U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY

BIBLIOGRAPHIC DATA SHEET

1. PB93-206183

2. PERFORMING ORGANIZATION REPORT NUMBER

3. PUBLICATION DATE

TITLE AND SUBTITLE

Research Plan for Masonry Shear Walls

AUTHOR(S)

S.G. Fattal

PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

SUPPLEMENTARY NOTES

NIST Category No.
NIST- 140

ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

A masonry research plan is presented based on studies of the behavior of masonry shear walls conducted at the National Institute of Standards and Technology (NIST). The purpose of the plan is to acquire additional information to allow formulation of a design methodology. It consists of experimental and analytical investigations of masonry shear walls subjected to simulated earthquake loads. The experimental program consists of tests of lightly-reinforced and partially-grouted specimens representing design and construction practices in regions of low-to-moderate seismicity. The analytical work consists of formulations of equations to evaluate strength and deformation limit states and numerical studies of discreet models.

KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

building technology; critical parameters; masonry; earthquake response; lightly-reinforced; partially-grouted; reinforced walls; shear strength; shear walls; test strength; ultimate deformations; ultimate strength

AVAILABILITY

- [X] UNLIMITED
- [ ] FOR OFFICIAL DISTRIBUTION. DO NOT RELEASE TO NATIONAL TECHNICAL INFORMATION SERVICE (NTIS).
- [ ] ORDER FROM SUPERINTENDENT OF DOCUMENTS, U.S. GOVERNMENT PRINTING OFFICE, WASHINGTON, DC 20402.
- [X] ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES

15. PRICE

ELECTRONIC FORM

PB93-206183

NISTIR 5117

Research Plan for Masonry Shear Walls

S. G. Fattal

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards and Technology
Gaithersburg, MD 20899

NIST

NISTIR 5117

Research Plan for Masonry Shear Walls

S. G. Fattal

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Gaithersburg, MD 20899

June 1993

U.S. DEPARTMENT OF COMMERCE
Ronald H. Brown, Secretary

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Arati Prabhakar, Director

ACKNOWLEDGEMENT

The author acknowledges the contribution of Mark B. Hogan who critically reviewed the manuscript as Washington Editorial Review Board Reader.

ABSTRACT

A masonry research plan is presented based on studies of the behavior of masonry shear walls conducted at the National Institute of Standards and Technology (NIST). The purpose of the plan is to acquire additional information to allow formulation of a design methodology. It consists of experimental and analytical investigations of masonry shear walls subjected reverse cyclic lateral loads. The experimental program consists of tests of lightly-reinforced and partially-grouted specimens representing design and construction practices in regions of low-to moderate seismicity. The analytical work consists of formulations of equations to evaluate strength and deformation limit states, and numerical studies of discrete models.

Key Words: Building technology; deformations; earthquakes; limit states; masonry; partially-grouted; reinforcement; shear strength; shear walls; strength design; tests.

CONTENTS

UNITS

SI units are used in this report. U.S. Customary Units are also included as a supplement to recognize the state of current masonry practices in the U.S. At the present time, masonry Codes and Standards, construction specifications and tolerances, and nominal and actual sizes of standard masonry units manufactured in the United States are all specified in U.S. Customary Units.

1. INTRODUCTION

The National Earthquake Hazards Reduction Act (NEHRA) passed by the U.S. Congress in 1977, and reauthorized in 1990 (P.L. 101 -G14), assigned the National Institute of Standards and Technology (NIST) the mission to carry out research and development to improve building codes and standards and practices for structures subjected to earthquakes. The NIST masonry research program is part of that mission. The program calls for analytical and experimental studies of the response of masonry shear walls under reversed cyclic loads. The research is an extension of the work carried out for the Technical Coordinating Committee for Masonry Research (TCCMAR) and its joint U.S.-Japan component (JTCCMAR).

The NIST masonry program has been implemented in part by the following studies.

The technical literature of experimental investigations of masonry shear walls conducted since 1975 in the U.S. and abroad were reviewed. About 700 tests were identified, analyzed, and classified according to the type and range of variables used in the tests [1].

The correlation of four equations for estimating the strength of fully-grouted masonry shear walls with test results was examined [2]. A similar correlation study was carried out for partially-grouted masonry shear walls using a strength-predictive equation proposed by Matsumura and experimental results (Equation 1, Ref. [3]). A modified equation, developed by the author of the same study (Equation 6, Ref. [3]), showed closer correlation with the test results of partially- and fully-grouted walls than that proposed by Matsumura.

The effect of critical parameters on load and deformation limit states of masonry shear walls were evaluated [4], based on test data and the modified equation developed earlier [3].

The experience gained from these studies brought into focus the scope of a research plan to develop a rational basis for the analysis and design of masonry shear walls. Section 3 defines the scope of the plan. Section 4 presents a statement of the problem which the plan will address. Section 5 describes the completed experimental and analytical tasks in support of the plan. Sections 6 and 7 describe the specific experimental and analytical tasks of the plan, respectively. Section 8 explains the criteria used in the development of the plan.

2. OBJECTIVE

The objective of the proposed research plan is to establish a data base which can be utilized to develop improved design guidelines for partially-grouted masonry shear walls. The report documents the plan in detail, including the definition and phasing of the experimental and analytical tasks, and explanation of the reasons for their inclusion in the plan.

3. SCOPE

The research plan has experimental and analytical components. The experimental plan calls for 52 lateral load tests of partially-grouted reinforced shear walls and diagonal compression tests of companion wallettes. Both hollow concrete block and hollow clay brick construction are represented. The concrete block specimens will be tested first. The walls will be tested in the NIST tri-directional testing facility (TTF) in the upright configuration, with the top and bottom surfaces kept rotationally fixed during testing. They will be subjected to a predefined reverse cyclic lateral displacement history. The displacements will be imposed at the top of the specimens.

The analytical work will be in phase with, and partly dependent on the results of the experimental tasks. Two analytical interactive tasks are planned. Expressions will be developed to estimate load and deformation limit states based on experimental observations of shear wall response mechanisms. Simultaneously, the use of available computer-based numerical analysis methods will be explored to aid the development of limit state equations and load-displacement response envelopes. The analytical tasks are dedicated to the development of a methodology that can serve as a basis for the analysis and design of masonry shear walls for construction in regions of low-to-moderate seismicity.

Two to three years will be required to implement the research plan and develop a design methodology. The scheduling and sequencing of the tasks were established according to a list of priorities so that the implementation of the earlier tasks can have a greater impact toward meeting the overall objective of the plan.

4. PROBLEM SIGNIFICANCE

Industry statistics [5] show that masonry construction represents seven percent of new construction in the United States. Worldwide, the majority of existing buildings use masonry construction, which is, for the most part, unreinforced. In the U.S., the masonry industry employs half a million people and has annual sales of $17 billion.

Generally, two types of masonry components are used in building construction: load-bearing and non-load-bearing walls. Both types behave as shear walls under seismic excitations.

Research information on the behavior of masonry shear walls is limited. According to an earlier NIST study [1], about 700 masonry shear wall tests of various types and configurations have been reported worldwide since 1975. Of these, about 60% are fully-grouted heavily-reinforced walls representing the type of construction practice suitable for high seismic risk areas; about 30% are plain wall tests, mostly conducted at NIST, representing construction in areas where seismic requirements do not govern their design; and about 10% are tests of partially-grouted walls, mostly conducted in Japan, suitable for regions of low-to-moderate seismicity, where most of the masonry construction in the U.S. occurs.

The amount of usable experimental data on masonry shear walls is considerably less than the available data from the 700 shear wall tests noted above. From the available test data base on reinforced walls, after elimination of tests of coupled, infilled, flanged and perforated specimens, and specimens built with scaled or substandard units, only 62 tests of fully-grouted specimens [2] and 72 tests of partially-grouted specimens [3] could be utilized for the purpose of evaluating research needs.

As a consequence of the scarcity of research information on the behavior of masonry shear walls in general, and lightly-reinforced walls, in particular, additional tests are needed to verify the adequacy of design equations in current codes.

5. COMPLETED TASKS

The research plan is presented in Figure 1. It consists of modular interactive tasks involving both experimental and analytical work with intermediate outputs. The tasks which have been completed, including that documented in this report, are shown above the heavy staggered line across the page. The completed tasks are described briefly in the following sections.

5.1 Experimental Tasks

The preparatory tasks of the experimental component of the research plan (Task 3) has been in progress since the start of the technical literature review (Task 3.1). The study ("SOA Report") is documented in an NIST publication [1].

Task 3.2

This study identified critical parameters using available test data of partially-grouted masonry shear walls and the strength-predictive equation developed as part of the analytical study of partially-grouted (PG) walls (Task 4.1.2). The results of the "Parametric Study" [4] were used extensively in the development of the experimental program (Tasks 3.3-3.6).

5.2 Analytical Tasks

The analytical component, Task 4, consists of two sets of interactive parallel tasks. Task 4.1 calls for the development of equations to predict shear cracking and strength capacities and their corresponding deformations on the basis of existing and future test results and observed mechanisms of shear wall behavior. Task 4.2 involves exploration of available computer-based numerical analysis capabilities of discrete models as research tools to aid the development of the predictive equations (Task 4.1) of shear wall limit states. A description of completed Tasks follows.

Task 4.1.1

Four strength-predictive equations have beên evaluated against existing test data of fully-grouted (FG) masonry shear walls from as many experimental programs. The study is documented in an NIST report [2].

Task 4.1.2

One strength predictive equation, proposed by Matsumura [7], and one modified equation developed at NIST, have been evaluated against existing test results of partially-grouted (PG) masonry shear walls from three experimental programs. The study ("PG Report") has been documented in an NIST report [3].

Task 4.2.1

Existing finite element software capabilities to model masonry shear wall behavior are being explored.

6. EXPERIMENTAL PROGRAM

The experiments will be carried out in stages (Tasks 3.7 and 3.8), with intermediate test reports for output, in the order of priorities identified in Task 3.4 (Figure 1). The specifics of the experimental program are presented in this section.

The significance of the problem stated in Section 4 underscores the need to develop a better understanding of the lateral-load response of partially-grouted masonry walls. This can be accomplished by experimental research on partially-grouted lightly-reinforced masonry walls so that design equations for these masonry building components can be verified or updated to reflect their observed behavior.

The test specimens have been designed to optimize the number and range of variables without compromising the credibility of results. The plan is modular, with the highest priority tests scheduled up front, for maximum impact. The flexibility of the plan allows for changes of direction or in scope, depending on the availability of resources, with minimum impact on completed tasks. The priorities have been established to optimize potential economic benefits to the industry (see Appendix A).

6.1 Shear Wall Response

To understand the shear wall response characteristics sought, this Section describes major events occurring in a shear wall in its response under lateral loads to failure. The response is characterized by six major events. These events are described below and identified in Figure 2 for a wall in which the top and bottom surfaces are rotationally fixed.

(1) Horizontal tensile cracks in the wall occur at diagonally opposite corners where flexural tensile stresses are high.

(2) Yielding of flexural steel in tension occurs at the same locations.

(3) Shear (tensile) cracking occur in the central region of the wall in the direction of the loaded diagonal causing a redistribution of stresses to reinforcing bars across the rupture surface.

(4) Shear cracks propagate to the loaded corners until a complete rupture plane develops, at which point, lateral loads are resisted by reinforcing bars crossing the rupture plane, and by aggregate interlock within high compression regions near the diagonally loaded corners.

(5) Reinforcement across the rupture plane yields in tension (horizontal bars), and in flexure (double-hinge formation of vertical bars).

(6) Crushing of masonry occurs in the high compression zones at the diagonally loaded corners.

These events do not necessarily occur in the sequence indicated. Furthermore, certain events, such as yielding of reinforcement (events 2 and/or 5) may not even occur, depending on the amount of reinforcement used, the level of axial stress, aspect ratio of the wall, and other factors.

6.2 Critical parameters

The effect of critical parameters on shear wall response was examined using the test results of partially-grouted and unreinforced masonry specimens. The data sources were, 51 PG masonry tests conducted by Matsumura in Japan [7,8], 15 unreinforced wall tests conducted at NIST [10, 11], and 10 PG masonry tests conducted at NIST [9]. As noted earlier, these were the only partially-grouted masonry shear wall tests reported since 1975 [1,3].

The major contribution to the lateral load-resisting capacity of masonry shear walls comes from the following five parameters which have been identified in an earlier study [4].

ρ_h = horizontal reinforcement ratio; the total horizontal steel area divided by the product of height and thickness of wall.

ρ_v = vertical reinforcement ratio; the total vertical steel area divided by the product of length and thickness of wall.

r = aspect ratio of wall (height/length, h/L).

q = axial stress corresponding to axial load Q on the gross horizontal section, A, of wall (Q/A).

f_m = compressive strength of the masonry.

6.3 Response Characteristics

The tests will be set up to generate the complete hysteretic load-displacement response diagrams of the specimens and their envelopes. Special attention will be given to measure the following four response properties identified in Figure 3.

(a) $v_c = V_c/A$ first diagonal cracking strength of the masonry; where V_c is the applied lateral load at first diagonal cracking, and A is the gross horizontal cross-sectional area (length times thickness) of the specimen,

(b) $d_c = D_c/h$ — deformation at first diagonal cracking; where D_c is the lateral displacement at first diagonal cracking, and h is the height of the specimen,

(c) $v_u = V_u/A$ — strength of the masonry at peak lateral load; where V_u is the peak lateral load, and A is the gross horizontal cross-sectional area of the specimen,

(d) $d_u = D_u/h$ — deformation at peak lateral load; where D_u is the lateral displacement at peak lateral load V_u.

These response characteristics will be utilized in the development of design formulations of load-deformation limit states.

6.4 Test Variables and Priorities

Figure 4 identifies the test variables, the fixed parameters, and the priorities which the experimental program will address (Tasks 3.3.1, 3.3.2, and 3.4). The list of variables and fixed parameters were selected from a menu of 15 items as shown. The selection of test variables was guided by the results of the studies identified in Figure 1, in particular, by the study of the effects of critical parameters (Task 3.2).

A. MENU ITEMS THAT ARE TREATED AS FIXED PARAMETERS (Task 3.3.2)

Item 4: Vertical Reinforcement Ratio, ρ_v

The value of vertical reinforcement ratio, ρ_v, the total area of vertical bars divided by the gross horizontal cross-sectional area, has been estimated to make the specimens fail in the shear mode by providing sufficient reinforcement in the outer cells to avoid premature flexural failure. Omission of vertical bars within the inner cells is driven by economic considerations, as explained in Section 8, Commentary.

Item 5: Compressive Strength of Masonry, f_m

Compressive strength, f_m of masonry is specified as a fixed parameter for each masonry type; concrete block and clay brick. The two specified strengths fall within the range of the respective strengths prevalent in masonry construction.

Item 6 Test Replication, R

All specimens are to be tested in duplicate ($R = 2$) to provide a measure of test variability.

Items 8 and 9: Displacement Frequency and Amplitude History

The cyclic displacement frequency and amplitude history will correspond to the sequential phased-displacement history used in the TCCMAR Program.

B. MENU ITEMS SELECTED AS TEST VARIABLES

Item 1: Aspect Ratio, r

Two aspect ratios (height-to-length ratios), 0.6 and 1.0, are selected to examine its effect on shear response. The likelihood of debonding failure (as vs. diagonal cracking through the units) is higher in walls having low aspect ratios, while in specimens of high aspect ratio the possibility of flexure-shear interaction is greater.

Item 2: Horizontal Reinforcement Ratio, ρ_h

Four different ratios, ρ_h = 0, 0.0005, 0.0012, and 0.0026, are selected. The default case, $\rho_h = 0$, addresses Priority 2 of Task 3.4, the effect of vertical reinforcement on response in the absence of horizontal reinforcement. This information will complement NIST tests of partially-grouted walls in which only horizontal reinforcement was used [9]. Three non-zero values of horizontal reinforcement ratios are needed to model non-linear effects. These values are considered as light reinforcement as explained in Section 8, Commentary.

Item 3: Axial Stress q

Two axial stresses, $q = 0$ and 1.38 MPa (200 psi), are selected. The default case, $q = 0$, is proposed because a substantial portion of masonry walls in buildings experience no axial load, including those that are retrofitted. The axial stress of 1.38 MPa (200 psi) is representative of axial stresses used in the design of masonry walls in buildings.

Item 7: Masonry Type, MT

The plan includes both concrete block and clay brick masonry tests, to gain insight on behavioral similarities and differences of the two common types of masonry used in building construction.

Item 12: Type of Horizontal Reinforcement, HT

Deformed reinforcing bars and joint reinforcement are proposed in consideration of Priority 1 of Task 3.4. The use of equivalent area of joint reinforcement in lieu of reinforcing bars will allow an assessment of its effect on response relative to conventional reinforcement. If they turn out to have equivalent effects, the finding will have a major positive economic impact upon the industry: joint reinforcement eliminates grouted bond beam courses needed for the placement of conventional reinforcing bars. In two earlier studies [1, 5], some evidence was found to indicate equivalence in the effectiveness of the two types of reinforcement.

C. MENU ITEMS NOT CONSIDERED IN THE TEST PLAN

The following menu items (Figure 4) will not be addressed as test variables for reasons explained in Section 8, Commentary.

Item 10: Distribution of horizontal reinforcement

Item 11: Distribution of vertical reinforcement

Item 13 Grout strength

Item 14: Mortar strength

Item 15: Size of specimens

6.5 Selection of Test Specimens

Figure 5 shows the values of the parameters selected for both concrete block and clay brick masonry tests (Tasks 3.6.2 and 3.6.3, respectively). The combinations that uniquely define each (duplicate) concrete masonry test specimen are specified to illustrate the modularity of the plan. The specimens are grouped according to the priorities specified in Task 3.4. For example, P_1, designating Priority 1, will be addressed by conducting six tests of specimens having the different combinations of parameters shown.

The combinations for the clay brick specimen tests are similar with one exception: Priority 1 will not be addressed because the tests prescribed for the concrete block specimens should provide a reasonably good indication of the effectiveness of joint reinforcement.

The total number of uniquely defined concrete block and brick specimens are 15 and 11, respectively. The 30 concrete block duplicate specimens will be tested first, in the order of the priorities specified in Figure 4, followed by the tests of the 22 clay brick specimens.

6.6 Specimen Sizes

The two specimen sizes are specified in Figure 6(a). The dimensions are consistent with the two aspect ratios selected. Running bond construction will be used throughout. Four types of concrete block units will be used: (1) standard 203x203x406-mm (8x8x16-in) stretcher units, (2) 203x203x203-mm (8x8x8-in) half units, (3) 203x203x406-mm (8x8x16-in) bond beam units, and (4) 203x203x406-mm (8x8x16-in) bond beam units. The hollow brick units will be selected in consultation with brick masonry trade associations to represent common U.S. practice and availability.

The sizes of partially-grouted and plain specimens tested in the past are shown in Figure 6(b). All the specimens shown in Figure 6 are drawn to scale to offer a visual comparison of the two sizes specified by this plan relative to those tested in the past. The specimen identifiers give their numbers, the first author's initial, and the reference number. For example, 13-W[13] designates 13 specimens tested by Woodward and Rankin, and documented in Reference [13]. The criteria used for the selection of sizes were, comparability with sizes used in previous tests, surface area or enclosure they provide, and headroom clearance requirements of the NIST TTF facility which will be used to test them.

6.7 Small Specimen Tests

(a) The masonry units will meet ASTM C90. Six replicate masonry units each, of hollow concrete block, grouted concrete block, hollow clay brick, and grouted clay brick, will be tested in compression according to ASTM C140. Prior to testing, the overall dimensions, the face shell thickness, the web thickness, and percent net volume will be measured in accordance with ASTM C140.

(b) Three 2-unit high and three 3-unit high hollow and grouted concrete masonry prisms, and three 5-unit high hollow and grouted brick masonry prisms will be fabricated with each pair (duplicates) of test specimens. The prisms will be fully bedded in stack bond, cured under controlled laboratory conditions, and tested after curing for at least 28 days.

(c) Cement-lime mortar with mix proportion conforming to the requirements of Type M mortar of ASTM C270 will be used in the construction of the test walls. Three 51-mm (2-in) mortar cubes will be fabricated with each new mortar batch and tested as per ASTM C109.

(d) Grout proportion will be selected to achieve a uniaxial compressive strength comparable to those of the concrete block units and clay brick prisms. The proportions selected will be within the limits of ASTM C476. Sampling and testing of grout will be as per ASTM C1019. Three 76-mm (3-in) square prisms will be tested for each design mix. Grout will also be sampled during placement in the walls. The grout prisms will be prepared, cured and tested according to ASTM C1019.

(e) Deformed reinforcing bars as per ASTM A615 will be used. A sample of three reinforcing bars for each bar size will be tested in tension as per ASTM E8, to measure yield and strength.

(f) Laddur type #9-gage cold-drawn steel wire for joint reinforcement to meet ASTM A82 will be used. Joint reiforcement will be tested in triplicate to measure yield strength.

(g) Three 813-mm (32-in) plain, and three 813-mm (32-in) fully-grouted square wallettes will be fabricated and tested as per ASTM E519 for each pair of specimens to determine diagonal tension cracking strength.

6.8 Testing Procedure

The axial load will be applied to the top of the specimen by two servo-controlled hydraulic actuators. The applied pressure will be held constant at 1.38 MPa (200 psi) on all specimens that will be subjected to axial load. A single servo-controlled hydraulic actuator will be used to apply to the top edge of the specimen a prescribed displacement history and displacement rate as specified in Task 3.3.2, Figure 4.

Testing will be monitored visually. Crack formation and propagation will be closely monitored and highlighted by markers. Photographs of the wall surfaces will be taken at periodic intervals and following major events.

6.9 Instrumentation and Measurements

The forces in the vertical and horizontal actuators will be measured by their respective load cells. The global lateral displacement of the toe bearing block will be measured by the displacement transducer located in the hydraulic actuator. Linear variable displacement transducers (LVDT's) located at the base and top edge of specimen will measure in-plane shear displacements, sliding and uplift.

7. ANALYTICAL PROGRAM

The plan specifies two analytical tasks to be performed in parallel with the experimental tasks: (a) formulation of a simplified method of analysis of shear wall limit states for application in design, and (b) utilization of available finite element software as a research tool. The development of finite element software or extensive modification of existing software is not within the scope of the plan.

7.1 Prediction of Limit States

The plan calls for the development of a capability to estimate cracking and strengths and corresponding deformations of masonry shear walls for use in the formulation of a design methodology (Task 4.1.3, Figure 1). The starting point will be the modified strength-predictive equation developed in an earlier study (Eq. 6,[3]). Feedback from the proposed tests will be used to refine that equation and formulate equations for evaluating the other limit states.

7.2 Finite Element Simulation

The feasibility of utilizing existing finite element software will be explored to supplement the test program and to support the development of a simplified approach (Task 4.1.3). The scope of this effort will depend on the availability of appropriate software capable of modelling correctly the lateral-load response of masonry shear walls.

8. COMMENTARY

The report on the effects of critical parameters on shear wall response [4] makes specific recommendations on the types and ranges of critical parameters which need to be considered in the preparation of an experimental program for masonry shear walls. It also discusses the basis in support of the recommendations. This Section supplements that study by providing additional explanations on the rationale used in the preparation of the research plan, including selections not included in the parametric study. The specific tasks of the plan are addressed in turn, by reference to the appropriate sections in the text.

<u>Section 5</u>

Figure 1 describes a two-stage process. The first stage, comprising of the tasks shown above the heavy line, utilized the available technical information to develop the basis for the second stage of the plan, as described by the items below the heavy line and the specific tasks defined in Figures 4 and 5.

Section 5 gives a brief review of the completed tasks identified in Figure 1 and in the text of Section 1. The following were accomplished by these studies.

* Research needs and priorities were identified based on the scope of masonry shear wall tests conducted since 1975 (Task 3.1, Ref. [1]).

* Several formulations for the prediction of the strength of fully- and partially-grouted shear walls were critically evaluated against available test results, and found to lack the consistency needed for use in design (Task 4.1.1, Ref. [2], and Task 4.1.2, Ref. [3]).

* It was established that the available experimental data base is not sufficient to develop formulations that can adequately predict deformation and cracking strength properties needed in design (Task 3.2, Ref. [4]).

* An improved equation was developed to predict the strength of partially- and fully-grouted walls based on observed mechanisms of shear wall response. The equation needs further refinement to improve its consistency in predicting the strength of walls in which light or no reinforcement is used (Task 4.1.2, Ref. [3]).

* Based on available test data, five critical parameters which control the lateral-load response of partially-grouted masonry shear walls were identified, and the relationships describing the effects of these parameters on response (linearity and sensitivity) were examined (Task 3.2, Ref. [4]).

* The feasibility of using the finite element approach as a research and design tool was explored partially by checking an available program [6] against test results of fully-grouted specimens. Final conclusions on the accuracy of the program to simulate shear response are pending.

Section 6

The definition of the problem and the method proposed for its solution can be explained by reference to Figures 2 and 3. As noted in the text, possible major events characterizing the lateral-load response of masonry shear walls may not all occur or occur in the sequence indicated in Figure 2. The evaluation of shear mode response is the object of the proposed study. The experiments are designed to trigger shear cracking (events 3 and 4) before premature compressive crushing occurs at the diagonally-loaded corners (event 6), to allow for experimental evaluations of post-cracking gain in strength and deformation capacity.

The four response characteristics identified in Figure 3 are deemed basic in the design of shear walls. For walls failing in the shear mode, the cracking strength and deformation (V_c and D_c, respectively), are needed to define a ductility criterion for design. As shear cracking limit states define the initial conditions of post-cracking response, they are needed in the development of equations for the prediction of strength and deformation limit states (V_u and D_u, respectively) by analytical means. A design methodology based on both shear cracking and limit states is not precluded because it takes into consideration economic as well as life safety factors in design.

The following statements explain briefly the selection of test variables and fixed parameters identified in Figure 4 in the numerical sequence shown in the menu.

A. FIXED PARAMETERS

Item 4: Vertical Reinforcement Ratio

Although the vertical reinforcement ratio has been identified as a critical parameter, it is estimated that assigning it a value of 0.003 will reduce the probability of premature flexural failure before the specimen can develop its full post-cracking shear capacity.

Item 5: Compressive Strength

The compressive strength of concrete block and clay brick masonry were established after consultation with the masonry industry (refer to text of CMR comments in the Appendix). The specified strengths are average values within the ranges of the respective masonry strengths used in building construction. Because of the large difference in the strengths of concrete block and hollow clay brick units, it is not practical to specify the same compressive strength for both. The aim is to use compressive strengths close to the specified values. The actual strengths will be determined by prism tests. All specified strengths are based on gross cross-sectional area. Refer to Sections 4.3C and 6.1 of Reference [4] for further comments on these selections.

Item 6: Replication

All tests will be conducted in duplicate to supplement the scarce information available on test variability of partially-grouted specimens (Section 4, Ref. [3]).

Items 8 and 9: Displacement History

The slow rate of loading and the displacement increments specified are similar to those used in past experiments in order to preserve continuity and comparability of results.

B. TEST VARIABLES

The proposed plan specifies five test variables: r, ρ_h, q, MT, and HT (Task 3.3.1, Figure 4). Two values of r, four values of ρ_h, and two values of q are specified in Figure 5. The selection of these parameters and the specified values are based mainly on the recommendations of the parametric study [4]. One of the values of ρ_h is the default case ($\rho_h = 0$), which addresses Priority 2 (Task 3.4, Figure 4); the contribution of ρ_v in the absence of horizontal reinforcement. It will complement available test information on the effect of ρ_h in the absence of vertical reinforcement [9].

The values selected for ρ_h fall within a range considered to be "light" reinforcement. There is no delineation between "light" and "heavy" reinforcement, which are relative terms. "Light" relates to the amount of reinforcement required by design to resist seismic forces prescribed for zones approximately equivalent to seismic Zones 2 and below specified by the 1988 Uniform Building Code, and "heavy" applies for Zones 3 and 4 of the same Code. The horizontal reinforcement used in the FG and PG specimens previously studied (ρ_h = 0.0013-0.0067 and 0.000234-0.00335, respectively, Refs. [2] and [3]), are approximately representative of heavy and light reinforcement although they overlap partially.

Both concrete block and clay brick masonry are represented (MT = 2). As a result, two values of "fixed" parameter f_m will be investigated. If it can be established that the two types of masonry behave essentially the same, and there is some evidence to indicate that they do, then f_m can be viewed as a test variable with two specified values.

C. EXCLUDED ITEMS

Item 10: Distribution of Horizontal Reinforcement

According to the parametric study [4], load and deformation are not sensitive to the distribution of horizontal reinforcement over the height of the wall as vs. clustering the reinforcement within the central region of the wall. Horizontal reinforcement will be placed at mid-height first, then in the adjacent courses above and below it next. The relatively light joint reinforcement will have to be distributed over the height of the specimen at each or every other bed joint.

Item 11: Distribution of Vertical Reinforcement

The amount of vertical reinforcement in the outer cells is governed by flexural considerations. Since failure in the shear cracking mode is the desired effect to be studied, sufficient reinforcement should be placed in the outer cells to mitigate the possibility of premature in-plane flexural failure. There is no experimental evidence to indicate that distribution of vertical reinforcement through the inner cells will improve response [2,3].

Items 13 and 14: Grout and Mortar strength

Grout and mortar are usually selected so that their compressive strengths are consistent with the strengths of concrete masonry unit or clay brick prisms.

Item 15: Specimen Size

The maximum specimen sizes are selected according to clearance and load capacity requirements of the testing facility. They are comparable to sizes used in past experiments.

Section 7

The analytical tasks will be dedicated to the development of improved capabilities for analyzing the lateral load response of masonry shear walls. The aim is to develop a capability for making reasonably consistent estimates of shear cracking and peak strengths and corresponding deformation properties for use in design. To the extent possible, emphasis will be placed on a rational approach based on observations of shear wall response mechanisms.

The plan makes no commitment to develop a finite element capability. Rather, it proposes the use of existing finite element software as a research tool to assist the development and independent verification of expressions for evaluating critical limit states. The implementation of this task is predicated on demonstrating the capabilities of existing software to correctly model the lateral-load response of masonry shear walls by verification against experimental results and by examining the engineering principles used in the algorithms of the software. The implementation of the plan is not predicated on the success of this task.

9. REFERENCES

1. Yancey C.W.C., Fattal S.G., Dikkers R.D., Review of Research Literature on Masonry Shear Walls, NISTIR 4512, National Institute of Standards and Technology, Gaithersburg, MD, February 1991.

2. Fattal S.G., Todd D.R., Strength of Masonry Shear Walls: Predictions vs Test Results, NISTIR 4633, National Institute of Standards and Technology, Gaithersburg, MD, October, 1991.

3. Fattal S.G., Strength of Partially-Grouted Masonry Walls, NISTIR 5147, National Institute of Standards and Technology, Gaithersburg, MD, June, 1993.

4. Fattal S.G., The Effect of Critical Parameters on the Behavior of Partially-Grouted Masonry Shear Walls, NISTIR 5116, National Institute of Standards and Technology, Gaithersburg, MD, June, 1993.

5. Research Needs for Masonry, Proceedings NSF Workshop, Clemson University, Clemson, SC, 1988.

6. Ewing Robert D., El-Mustapha Ahmad M., Kariotis John C., FEM/I, Finite Element Computer Program for the Nonlinear Static Analysis of Reinforced Masonry Building Components, Report No. 2.2-1, Ewing and Associates, Rancho Palos Verdes, CA, June, 1990.

7. Matsumura Akira, Shear Strength of Hollow Unit Masonry Walls, Second Meeting of the U.S-Japan Joint Technical Coordinating Committee on Masonry Research, Keystone, CO, September, 1986.

8. Matsumura A., Shear Strength of Reinforced Hollow Unit Masonry Walls, Proceedings, 4th North American Masonry Conference, Paper No. 50, Los Angeles, CA, 1987.

9. Yancey Charles W.C., Scribner Charles F., Influence of Horizontal Reinforcement on Shear Resistance of Concrete Block Masonry Walls, NISTIR 89-4202, National Institute of Standards and Technology, Gaithersburg, MD, October, 1989.

10. Woodward Kyle, Rankin Frank, Influence of Aspect Ratio on Shear Resistance of Concrete Block Masonry Walls, NBSIR 84-2993, National Bureau of Standards, Gaithersburg, January, 1985.

11. Woodward Kyle, Rankin Frank, Influence of Vertical Compressive stress on Shear Resistance of Concrete Block Masonry Walls, NBSIR 84-2929, National Bureau of Standards, Gaithersburg, MD, October, 1984.

12. Woodward Kyle, Rankin Frank, Influence of block and mortar strength on shear resistance of concrete block masonry walls, NBSIR 85-3183, National Bureau of Standards, Gaithersburg, MD, April, 1985.

13. Hidalgo Pedro A., Mayes Ronald L., McNiven Hugh D., Clough Ray W., Cyclic Loading Tests of Masonry Single Piers, Volume 3 - Height to Width Ratio of 0.5, Report No. UCB/EERC-79/12, University of California, Berkeley, CA, May, 1979.

14. Chen Shy-Wen J., Hidalgo Pedro A., Mayes Ronald L., Clough Ray W., McNiven Hugh D., Cyclic Loading Tests of Masonry Single Piers, Volume 2 - Height to Width Ratio of 1, UCB/EERC-78/28, University of California, Berkeley, CA, December, 1978.

15. Hidalgo Pedro A., Mayes Ronald A., McNiven Hugh D., Clough Ray W., Cyclic Loading Tests of Masonry Single Piers, Volume 1 - Height to Width Ratio of 2, University of California, Berkeley, CA, November, 1978.

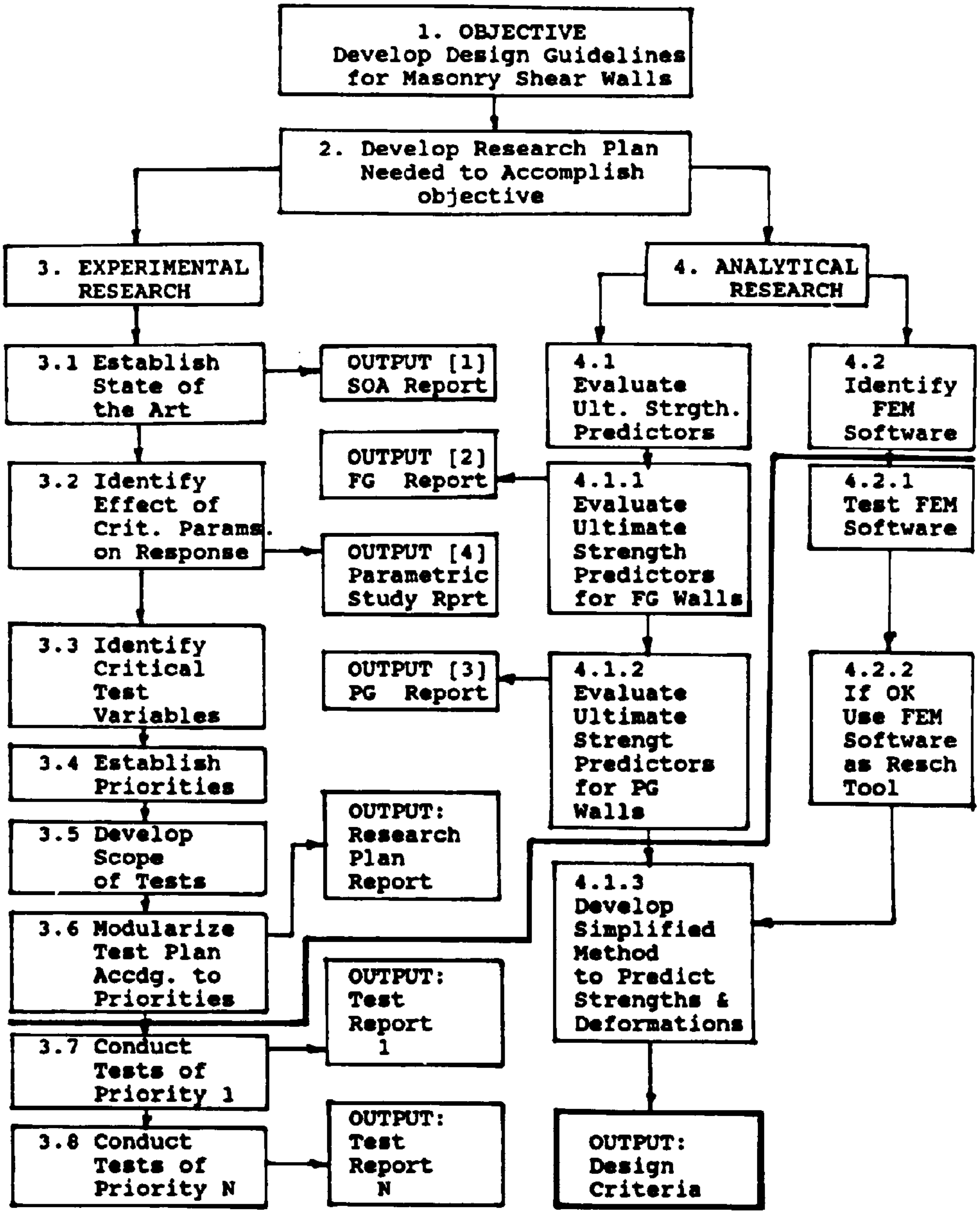
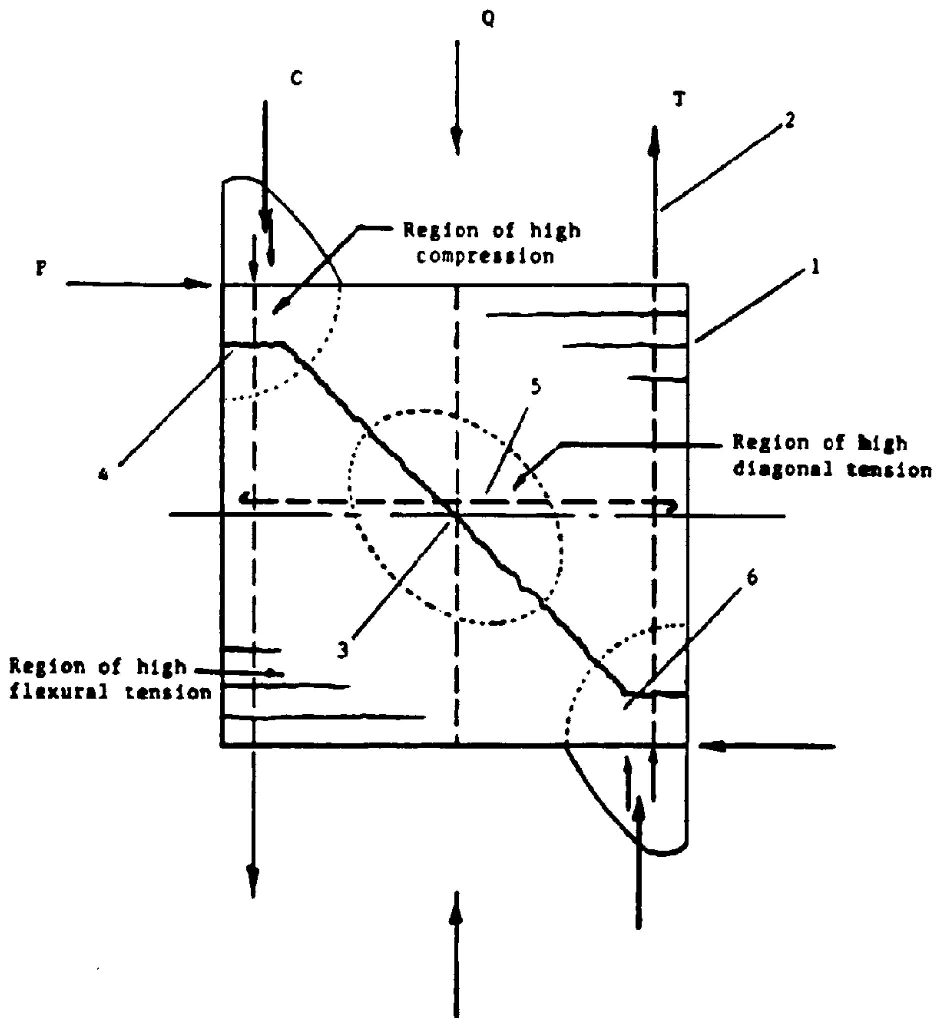
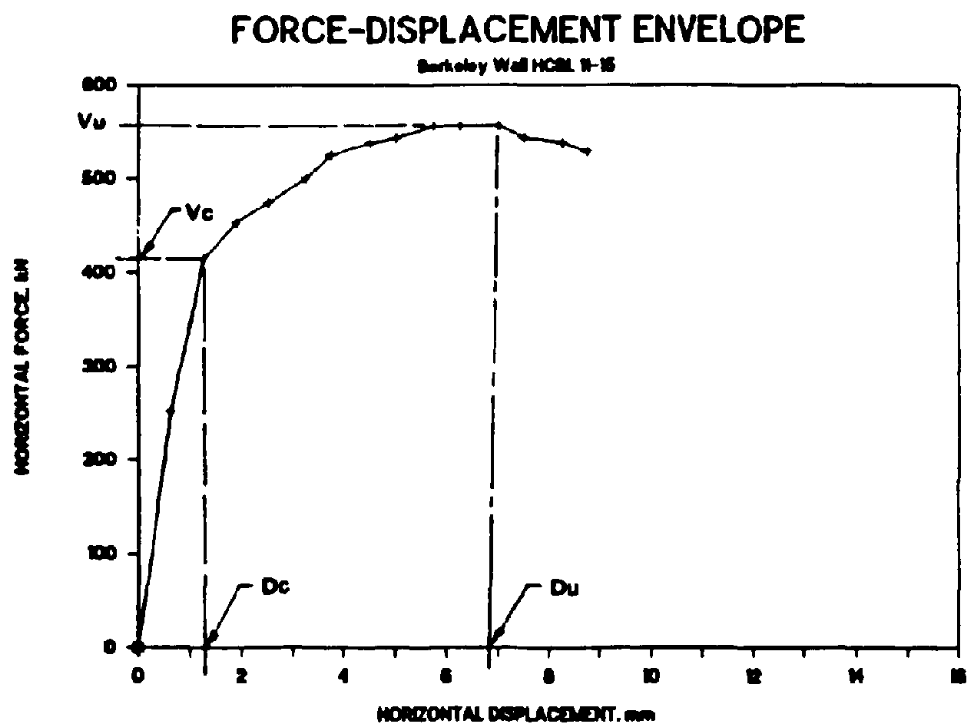


Figure 1. NIST Masonry Research Plan



1. Tensile cracking in high flexure zones
2. Vertical bars yield in high flexure zones
3. Tensile shear-induced cracking near center of wall
4. shear cracks propagate to form rupture plane
5. yielding of hor. and vert. steel
6. crushing of masonry in compression at loaded corners

Figure 2. Major events in shear wall response



Vc = Cracking strength of masonry

Dc = Cracking deformation

Vu = Ultimate strength of shear wall

Du = Deformation at ultimate strength

Figure 3. Response characteristics of masonry shear walls

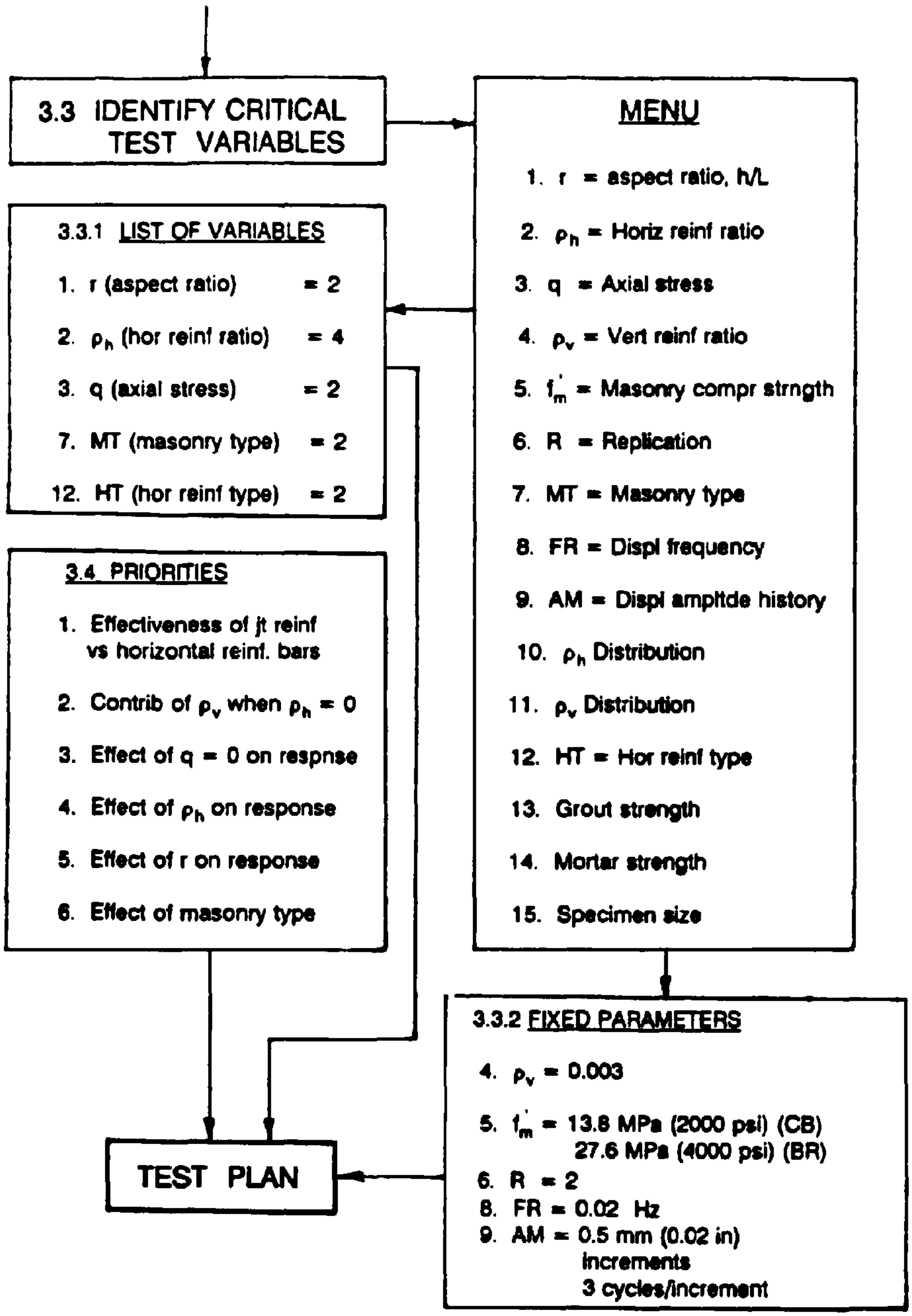


Figure 4. Masonry test plan

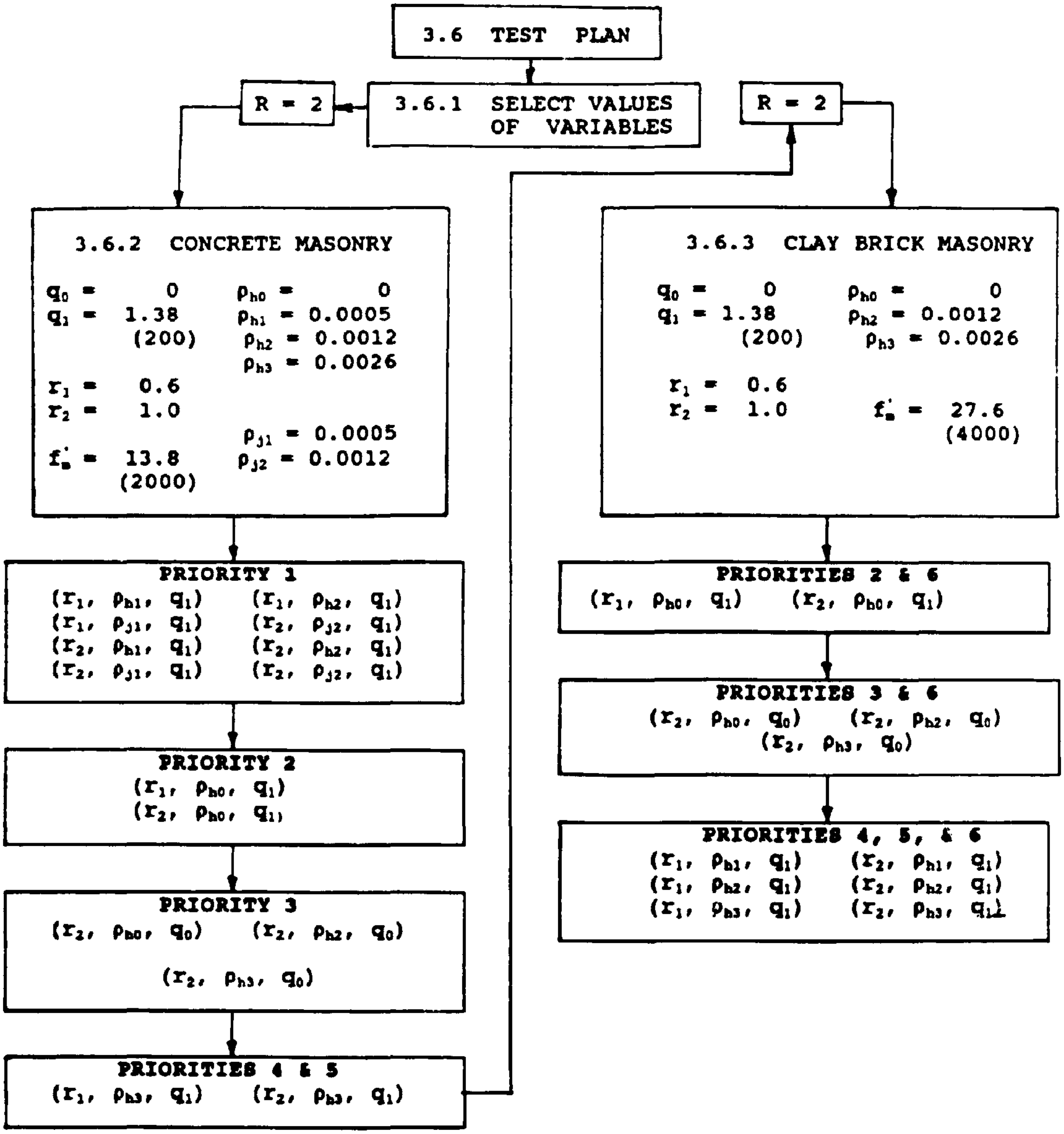
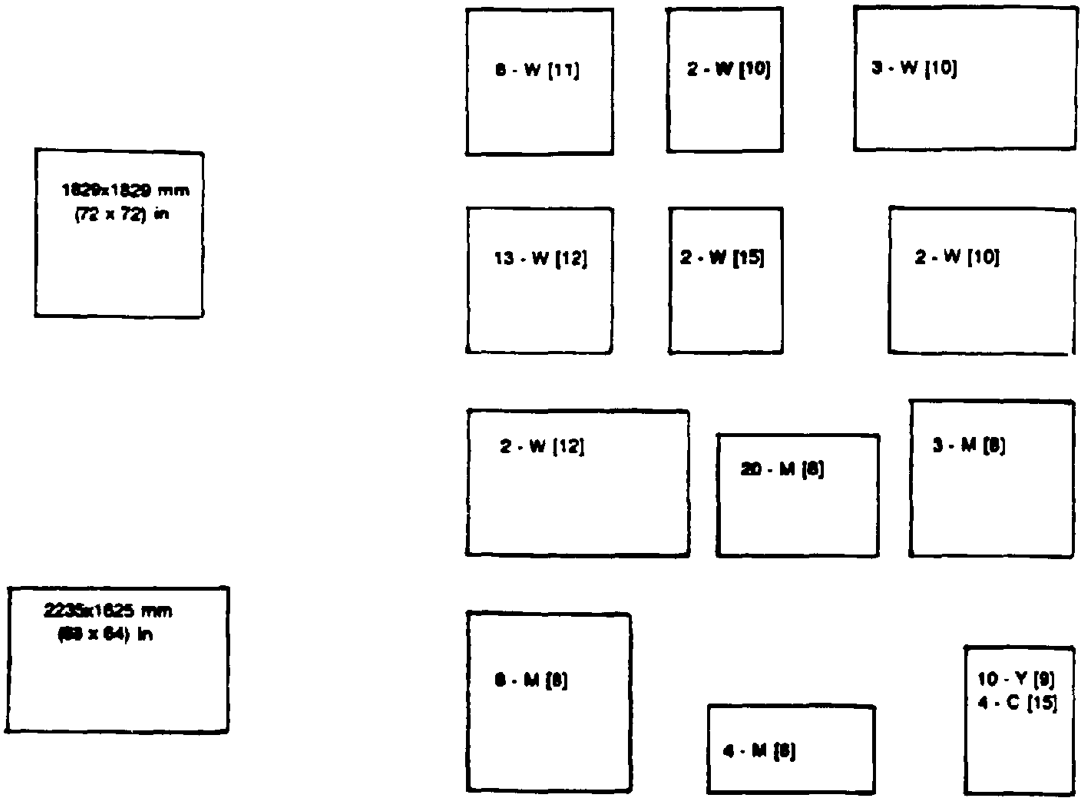


Figure 5. Definition of test specimens



(a) Sizes specified in
in research plan

(b) Sizes of specimens
tested in the past

Figure 6. Relative sizes of test specimens

APPENDIX

I. CMR COMMENTS ON MASONRY RESEARCH PLAN

This summary highlights the comments and suggestions by the Council for Masonry Research (CMR) representatives at the January 31, 1992, meeting on a draft NIST masonry research plan. Reference is made to the tasks of the flow chart of the research plan (Figures 1, 5 and 6 of text). These comments contributed significantly to the refinement of the research plan presented in this report.

1. NIST REPORTS

Effect of Tensile Strength

On the improved predictive equation documented in the PG report [3], the question was raised on whether the tensile strength appears explicitly in its formulation. The question came up in connection with the finite element study which uses the tensile strength of masonry as input. The predictive equation uses the compressive strength of masonry as a parameter in its formulation but not the tensile strength. It was noted that tensile stresses, as they relate to the diagonal shear cracking phenomenon, dissipate after shear cracking takes place, which explains why it does not appear explicitly in the post-cracking strength predictive equation developed at NIST..

In conjunction with finite element studies (Tasks 4.2.1, 4.2.2, and 4.2.3), in which the tensile strength of masonry is specified as an input parameter, CMR suggested the idea of pilot tests of brick and concrete block specimens of equal compressive strength using tensile strength as a test variable. CMR indicated the direct tensile strength is in the neighborhood of 0.79 MPa (115 psi) for concrete block masonry having a compressive strength of 13.8 MPa (2000 psi) on the net area.

2. PRIORITIES AND CHOICES OF PARAMETERS

First Priority

There was unanimous agreement on the test plan's first priority to study the effectiveness of joint reinforcement relative to conventional rebars for horizontal reinforcement (Item 1 of Task 3.4). CMR corroborated the reasons for proposing this investigation as described in the research plan. It was recommended that the Laddur type of joint reinforcement be used because it is more easily placed than the Truss type. CMR indicated that #9 gage joint reinforcement is the standard for the industry. Sometimes #8 gage is also used, but a warning was flagged about its possible weakening effect of masonry strength in the plane of the bed joints.

Other Priorities

It was requested that CMR provide NIST further assistance in establishing the order of the other priorities identified in Task 3.4.

Grout Strength

On the question of selecting an appropriate strength of grout, CMR noted that the 1988 UBC Code calls for matching grout strength of brick masonry to its prism strength and that of concrete block specimens to its unit strength. UBC also places a minimum limit of 13.8 MPa (2000 psi) on grout strength.

Unit Sizes and Specimen Thickness

CMR noted the need to consider the availability of hollow brick unit sizes in the design of the test specimens. It was noted that 203 x 406-mm (8 x 16-in) units are scarce, 152-mm (6-in) high units are more common, and 102 x 305-mm (4 x 12-in) size units are the most readily available.

CMR brought up the subject of specimen thickness. It was noted that most of the TCCMAR tests use 152-mm (6-in) thick units while most of NIST tests have used 203-mm (8-in) thick units. Limitations of ram capacity and slenderness effects are factors influencing the choice. The test plan specifies the thicker units because ram capacity is not a factor and the study of slenderness effects is not the object of the plan.

Selection of Axial Stresses

The choice of q, the axial stress level, was discussed. A code design limitation of 0.225 f'_m was mentioned. It was noted that in-situ axial stress is generally low. Ballpark figures of 0.69 MPa or 100 psi (0.35 MPa or 50 psi for a three-story building) were mentioned.

Distribution of Vertical Reinforcement

The question of vertical reinforcement distribution was discussed at some length. The test plan calls for placement of vertical bars in the end cells only. Since cost of grouting is a significant factor, placement of additional vertical rebars in the interior cells is not justifiable from that standpoint.

CMR commented on US practices on the maximum spacing of vertical reinforcement: the use of fully-grouted walls constructed with bond beam units and vertical reinforcement placed at 1.22-m (4-ft) intervals is a common practice west of the Rockies. East of the Rockies, spacing of vertical bars is driven by consideration of out-of plane flexural requirements.

CMR indicated that spacing of vertical bars in excess of 1.22 m (4 ft) is a question of high priority to the industry. They indicated the need to investigate 2.44 m (8 ft) or even 3.66 m (12 ft) spacing. The question was brought up on the feasibility of using 2.44 x 3.66-m (8 x 12-ft) long specimens, within the scope of the current test plan, to investigate the response of shear walls in which vertical bars are placed at 2.44 or 3.66 m (8 or 12 ft) intervals. It was agreed that this is a question which needs to be addressed, either within the framework of the present test plan, or as a possibility of a follow-up program. Information from the industry on the incremental cost of grouting relative to the construction of plain walls would be relevant in decisions on the amount and spacing of vertical reinforcement. As noted earlier, in practice, these parameters are selected according to out-of-plane flexure and ductility considerations.

Horizontal Reinforcement

CMR indicated that out-of plane flexural requirements will govern the minimum amount of horizontal reinforcement as well. It was noted that a horizontal reinforcement area equivalent to #9-gage wire at 406 or 610 mm (16 or 24 in) on center is just about the lowest practical amount.

Concrete Block vs Clay Brick Masonry

The selection of two types of masonry construction and two different compressive strengths called for in the test plan may be interrelated. CMR noted again that TCCMAR tests indicate there are no appreciable differences in the nature of response of fully-grouted brick and block shear walls. If this were true for partially-grouted walls as well, then by testing the two types of masonry walls, f_m would become a test variable with two levels of specified strength (high and low). CMR suggested consideration of tests to verify their equivalence for partially-grouted walls.

Range of Compressive Strength

CMR provided guidance on the values of compressive strength selected (Figures 4 and 5). It was noted that the range for concrete block masonry is 10.35-24.15 MPa (1500-3500 psi), with the narrower range of 10.35-17.25 MPa (1500-2500 psi) most commonly used in practice. The lower limit of 10.35 MPa (1500 psi) corresponds to a unit strength of 34.5 MPa (5000 psi). It was also pointed out that a compressive strength of 27.6 MPa (4000 psi), corresponding to a unit strength of 55.2 MPa (8000 psi), is about the lowest for hollow brick masonry construction.

II. MASONRY INDUSTRY NEEDS AND PRIORITIES

The following two high priority research topics, from the masonry industry's viewpoint, were identified:

(a) The need to investigate the adequacy of lightly-reinforced masonry shear walls with maximum vertical reinforcement spacing of 2.44 to 3.66 m (8 to 12 feet), for construction in regions of low-to-moderate seismicity.

(b) The need to establish the effectiveness of horizontal joint reinforcement relative to conventional reinforcement of equal area.

Three additional topics of interest to the masonry industry were also brought up at the meeting but were not discussed at length because of time constraints. These were,

(c) The need to investigate the effect an alternative method for the placement of grout as a means of controlling labor costs in masonry construction. The industry is contemplating the feasibility of pouring in lieu of pumping grout in fully- or partially-grouted masonry walls.

(d) The need to investigate the response of prestressed masonry shear walls. Prestressing has been used in a relatively limited number of masonry structures.

(e) The feasibility of using mortar in lieu of grout in masonry walls.