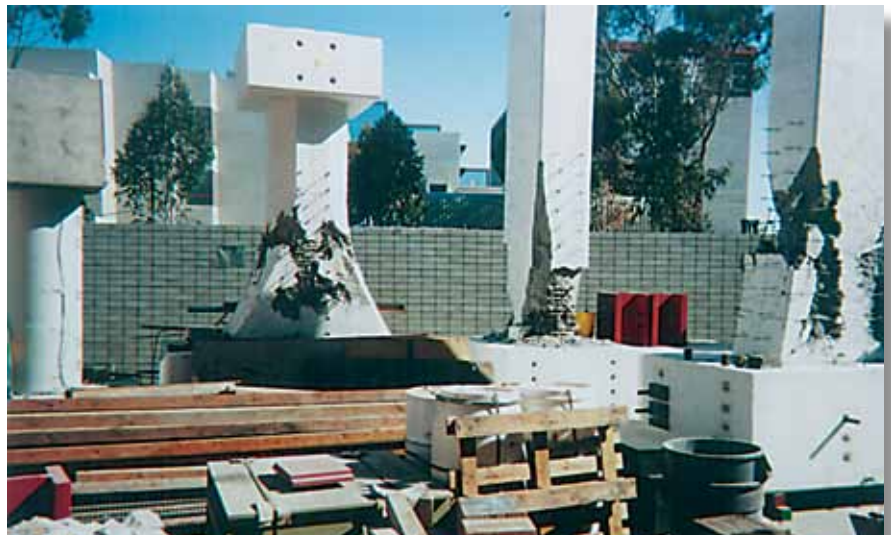


## Specimen Storage Areas

- Various types of specimen configurations after test programs were completed



- Additional specimens showing close up view of damaged areas



- Close up view of column steel reinforcement showing strain gage wiring



# Large Laboratory Design Discussion

This paper was prepared as an introduction to design issues that should be considered when planning for a large scale Civil Engineering Laboratory.

One critical criteria that needs to be established early in the process is the primary charter of the laboratory. Depending on this charter, the facility and equipment needs may vary significantly. MTS would like to work closely with your engineers as you enter into the early planning stages so that we could propose solutions to your testing requirements. As we understand those requirements, our recommendations will change accordingly.

As an initial step, we have prepared this paper to focus primarily on Civil Engineering testing requirements, but with the idea that this facility will also be used for other structural and full scale testing of steel products used in other industry sectors. Any modern laboratory that is constructed for 21st century testing programs will need to be designed for extreme flexibility. As new composite materials and high strength concretes are being developed and applied to all industries, verification of material behaviors as applied to real life solutions will play an ever important role. Those companies that choose to invest in advanced solutions for Civil Engineering applications with cost effective new materials will be leaders and will play a dominant role in the world construction industry. The market for advanced solutions using composite materials applied to Civil Applications is only in its infancy today and will surely thrive over the next 20 years.

The final consideration which must be addressed early in the process is the magnitude of the investment required to complete a facility. While many projects are completed in phases, the initial capital for site development, foundation requirements, utility services, physical plant facilities, structural fabrication, strong floors, strong walls, etc. can range from \$2,000,000 US to \$15,000,000 US depending on the size and quality of construction. This estimate may not include the price of the land or the architectural and engineering fees to

design the laboratory. In addition, the supporting equipment for material handling, specimen preparation and full scale testing can range \$2,000,000 US to \$20,000,000 US again depending on the testing charter of the laboratory. Therefore, it is very probable that a total typical investment for a new facility can range from \$4,000,000 US to \$35,000,000 US depending on the final requirements or the charter of the laboratory.

As a supplier of testing solutions, MTS Corporation has 35 years of experience in dealing with large scale custom projects similar to this and can help to manage major portions of your project. Our core experience is in project management and coordination of large scale testing equipment and corresponding facilities to support the supplied equipment. We look forward to continued correspondence on this project.

After reviewing this paper, if you can indicate the charter of the laboratory and the types of work areas that are anticipated for this new facility, MTS could propose various hardware configurations to meet those needs. We should also have some understanding of the budget planning cycle so that we could recommend logical equipment phases to match possible funding sources. We would also like to know the timing of the project phases if the whole project is not completed in one phase.

## **Key Work Areas of a Typical Civil Engineering Laboratory**

The total area required for a new facility can vary widely depending on the charter of the facility. A fully equipped laboratory will consist of elements of the following work areas. The physical size can vary significantly depending on final needs, land restrictions, and building code limitations.

### **Main Testing Hall**

- Strong Floor
- Strong Walls
- Test Control Areas
- Incoming Material and Specimen Storage
- Workshop
- Loading and Unloading Areas for Incoming Supplies

- Specimen Preparation and Storage Areas
- Previously Tested Specimen Storage Areas
- Portal Frame Storage Areas
- Actuator Storage Areas
- Hose and Hydraulic Manifold Storage Areas

#### **Control Room for Main Hall**

- 1st or 2nd Floor View Behind Glass Windows

#### **Secondary Testing Areas in Main Hall**

- High Force Frames for Large Component Testing (5 MN to 20 MN)
- Medium Force Frames for General Purpose Applications (1 MN to 5 MN)

#### **Secondary Testing Areas in Adjoining Laboratories**

- Concrete Specimen Preparation Area
- Concrete Testing Equipment
- Rock Testing Equipment
- General Purpose Materials Testing Laboratory
- Composite Research Area
- Metallurgy Laboratory
- Environmental Conditioning or Long Term Creep Laboratories
- Instrumentation Laboratory

#### **Additional Office Space Common to Many Laboratories**

- Management Staff
- Research & Engineering Staff
- Technical Staff
- Support Staff
- Computer Equipment and Central Data Storage
- On-Site File, Video, Computer Disk Storage
- CAD/CAM, Finite Element Modeling, Drafting Stations
- Meeting Rooms for Internal Staff (several)
- Conference Rooms for External Clients and Vendors
- Seminar Room (not as common depending on other facilities available.)
- Observation Area to View Large Scale Testing Without Walking or Standing Near Strong Floor.
- Reception Area
- Lunch Area
- Library / Quiet Reading Rooms / On-Line and Internet Access Computers
- Document Preparation Room / Copy Room
- Mail Room / Fax Room / Communication Room

- Smoking Rooms
- Washrooms / Bathrooms
- First Aid Room

#### **Other Building Areas that Require Floor Space**

- Mechanical Systems, Furnace/Air Conditioning, Air Compressors, Water Circulation/Chilling, Electrical Systems, General Walkways, Halls, Stairways, Emergency Accesses, Strong Wall thicknesses, etc.
- Hydraulic Power Supply Room (Basement location typically)
- Janitor and Maintenance Rooms

#### **Outdoor Areas**

- Specimen Holding Area Until Program Completed, Demolition Area and Long Term Storage of Specimens
- Parking for Employees
- Exercise Areas and Walking Path for Good Mental and Physical Health of Employees
- Recreation Areas for Employees

Once the functionality of the building is decided, the next step is to determine the approximate size of the work areas. Again, these sizes can vary significantly and are influenced by total budget, land restrictions, charter of the laboratory, etc.

#### ***Review of Several Large Scale Laboratories***

To provide you with examples of the size of the testing area or Main Testing Hall of large scale Civil Engineering Laboratories, a few examples of key laboratories are listed below.

The physical size mentioned applies to only the “Main Testing Hall”. Additional office space, secondary support areas, staging and specimen preparation areas, etc. are additional to the test floor area.

#### ***University of California, San Diego, Primary Structural Laboratory***

This facility is used to verify large scale Civil Engineering solutions. Several years of research were concentrated on Pseudodynamic Testing to simulate seismic records of varying degrees and to determine methods to reinforce existing or damaged buildings. A 5 story tall structure was tested with 10 servo channels. More recent investigations have concentrated on testing



highway and bridge infrastructure components and how to retrofit such existing structures to make them more earthquake resistant. Also, a significant amount of current research involves composite materials and how they can be applied to Civil Applications both in building research and in road construction.

#### **Strong Floor of Main Structural Laboratory**

- 37 meters x 15 meters
- 4 cell RC box girder
- Floor thickness 0.91 meters (3 feet)
- Tie down points on .61 x .61 m grid or 2 x 2 feet
- Load per anchor point , 1334 kN or 300 kips
- Moment Capacity - 108,600 kN-m or 80,000 ft-kips
- Special Permit Test Load Moment, 183,200 kN-m (135,000 ft.-kips)

#### **Strong Wall of Main Structural Laboratory**

- 15 meters high x 9 meters wide two cell, post tensioned concrete box girder
- Tie down points on .61 x .61 m grid or 2 x 2 feet
- Load per anchor point , 1334 kN or 300 kips
- Test Shear Capacity, 11,876 kN or 2,670 kips
- Test Load Moment Capacity , 108,600 kN-m (80,000 ft. - kips)
- Special Permit Test Load Moment, 183,200 kN-m (135,000 ft.-kips)

#### ***University of California, San Diego, New Structural Component Laboratory***

This facility was completed in 1993 with a primary focus on component testing and to further advance the use of composites in the building industries.

#### **Strong Floor**

- 13.5 meters x 21 meters
- 6 cell RC box girder
- Tie down points on .61 x .61 m grid or 2 x 2 feet
- Floor thickness 0.91 meters (3 feet)
- Tie down points on .61 x .61 m grid or 2 x 2 feet
- Load per anchor point , 1334 kN or 300 kips
- Moment Capacity - 890 kN-m/m or 200 ft-kips/ft
- Special Permit Test Load Moment, 1,514 kN-m/m (340 ft.-kips/ft)

#### **Strong Wall**

- 9 meters high x 19 meters wide
- 1.1 meter (3.5 feet) deep post tensioned concrete wall
- Tie down points on .61 x .61 m grid or 2 x 2 feet
- Load per anchor point , 1334 kN or 300 kips
- Test Shear Capacity, 1,459 kN/m or 100 kips/ft
- Test Load Moment Capacity , 890 kN-m/m (200 ft- kip/ft)
- Special Permit Test Load Shear Capacity 2,481 kN-m (170 kips/ft)
- Special Permit Test Load Moment 1,541 kN-m/m (340 ft-kips/ft)

#### ***Lehigh University (Pennsylvania)***

This facility was initially established to serve as a national focal point for research in the U.S. construction industry. Dr. John Fisher is a leading US researcher in the area of bridge and building consulting and heads the Advanced Technology for Large Structural Systems (ATLSS) program. This facility has a unique 3 sided wall design to allow in and out of plane, multi-axial loading to a common specimen.

#### **Strong Floor**

- 31 x 12 meters
- Floor thickness varying from 1.9 meters to 3.2 meters depending on location relative to main wall
- Tie down points on 1.5 x 1.5 m grid or 5 x 5 feet
- Box girder design
- Load per anchor point , 1334 kN or 300 kips axial
- Load per anchor point , 2500 kN or 500 kips shear
- Moment varies with wall height and floor thickness.

#### **Strong Wall**

- Walls vary in length and height. The floor has 3 sides of walls with varying height and widths.
- Primary Wall 15 meters high x 12 meters wide
- Secondary Wall 31 meters wide by different heights.
- Box girder stiffened design with cells up to 4 meters deep.
- Tie down points on 1.5 x 1.5 m grid or 5 x 5 feet
- Moment at base of wall 4500 K-ft/ft width

### **University of Reno, Nevada**

The facility was completed in the 1992 time frame with its primary charter focusing on bridge research. In addition to a large structural laboratory, this facility will incorporate multiple uniaxial seismic tables to simulate bridge and roadway support infrastructure to test large scale spans of single and double decker road and bridge sections under seismic events.

#### **Strong Floor**

- 31 x 17 meters
- Floor thickness 0.91 meters (3 feet)
- Tie down points on .61 x .61 m grid or 2 x 2 feet
- 63 mm diameter socket holes
- 4 cell box girder design
- Load per anchor point , 1334 kN or 300 kips upward or 1070 kN (240 kip downward)

#### **Strong Wall**

- 5.8 meters high x 6 meters wide
- 0.61 m (2 feet) thick post tensioned
- Tie down points on .61 x .61 m grid or 2 x 2 feet

In addition to a conventional strong wall, this facility incorporates portable RC blocks that can be located throughout the laboratory for temporary wall sections to react loads and moments. This building block approach can offer a wide range of flexibility for a multi-purpose laboratory.

### **Kajima Construction Company (Japan)**

This testing laboratory was designed for both high performance dynamic and static testing. The facility is constructed with a strong wall located in the center section of the strong floor through the width of the floor. It effectively divides the laboratory into two unique test areas. Research is performed on all aspects of construction such as nuclear power plants, large-span bridges, marine structures and high-rise buildings.

#### **Strong Floor**

- 2.1 m thick effective area 890 square meters

#### **Strong Wall**

- 3 meters thick, prestressed concrete
- 12 meter high x 16 meters wide
- Bending moment, 14,560 t-m, maximum, Varies according to wall location, shear force, 4640 ton maximum

### **Centre for Frontier Engineering Research, CFER (Edmonton, Canada)**

This facility was established as an "Offshore Structures" laboratory studying the frontiers of the Arctic and offshore structures and as a Downhole Tubular testing facility for evaluating heavy oil and oil sands operations for the Canadian Oil industry.

#### **Strong Floor and Strong Wall Testing Areas**

This facility has several strong walls and strong shafts used for applying loads. The combined strong floor effective area approximates 300 square meters both on the top surface and in the lower cell areas for a total area of 600 square meters. The lower area cells are used as containment walls for pressure testing applications.

There are two usable strong walls each approximately 140 square meters.

For long tubular tests, a strong shaft has been incorporated to apply multi-directional or constrained loading which is 290 square meters in surface area.

In addition to the large test areas, this facility includes a large cold chamber capable of continuous operation to -60 Centigrade. This chamber is 120 square meters with a 9.5 meter ceiling height and can completely move over a 15 MN MTS load frame for long term full scale testing of components in the Arctic environment.

### **Laboratorio Generalitat (LGAI), Barcelona, Spain**

This testing laboratory was designed as a general purpose testing laboratory for various disciplines of including Civil Engineering, Automotive Engineering, and various Materials Science Engineering applications.

#### **High Force Testing Frame with Large Capacity Reaction Floor**

This testing frame has the capability to apply test loads to 15 MN capacity with a vertical test space of approximately 8 meters. Additionally, the reaction floor was integrated to allow specimens up to 10 meters in length to be tested with moments in excess of 15 MN-meters for large scale bending test applications. Additionally, portal frames can be erected over the reaction floor area and serve as a small test area when high capacity loading is required.

#### **12 meter by 12 meter reaction bedplate**

This laboratory design utilized a steel bedplate with supporting foundation. The bedplate provided T-slots spaced at 0.5 meter intervals versus a concrete box beam style of strong floor. Most tests were anticipated to be under 100 MTons capacity for this part of the laboratory with many tests under 25 Mtons. Such a solution while more expensive overall, provided a very flexible testing capability that could be easily adapted to any of the testing disciplines.

In addition to the reaction floor, this customer also had the ability to move around 2 meter high portable reaction walls that could also be stacked to 4 meters height for added flexibility and multiple actuator test configurations.

More recent examples of large scale laboratories that MTS was involved with include:

#### **Daewoo Construction Company (Korea)**

This testing laboratory was designed for high loading static testing with additional dynamic capabilities. The facility is constructed with a strong wall dividing the laboratory into two unique test areas. Research will be performed for various Civil Engineering disciplines in the building industries.

##### **Strong Floor**

- 39 meters x 17.5 meters
- 4 cell RC box girder with post tensioning
- Tie down points on 0.5 m x 0.5 m grid
- Floor thickness 1.5 meters
- Load per square meter, 150 mtons
- Moment Capacity - 10,000 ton meters

##### **Strong Wall**

- 12 meters high x 14 meters wide
- 2.5 meter reinforced and post tensioned concrete wall
- Tie down points on 0.5 m x 0.5 meter grid
- Load per square meter, 150 mtons

#### **Hyundai Construction Company (Korea)**

This testing laboratory was designed both static and dynamic testing. The strong wall is L shaped running the entire length of the floor with a 5 meter extension for multi-axial testing capabilities. This facility will be used for testing a variety of building industry structures as well as other multi purpose needs.

##### **Strong Floor**

- 27 meters x 12 meters
- 6 cell RC box girder concept
- Tie down points on 0.5 m x 0.5 m grid
- Floor thickness 1.0 meters
- Load per square meter, 2668 kN

##### **Strong Wall**

- 27 meters length x 8 meters height x 2 meters thick in long direction
- 5 meters length x 8 meters height x 2 meters thick in short direction
- 2.0 meter reinforced and post tensioned concrete wall
- Tie down points on 0.5 m x 0.5 meter grid
- Shear Capacity, 2668 kN per 1 meter strip
- Moment Capacity, 8,650 kN per 1 meter strip
- Post-Tensioning, 5438 kN per 0.5 meter strip

#### **Hanyang University (Korea)**

This laboratory will be used as both an academic and general purpose testing facility. It consists of a buttress style strong wall integrated into the strong floor.

##### **Strong Floor**

- 11 meters x 11 meters
- RC box girder
- Tie down points on 0.5 m x 0.5 m grid
- Floor thickness 0.6 meters

##### **Strong Wall**

- 8 meters high x 11 meters wide
- Tie down points on 0.5 m x 0.5 meter grid

#### **NCREE, National Center for Research on Earthquake Engineering (Taiwan)**

This laboratory is one of the largest facilities for comprehensive engineering studies. It includes both a large scale six degree of freedom seismic table and a structural testing laboratory consisting of an extended multi-height strong wall. Additionally, the laboratory was designed for both static and high performance dynamic testing and has over 3800 lpm of available oil for dynamic testing.

##### **Strong Floor**

- 50 meters length x 15 meters
- RC box girder
- Tie down points on 0.5 m x 0.5 m grid



## **Strong Wall**

- L shaped wall design
- 15 meters high x 15 meters wide on short end
- 12 meters, 9 meters and 6 meters height along long direction for full 50 meters length.
- RC box girder construction
- Tie down points on 0.5 m x 0.5 meter grid

The above examples are illustrations of laboratories that are actively performing tests in various Civil Engineering disciplines. Depending on the scope of your testing program, a laboratory facility similar to any of the above examples may be of interest to your organization. MTS could support your application with consulting services on facility issues or could make generic recommendations as your program evolves. Please feel free to contact us at any time.

## **Suggestions for Various Critical Test Areas**

The following recommendations are very general and are meant only to help determine the physical size and make up of a new laboratory. The sizes must be adjusted according to each individual application and can have significant impact on the total scope and cost of the project. A project coordinator should carefully study your testing needs and should visit several laboratories to get a first hand feeling for the size and importance of the various testing areas.

### **1. General Test Hall**

If the charter of the laboratory is for testing large scale components, the idea of a strong wall dividing up the strong floor adds flexibility to the laboratory. Some tests may be of long duration and physically dividing the laboratory has advantages. The strong wall can be placed at a strategic location such as 1/3 to 2/5 of the length of the floor to allow major testing research on either side of the wall.

#### **1.1 Strong Floor**

15 m wide x 60 meters length 900 m<sup>2</sup>. If divided, one section could be 15 x 40 meters and the other side, 15 x 20 meters. Such dimensions are typical of the larger laboratories. The strong wall will be 2 to 4

meters thick depending on the load and moment capacity required and can either reduce the overall test area available or can be accounted for making a longer building.

### **1.2 Strong Floor Cells in Basement**

A box beam style of strong floor is practical and efficient for civil laboratories. The inherent design of such a building provides benefit by having a lower area which can be used for storage or can be designed to carry loads. It is highly recommended to design a large access area from the top floor surface to allow large items to be placed and stored in the basement. Access can be via pit, ramp or elevator.

### **1.3 Strong Wall**

15 m wide x 10 to 15 m high depending on the testing programs and the building height. The strong wall can divide the strong floor across the width and one additional wall can be constructed on a portion of a side wall to form an L-shaped strong wall to allow multi-axial requirements. The size and location of a side wall has to complement the plans of the facility.

### **1.4 Control Room Areas**

20-30 m<sup>2</sup> per room.

If the above approach is desired, several control rooms should be planned. A minimum of one control room should be assigned to each test area. If the the strong floor test area is large, several control rooms may be desirable depending on how many testing programs will be run simultaneously. Keep in mind that many test will take several weeks to a month for initial set up and several months to perform the required work and analysis before complete removal from the work area. In those situations, multiple control rooms allow good visibility to each test area without compromising any one test.

Additionally, many researchers like to have a second floor control room for visibility of the overall laboratory and as an observation area for visitors or customers. A glassed in area such as this allows the flexibility to either use the space as an observation area or as a control room.

Also realize that not all tests are set up in a control room. Many short duration or component tests are often set up with the controller/operator stationed on the test floor very near to the specimen. The controls should allow for such flexibility.

**1.4 Incoming Material and Specimen Storage**  
50-80 m2.

This can vary significantly but allow for the storage of specimens and construction materials. There could be storage areas on both the street level floor and the basement level floor.

**1.5 Workshop**  
80 - 100 m2.

Used to assist in making specimens, form work, adapter plates, prototypes, etc. Includes table saw, grinders, welders, lathe, drill press, bridgeport mill, sander, etc.

**1.6 Loading and Unloading Areas**  
50 m2.

An area in front of the loading doors for loading and off-loading supplies, specimens, etc. near the Incoming Materials and Specimen Storage Area. This should have crane access and be located close to the basement pit access if lower storage is planned. Also, it would be desirable to have a offset to allow fork lift trucks direct access on and off trucks.

**1.7 Specimen Preparation**  
150 m2.

Allows construction of test specimens. to strong floor dimensions

**1.8 Portal Frame Storage Areas**  
50 m2.

This area can vary according to the size and quantities of portal frames used and the design of the walls. Some defined area is required however to store the large I beams and Channels that make up a flexible portal system. While these items can be stored outdoors it is recommended to provide indoor storage to prevent weathering and corrosion to allow easier assembly.

**1.9 Actuator Storage Areas**  
25-40 m2.

This area should be close to the strong floor and should allow easy access to selecting a specific actuator. Either convenient racks with fork lift devices or good overhead access to all actuators should be provided. Some large structural actuators may approach 3 meters length.

**1.10 Hose and Hydraulic Storage Area**  
20 m2.

Convenient storage racks for hydraulic hoses should be planned. Many hoses of different diameters and lengths will always be in storage. Racks should be 10 meter or more length to accomodate long hoses. Hoses can be bent 180 degress depending on the diameter to keep the total length down. Each rack should be at least 0.75 to 1 meter deep. Other shelving should be provided for misc. fittings. Additionally, Hydraulic Service Manifolds can be stored in same location.

The above are rough estimates based on some experience and from what has been successful at other laboratories. The areas all have to be adjusted to meet your specific needs however.

Once we receive some comments from you, we can suggest other room sizes for areas in which we are familiar. Before we try to comment on all the possible office spaces or secondary test equipment areas, we would like to determine the laboratory intent and the types of equipment that may be considered.

If we receive such information, we can work directly with your engineers and help recommend some configurations and suggestions regarding facility issues particular to the MTS equipment such as the HPS facilities, hardline, etc.

## Partial Customer List of Structural Test System for Civil Engineering Applications

Customer	Country
AICHI	Japan
Asian Institute of Technology	Thailand
Alga Milano	Italy
Auburn University	Auburn, Alabama, USA
Braunschweig Technical University	Braunschweig, Germany
Centro Nacional De Prevencion De Desastres (CENAPRED)	Mexico City, Mexico
Chongqing Architectural Inst.	Chongqing, China
Cottbus Technical University	Cottbus, Germany
Daewoo Construction Company	Suwon, Korea
Daido University	Nagoya, Japan
Dalian Institute of Technology	Dalian, China
Dankook University	Kiheung, Korea
Dong-A University	Pusan, Korea
Fuzhou University	Fuzhou, China
Georgia Institute of Technology	Atlanta, Georgia, USA
Graz University	Graz, Austria
Hannam University,	Korea
Hanyang University	Ansan, Korea
Hebei Institute of Technology	Tangshan, China
Hong Kong Polytechnical Univ.	Hong Kong, China
Hong Kong University	Hong Kong, China
Hyundai Construction Company	Mabuk-Ri, Korea
Inha University	Inchon, Korea
Iowa State University	Ames, Iowa, USA
Institute Teknologi Sepuluh Nopember (ITS)	Indonesia
Kajima Institute of Construction Technology	Chofu, Japan
KEERC	Korea
KICT	Korea



<b>Customer</b>	<b>Country</b>
KIMM	Daejon, Korea
Klockner Institute	Prague, Czech Republic
Kookmin University	Korea
Korea Advance Institute of Science and Technology (KAIST)	Daejeon, Korea
Korea Maritime University	Pusan, Korea
Korea University	Seoul, Korea
KRISS	Daejon, Korea
KTH	Stockholm Sweden
Laboratori General d' Assaigs investigacions	Barcelona, Spain
McMaster University	Ontario, Canada
Middle Eastern Technical University	Ankara, Turkey
Ministry of Construction	Tsukuba, Japan
Mitsui Construction Company	Tsukuba, Japan
Myungji University	Yongin, Korea
Namseoul University	Korea
Nanyang Tech. University	Singapore
National Center for Research on Earthquake Engineering (NCREE)	Taipei, Taiwan
National Cheng Kung University (NCKU)	Taichung, Taiwan
National Research Institute of Agricultural Engineering (NRIAE)	Tsukuba, Japan
National Taiwan Inst. of Tech. (NTIT)	Taipei, Taiwan
National Taiwan University (NTU)	Taipei, Taiwan
National Technical University	Athens, Greece
National University of Singapore	Singapore
Nippon Kokan Steel Company	Kanayawa, Japan
NKFUST	Taiwan
North Carolina State University	Raleigh, North Carolina, USA
Northern Jiaotong University	Beijing, China
NRIAE	Japan
NTI	Norway
Oregon State University	USA
Patras University	Patras, Greece
Pavia University	Pavia, Italy

## Customer

Pennsylvania State University  
Pente Ocean Construction Co.  
Politecnico Catalunya University  
Pontifica University Catolic de Chile  
Pukyung National University  
Purdue University  
Pusan University  
Pusan University  
Research Institute of Science and Technology (RIST)  
Seoul City University  
Seoul National University  
Shanghai Jiaotong University  
Shantou University  
South China University of Technology  
South Western Jiaotong Univ.  
State University of New York  
Sungkyunkwan University  
Suzhou College of Urban Construction  
Taejeon University  
Telecommunication Laboratory  
Technical Hochschule  
Thessaloniki Inst. of Tech.  
Tokyo Metropolitan Univ.  
Trento University  
Tsinghua University  
Universidad de Los Andes  
University of California  
University of California  
University of California  
University of Colorado

## Country

USA  
Tokyo, Japan  
Barcelona, Spain  
Chile  
Korea  
West Lafayette, Indiana, USA  
Pusan, Korea  
Pusan, Korea  
Kiheung, Korea  
Seoul, Korea  
Seoul, Korea  
Shanghai, China  
Shantou, China  
Guangzhou, China  
Emei, China  
Buffalo, New York, USA  
Suwon, Korea  
China  
Korea  
Taiwan  
Darmstadt, West Germany  
Thessaloniki, Greece  
Tokyo, Japan  
Trento, Italy  
Beijing, China  
Peru  
Berkeley, California, USA  
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**Customer**

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University of Delaware  
University of Kansas  
University of Illinois  
University of Istanbul  
University of Michigan  
University of Minnesota  
University of Nebraska  
University of Nevada-Reno  
University of Rhode Island  
University of Ottawa  
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USACE  
University of Utah  
Vacuum Technologies  
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**Country**

Costa Rica  
USA  
USA  
Champaign, Illinois, USA  
Istanbul, Turkey  
Ann Arbor, Michigan, USA  
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Omaha, Nebraska, USA  
Reno, Nevada, USA  
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