Earthquake Engineering, Tenth World Conference © *1992 Balkema, Rotterdam. ISBN 90 5410 060 5*

A hollow clay tile wall seismic performance program overview

J.E. Beavers, W.D. Jones & W.C.T. Stoddart
Center for Natural Phenomena Engineering, Martin Marietta Energy Systems Inc., Oak Ridge, Tenn., USA

ABSTRACT: An overview of a multiyear hollow clay tile wall (HCTW) program being conducted by Martin Marietta Energy Systems, Inc., at the Oak Ridge Y-12 Plant,[1] for the U.S. Department of Energy is presented. The purpose of the HCTW program is to determine the load capacity of unreinforced infilled HCTW buildings when subjected to earthquakes. Progress to date tends to indicate that extensive retrofit of such structures may not be warranted in low-to-moderate seismic zones.

1 INTRODUCTION

Many structures in the United States, especially the central and eastern United States, are constructed of unreinforced masonry. One type of unreinforced masonry, hollow clay tile (HCT), was used extensively as an infill during building construction throughout the United States, especially during the early to middle 1900s. As a result, the U.S. Department of Energy (DOE) has a significant inventory of buildings with infill walls constructed of unreinforced HCT. These buildings do not meet today's seismic standards for new construction.

Bennett and Flanagan (1992) conducted an extensive literature review that revealed no relevant research on the performance of hollow clay tile walls (HCTWs) under seismic loading. To determine the seismic performance of HCT buildings, the Center for Natural Phenomena Engineering (CNPE) of Martin Marietta Energy Systems, Inc. (MMES), is conducting a HCTW testing and analytical program for DOE. The program was initiated in the spring of 1990 and includes in situ, laboratory, full-scale building, and shake table tests; nondestructive evaluation (NDE) development; and analytical studies. The program is focused on the goals of providing information and guidance in the use of this information for assessing the behavior and, if required, identifying cost-effective methodology for retrofitting these buildings.

Nineteen types of in situ and laboratory tests are being performed, ten of which are both in situ and laboratory. The total number of tests to be performed is approximately 110 in situ and 190 laboratory. The NDE program consists of developing techniques to determine HCTW construction quality and infill boundary conditions. The analytical portion of the project consists of research on existing analysis methods and on the development of analytical evaluation techniques for buildings and components.

Building analysis consists of modeling and analyzing entire structures. Potential analysis techniques are either equivalent static analyses (such as the UBC code R_w factors) or dynamic methods, such as time history analysis. Modeling of the HCT infills may need to be simplified, using, for example, equivalent struts. Component analysis involves developing an appropriate constitutive model for the HCT and an appropriate idealization. All components that are tested, such as prisms, in-plane infills, and out-of-plane infills (air bag tests), will be analyzed, and parametric studies will be performed. It is expected that this approach will lead to the development of simpler idealizations that can be used in the analysis of entire building structures.

Following the Loma Prieta earthquake of October 18, 1989, a significant number of buildings constructed of HCT in the San Francisco area were found to be damaged, including the city hall of Oakland, California. In addition, those that were not damaged or experienced little damage are being examined for the need for retrofit. The results of this HCTW program will provide significant insight into the performance of such structures and provide a methodology for evaluating HCT buildings that better represents their performance. In fact, in low-to-moderate seismic zones, the results may indicate that, although many such structures were not designed for seismic loads, major retrofit may not be required, as might be indicated from using conventional analysis techniques in the evaluation process.

2 SPECIFIC GOALS AND BUILDING CODES

As noted above, the general goal of the HCTW program is to develop recommendations for assessing the behavior of buildings constructed of infilled, unreinforced HCTWs. The program focuses on HCTW

---

[1] Managed by Martin Marietta Energy Systems, Inc., for the U.S. Department of Energy under contract DE-AC05-84OR21400.

buildings located in zones of low-to-moderate seismicity, although the results are directly applicable to high seismicity zones. If infilled, unreinforced HCTW building construction can be shown to have inherent capacity above that normally assumed by design codes, retrofit may not be required in low-to-moderate seismicity zones if a risk-based approach is adopted. A risk-based approach is based on the principle that, while the building may not meet today's codes and standards requirements, the expected seismic performance is reasonably understood and has sufficient margins of safety. To help accomplish these goals, testing and improved understanding are required.

A second principle that has an impact on the issue of whether or not to retrofit in low-to-moderate seismicity zones is the cost increment for retrofitting. In many cases, the cost for retrofitting a building to a higher seismic capacity rather than to a lower seismic capacity is not much more than the cost for retrofitting to the lower seismic capacity; hence, the incremental cost may be very low. For example, the cost for installing a 1-in.-diameter (25.4-mm) bolt required for the retrofit of a building in a moderate or high seismic zone is basically the same cost as that for installing a 0.5-in.-diameter (12.7-mm) bolt in the same building for retrofit in a low seismic zone. Thus, the most significant cost impact for retrofitting buildings in low-to-moderate seismic zones is not the seismic capacity level of retrofit, but the decision, or requirement, to retrofit.

Building codes in the United States generally specify that the capacity of unreinforced masonry, due to its brittle nature, be limited to a stress less than the stress that causes cracking. However, the overall seismic capacity of an infilled masonry building panel can be an order of magnitude higher than its load capacity when the first crack occurs or as indicated by baseline design codes. This leads to a key proposition in the risk-based approach to a "no retrofit philosophy" for existing construction in low-to-moderate seismic zones. This proposition is that, even though HCTWs may crack when earthquakes occur, overall stability (no collapse) will be maintained. Thus, significant cracking of infilled walls is being described by the authors as acceptable damage for buildings in low-to-moderate seismic zones. Therefore, the principal basis of the research and development program on HCTWs described in this paper is to investigate and develop understanding and computational methods for determining post-cracking behavior, including ultimate load capacity, of infilled, unreinforced HCTW building construction.

3 HCTW PROGRAM DESCRIPTION

The HCTW program at MMES is divided into four elements of work in a classical engineering work breakdown structure (WBS), shown in Fig. 1.

WBS 1.2 is HCTW testing which represents the part of the program that includes static, in situ, and laboratory testing of HCTWs and wall components. WBS 1.3 is analytical modeling and analysis, which consists of research of methodologies, pre- and post-test analyses, and the development of evaluation methodologies that incorporate the results of all research efforts. WBS 1.4 is the seismic shake table facility, which is designed to show that the evaluation methodologies selected, based on static testing, are conservative when tested dynamically. Thus, the evaluation methodology selected will provide a better, but still conservative, seismic performance estimate of HCTW buildings. The final element of the HCTW program is WBS 1.8, NDE research and development. For proper evaluation of an existing HCTW building, it is imperative that the existing condition of the HCTWs and the boundary conditions between the HCTWs and the structural framing be determined. Thus, a significant amount of effort in the HCTW program is the establishment of NDE techniques that can correlate controlled laboratory-constructed specimens to in situ wall construction and that can be relied on to properly define key parameter inputs to the evaluation methodologies.

4 DESCRIPTION OF HCTWS

The specific infilled, unreinforced HCTWs studied in this program are constructed of multi- or single-wythe HCT, usually 8 in. (203.2 mm) or 12 in. (304.8 mm) in width, using running bond, with all cores laid horizontally. Double-wythe walls in this program are constructed of 4-in. (101.6-mm) and 8-in. (203.2-mm) HCTs staggered to give overlapping head joints, as shown in Fig. 2. The 4-in. (101.6-mm) and 8-in. (203.2-mm) tiles are also staggered from course to course. In this type of construction, no continuous collar joint exists; however, in each row, the 4-in. (101.6-mm) and 8-in. (203.2-mm) tiles are separated by a 0.5 in. (12.7 mm) to 1 in. (25.4 mm) gap. In forming the full wythe bed joint, some mortar has fallen into this gap. There is no vertical or horizontal reinforcement in the walls. The HCTWs are placed within the steel and concrete framing with varying offsets to the framing centerline depending on the particular building. In some cases, HCT pilasters, integrated with the continuous HCTW, are actually framed around a column as the HCTWs transverse the length of a building.

5 PREVIOUS HCTW PROGRAM ACTIVITIES

Aspects of the HCTW program have been going on since 1989; however, the program was not fully developed, as shown in Fig. 1, until mid-1990. Beavers, Bennett, and Flanagan (1991) discussed an earlier version of the program and referred to some test results, while Fricke and Jones (1990, 1991) described the results of some of the earlier tests of element WBS 1.2, defined as a subelement WBS 1.2.1, push-test. Nine push-tests to measure the shear strength of the mortar bed joint were reported. The average shear strength was found to be 99 psi (683.1 kPa), with a standard deviation of 32.5 psi (224.3 kPa). Butala, Jones, and Beavers (1991) have described some of the work in WBS 1.3.2, pre- and post-test analyses in preparation of testing activities of WBS 1.2.14, wall-column bending. By examining analytically the potential implications of story drift on the out-of-plane performance of such walls, they found that building drift in the out-of-plane direction imposed more bending stress on a wall panel than did inertial forces on the wall

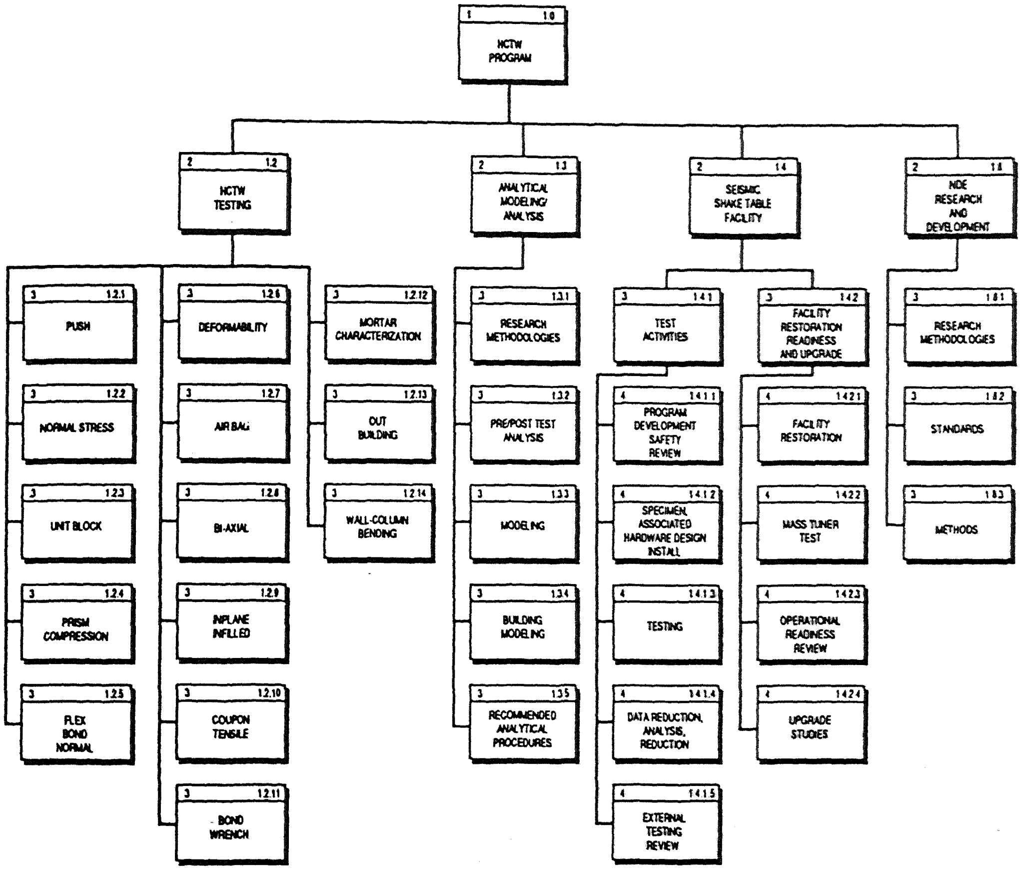

Fig. 1. HCTW program work breakdown structure.

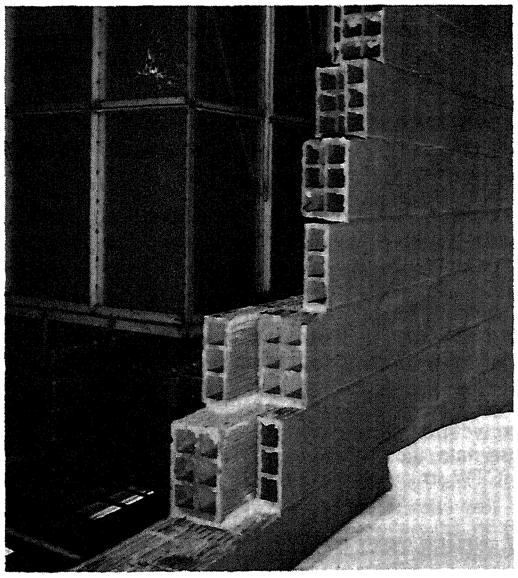

Fig. 2. Cut-section of an infill HCTW.

panel itself. This stress caused horizontal cracking to occur at a "g" level less than 5% (5%g). They also reported that the cracking would occur along several mortar joints, such that the steel framing would act independently at a frequency of 0.75 Hz; therefore, the inertial forces acting on the wall would be small, and it would remain stable and standing. The question posed here is, How much in-plane strength remains, given the out-of-plane horizontal cracking? This concern will be further addressed by testing in WBS 1.2.14.

Chua (1991), using existing analysis methodologies, conducted a parametric study of boundary conditions, Poisson's ratio, and other parameters to determine a best approach to estimate ultimate out-of-plane behavior of infilled HCTWs. As noted by Beavers, Bennett, and Flanagan, Chua found that for static out-of-plane loads, the modulus of rupture and the modulus of elasticity had the most significant effect on first panel cracking, while Poisson's ratio and shear moduli had little effect.

6 RECENT HCTW PROGRAM RESULTS

Under the HCTW testing element WBS 1.2, one major subelement is the air bag test, identified as WBS 1.2.7.

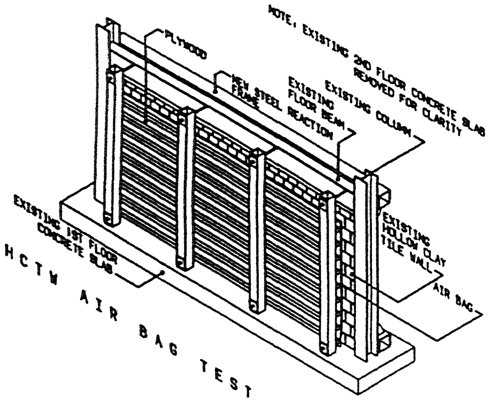

Fig. 3. Isometric schematic of HCTW air bag test.

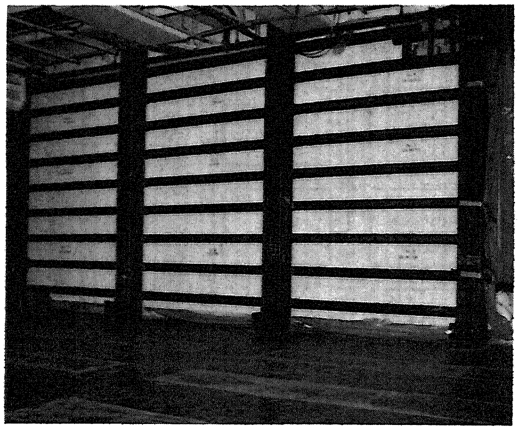

Fig. 4. Air bag test HCTW with loading frame.

An air bag test is the application of out-of-plane loading to an infilled wall using a pressurized air bag (Dawe and Seah 1989). The first air bag test (Fricke, Huff, and Jones 1992) was conducted in October 1991. The test was conducted on a 8-in. (203.2-mm) single-wythe HCTW 28 ft (8.53 m) wide by 12 ft (3.66 m) tall infilled within a steel frame of W14X142 columns, a W30X108 overhead beam, and a concrete floor slab. This test was conducted on the first floor of a five-story building. A schematic of the test setup is shown in Fig. 3, with the actual wall and corresponding reaction frame shown in Fig. 4.

For design purposes, conventional methods using code allowables and a static analysis would generally be based on one-way action in the short (vertical) direction. This procedure would predict a uniform loading limit equivalent to an inertial load of approximately 0.1*g*. However, as discussed by Fricke, Huff, and Jones, the test results revealed an equivalent inertial load capacity of around 3*g*, thirty times their results obtained from the conventional approach. These researchers also looked at other alternative conventional evaluation methods and compared the results to their test results. In all cases, the test results revealed a minimum in situ out-of-plane seismic capacity of 13 times the least conservative conventional method. The basic reason for the underestimated capacity resulting from conventional methods is the lack of consideration of two-way arching action that actually occurs in infilled walls. The load deflection curve for the central point of the wall is shown in Fig. 5.

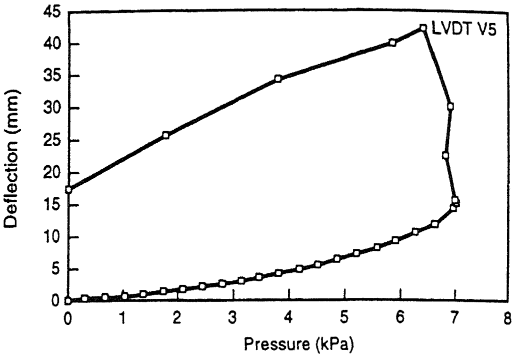

Fig. 5. Air bag test HCTW central point load-displacement curve.

More recently, Flanagan, Bennett, and Barclay (1992) conducted three laboratory in-plane tests, on full-scale infilled HCTWs. These tests were part of a sixteen-test program under subelement WBS 1.2.9, designed to study failure mode, shear wall performance, load transfer mechanism, energy absorption, and hysteretic behavior of HCTW infilled frames having various frame to infill stiffness ratios. The walls were 8 ft (2.4 m) in height and width, constructed with single-wythe 8-in. (203.2-mm) HCTs, placed between the flanges and against the column webs, as is much of the construction of DOE facilities. For each test, the overhead beam size was held constant at W12X35 while the column sizes for each test varied (W10X12, W10X30, and W10X45).

For determining the in-plane capacity, conservative conventional analyses usually result in defining that capacity as being the load at which the first shear crack occurs in the infilled wall. The results of the three tests when applied to a first floor interior wall of a typical three-story DOE building showed that the equivalent in-plane seismic capacity was approximately 0.3*g* at first panel cracking. Applying the ultimate capacities of the tests to this typical building indicated an equivalent in-plane seismic capacity of approximately 0.8*g*. A typical failure mode at the completion of each test is shown in Fig. 6, while Fig. 7 shows a typical hysteretic curve of the in-plane load versus deflection.

Again, the analysis of these tests showed that conventional analysis techniques are inadequate to estimate the ultimate performance of unreinforced HCTW structures of the type described herein.

7 OTHER TEST RESULTS

As shown in Fig. 1, unit block tests (WBS 1.2.3), bond

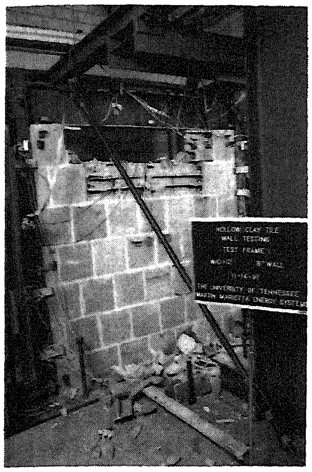

Fig. 6. In-plane laboratory HCTW test cyclic failure mode.

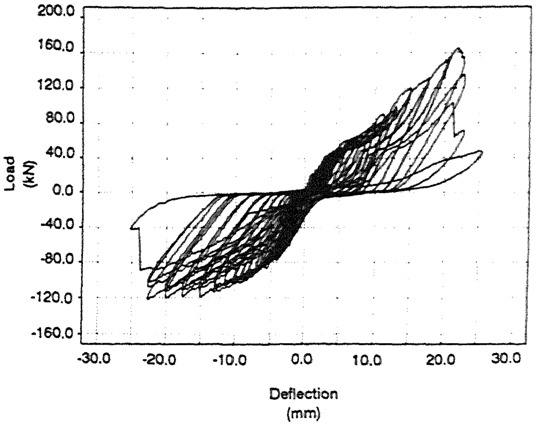

Fig. 7. In-plane laboratory HCTW test load-displacement hysteretic curve at top of wall.

wrench tests (WBS 1.2.11), and prism compression tests (WBS 1.2.4) are also being conducted in support of the overall program. Fifteen unit block tests (ten in compression parallel to cores and five splitting tensile strength perpendicular to cores) have been conducted with an average net compression stress of 5539 psi (38,194 kPa) and a standard deviation of 634 psi (4,391 kPa). The average splitting tensile strength was 351 psi (2420 kPa) with a standard deviation of 106 psi (731 kPa). The results of prism compression tests showed an ultimate capacity of 228 psi (1573 kpa) when loaded perpendicular to the cores.

Preliminary bond wrench tests on the air-bag-damaged wall have shown an average ultimate tensile capacity of the bed joint mortar to be 16 psi (110 kPa). As the HCTW testing program continues, additional tests and corresponding results will be reported.

8 SUMMARY AND CONCLUSION

The HCTW program is a multiyear testing and analytical effort to address the seismic performance of steel and concrete frame structures with infilled HCTWs. The first year of an approximate three-year program has been completed. Results to date support the assertion that infilled HCTW structures can have significantly more inherent strength than conventional analysis and code allowable stresses would imply, and must be treated as structural systems.

Some progress has been made in developing alternative analytical methods, but more test data are needed to support current results. The program is being documented, with technology transfer as one of its goals. As further testing is conducted and analytical techniques verified and/or developed, results will be published. Based on the preliminary results of the HCTW program, it is believed that many unreinforced HCTW buildings in low and moderate seismic zones may not require retrofit, when evaluated using a risk-based approach. Further testing and analytical development are expected to confirm this assertion.

REFERENCES

Beavers, J.E., R.M. Bennett, & R.D. Flanagan. 1991. Research on unreinforced hollow clay tile walls and developments of computational mechanics. *U.S./China Joint Workshop on Computational Mechanics*, September 24-28, Beijing, China.

Bennett, R.M. & R.D. Flanagan. 1992. *Structural Testing of Clay Tile Walls: Testing and Evaluation Program*, Y/EN-4325, Center for Natural Phenomena Engineering, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, USA.

Butala, M.B., W.D. Jones, & J.E. Beavers. 1991. Out-of-plane behavior of hollow clay tile walls infilled between steel frames. *Proc. of the Third Department of Energy Natural Phenomena Hazards Mitigation Conference*, October 15-18, St. Louis, Missouri, USA.

Chua, L.S. 1991. Out-of-plane behavior of unreinforced hollow clay tile masonry infilled wall panels. Thesis presented for the Master of Science degree, University of Tennessee, Knoxville, Tennessee, USA.

Dawe, J.L. & C.K. Seah. 1989. Behavior of masonry infilled steel frames. *Canadian Journal of Civil Engineering*, 16: 865-76.

Flanagan, R.D. & R.M. Bennett. 1991. Analytical modeling of masonry infilled steel frames. *Proc. of the Third Department of Natural Phenomena Hazard Mitigation Conference*, October 15-18, St. Louis, Missouri, USA.

Flanagan, R.D., R.M. Bennett & G. Barclay. 1992. Experimental Testing of Hollow Clay Tile Infilled Frames. *Proc. of the Sixth Canadian Masonry Symposium*, University of Saskatchewan, July 15-17, Saskatoon, Saskatchewan, Canada.

Fricke, K.E. & W.D. Jones. 1990. A test program to determine the structural properties of unreinforced hollow clay tile masonry walls of the DOE Oak Ridge plants. *Proc. of the Fifth North American Masonry Conference*, University of Illinois, Champaign, Illinois, USA: 747-758

Fricke, K.E. & W. D. Jones. 1991. A test program to determine the structural properties of unreinforced hollow clay tile masonry walls of the DOE Oak Ridge plants. *Masonry Society Journal* 9: 56-63.

Fricke, K.E., T.E. Huff & W.D. Jones. 1992. In situ lateral load testing of an unreinforced masonry hollow clay tile wall. *Proc. of the Sixth Canadian Masonry Symposium*, July 15-17, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.