A simplified static analysis methodology is presented for qualifying equipment in moderate and high-hazard facility-use category structures, where the facility use is defined in Design and Evaluation Guidelines for Department of Energy Facilities Subjected to Natural Phenomena Hazards, UCRL-15910.¹

Currently there are no equivalent simplified static methods for determining seismic loads on equipment in these facility use categories without completing dynamic analysis of the facility to obtain local floor accelerations or spectra. The requirements of UCRL-15910 specify the use of "dynamic" analysis methods, consistent with Seismic Design Guidelines for Essential Buildings, Chapter 6, "Nonstructural Elements," TM5-809-10-1,² be used for determining seismic loads on mechanical equipment and components. Chapter 6 assumes that the dynamic analysis of the facility has generated either floor response spectra or model floor accelerations. These in turn are utilized with the dynamic modification factor and the actual demand and capacity ratios to determine equipment loading. This complex methodology may be necessary to determine more exacting loads for hard to qualify equipment but does not provide a simple conservative loading methodology for equipment with ample structural capacity.

In the paper, reasonably conservative static loading criteria are established in place of the required complex dynamic loading for the seismic evaluation of equipment in moderate and high-hazard facilities.

The loading criteria are established as function of building response consistent with the following criteria:

1. Lateral load resisting systems (i.e., Rw factors)
2. Building floor response (diaphragm action)
3. Building size (numbers of floors, mass)
4. Equipment type and operability (i.e., ducts versus pumps)
5. Equipment support (flexible or rigid)
6. Damping values (elastic or post yield)
7. Building load demand versus elastic capacity
8. Secondary amplification

¹UCRL, 1987, Design and Evaluation Guidelines for Department of Energy Facility Subjected to Natural Phenomena Hazards, UCRL-15910, Lawrence Livermore National Laboratory, Livermore, California

ABSTRACT

A seismic test facility located at the K-25 Site in Oak Ridge, Tennessee, has been refurbished after being shutdown since 1985. The facility shake table is being recertified in order to provide seismic testing capability to an extensive multi-year evaluation program of hollow clay tile walls in buildings at the DOE site in Oak Ridge. The program, directed by the Center for Natural Phenomena Engineering at Martin Marietta Energy Systems, Inc., the managing contractor for DOE in Oak Ridge, is reviewed. Emphasis is given to the recertification efforts for the seismic test facility, and results of facility and specimen testing to date are discussed and plans for future testing are reviewed. Features and capabilities of the shake table are presented. The dynamic testing of masonry structures is reviewed, and a hollow clay tile wall testing program is projected based on the shake table capability.

INTRODUCTION

The U.S. Department of Energy (DOE) Order 6430.1A, "General Design Criteria," emphasizes the importance of determining the adequacy and safety of both new and existing facilities for natural phenomenon hazards. Most of the buildings at the DOE Oak Ridge sites were constructed over 45 years ago. Some of the buildings have steel frameworks which utilize unreinforced masonry hollow clay tile as infilled walls between columns and floor beams. Seismic evaluations of some of these buildings have assumed these infilled walls to be a substantial part of the lateral force resistance capability for the buildings.

However, to obtain a more realistic assessment of the seismic capability of the buildings, a better mathematical model and better material properties of the hollow clay tile wall are needed. Thus, it has become very important to accurately predict the behavior of these hollow clay tile walls.

Until recently, little information has been available on hollow clay tile masonry, its structural properties, and behavior. Also, the in-situ condition of the tile walls is suspect because of their age and exposure to corrosive environments. Data that have been used from the literature have been questioned because much of the published information is not specifically for hollow clay tile, but for other types of masonry. Therefore, as a result of lack of information, a test program is under way at the Oak Ridge sites to obtain material properties and data on the static and dynamic behavior of the hollow clay tile walls. These data should permit a more reliable prediction of building response to natural phenomena events.

The testing program has many facets, including static tests, nondestructive tests (NDE), analysis, and dynamic tests (Fig. 1). These tests include basic material property...
parameters, unit block tests, prism compression tests, flexural tests, and in-plane masonry shear tests. Also, in-situ normal stresses and shear strength are being obtained through in-filled frame static tests. Out-of-plane tests of in-situ wall panels are planned using air bags, [1]. Finally, dynamic tests on a shake table are planned to complement the total program.

The hollow clay tile units under evaluation are primarily of two sizes, an 8-in. thick unit, and a 4-in. thick unit. Outside walls which are 13-in. thick, utilize 12 x 12 x 8-in. tiles and 12 x 12 x 4-in. tiles using a running bond side construction, with the 8-in. and 4-in. tile alternating rows. A typical wall is shown in Fig. 2. Interior walls are either similar to the outside walls or 8-in. thick using single 8-in. units in running bond side construction.

DYNAMIC TESTING PROGRAM

The dynamic testing program was formulated to support numerical analysis and tests planned for the hollow clay tile wall evaluation program. Plans to accomplish this include observation and quantification of the behavior of hollow clay tile wall (HCTW) specimens under seismic excitation. This will enable appropriate numerical models to be developed and will help to resolve questions as to the dynamic behavior of the HCTW in existing buildings. For example, numerous methods have been suggested for analyzing out-of-plane behavior of in-filled steel frames. These have ranged from considering the frame to be completely rigid and the wall to act as a plate to considering the HCTW to be excited only through deformations that are transmitted from the frame. In-plane studies have indicated that the amount of restraint at the beam-to-column connection can have a significant effect on the failure mode of the in-fill during dynamic excitation [2].

The purpose of the shake table tests will be primarily to verify and develop analytical models, [2]. Actual replication of full-scale wall structures representative of buildings at the Oak Ridge site will not be possible on the shake table as it now exists. However, representative specimens of the walls can be produced which will provide valuable data to the program. At this time, the specimen test program is in development. Consideration is being given to the attachment of a "head expander" to the table which would allow testing of up to 12-ft wide specimens. If this concept proves to be too costly or requires table accelerations that are not attainable, then a simpler arrangement is possible with provision for testing 6-ft wide walls. Plans include both in-plane and out-of-plane wall specimen tests. Both horizontal and vertical motions can be applied by the shake table. Initial test specimens are planned to be simple cantilever masonry wall specimens.

A description of the Seismic Test Facility (STF) to be used for this test program and an overview of the planned...
hollow clay tile wall specimen seismic testing program
follows.

SEISMIC TEST FACILITY (STF)

The STF is located in Building K-1600 at the K-25 Site in Oak Ridge. An overview of the facility showing the shake table and supporting facilities is shown in Fig. 3. The shake table features the following:

- computer controlled biaxial seismic motion simulator system,
- computer based data acquisition and analysis system,
- control room monitoring and controlling of the simulator machinery,
- hydraulic power room for supplying the driving force for the exciter,
- top surface of the table level with the building floor.

The STF, constructed under contract by the MTS corporation, had its final acceptance test in 1982, [3]. The facility was utilized for testing until 1985, at which time the project for which it was constructed was terminated and the STF was ordered to be closed down. A detailed history of the facility and the subsequent recommissioning is given in a paper and poster session at this conference, [4]. Some of the major features and capabilities of the facility are shown in Fig. 4 and details are listed in Table 1.

The upper table top of the STF is a solid block of steel with 6 x 6 x 3-ft dimensions. The entire upper table assembly is made of four solid steel casings weighing about 50,000 lb. The top surface of the upper table has tapped mounting holes (Fig. 5) for attaching fixturing to hold the specimens to the table. This table is guided in pure vertical and horizontal motion by hydraulic bearings sliding on surfaces in the foundation and on the secondary table. The upper table is actuated vertically by the lower table and horizontally by an actuator reacting to the ground. The upper table slides horizontally with respect to the lower table on two hydraulic pressure balanced bearings and is preloaded to the lower table by a third pressure balanced bearing.

A mechanical stop system is provided that consists of 16 Efdyn shock absorbers mounted on the lower table assembly. Four shock absorbers react to the over-travel movement of the tables in the + or - horizontal direction for the upper table and the + or - vertical direction for the lower table.

The lower table assembly is a 25,000 lb box-shaped steel plate with dimensions of 1 x 6 x 5 ft that is guided vertically by the walls of the foundation.

The two-part table configuration completely uncouples the vertical motion from the horizontal. The horizontal actuator is compensated electronically for its arcing motion by the cross-coupling circuitry in the horizontal controller. Two nitrogen spring cylinders support the weight of the tables and the specimen.

MASS TUNER (TEST MAST)

As stated previously, the STF had been in a shut-down mode for approximately 5 years prior to the present efforts to recommission the facility. In the process of recertification and recalibration of the STF, it was decided that a test specimen with known mass and stiffness characteristics would provide valuable information about the table.
capability. This specimen could not only be utilized to calibrate the STF but would help to determine the maximum operating envelope of the table under a payload which was at the stated limit of the system. During original table acceptance testing, a payload of about 50% of the stated limit payload of 15,000 was used.

Design, analysis and fabrication of a test specimen to meet the stated goals was accomplished. This structure, referred to as the shake table test mast (STTM) consists of a large diameter cylinder and stiffening “T” flange members welded to a common baseplate (Fig. 6). Large rectangular weights are mounted on top of the cylinder portion of the mast to provide the required total mass and center of gravity control. All material of the STTM is A36 steel. The baseplate is 1.5 in. thick and is bolted to the shake table top using twenty-four 1.25-in, diam high strength bolts. The STTM was designed to have a first mode frequency in the direction of table horizontal motion of greater that 25 Hz in order to prevent any resonance with the table input.

ANALYSIS OF THE STTM

In order to verify the design of the STTM, a finite element model of the structure was formulated and analyzed with the MSC/NASTRAN code, [5]. The objective of the analysis was to check that the first mode of vibration of the STTM in the excited plane was at least 25 Hz and also to check stress levels in the STTM structure for the proposed tests. A PATRAN, [6], model of the STTM was created.
Table 1. STF Major Features and Capabilities

<table>
<thead>
<tr>
<th>Major features:</th>
</tr>
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<tbody>
<tr>
<td>- Test Table: 6 x 6 ft, level with building floor</td>
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<tr>
<td>- Payload (specimen weight): 15,000 lb</td>
</tr>
<tr>
<td>- Primary Table Weight: 55,000 lb solid steel</td>
</tr>
<tr>
<td>- Secondary Table weight: 25,000 lb solid steel</td>
</tr>
<tr>
<td>- Foundation/Reaction Mass: 1.6 million lb</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Safety Features:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Limiting Interlocks</td>
</tr>
<tr>
<td>- Overtravel Shock absorbers</td>
</tr>
<tr>
<td>- Retaining Structure</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Shaker System Capabilities:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Frequency range from 0.1 to 20 Hz</td>
</tr>
<tr>
<td>- Displacement up to +/- 7.6 in.</td>
</tr>
<tr>
<td>- Velocity up to +/- 12.0 in/s</td>
</tr>
<tr>
<td>- Acceleration up to 0.25 g</td>
</tr>
<tr>
<td>- Tilt requirement of &lt; 0.001 rad</td>
</tr>
<tr>
<td>- Power 125 HP</td>
</tr>
<tr>
<td>- Overturning moment 125 kip-ft</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vertical Actuator:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- MTS modified 204.60 s</td>
</tr>
<tr>
<td>- Force rating: 27 kip</td>
</tr>
<tr>
<td>- Stroke: 19 in.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Horizontal Actuator:</th>
</tr>
</thead>
<tbody>
<tr>
<td>- MTS Modified 204.63 s</td>
</tr>
<tr>
<td>- Force rating: 22 kips</td>
</tr>
<tr>
<td>- Stroke: 19 in.</td>
</tr>
</tbody>
</table>

(31) and modal and stress analysis were performed with the MSC/NASTRAN code, Version 66. The finite element model had a simulated weight of 15993.6 lb and the center of gravity was located at 104.55 in. above the bottom of the baseplate or the table top.

As the analysis of the STTM proceeded, a major concern arose with the number and size of the attachment bolts available for bolting of the STTM to the top of the shake table. As shown in Fig. 4, the pattern of bolts in the table surface required using 12 main attachment bolts, 1.25 in. in diameter and four secondary bolts of 5/8-in. diam. Early analysis conservatively assumed that only the bolt locations were fixed in the model and this assumption indicated a first mode frequency of much less than the desired value of 25 Hz, while results, with an assumption of full fixity at the base of the model, gave a first mode frequency of 29.9 Hz. This resulted in a study of the number of bolts required, bolt preload requirements, and eventually resulted in the redrilling of the small diameter (5/8-in.) holes to make them the same size and depth as the larger holes in the table (1-1/4-in. holes, 3 in. deep). After the baseplate redesign and bolt change, the fundamental frequency of the STTM was determined to be 25.8 Hz with the assumption of the baseplate supported only at the bolts and 30.2 Hz with the entire baseplate assumed fixed. This indicated that the design requirement had been achieved.

An investigation of the stresses in the STTM resulting from the proposed tests was also performed with the finite element model. The model was subjected to combined deadweight and equivalent lateral load of 0.25 g in the plane of excitation. Stresses were found to less than 2000 psi for both base fixity conditions described above.

To date, checkout of the STTM has been performed, actual weights and center of gravity were obtained as well as a modal survey of the STTM with an impact hammer system. Results of these surveys and comparison with the finite element model and its prediction show that a very close correlation is obtained between the STTM weight, center of gravity (CG) location and its fundamental frequency.

A series of tests are planned for the shake table, essentially following the original acceptance tests performed by MTS in 1982, [3]. However, one problem that has risen during the recommissioning process is the operation of the control system computer software on the shake table. Attempts to read archived computer tapes of the system software have been unsuccessful, and options are being studied for either reworking the old control system or upgrading it with a newer system. Until this issue is resolved, testing will proceed with simpler table input motions. Sinusoidal sweep tests will be the first type of tests performed. Later, wave-form earthquake, table angular motion, table cross-axis motion, fail safe/actuator shutdown, and power failure shutdown tests are scheduled.

As mentioned, it will be very important for the STTM testing program to verify the table capability envelope (Fig. 8). This information will aid to determine the configuration of wall specimen which can be tested on the table.

HCTW SPECIMEN SEISMIC TESTING PROGRAM

A literature review was conducted to assess the current state-of-the-art of shake table testing of masonry structures, [8]. For some 20 years, researchers have studied the dynamic response of in-filled frames, although with
many divided opinions about the role of in-fills. Generally, testing has been grouped into either in-plane behavior, out-of-plane behavior or a combination of both.

Seismic In-Plane Behavior

The purpose of an investigation by Mann, Konig, and Otes, [9], was to examine the behavior of unreinforced brick masonry walls subjected to in-plane horizontal dynamic loading. The wall sizes were 1.25 x 1.25 x 0.115 meters with a variety of brick joint and applied vertical stress configurations. Units with lower applied vertical loading imposed on the wall developed diagonal stepped cracks along the mortor joints. Units with high vertical loading formed sudden relatively straight diagonal cracks, and failure was by sudden collapse. It was found that the crack formation coincides in principle with that produced by static loading, with the additional feature that the cracks crossed one another due to the changing direction of the acceleration.

Clay brick masonry wall tests were conducted by McNiven and Mengi, [10], and a mathematical model was developed for predicting the nonlinear, dynamic shear behavior, and its damping coefficients.

Dawe, Schriver, and Sofocleous investigated the behavior of steel frames in-filled with brick masonry under earthquake type loading, [11]. A one-bay, one story frame was subjected to in-plane ground motion on a shake table to determine the increase in strength of the system due to the presence of the masonry panel. The effects of frame stiffness and roof slab rigidity on the system response were also determined and simple analytical models to predict the behavior of the coupled frame-wall system was developed. The study revealed that brick masonry in-fill markedly increases the dynamic strength and stiffness of the system as do stiffer frames and rotationally rigid joints.
Seismic Out-of-Plane Behavior

A series of out-of-plane shake table tests of clay brick walls is presented by Bariola et al., [12]. Walls were single standing and subjected to its own weight. There were no columns or reinforcement. Variables of the study were slenderness ratio (height/thickness) of the wall and thickness of the wall. Unexpectedly, the results showed that the motion intensity required for wall failure did not seem to decrease for increasing slenderness.

CANTILEVER WALL SPECIMEN TESTING

The first series of specimens planned for testing on the shake table are to be simple unrestrained walls (cantilever) constructed from full size hollow clay tiles, [13]. It was decided that these first specimens should be simple yet applicable to the behavior of in-filled hollow clay tile walls. As detailed in the literature review, testing of this type of specimen has been done, but on materials other than hollow clay tiles. Early plans call for testing these walls for seismic excitation in both in-plane and out-of-plane directions. A typical test setup of a wall is shown in Fig. 9.

After tests on a series of cantilever walls are completed, it is planned to proceed to tests for in-filled walls. For these tests, columns and beam members would have to be added to the test specimen. Plans are under way to design and build the specimen supporting structure to accommodate the variety of test configurations. This test hardware which bolts to the shake table head and supports the various specimens is generally referred to as the “universal beam structure.”

Initial plans for sizing test specimens of a tile wall indicated that wall widths of up to 12 ft and heights of 10 ft were desirable. Given the restricted width of the shake table of 6 ft, a structure which would act as a “head expander” was required. The design of structural hardware to
accomplish these goals has proceeded. Total weight of specimen and universal beam hardware was a major concern because of shake table limitations on payload and acceleration. The design of a universal beam structure was completed with close attention given to weight, stiffness, and stress levels for projected maximum wall specimen weights and sizes.

Initial costs estimates for fabrication of this universal beam structure have been much higher than expected, and this has caused a reexamination of the specimen sizes necessary to provide support to the hollow clay tile program. Efforts are now under way to design a fixture which will accommodate only a 6-ft wide specimen and will be simple to construct. Since the objective of the shake table tests of wall specimens is to provide information to support analytical predictions, it is believed that 6-ft wide wall specimens will satisfy this goal.

ADDITIONAL TESTING PROGRAMS

Planned tests for the STF after the Hollow Clay Tile Wall Program will depend on applicability and capability to other programs being conducted. However, it is thought that the STF is a valuable asset to the DOE and may be used by researchers from industry, government, and universities.

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Fig. 6. Photo of STTM Mounted to Table Top
Fig. 7. PATRAN Model of STTM
Fig. 8. STF Capability Envelope

REFERENCES


Fig. 9. Typical Wall Specimen setup on STF

Note: Catch net removed for clarity


