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Influence of Aspect Ratio on Shear Resistance of Concrete Block Masonry Walls

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NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

The results from tests on seven ungrouted and unreinforced concrete block masonry walls are presented. The emphasis of the reported research is on the influence of aspect ratio (wall height-to-length) on the relationship between lateral in-plane load resistance and vertical in-plane compressive stress. The walls are fabricated from similar materials by the same experienced mason. The masonry units are hollow concrete blocks having a nominal compressive strength of 1800 psi based on the gross area. The mortar is proportioned as a Type S. The walls have nominal heights and thicknesses of 64 in. and 8 in., respectively. Three different wall lengths are used: 48 in., 80 in., and 96 in. The walls are tested in the NBS Tri-directional Testing Facility using fixed ended boundary conditions at the top and bottom of the walls. Lateral in-plane displacements are applied at the top of the wall while maintaining a constant compressive axial (vertical) stress. The vertical compressive stress is varied for each of the different wall lengths. The test results indicate a relatively weak effect of aspect ratio on the shear stress at diagonal cracking for aspect ratios less than or equal to one and a nearly linear relationship between maximum shear stresses and vertical compressive stresses.

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1. INTRODUCTION

This report presents data from tests on seven masonry walls having different aspect ratios and subjected to in-plane lateral displacements in combination with various compressive vertical stress levels. All of the walls are ungrouted, unreinforced, and fabricated from similar concrete block and mortar. All of the walls have nominal heights and thicknesses of 64 in. and 8 in., respectively. Three different wall length-to-height ratios are achieved by using three wall lengths: 48 in., 80 in., and 96 in. The hollow concrete block has a unit compressive strength of approximately 1800 psi based on the gross area of the unit. The mortar is proportioned as a Type S mortar.

This interim report is the second in a series of reports which document an experimental investigation undertaken as part of an overall program of research on masonry walls. The purpose of this and other reports in the series is to present the results to researchers, designers, and code writers in a timely manner. Detailed data analysis and interpretation are not included in this report. Instead, the analysis and interpretation of the data are presented in summary reports which are issued periodically as sufficient data become available to more fully address a particular issue. Since this is one report in a series, certain information and descriptions common to all reports have been placed in appendices in a effort to limit redundancy. The main body of this report contains abbreviated presentations of material properties and test specimen details. Full descriptions may be found in the appendices.

A brief review of the overall masonry research program, is presented in appendix A. Abbreviated descriptions of the material properties, wall panel details, and test setup are presented in chapter 2, while full descriptions are included in appendices B, C, and D, respectively. A description of each wall test is presented in chapter 3. Limited data interpretation is described in chapter 4. Chapter 5 includes the summary and conclusions.

2. WALL DETAILS AND TEST SETUP

This chapter presents a condensed description of the relevant properties and details of the wall panel test specimens. A brief description of the test setup and instrumentation is also presented. Further information may be found in appendices B, C, and D.

2.1 WALL DETAILS

The properties of the hollow concrete block units are listed in table 2.1. The mortar is proportioned as a Type S mortar having the proportions 1:3/8:4 with 1 part by volume of cement, 3/8 part by volume of lime, and 4 parts by volume of sand. The compressive strength of the mortar is determined by testing 2 in. x 2 in. x 2 in. mortar cubes and their strengths are listed in table 2.2.

Seven wall panels are included in the test series reported herein. Each wall is fabricated using concrete block taken from the same lot and mortar mixed using the same proportions of cement, lime, and sand. Three-unit high, stack bonded prisms are also fabricated with each wall and subsequently tested to determine their uniaxial compressive strength. The details of each wall panel are listed in table 2.2 and a representative wall is shown in figure 2.1. The wall panel identifier in table 2.2 is a two part mnemonic with the two parts separated by a hyphen. That part of the identifier preceeding the hyphen has the form mHHn where m and n are numbers and HH indicates that the block and mortar are high strength. The term high is used only as a relative indicator of strength for the materials used in this research program. The value of m is the length of the wall panel in inches. The value of n is the approximate vertical (axial) compressive stress (psi - based on net cross-sectional area) applied to the wall panel in combination with the lateral displacement. That part of the identifier following the hyphen is a construction code providing unique identification of each wall. The other entries in table 2.2 are self-explanatory.

2.2 TEST SETUP AND INSTRUMENTATION

The test setup (figure 2.2) is the NBS Tri-directional Test Facility, a permanent loading apparatus designed to test building components using three-dimensional loading histories.

The instrumentation used to monitor the test of a wall panel can be divided into two groups. The first group consists of load and displacement transducers mounted on the hydraulic actuators. The second group of instrumentation directly measures the behavior of the wall panel as it is loaded. All of the instrumentation is directly connected to a computer-based analog-to-digital converter which has a sample rate of 50,000 data readings per second. The in-plane displacement of the wall panels is measured by linear variable differential transformers (LVDTs) which are displacement transducers. The LVDTs are placed as shown in figure 2.3 with four LVDTs located on each end surface of the wall. The actual positions of the LVDTs are listed in table 2.3. The LVDTs are mounted such that they measure the displacement of the wall with reference to a fixed reference (tiedown floor). In addition to the overall measurement of

Table 2.1 Dimensions and Properties of Concrete Masonry Unit

	Hollow* Stretcher	Hollow* Corner/Sash Groove
Width (in.)	7.63	7.63
Height (in.)	7.59	7.57
Length (in.)	15.62	15.64
Minimum Face Shell Thickness (in.)	1.30	1.30
Gross Area (in.^{2})	119.2	119.3
Net Solid Area (in.^{2})	61.5	67.0
Gross Ultimate Compressive Strength (psi)	1813	1795
Density (lb/ft^3)	102.4	104.5
Absorption (lb/ft^3)	10.8	10.2

* Average of measurements from 6 units.

Table 2.2 Wall Panel Details

Wall Panel Identifier	Wall Age at Test (Days)	Mortar Cube Ultimate Compressive Strength* 28 Day - (psi) [Days]	Prism Bedding	Prism Ultimate Compressive Strength** (psi) [Days]
48HH150-3L06	134	1847 - 2675 [154]	Full Area	2661 [91]
48HH450-3L05	132	2055 - 2750 [154]	Full Area	2645 [90]
80HH250-3L07	147	1994 - 2829 [154]	Face Shell	1867 [185]
80HH400-4L01	135	3254 - 3817 [140]	Face Shell	2050 [164]
96HH200-4L03	123	3076 - 3273 [140]	Face Shell	1917 [167]
96HH300-4L02	130	2746 - 3350 [140]	Full Area	2615 [166]
96HH400-4L04	120	2425 - 2919 [140]	Full Area	2783 [168]

* The stress is based on an area of 4 sq. in. The first value is the average of three cube tests at 28 days and the second value is the average of three cube tests at the number of days shown in the square brackets. Mortar cubes were removed from the molds after 24 hours and air cured in the laboratory environment until testing.

** Each stress value is the average of three prism tests and the stress is based on a net cross sectional area of 61.5 sq. in. (table 2.1). The number in square brackets is the age of the prisms on the day of their tests.

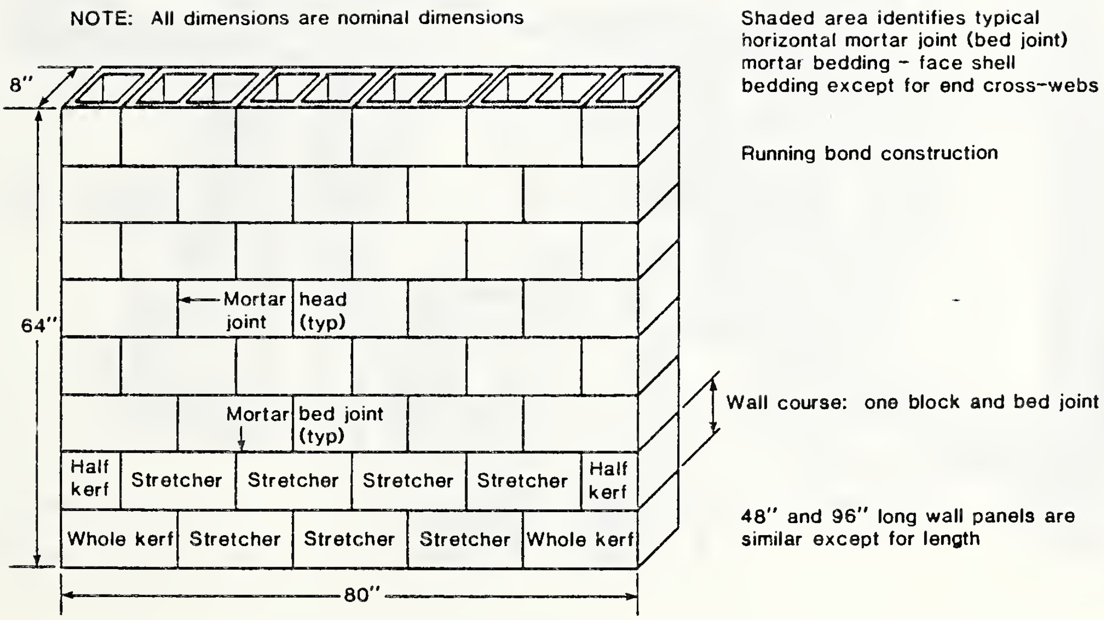


Figure 2.1. Typical wall panel

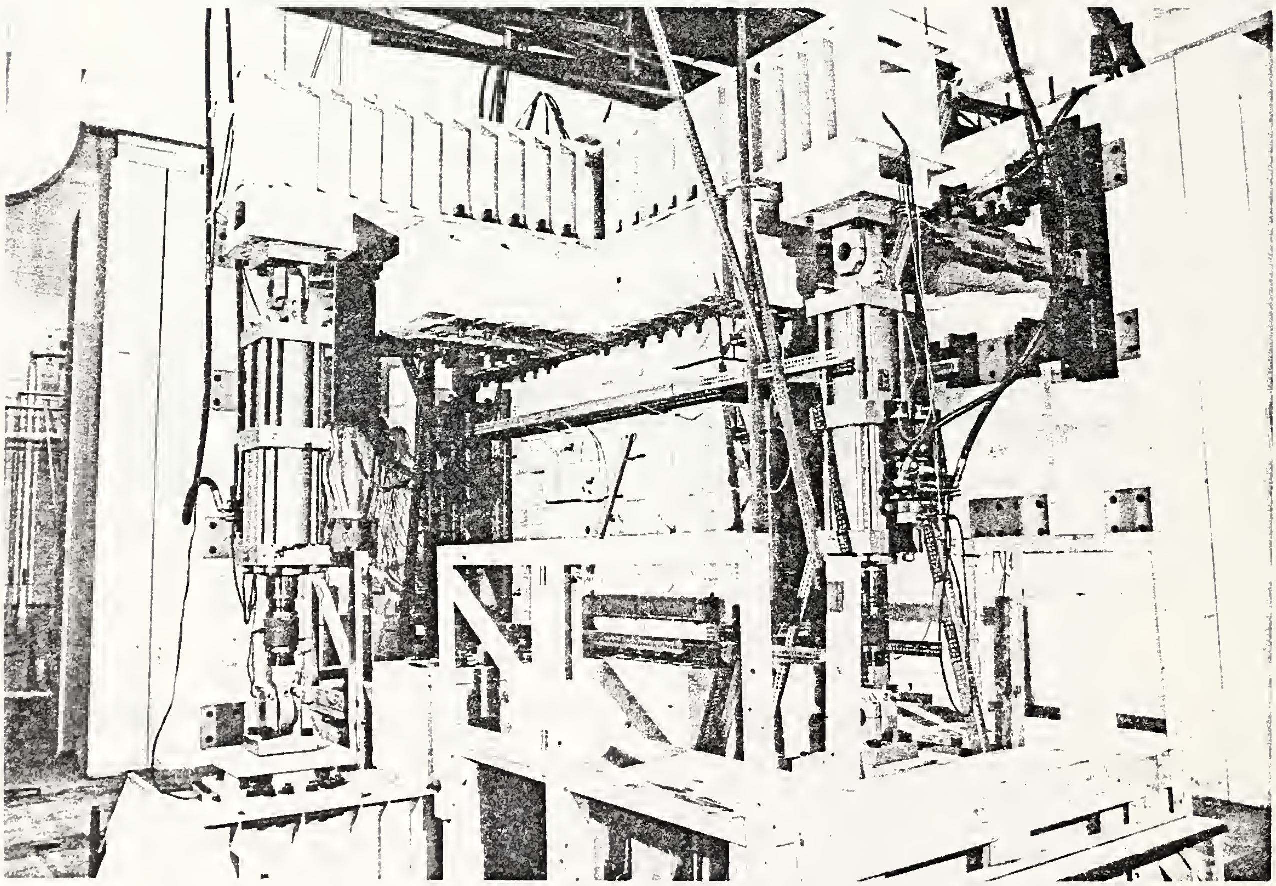


Figure 2.2. Test setup

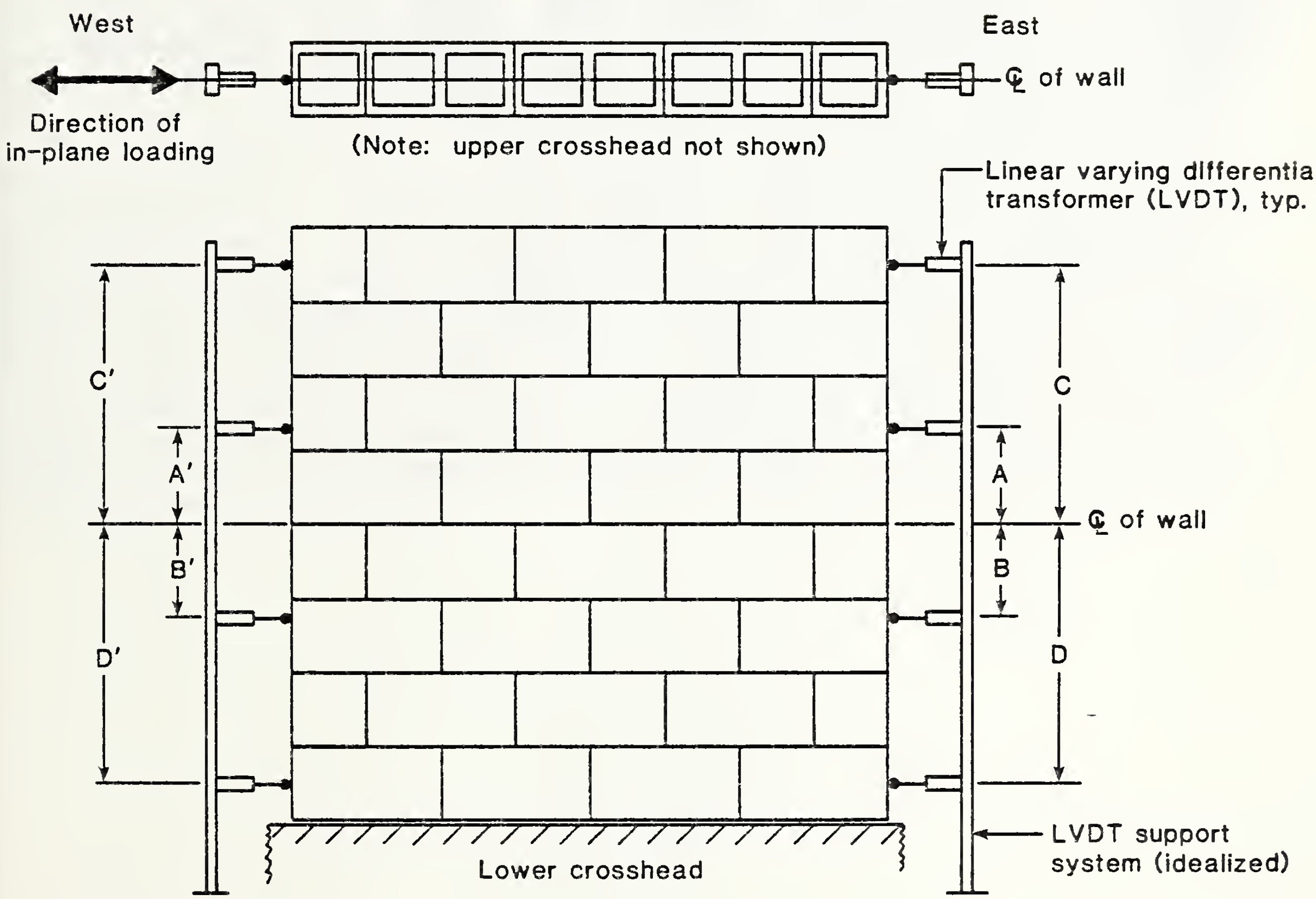


Figure 2.3. Wall panel LVDT layout

Table 2.3 Wall Panel Horizontal LVDT Location Dimensions

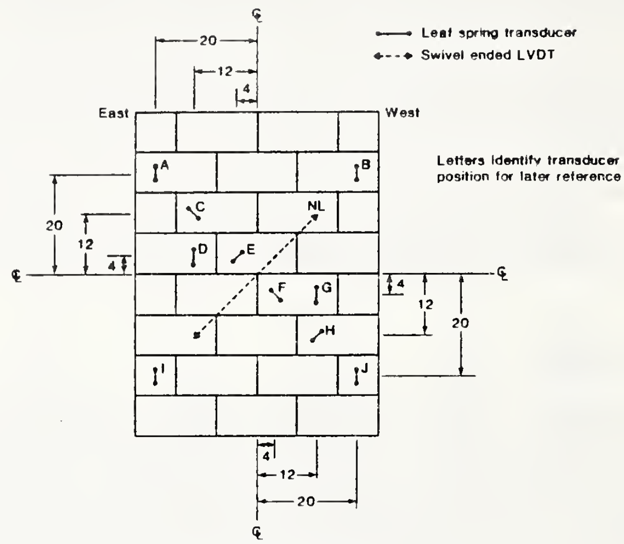
Refer to fig. 2.3 for identification of dimension locations A,B,C,D,A',B',C' and D'.

Wall Panel Identifier	A (in.)	B (in.)	C (in.)	D (in.)	A' (in.)	B' (in.)	C' (in.)	D' (in.)
48HH150	10.50	10.50	28.00	27.50	10.38	10.63	27.25	27.38
48HH450	10.38	10.63	27.88	27.75	10.63	10.50	27.25	27.25
80HH250	10.25	10.63	28.00	27.50	10.88	10.38	27.50	27.00
80HH400	10.25	10.63	28.00	27.50	10.88	10.38	27.50	27.00
96HH200	10.50	10.50	28.13	27.38	10.88	10.25	27.50	27.00
96HH300	10.63	10.63	28.13	27.50	10.88	10.13	27.63	27.00
96HH400	10.50	10.50	28.13	27.38	10.88	10.13	27.50	27.00

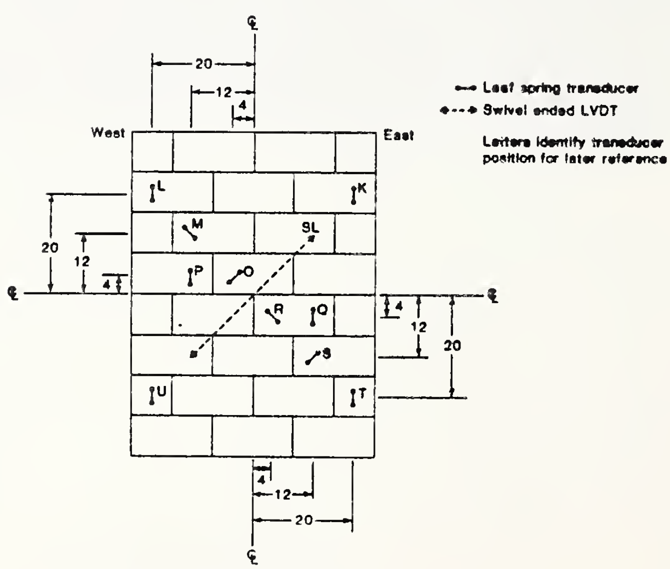
the wall displacement, local measurements of displacement are made on each of the wall panel face shells. These displacement measurements are taken between points on the wall and not referenced to a fixed position. The local displacement measurements are made at the locations shown in figures 2.4, 2.5, 2.6, and 2.7 using specified gage lengths so that strain could be computed. Local displacement measurements are made using either leaf spring transducers (LSTs) or LVDTs mounted between supports attached to the wall surfaces. The LSTs have gage lengths of 1 in. and are placed to provide an indication of the strain field in the wall. The diagonally mounted LVDTs have gage lengths of approximately 34 in. and are used to measure a strain along a diagonal of the wall panel.

2.3 TESTING A WALL PANEL

A typical test proceeded in the following steps. The data channels were checked for unusual variations in output and a measure of the ambient voltage oscillation was obtained. A first set of data was acquired to use as the "zero" condition of the test. The hydraulic actuators were pressurized and another set of data was acquired. The desired vertical compressive load was applied to the specimen with data acquired at regular intervals. After reaching the desired compressive vertical load, in-plane lateral displacement was applied to the wall panel. The lateral displacement was applied with the upper crosshead maintaining a "zero" rotation condition. The vertical displacement of the upper crosshead varied to maintain the desired axial load. The initial direction of displacement was always to the west (figure 2.8). The displacement pattern varied slightly between tests but generally, displacement was increased in the initial direction until a diagonal crack was fully formed. Afterwards, the displacement was either reversed or increased until the wall could not support the imposed vertical load. Data was acquired at regular intervals during the test. The intervals coincided with lateral displacement increments of approximately 0.005 in.

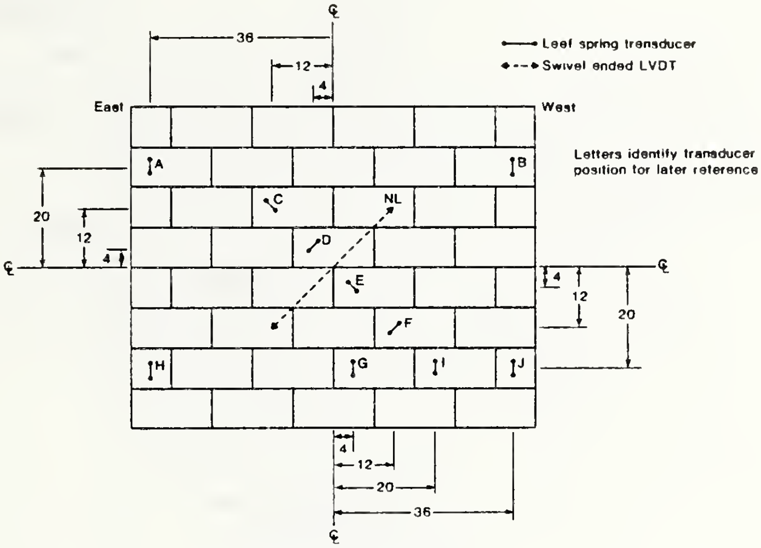


NORTH SIDE OF WALL PANEL
(48HH450 & 48HH150)



SOUTH SIDE OF WALL PANEL
(48HH450 & 48HH150)

Figure 2.4. Wall panel instrumentation (48HH)



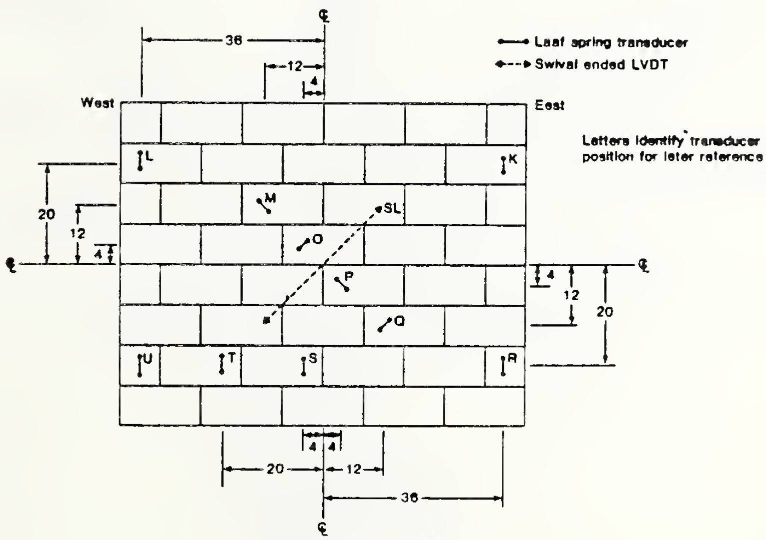
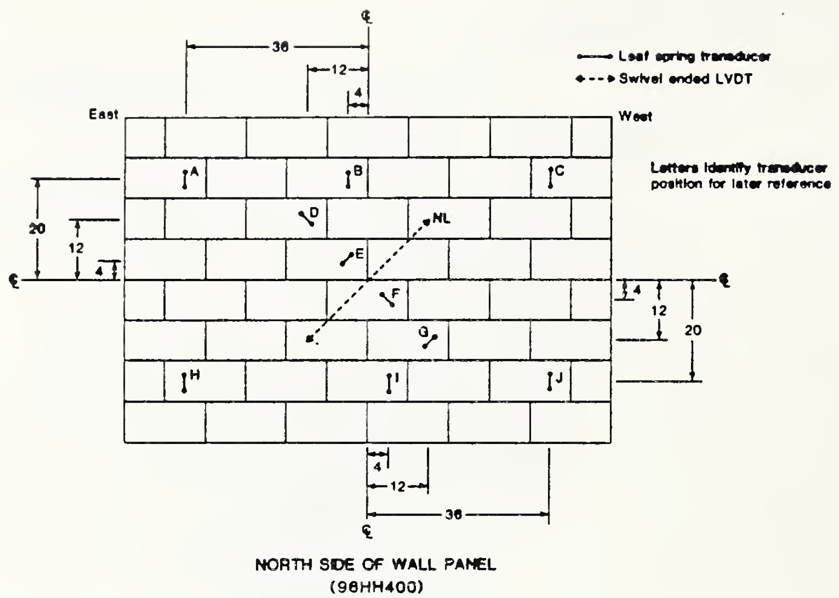


Figure 2.5. Wall panel instrumentation (80HH)



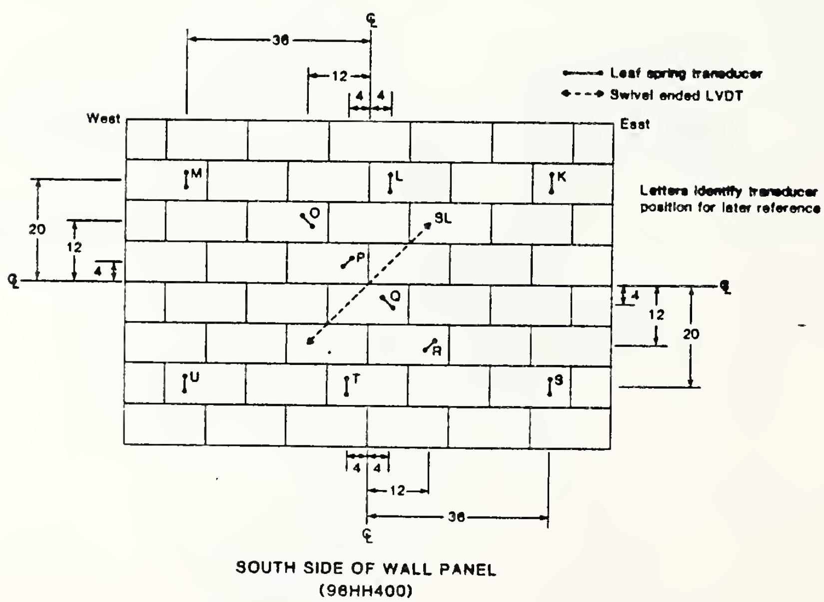
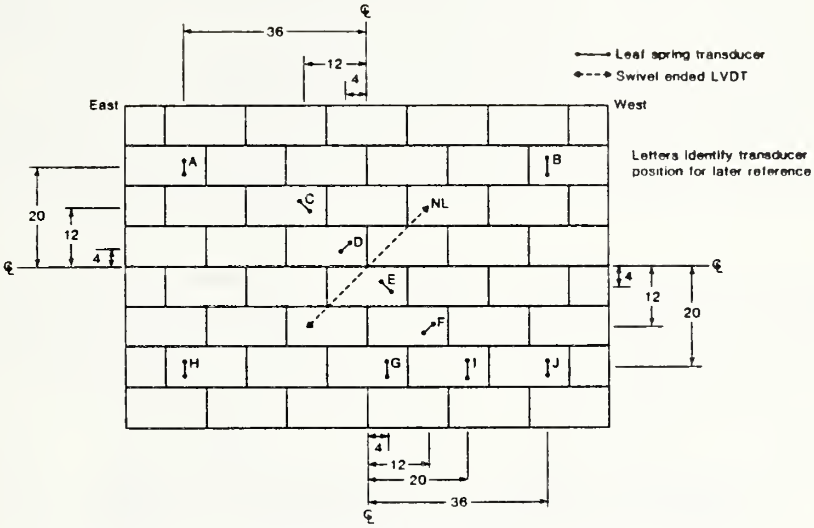
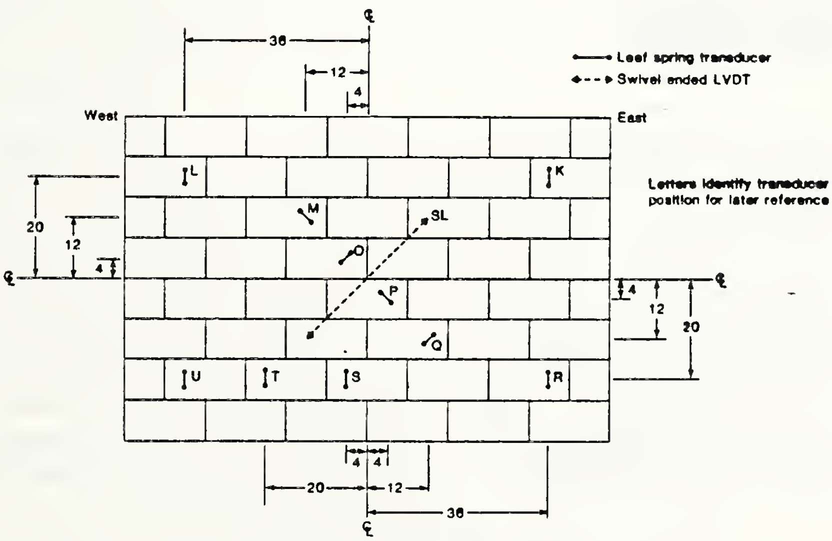


Figure 2.6 Wall panel instrumentation (96HH)

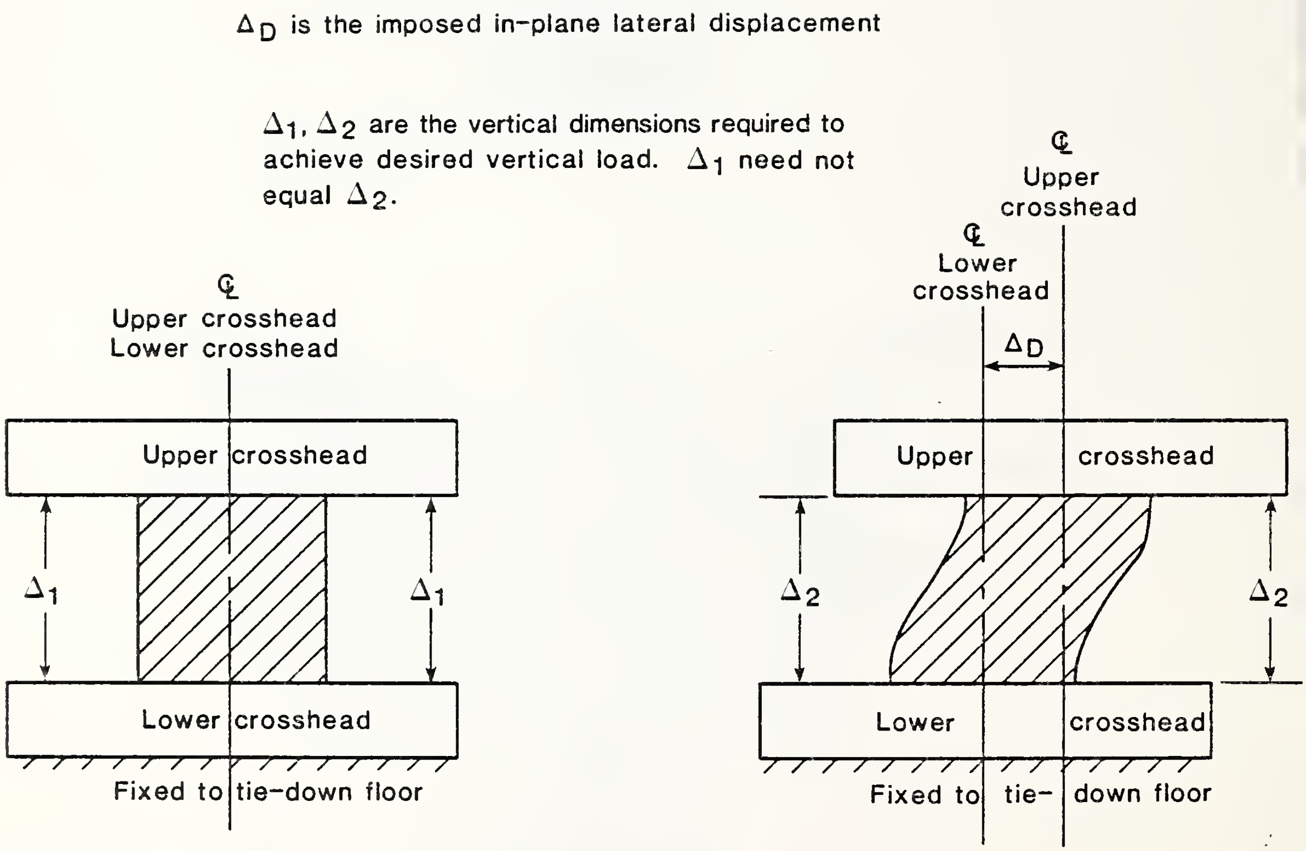


NORTH SIDE OF WALL PANEL
(96HH200 & 96HH300)



SOUTH SIDE OF WALL PANEL
(96HH200 & 96HH300)

Figure 2.7. Wall panel instrumentation (96HH)



SIMPLIFIED DESCRIPTION OF IMPOSED DISPLACEMENT

Figure 2.8. In-plane displacement method

3. WALL PANEL TEST DESCRIPTIONS

In this chapter, a brief description of each wall test and its observed behavior is presented. All of the descriptions share a common format consisting of a load-displacement curve, a crack pattern map, and a short narrative highlighting the information contained in the two figures. In general, the combination of the load-displacement curve and crack pattern map provides sufficient information to broadly describe the behavior exhibited by a test specimen. Other information such as data from the LSTs is not presented since for the purposes of this report the wall behaviors are adequately described by their load-displacement relationships.

The load-displacement curves describe the complete loading (displacement) history for each wall test and provide a primary indicator of wall behavior. The load used in developing the curves is the horizontal load acting in the plane of the wall as measured by the hydraulic actuator load transducers. The load is referred to as the global in-plane load. The displacement used in the curve is the horizontal displacement of the upper crosshead in the plane of the wall (figure 2.8). This displacement is referred to as the global in-plane displacement to differentiate it from the in-plane wall displacement measured by the horizontal LVDTs mounted to the wall (figure 2.3). The global in-plane displacement (GID) is determined by the displacement transducers in the hydraulic actuators. The GID and the wall displacement measured directly by LVDTs are not necessarily the same. The GID is affected by total apparatus displacement while the direct LVDT displacement more nearly measures an absolute in-plane displacement of the wall. However, the direct LVDT displacment can be strongly affected by the breakup of a wall after cracking. Spalling and splitting in the region near a wall LVDT can produce large distortions in the apparent displacement. In general, the GID is a consistent measure of displacement which is unaffected by local wall distortions and, as a result, is best for general comparisons between tests.

The crack pattern maps reflect the observations of wall cracking at selected points during the tests. The crack patterns provide useful information on the physical reponse of a wall to an imposed loading history. The patterns serve as a guide to identifying regions of high stress, general stress flow, and physical load resisting mechanisms. It is desirable that the points during a test at which crack patterns are recorded be identified on the load-displacement curves. This is accomplished by using an identifying symbol which marks a location on the load-displacement curve corresponding to an associated crack pattern on the map. The symbols are captial letters starting with the letter A. Thus, in the narrative of each description reference will be made to specific points on the load-displacement curve identified by the symbols and by implication the crack pattern also associated with that symbol. The symbols are unique within a description, but not between tests. Symbol A does not refer to the same point on every load-displacement curve.

3.1 48HH150-3L06

The loading history for this 48 in. wall was essentially one cycle between fully reversed displacement limits (figure 3.1). The vertical (axial) compressive stress on the wall was maintained during this cycle at about 150 psi based on the net cross sectional area of the wall. The test continued after the one cycle with an increased vertical compressive stress (300 psi) and increased lateral displacement until the wall was unable to sustain the imposed vertical stress. The load-displacement curve for the wall exhibited some rounding as the displacement reached the point where diagonal cracking occured (figure 3.2). The rounding was probably due to the influence of some flexual distress as horizontal flexure cracking was observed in the top and bottom mortar joints. The lateral load resistance decreased sharply with the formation of the diagonal crack. The load-displacement curve exhibited much the same characteristics when the lateral displacement was reversed. The diagonal cracking occurred along a line which included both block units and mortar joints.

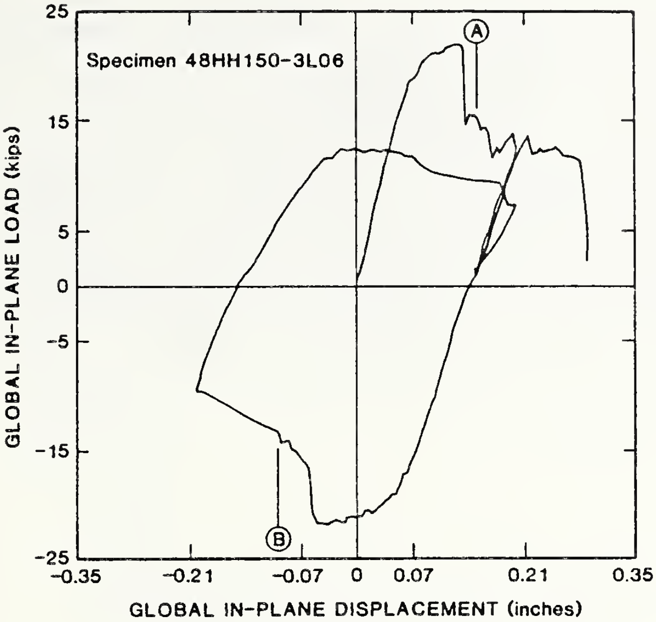


Figure 3.1. Specimen 48HH150-3L06 load-displacement curve

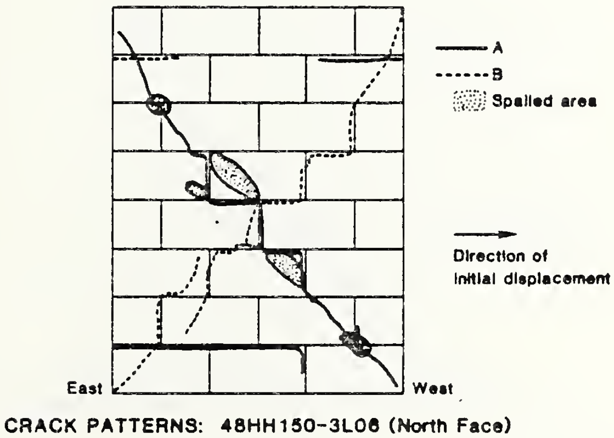


Figure 3.2. Specimen 48HH150-3L06 crack pattern

3.2 48HH450-3L05

The loading history for this wall was monotonic as indicated by the load-displacement curve (figure 3.3). The vertical compressive stress on the wall was maintained at 450 psi throughout the test. The load-displacement curve exhibited a nearly linear relationship until the formation of a diagonal crack in the wall (figure 3.4). The diagonal crack did not fully develop. The crack formed only in the central region of the wall. The decrease in lateral load which occurred with the diagonal crack formation was sudden, but with increased lateral displacements the lateral load resistance increased until it had almost reached the same level as before cracking. However, the increased displacement caused further cracking which finally developed (denoted by symbol D in figure 3.4) to such a degree that the wall was unable to sustain the vertical compressive stress.

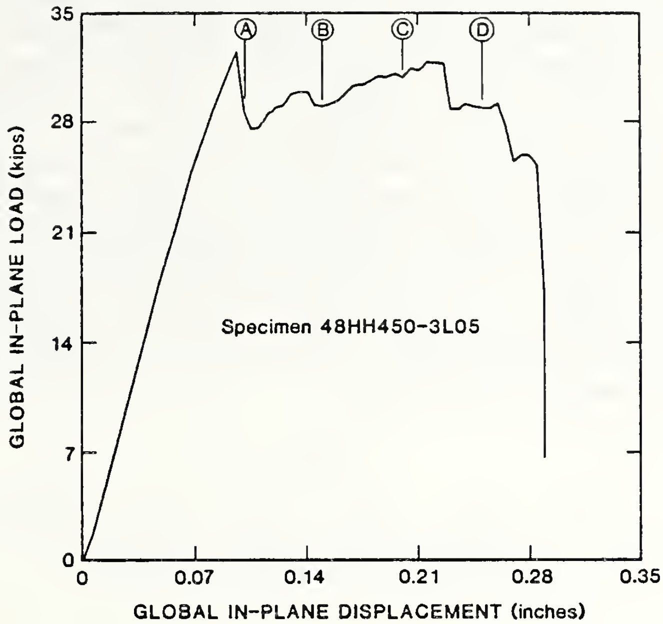


Figure 3.3. Specimen 48HH450-3L05 load-displacement curve

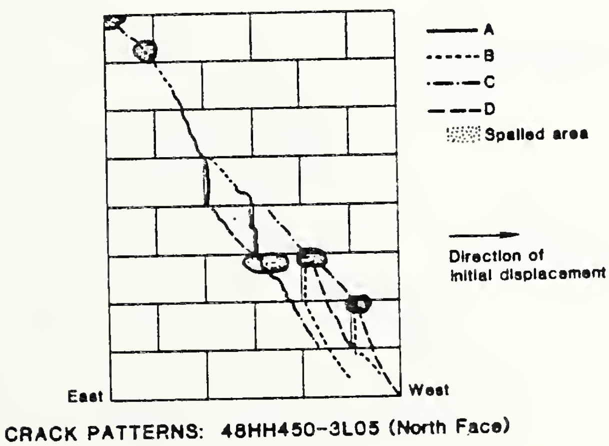


Figure 3.4. Specimen 48HH450-3L05 crack pattern

3.3 80HH250-3L07

The vertical compressive net cross sectional area stress was maintained at approximately 250 psi throughout the test. The wall was 80 in. long. The loading history was a three-quarter cycle with fully reversed displacement limits. The load-displacement curve (figure 3.5) exhibited a nearly linear relationship as the lateral displacement was initially increased. A displacement was reached, however, which resulted in a small, but sharp decrease in lateral load resistance and the formation of a diagonal crack (figure 3.6). The lateral load resistance remained essentially constant at a fairly high level as the displacement was increased, but a displacement (approximately 0.26 in.) was reached where the lateral load resistance again decreased suddenly and by a larger amount than previously. The lateral load resistance was still relatively high. The load-displacement curve exhibited a slightly different behavior when the lateral displacement was reversed. The lateral load resistance decreased steadily after reaching the maximum lateral load resistance in the opposite direction.

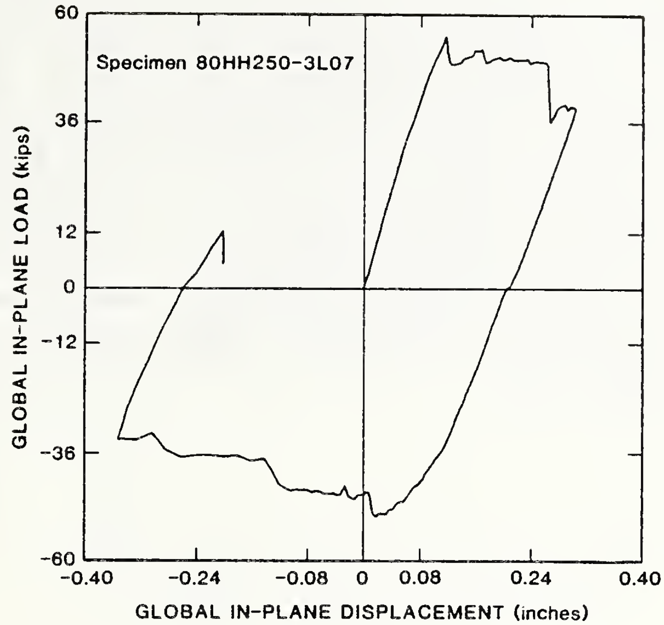


Figure 3.5. Specimen 80HH250-3L07 load-displacement curve

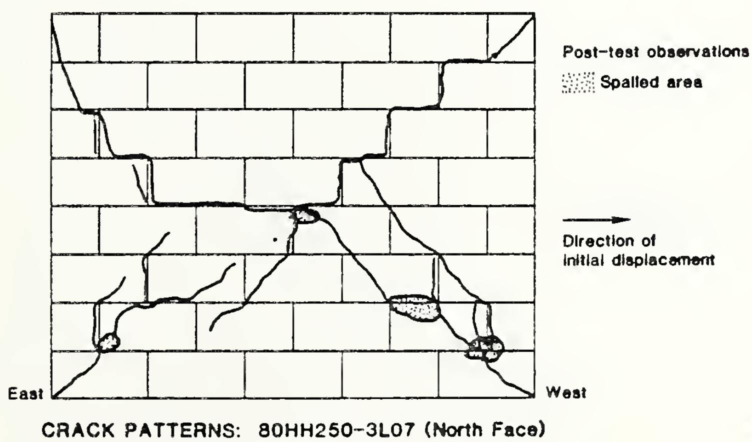


Figure 3.6. Specimen 80HH250-3L07 crack pattern

3.4 80HH400-4L01

The loading history for this 80 in. long wall was nearly monotonic to failure. The vertical compressive stress was maintained at about 400 psi on the net cross sectional area. The load-displacement curve (figure 3.7) exhibited only a slight rounding as the lateral displacement was applied. The lateral load resistance decreased abruptly at a lateral displacement of about 0.1 in., but increased again as the displacement was increased past 0.1 in. The diagonal cracking which also occured at about 0.1 in. of lateral displacement did not extend along the entire wall diagonal (figure 3.8). The first cracks were mainly in the mortar joints with extensions into the block units. At a lateral displacement denoted by the symbol B in figure 3.7 a second series of cracks formed accompanied by a slight decrease in lateral load resistance. The lateral load resistance remained relatively constant until crushing of the wall occurred in the lower west corner. The vertical compressive stress was not sustainable and the test was terminated.

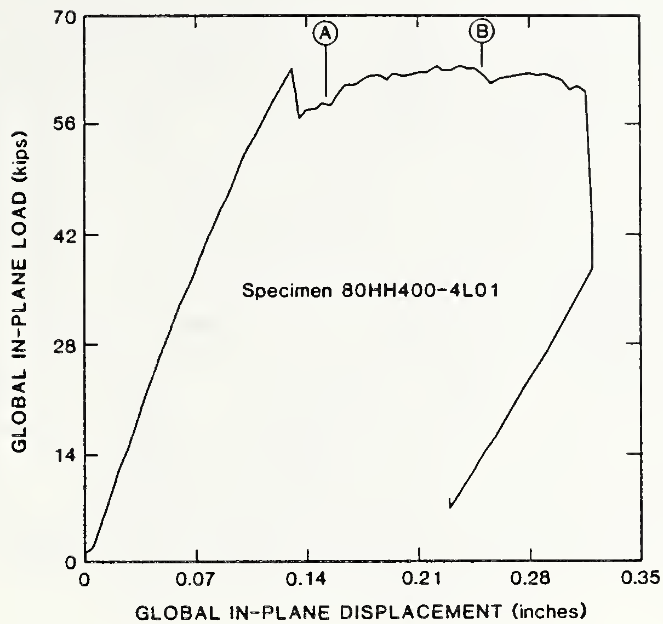


Figure 3.7. Specimen 80HH400-4L01 load-displacement

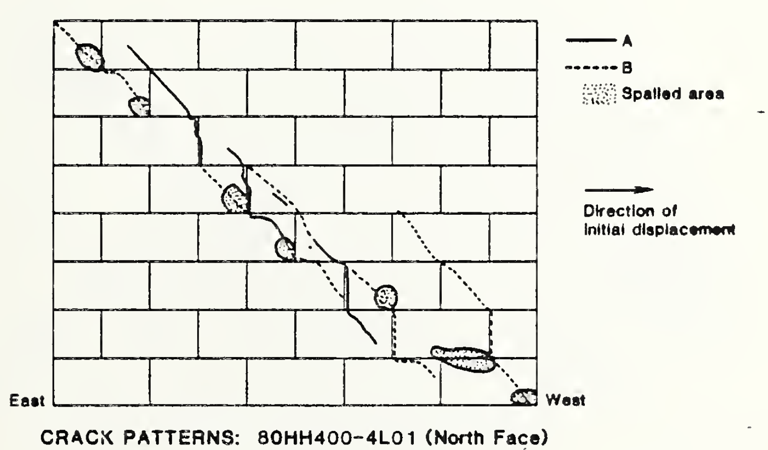


Figure 3.8. Specimen 80HH400-4L01 crack pattern

3.5 96HH200-4L03

The loading history for this 96 in. long wall was two cycles between fully reversed lateral displacement limits. The vertical compressive stress was maintained at 200 psi throughout the test. The load-displacement curve (figure 3.9) exhibited little rounding as the lateral displacement was increased until at the maximum lateral load resistance there was a slight plateau before the resistance decreased rapidly, though not by a large amount. The diagonal crack which formed just prior to the drop in resistance followed a stair-step pattern along the mortar joints (figure 3.10). The orientation of the crack was basically along a 45 degree line from the upper east corner until the crack reached the bottom mortar joint. The crack extended horizontally along the bottom mortar joint to about the middle of the bottom west corner block. The lateral load resistance remained constant after the drop in load despite increased lateral displacement. As the displacement was increased the diagonal crack extended to the extreme wall corners as shown by the cracks denoted by symbol B in figure 3.10. It appeared that the completed diagonal/horizontal crack line served as a slip line along which the upper right segment of the wall translated relative to the lower left segment. The load-displacement curve exhibited similar behavior when the lateral displacement was reversed. The final failure of the wall was the result of wall crushing in the lower west corner.

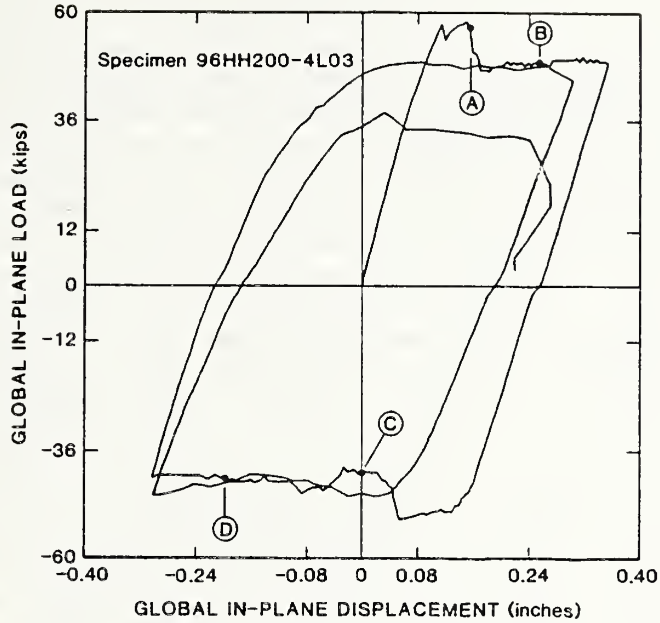


Figure 3.9. Specimen 96HH200-4L03 load-displacement curve

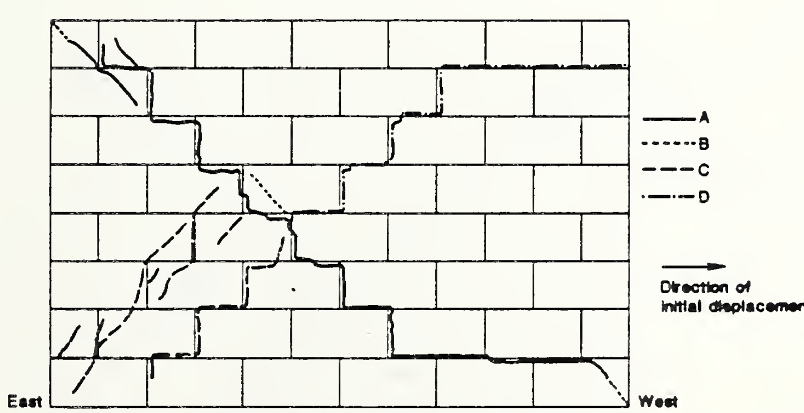


Figure 3.10. Specimen 96HH200-4L03 crack pattern

3.6 96HH300-4L02

The vertical compressive stress was maintained at about 300 psi based on the net cross sectional area of the wall. The wall was 96 in. long and the loading history was basically a single cycle between fully reversed displacement limits. The initial portion of the load-displacement curve (figure 3.11) exhibited the usual nearly linear relationship, but at about the lateral displacement denoted by symbol A in figure 3.11 the general slope of the curve changed significantly. There was a slight temporary reduction in lateral load resistance, but the lateral load resistance increased with increased displacement such that the lateral load resistance subsequently exceeded the lateral load resistance prior to the change in slope of the curve. Cracking began at about the displacement where the slope changed. The cracking (figure 3.12) had the same general appearance as the cracking for specimen 96HH200. The cracking propagated in a stair-step fashion following the mortar joints along a 45 degree line extending from the upper east corner of the wall. However, the cracking did not yet extend corner to corner (crack line denoted by the solid line in figure 3.12). Once the lateral displacement increased past the displacement where the overall maximum lateral load resistance occurred (approximately 0.2 in.) the lateral load resistance decreased gradually and the diagonal crack propagated to the upper east and lower west corners creating a plane along which sliding of the upper right wall segment occurred. The lateral displacement was reversed to a displacement where the lateral load resistance was about zero. The lateral displacement was then again increased to a displacement slightly larger than the previous limiting displacement. There did not appear to be any effect on the wall behavior as a result of this partial reversal. The lateral displacement was then fully reversed. The load-displacement curve exhibited similar characteristics with a relatively constant maximum lateral load resistance. The final cause of failure was crushing of the lower west corner of the wall resulting in an inability to sustain the vertical compressive stress.

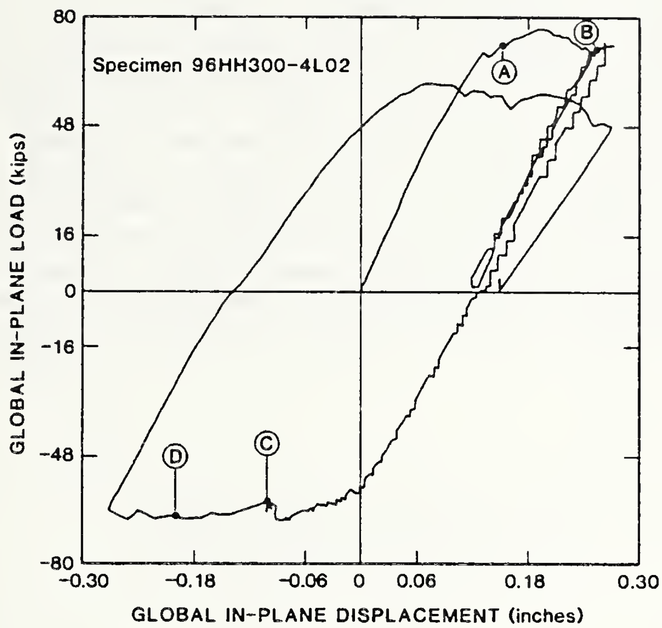


Figure 3.11. Specimen 96HH300-4L02 load-displacement curve

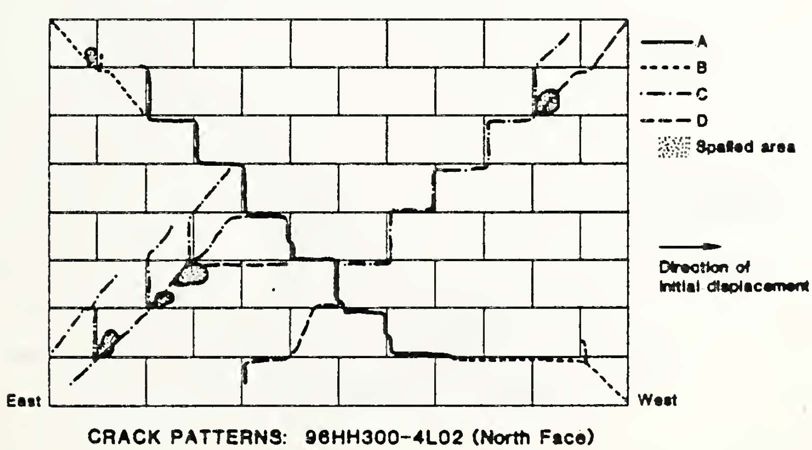


Figure 3.12 Specimen 96HH300-4L02 crack pattern

3.7 96HH400-4L04

The loading history was monotonic with a constant vertical compressive stress of about 400 psi. The load-displacement curve (figure 3.13) was similar in form to the curve for test specimen 96HH300. There was an initial relatively linear ascending branch followed by a slight drop in lateral load resistance and then another ascending branch with a reduced slope compared to the initial branch. A maximum lateral load resistance was reached whereupon there was a sharp, moderate decrease in resistance and subsequent increased displacement produced relatively little change in lateral load resistance. The cracking pattern (figure 3.14) looked similar to that which occurred in the other two 96 in. walls. There were slightly more areas where crushing and spalling of the mortar and block were observed. The wall finally failed as the apparent result of severe crushing of the mortar bed joint near the lower west corner of the wall. The wall was unable to support the vertical compressive stress.

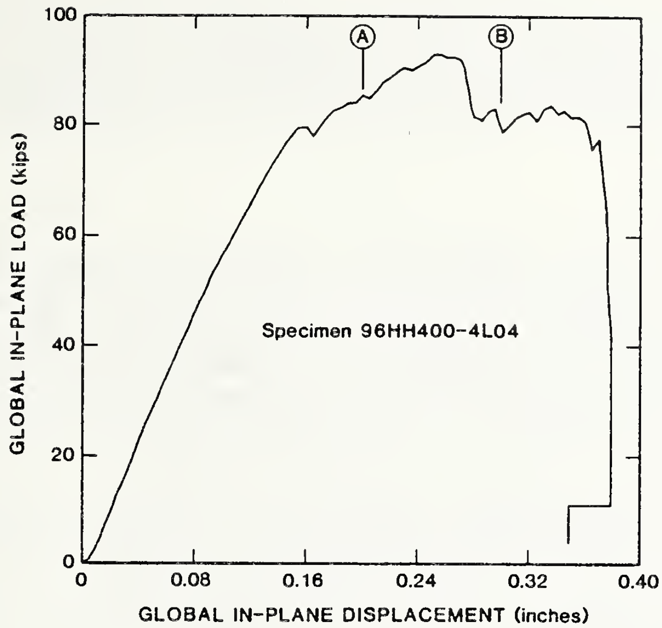


Figure 3.13. Specimen 96HH400-4L04 load-displacement curve

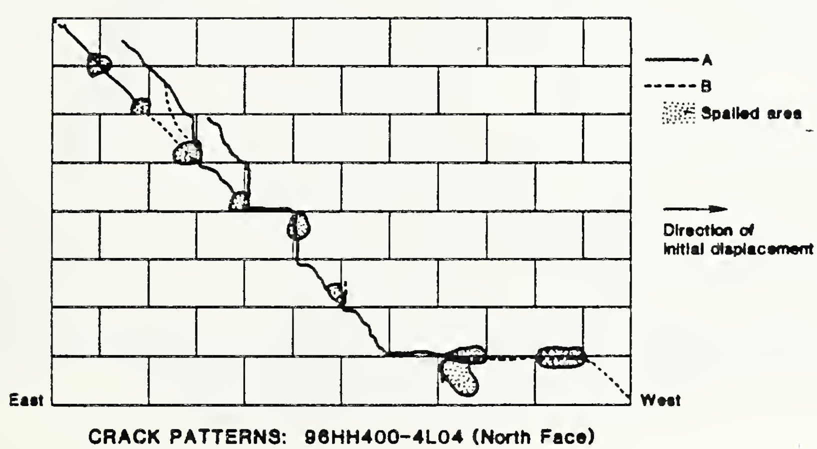


Figure 3.14. Specimen 96HH400-4L04 crack pattern

4. DISCUSSION OF RESULTS

The discussion which follows is limited to the wall panels described in this report. Detailed data analysis is not presented, but is left to a future report when other test results will be available. A general overview of the apparent behavior is presented with trends noted where evident.

4.1 GENERAL BEHAVIOR

Each of the seven wall panels exhibited a diagonal-tension type of shear distress. However, the diagonal-tension distress did not necessarily mean the wall failed catastrophically. Most of the walls exhibited a stable, if reduced, lateral load resistance at displacements at least twice the lateral displacement coincident with the formation of the first diagonal cracks. Catastrophic failures, large loss in resistance to both vertical and lateral forces, were the result of crushing in the high compression regions of the walls.

The predominant crack pattern was diagonal (or inclined) cracking. The orientation (angle) of the cracking changed as the aspect ratio of the walls was changed. The angle of the diagonal cracking in the 48 in. walls tended to coincide with the true diagonal of the wall, making the angle somewhat steeper than 45 degrees. In the 80 in. and 96 in. walls the diagonal cracking was aligned generally along a 45 degree line from the upper corner of the wall in compression. An example of this tendency was exhibited by the crack pattern for specimen 96HH300 in figure 3.12. Apparently, crack orientation was not affected by variations in the axial (vertical) compressive stress.

Within the range of aspect ratios used in this test program, the aspect ratio did not affect the lateral displacement at which diagonal cracking occurred when the wall behavior was not significantly influenced by flexure. The behavior of the walls after cracking, however, was affected by both the aspect ratio (wall length) and axial compressive stress. The differences were most probably the result of the impact of these two parameters on the effectiveness of a second load resisting mechanism, shear friction along the cracks. The resistance due to shear friction was increased for higher compressive stresses and longer (larger area) cracks. If the resistance by shear friction was sufficiently high then the lateral load resistance of the wall was maintained even after diagonal cracking occurred. However, if the shear friction resistance was significantly lower than the resistance of the wall prior to cracking then the decrease in lateral load resistance after cracking was pronounced. It was evident that specimen 96HH400 had the advantages of both increased crack length and increased compression which resulted in its ability to exhibit increased lateral load resistance after diagonal cracking occurred (figure 3.13). However, there were limits to the positive effects, since walls with higher vertical compression tended to suffer more crushing.

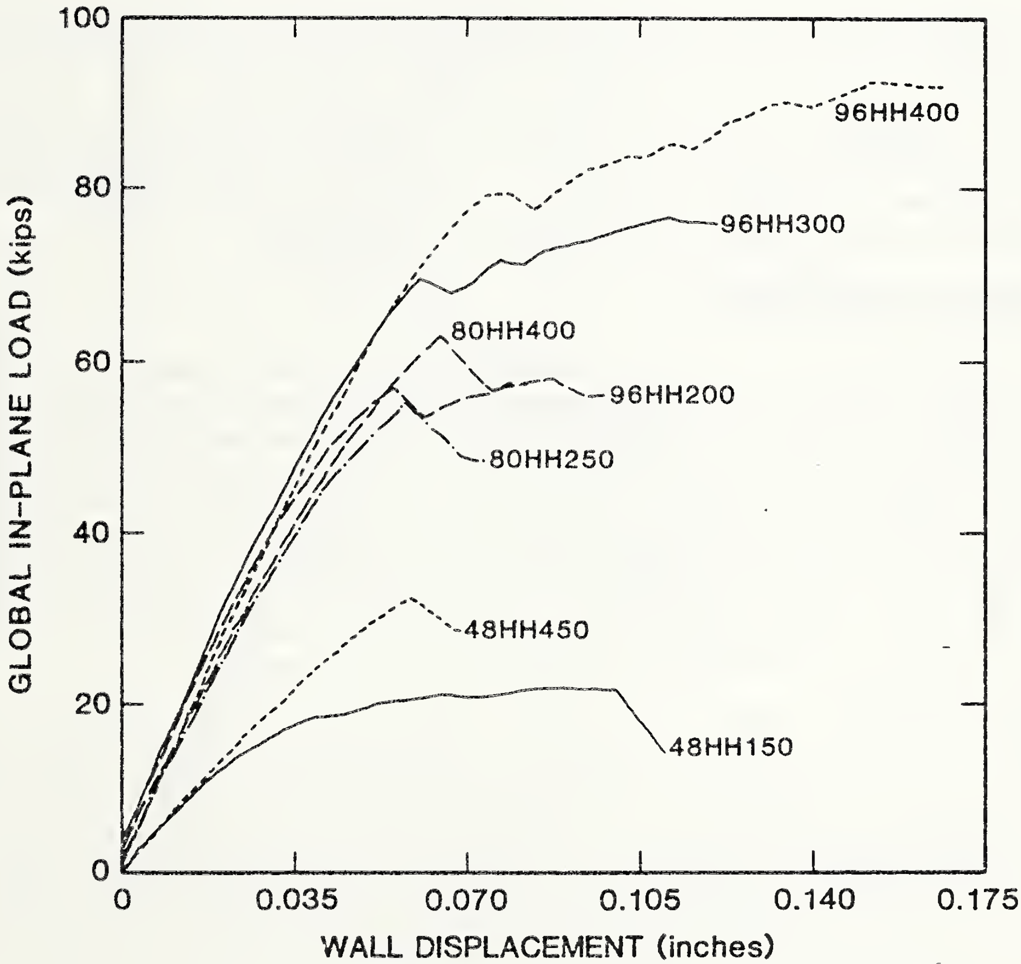


Figure 4.1. Combined load-displacement curves

4.2 LOAD-DISPLACEMENT RELATIONSHIPS

The load-displacement curves for the seven wall panel tests are shown in figure 4.1. The load is the global in-plane load while the deflection is the displacment of the top course of the wall measured by the top west horizontal LVDT (figure 2.3). The curves only include that portion of the relationship between the unloaded condition and a displacement slightly past that at which the maximum lateral load resistance occurred. There does appear to be a common displacement at which the lateral load resistance first peaks. The term first peak refers to the lateral load resistance just prior to the first drop in load. In some wall tests the resistance increases to a higher value than the first peak value when the displacement is subsequently increased. Walls 48HH150 and 96HH400 are exceptions which are explainable by their slightly different failure modes. Wall 48HH150 is influenced by flexure as evidenced by the flexural cracking (figure 3.2). Wall 96HH400 has the most beneficial combination of high axial compressive stress and a longer wall length.

A slightly different view of the same information is obtained by dividing the global in-plane load by the net cross sectional areas of the different walls. For simplicity, the resulting stress is termed shear stress, but it is recognized that the computed value does not directly relate to the diagonal-tension type of failure. However, the shear stress is a convenient means of accounting for the different wall lengths (areas). The combined shear stress versus displacement curves are shown in figure 4.2. Clearly, the curves tend to form a more uniform pattern especially in terms of "stiffness".

4.3 DIAGONAL TENSION STRAIN

Numerous strain measurements are available for each wall panel test. However, for this report the data from only one of the locations is presented. The strain measured by an LVDT mounted parallel to the diagonals provides an excellent general indication of overall wall strain. Since the cracking appears to form as a result of diagonal tension the strain measured by the north side LVDT (e.g., figure 2.4) provides a measure of the diagonal tensile strain in the wall. The local displacements measured by the diagonally mounted wall LVDTs are divided by the initial gage length to arrive at a strain value. The gage length used in all computations for the diagonally mounted LVDT strain is 33.941 in. which is the diagonal length of a 24 in. square.

The computed diagonal strain versus wall in-plane displacement relationship is shown for all seven walls in figure 4.3. The curve for 48HH150 is shown for completeness, but its behavior is strongly influenced by flexure which accounts for its divergent characteristics compared to the other walls. As in the previous two figures, only the initial portion of the curves are plotted. Each curve has the same general form, an initial linear portion having a modest slope followed by a sudden change in the curve where large changes in strain occur for small changes in displacement. The breakpoint in the curve is, of course, related to the formation of cracks in the wall. The curves for the 80 in. and 96 in. walls indicate that the displacement at which cracking first occurs (curve breakpoint) is affected by the level of vertical compressive stress on the wall. Also of interest in the curves, is the value of strain at which the

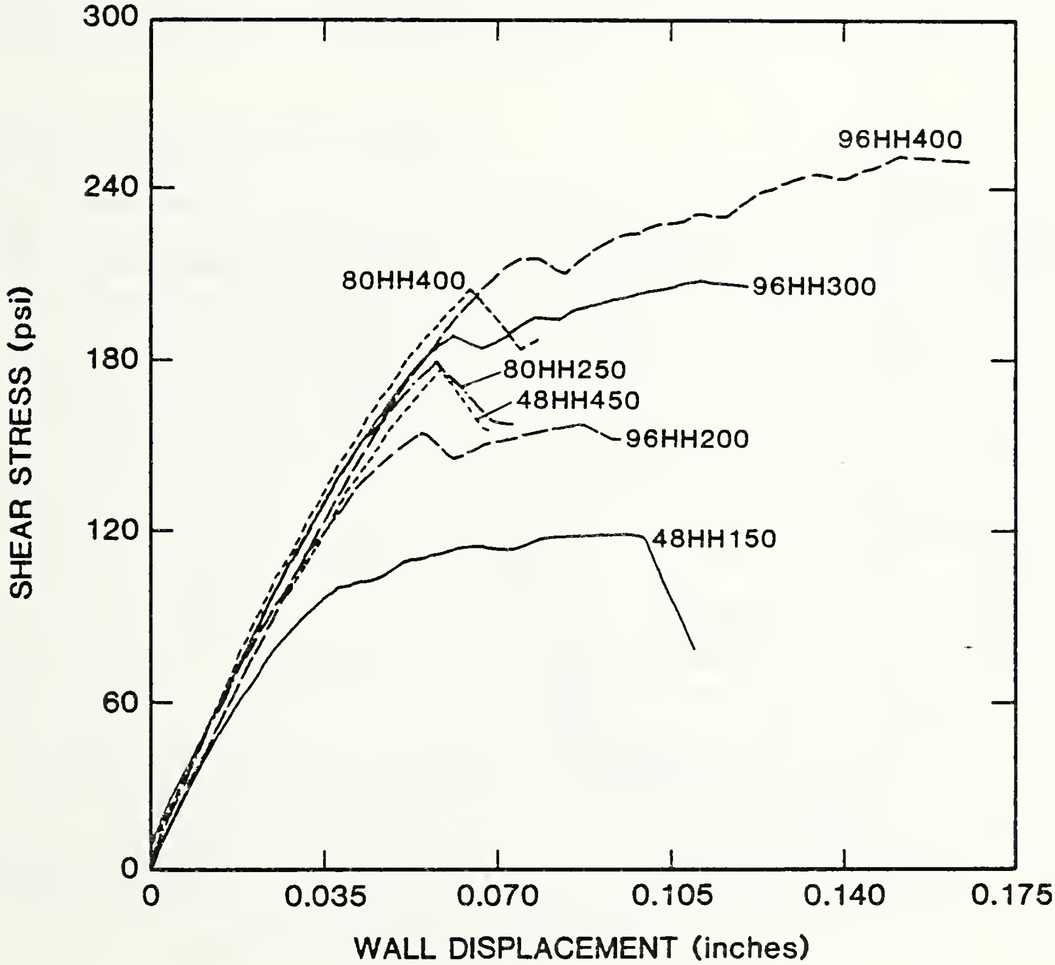


Figure 4.2. Combined stress-displacement curve

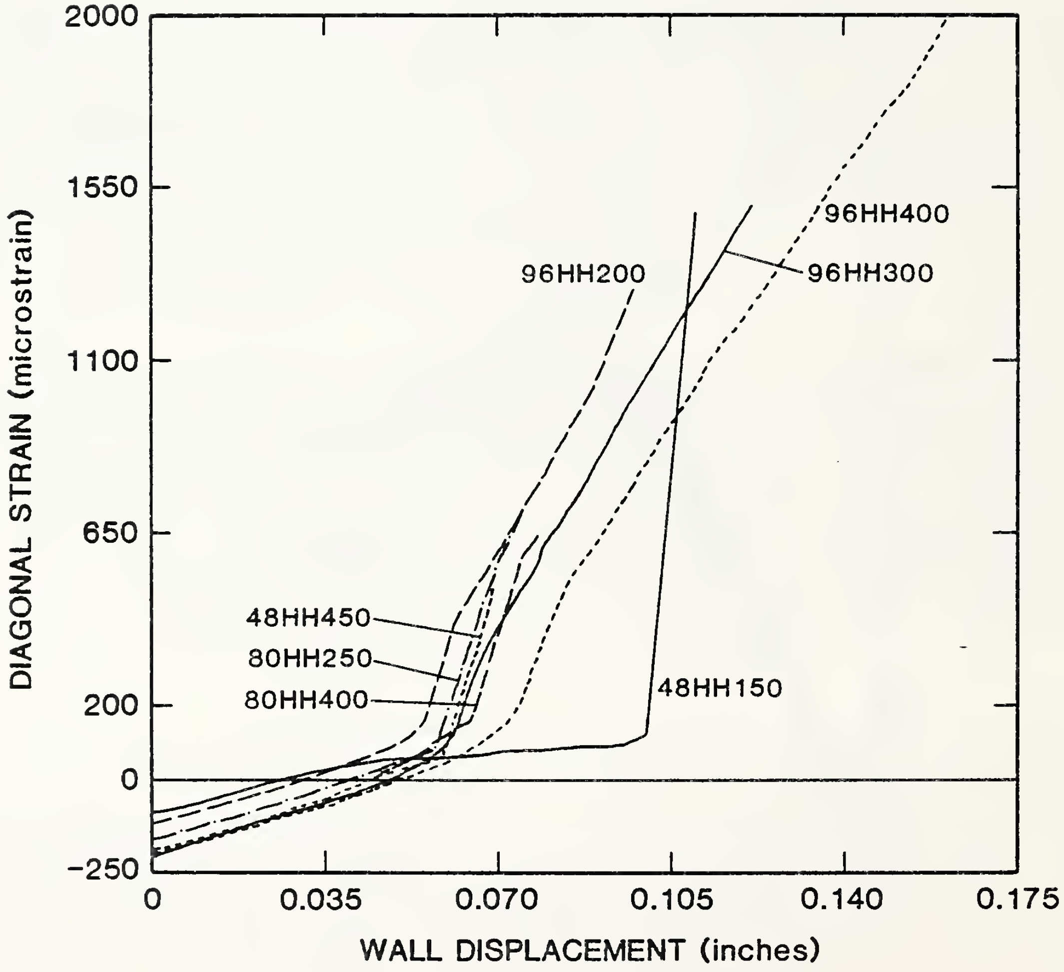


Figure 4.3. Combined diagonal strain-displacement curves

cracks occur. The breakpoints in the curves all occur at approximately the same tensile (+) strain. A slightly different way of observing the strain relationship is presented in figure 4.4 which is a plot of the relationships for shear stress and strain for each of the walls. The curves, again, have the same general form, two distinct branches with well-defined breakpoints. The curves clearly illustrate that the breakpoints occur at similar strain values and define the first peak lateral load (shear) resistance. The same information using a larger scale is shown in figure 4.5. It appears that the criterion which best defines the onset of diagonal cracking is the diagonal tension strain. The threshold strain value is in the range of 75 to 150 microstrains (tension). The apparent effect of the increased vertical compressive stress is to increase the compression prestress in the wall prior to the application of lateral displacement. As shown in figure 4.5 the compressive diagonal strain induced in the wall by the vertical compressive stress increases with increased compression. Since the slope of the shear stress versus diagonal strain is relatively constant for all of the walls and the threshold strain is also constant then the result of increasing the initial compressive prestrain is to increase the shear stress associated with the threshold strain as illustrated by figure 4.6.

4.4 MAXIMUM LATERAL LOAD RESISTANCE

The maximum lateral load resistance exhibited by each of the seven walls is listed in table 4.1. The maximum value is the maximum resistance occuring during the entire test. The entries for the 96 in. walls show two maximum values. The first value is the overall maximum resistance. The second value is that associated with the first peak resistance and the formation of the diagonal crack. The relationship between computed shear stress (net cross sectional area) and axial compressive stress is illustrated in figure 4.7. Several observations can be made about the information presented in figure 4.7. The trend of the relationship between shear stress and axial stress for the 48 in. walls is not the same as for the longer walls. If the trend actually exists and is not merely the result of a spurious test result it may be attributable to the altered angle of diagonal cracking. The first peak shear stress values for the 96 in. walls follow the general trend quite closely, but the additional resistance available due to shear friction causes the overall maximums to be larger than would otherwise be expected. It is suggested that for the aspect ratios less than or equal to 1 (wall length $\geq$ wall height) the effect of aspect ratio on the shear stress at which diagonal cracking occurs (first peak) is minimal. The effect of aspect ratio does have a noticable impact on the overall maximum shear stress for the 96 in. walls, but a question arises as to whether this additional resistance is useful from a design point of view. The wall would have cracked and undergone significant lateral displacement in order to mobilize the additional resistance. The limited data on the 48 in. walls does not warrant a conclusion as yet on the effect of aspect ratios greater than 1.

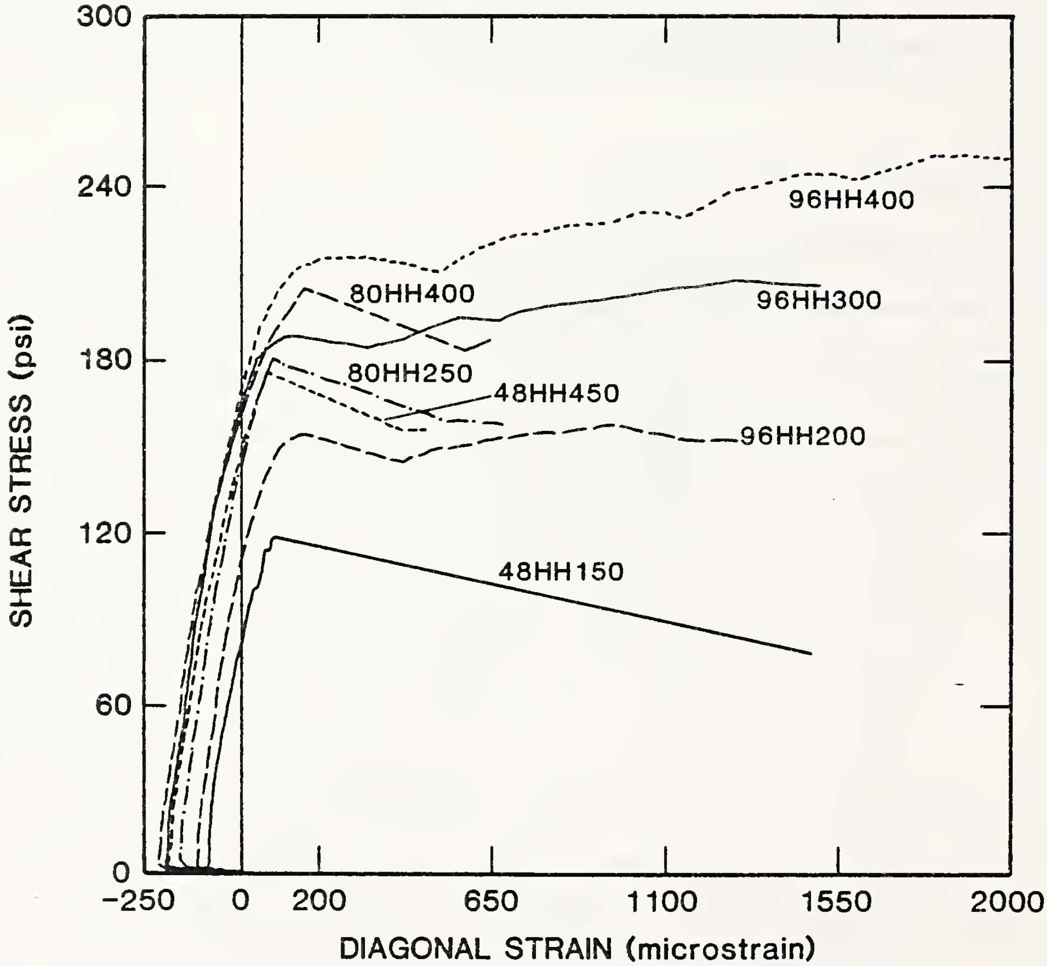


Figure 4.4. Combined stress-diagonal strain curves

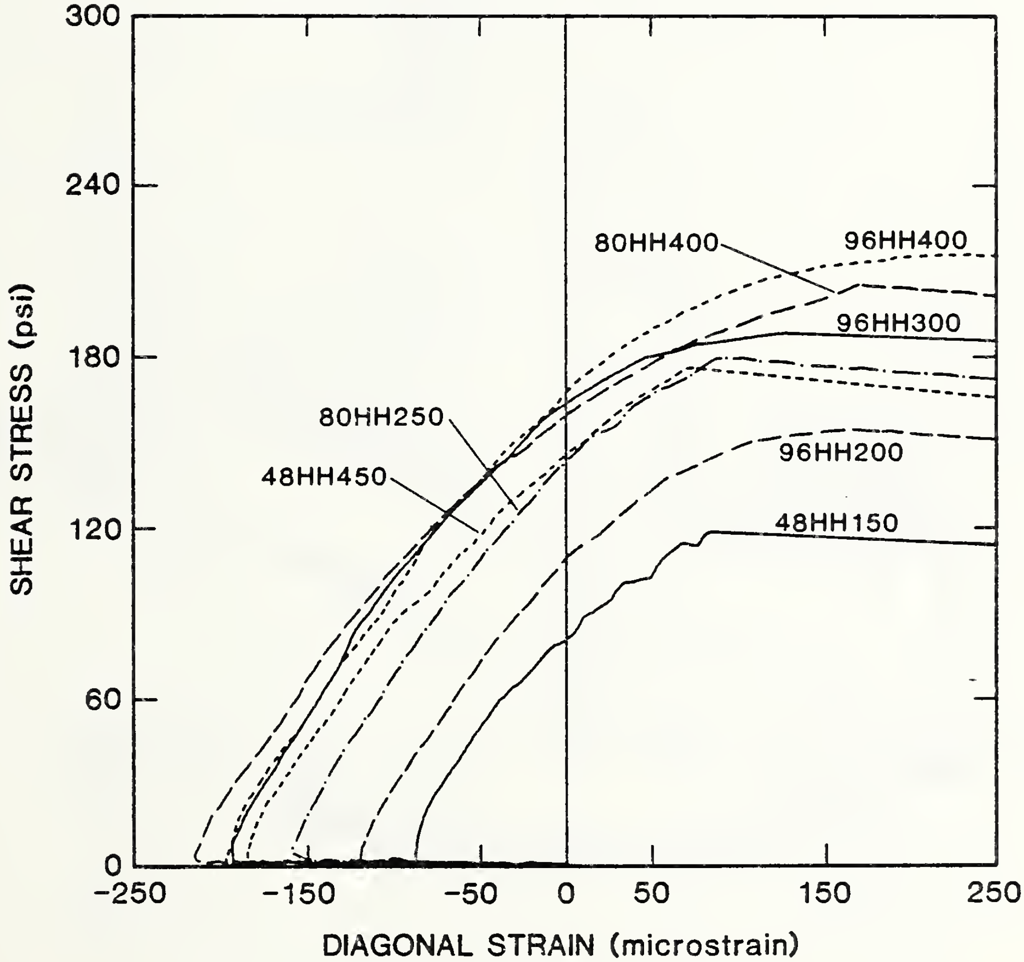


Figure 4.5. Combined stress-diagonal strain curves

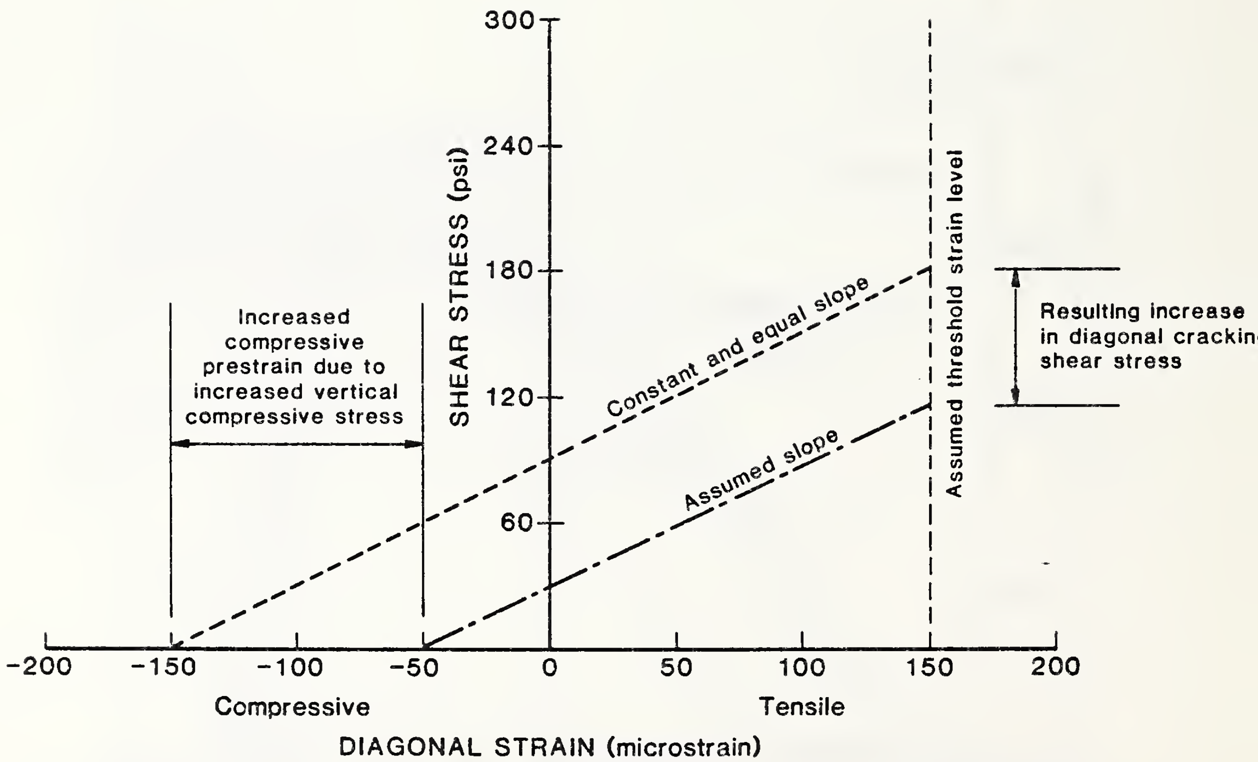


Figure 4.6. Effect of compressive prestrain

Table 4.1 Wall Panel Maximum Lateral Loads

Wall Panel Identifier	Axial Compressive Stress (psi)*	Maximum Lateral Resistance Load (kips)	Shear Stress (psi)*	Wall Displacement at Maximum Resistance (in.)**
48HH150-3L06	163	21.6	117	0.196
48HH450-3L05	434	32.2	175	0.059
80HH250-3L07	228	54.6	178	0.058
80HH400-4L01	390	62.2	202	0.065
96HH200-4L03	217	58.1 [56.5]***	157 [153]	0.089
96HH300-4L02	312	76.7 [69.3]	208 [188]	0.111
96HH400-4L04	407	92.8 [79.1]	251 [214]	0.156

* Stress is based on a net cross sectional area.

** Displacement as measured by top west horizontal LVDT.

*** Values in brackets are at first peak rather than maximum.

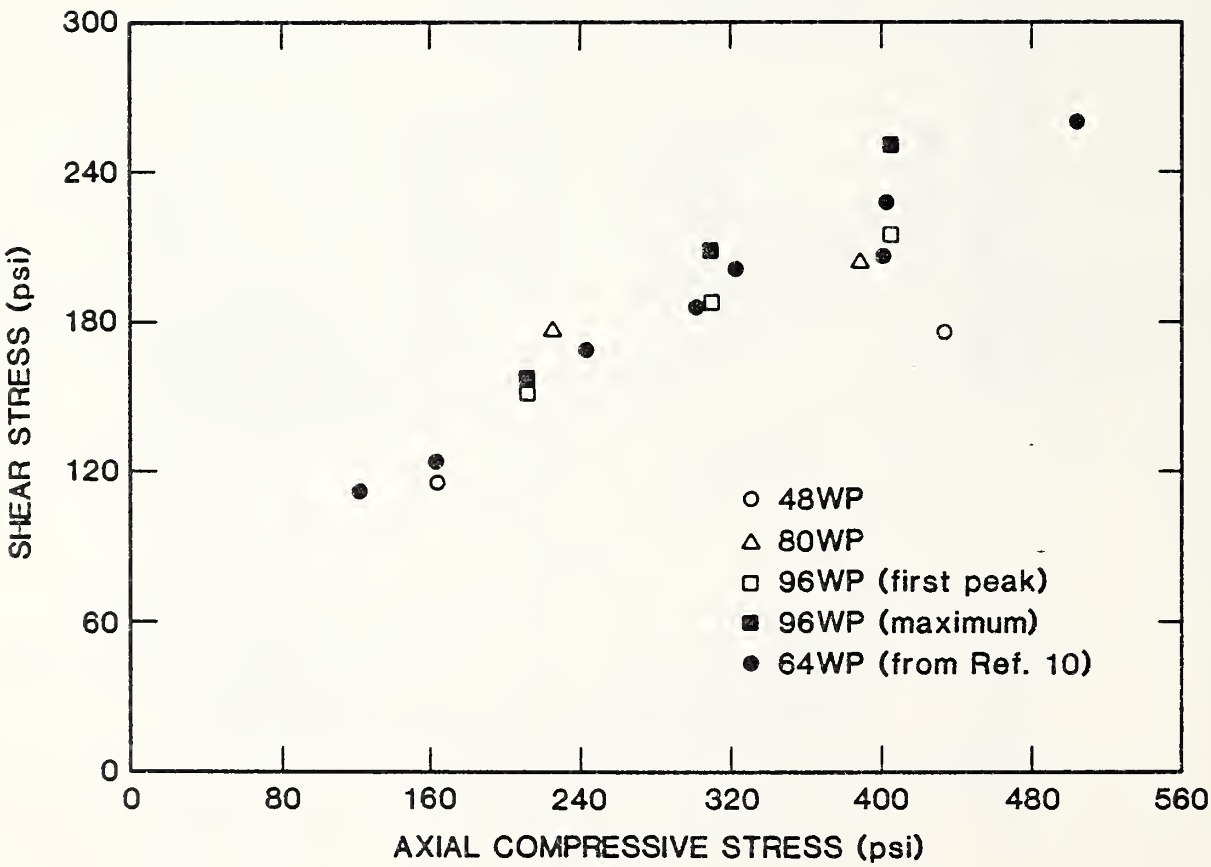


Figure 4.7. Maximum shear stress versus axial stress

5. SUMMARY AND CONCLUSIONS

5.1 SUMMARY

Experimental data were presented from seven wall panel tests. Each wall panel had a nominal height and thickness of 64 in. and 8 in., respectively. Three different wall lengths were used: 48 in., 80 in., and 96 in. All of the wall panels were ungrouted, unreinforced, and built from similar materials. The walls were subjected to a lateral in-plane displacement at their top surface while the bottom surface was fixed. The two variables were wall height-to-length (aspect) ratio and axial (vertical) compressive stress. The acquired data included forces and displacements imposed on the wall panels and local strain measurements on each of the two face shell surfaces of the walls. A limited presentation of data interpretation indicated a relatively weak effect of aspect ratio on the shear stress at diagonal cracking for aspect ratios less than or equal to 1 and a nearly linear relationship between axial compressive stress and maximum lateral resistance.

5.2 CONCLUSIONS

The conclusions presented below are based solely on the data reported herein.

- The lateral wall displacement at which the diagonal crack developed was relatively unaffected by wall aspect ratio for walls not influenced by flexure.

- The diagonal tension strain which defined the onset of diagonal cracking was unaffected by aspect ratio and was in the range 75 to 150 microstrains.

- The maximum lateral load resistance was affected by aspect ratio for higher levels of axial compressive stress.

- The longer walls developed maximum lateral load resistance greater than that resistance associated with diagonal cracking due to shear friction along horizontal cracks in the highly compressed regions of the walls.

6. ACKNOWLEDGMENTS

The concrete block units and the mason who fabricated the wall panels and prisms were provided by the National Concrete Masonry Association.

The authors wish to thank Dr. Spencer Wu, Dr. John Gross, and Dr. Nicholas Carino for their review of this report. The authors also acknowledge the help of Frank Davis and Allan DeLorme during the physical testing of the specimens.

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Appendix A. OVERVIEW OF MASONRY RESEARCH PROGRAM

The principal objective of the overall program of research is directed towards defining the shear capacity and behavior of shear-dominated masonry walls. The prediction of shear capacity and behavior of masonry has been identified as an area in which there is a serious deficiency of supporting research. The NBS/BSSC review committee for the ATC3-06 masonry design provisions [1] suggested that research was needed to substantiate and improve the current design recommendations for shear capacity.

The main variables which are to be investigated in the NBS masonry research program are axial compressive stress, aspect ratio (wall length-to-height), masonry type, mortar type, grout, vertical and horizontal reinforcement, out-of-plane loadings, and loading history. Analytical studies are coordinated with the experimental investigations so that a predictive model can be developed for defining the shear capacity and behavior of a masonry wall. The predictive model will lead to improved design standards, but in the interim the experimental test results will aid in substantiating and improving the current design provisions for shear in masonry walls.

Appendix B. MATERIALS

All materials used in the wall panel construction and associated prisms were commercially available and were representative of those commonly used in building construction.

B.1 CONCRETE MASONRY UNITS

Two concrete masonry unit shapes are used in the construction of the wall panels:

1. 8 in. x 8 in. x 16 in., 2 core hollow stretcher block.

2. 8 in. x 8 in. x 16 in., 2 core hollow kerfed corner block with a steel sash groove in one end.

The dimensions represent nominal sizes. Typical measured dimensions and physical characteristics of the units is presented in table B.1. The measurements are made in accordance with the procedures set forth in ASTM C140 [2]. The units are illustrated in figure B.1. The half blocks at each end of alternating wall courses are made by sawing kerfed corner blocks in half through the kerf. Both halves produced by this procedure are used in the wall panels.

All of the concrete masonry units used in the wall panels and prisms were manufactured on the same day by a commercial block manufacturer. The mixture proportions were set to produce a unit having an ultimate compressive strength of 2000 psi measured over the gross area of the unit. The mixture proportions were:

1950 lbs lightweight expanded shale aggregate
1250 lbs sand
260 lbs portland cement
190 lbs NewCem

The mixture used in producing the units made 115 units with 3.91 lbs of cementitious materials per unit.

NewCem is the proprietary name for a very finely ground water granulated blast furnance slag manufactured by Atlantic Cement Co., Inc. and is used as a partial replacement for portland cement. It meets the requirements of ASTM C989, grade 120 [3] and when blended within the range of 25 to 65 percent with portland cement, meets the requirements of ASTM C595 [4]. The preceeding description of NewCem is presented only for purposes of information and is not an endorsement of the proprietary product.

B.2 MORTAR

One type of mortar was used in constructing all of the wall panels and prisms. The mortar was a portland cement-lime mortar that was proportioned within the limits of a Type S mortar according to the specifications of ASTM C270 [5]. The materials used in the mortar were:

1. Sand - a natural bank sand that was dug locally with its primary use being for masonry mortar. Sieve analyses were performed on the sand upon delivery. The analyses were done according to the specifications in ASTM C144 [6] and the results appear in table B.2. The fineness modulus was 1.57.

2. Portland cement - a commercially available, bagged, 94 lbs per bag, Type I portland cement identified as meeting the specifications of ASTM C150 [7].

3. Lime - a commercially available bagged, 50 lbs per bag, hydrated lime, Type S, identified as meeting the specifications of ASTM C207 [8].

These materials were porportioned 1:3/8:4 with 1 part by volume of cement, 3/8 part by volume of lime, and 4 parts by volume of sand. The parts were mixed in a typical motorized mortar mixer (fixed horizontal drum with rotating blades) for a period of not less than 3 minutes after all cement, lime, sand, and most of the water was added. Finally, small amounts of water were added to produce mortar of a consistency acceptable to the mason.

Immediately upon leaving the mixer, the time was recorded and a sample was taken for determining the initial flow rate. The air content of the mortar was measured for selected mortar batches. Six mortar cubes (2 in. x 2 in. x 2 in.) were made during the early part of the wall panel construction. After completing the wall panel, the mason constructed three prisms. Thus, each batch of mortar produced a wall panel, six mortar cubes, and three prisms. Retempering of the mortar, if required, was permitted only once per batch.

Table B.1 Dimensions and Properties of Concrete Masonry Units

	Hollow* Stretcher	Hollow* Corner/Sash Groove
Width (in.)	7.63	7.63
Height (in.)	7.59	7.57
Length (in.)	15.62	15.64
Minimum Face Shell Thickness (in.)	1.30	1.30
Gross Area ($in.^2$)	119.2	119.3
Net Solid Area ($in.^2$)	61.5	67.0
Gross Ultimate Compressive Strength (psi)	1813	1795
Density (lb/ft^3)	102.4	104.5
Absorption (lb/ft^3)	10.8	10.2

* Average of measurements from 6 units.

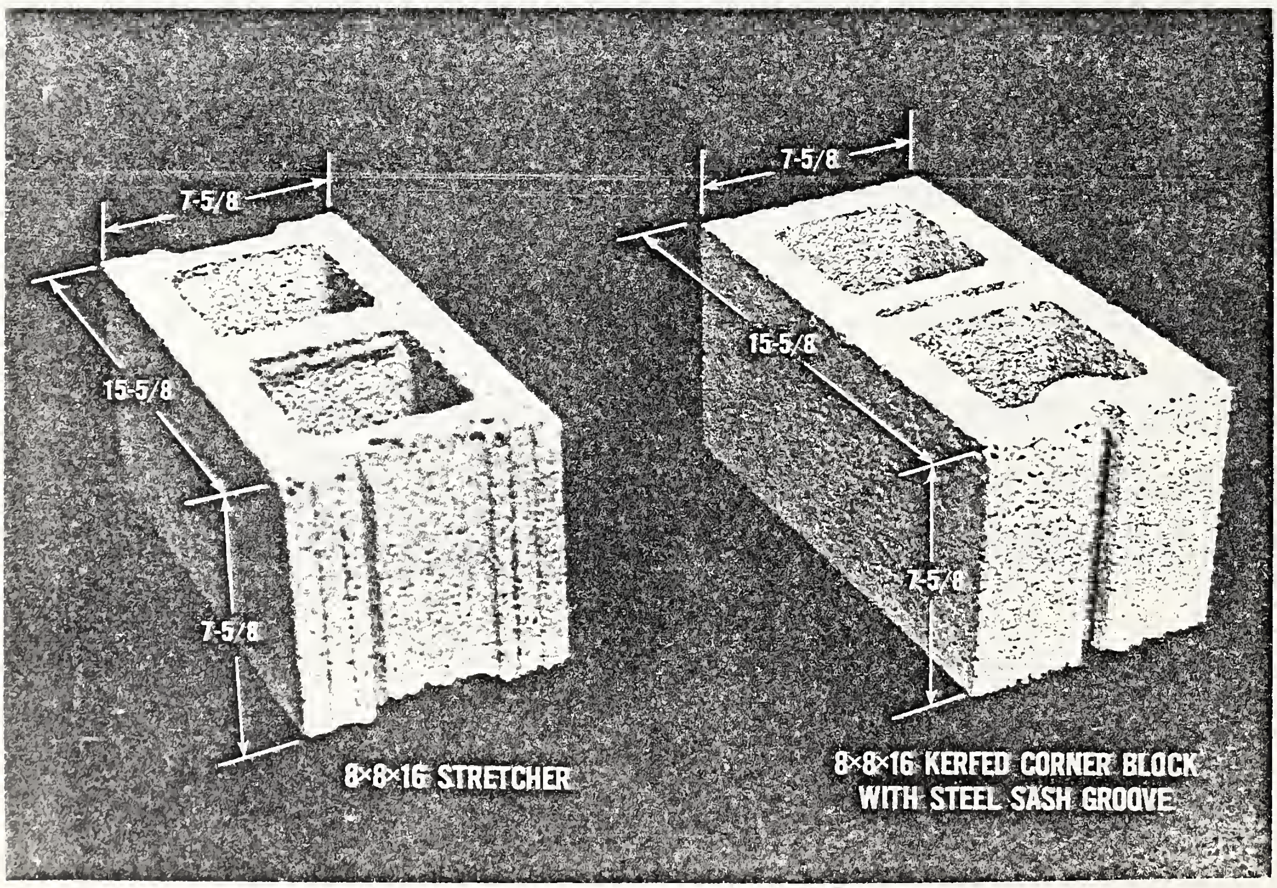

Figure B.1. Concrete block units

Table B.2 Masonry Sand Sieve Analysis*

Screen Size Number	Cumulative Percent Retained
4	0.1
8	0.6
16	2.0
30	11.0
50	56.9
100	86.6
100+	....

Total 157.2 ÷ 100 = 1.57 Fineness Modulus

* Average of three samples taken upon delivery of sand.

Appendix C. WALL PANEL DESCRIPTION

Seven wall panels were fabricated using concrete block taken from the same lot and mortar mixed using the same proportions of cement, lime, and sand. As companions to each wall six mortar cubes (2 in. x 2 in. x 2 in.) were made and three prisms were fabricated. The companion specimens were tested to provide information on mortar compressive strength and wall panel compressive strength.

C.1 WALL PANEL FABRICATION

The wall panels were constructed in running bond with 50 percent overlap of block in alternate wall courses (figure C.1). The wall panels had overall nominal dimensions of 64 in. in height, 8 in. in thickness, and either 96 in., 80 in., or 48 in. in length. The wall panels (and prisms) were constructed by an experienced mason using techniques representative of good workmanship. The wall panels were fabricated in a controlled environment laboratory from materials stored in the same environment for at least 30 days. The temperature and relative humidity of the laboratory were maintained at approximately 73°F and 50 percent, respectively.

The bottom course of block was laid on a steel beam (channel) section without bedding mortar. The steel beam and first course were then leveled using shims as necessary. The first block laid in the bottom course was a whole kerf unit with no head joint mortar. Head joints were subsequently formed by buttering the end of the next block to be laid with mortar. The head joint mortar was only placed as deep as the face shell thickness. All head joints were "shoved" joints with no closure units or backfilling of head joints. The mortar bed joints were formed by placing mortar along the face shells of the previously laid course of blocks. No mortar was placed on the cross-webs except for the end cross-webs. Each course was laid to maintain a course height of 8 in. The level of each course was fixed by a level string spanning between two vertically plumb posts. The end blocks were plumbed using a 4 foot level to maintain plumb end surfaces of the wall panel. All joints were struck flush with a trowel, but not tooled.

C.2 PRISM FABRICATION

Three prisms were made with each wall panel using mortar from the same batch as was used for the wall panel. Each prism was made by stack bonding three stretcher units (figure C.2). The mortar bedding between the blocks was either face shell only or full area bedding. Within each group of three prisms the bedding was the same. The mason used a 4 foot level to maintain the level of each block and to plumb the prism. The ultimate compressive strength of the prisms was determined by testing the prisms in a uniaxial testing machine having a total capacity of 400,000 pounds force. A spherically seated upper bearing block covered the entire bearing surface of the prisms. The load on the prism was applied at any convenient rate for the first 40,000 pounds force while the remaining load was applied at a rate of 40,000 pounds per minute until failure occurred. The maximum load sustained by the prism was used in computing the ultimate compressive stress.

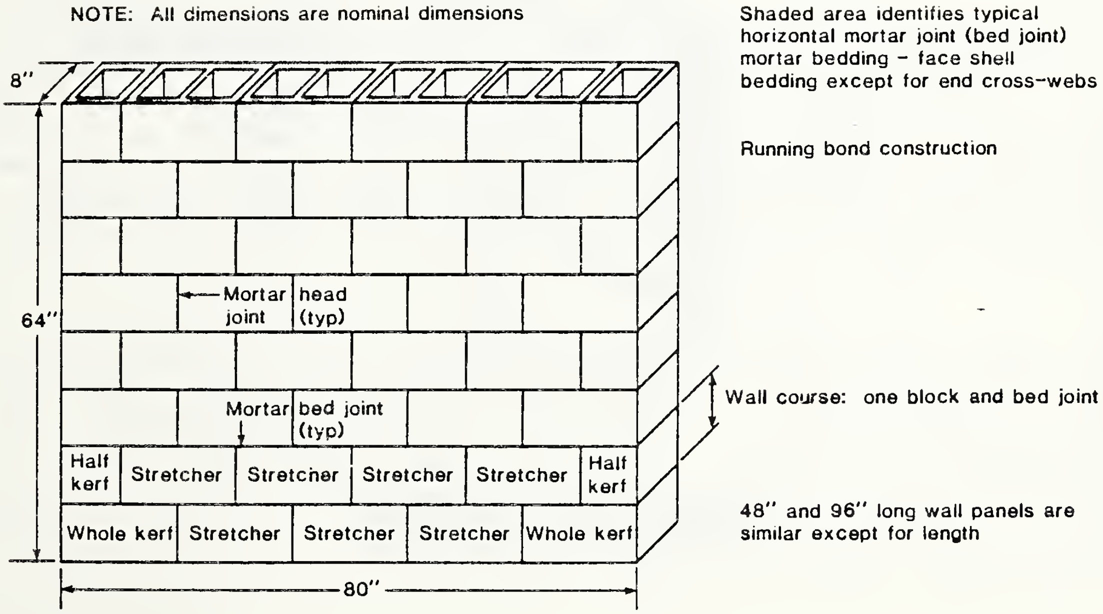

Figure C.1. Typical wall panel

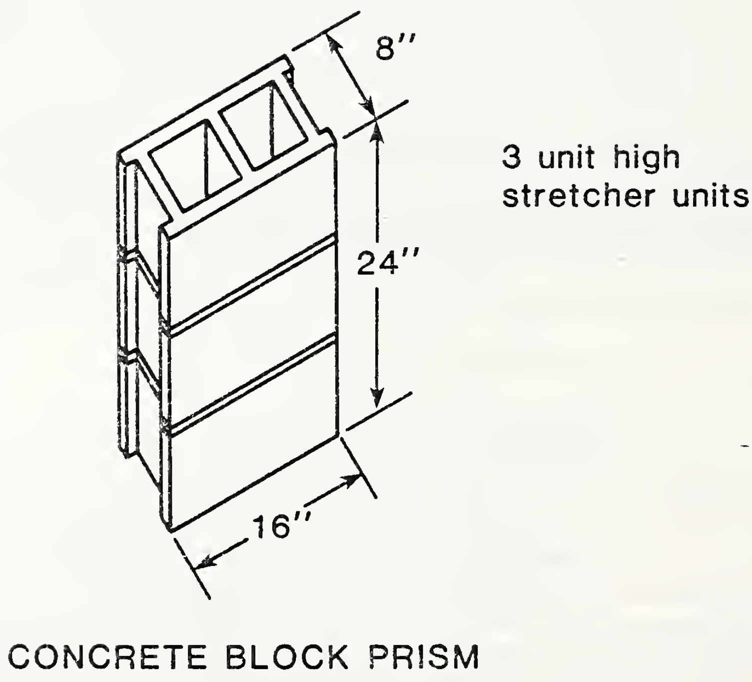

Figure C.2. Typical prism

Apendix D. WALL PANEL TESTS: SETUP AND PLACEMENT

D.1 TEST SETUP

The test setup (figure D.1) is the NBS Tri-directional Test Facility (NBS/TTF), a permanent loading apparatus designed to test building components using three-dimensional loading histories. The NBS/TTF is described in a separate report [9], but for purposes of completeness a brief summary is presented in this section.

The NBS/TTF is a computer-controlled loading apparatus which can apply forces/ displacements in all six degrees of freedom at one end of a test specimen. The other end of the specimen is fixed. The six degrees of freedom are the translations and rotations in and about three orthogonal axes. The application of such actions are accomplished by seven closed-loop, servo-controlled hydraulic actuators which receive their instructions by means of computer generated commands. The major components of the NBS/TTF are shown in figure D.1. The reaction system is composed of the structural tie-down floor and two vertical buttresses. The load distribution system consists of the two x-shaped steel crossheads, one at the bottom and the other at the top of the test specimen. The load application system is made up of the seven hydraulic actuators. The control system is not visible in the figure, but includes the servo-control electronics, the data acquisition equipment, and a minicomputer.

D.2 WALL PANEL PLACEMENT

The wall panels were handled by attaching a carrying harness to the panel (figure D.2). The harness had attachment points for lifting the wall and a clamp ing arrangement which held the harness against the ends of the panel. The overhead crane was used to place the wall panel in the NBS/TTF and a special device was fabricated which permitted the wall to be placed under the upper crosshead. The special device was a large welded assembly in the shape of a "C" (figure D.3). The shape permitted the crane hook to be centered above the wall panel without interfering with the upper crosshead during placement (figure D.4).

The walls were set in place using mechanical stops which fixed the walls in their horizontal position. The walls were aligned vertically using small wedges set at four places under the face shells of the walls. The walls were fastened to the lower crosshead first, using an epoxy mortar along the bottom face shells and end cross-webs. The upper crosshead was then lowered onto the wall whose top face shell and end cross-webs were also mortared with the epoxy mortar. A small vertical compressive load (1,000 to 2,000 pounds) was applied to the wall to ensure contact between the wall and epoxy mortar. The upper crosshead was locked in position and the epoxy mortar was allowed to cure at least 16 hours before testing the wall.

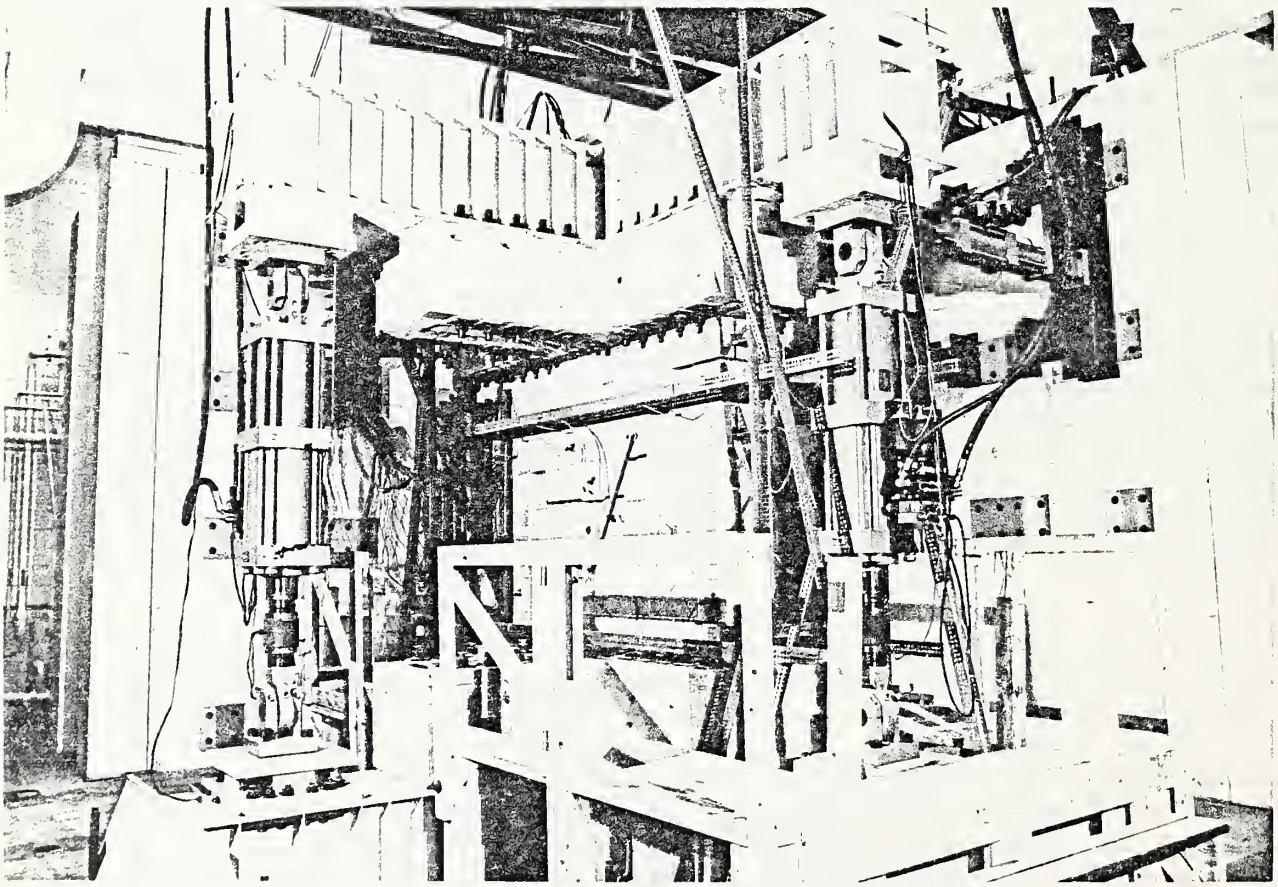

Figure D.1. Test setup

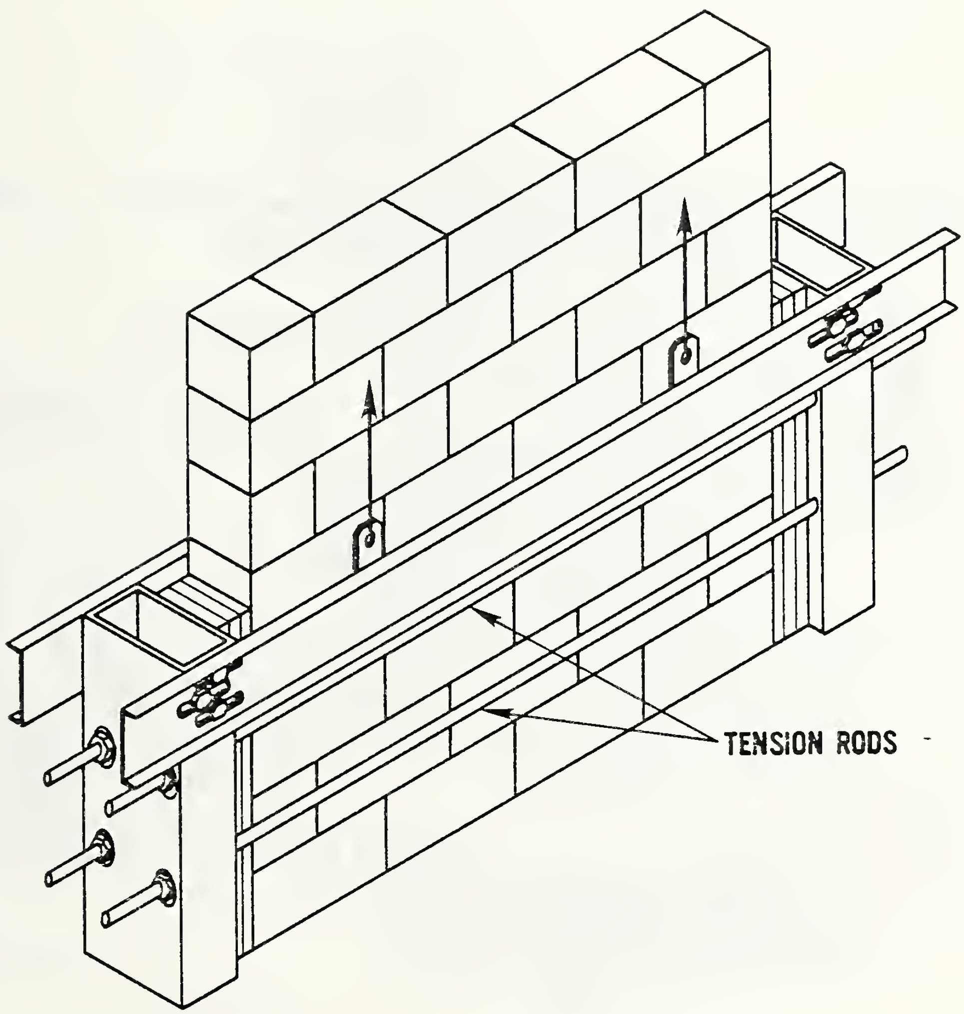

Figure D.2. Wall panel transport harness

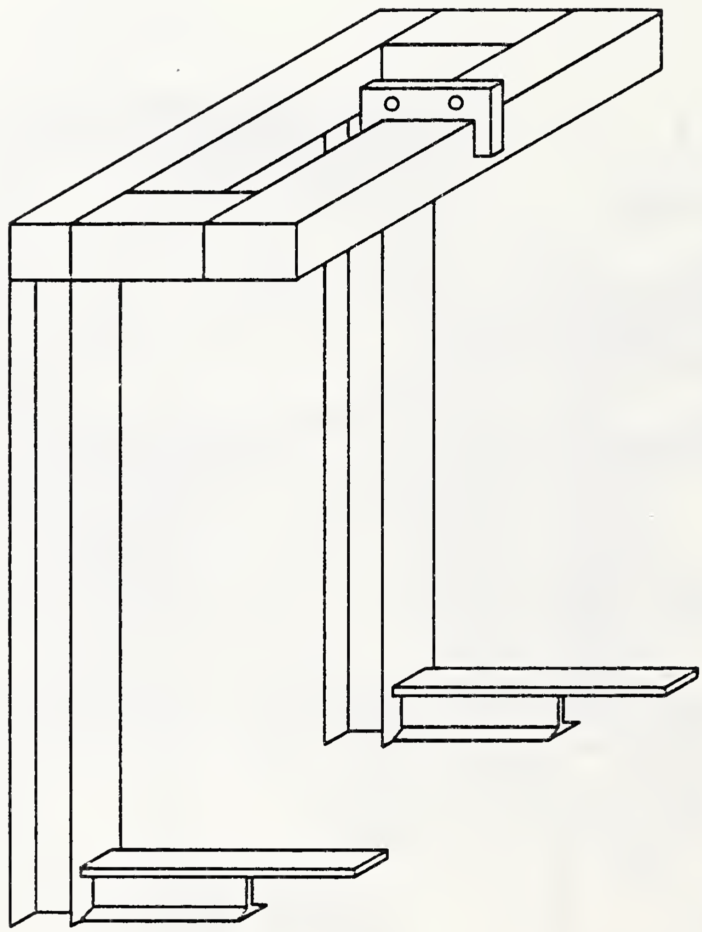

Figure D.3. Wall panel lifting hook

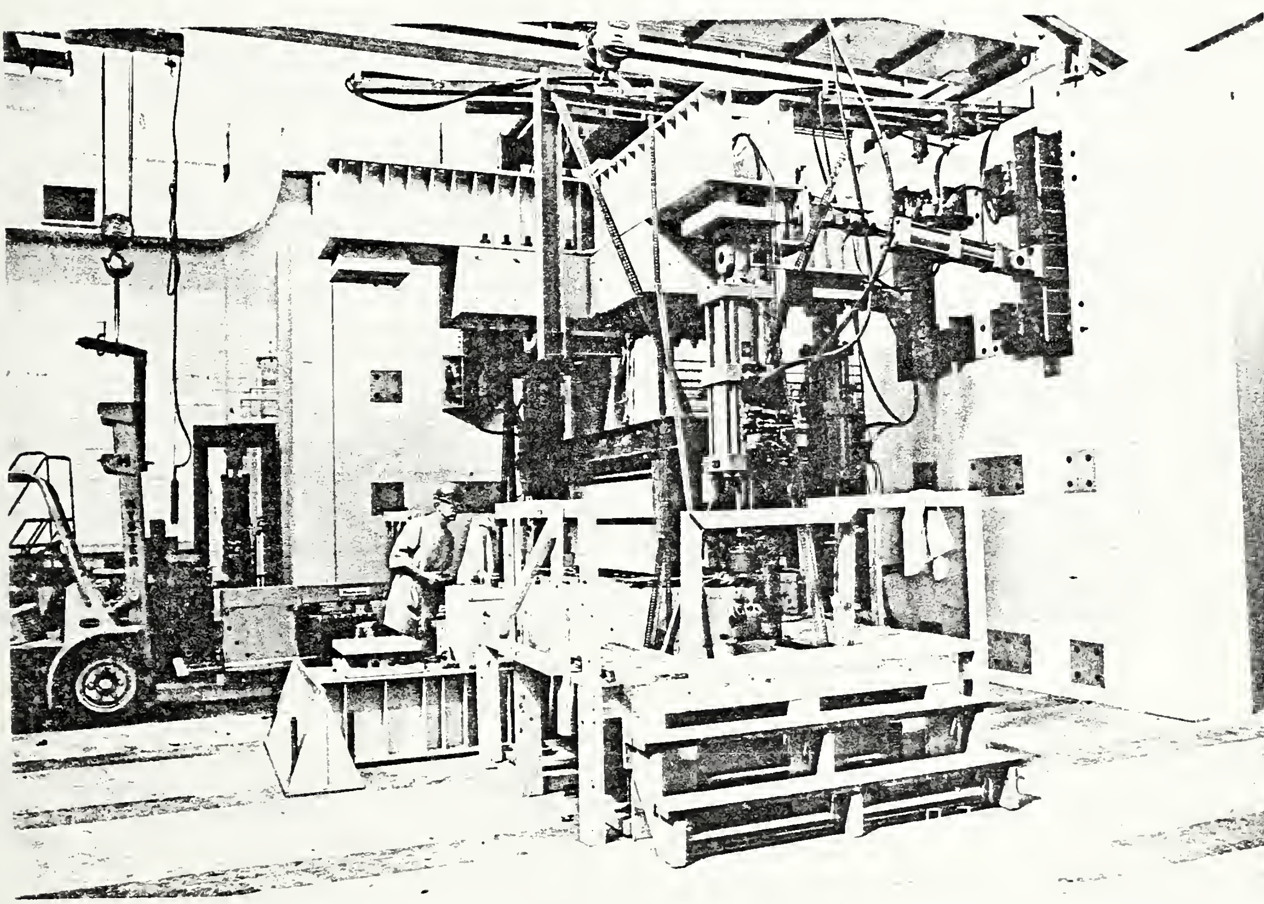

Figure D.4. Placing a wall panel

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9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (Street, City, State, ZIP)

Same as 6 above

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

The results from tests on seven ungrouted and unreinforced concrete block masonry walls are presented. The emphasis of the reported research is on the influence of aspect ratio (wall height-to-length) on the relationship between lateral in-plane load resistance and vertical in-plane compressive stress. The walls are fabricated from similar materials by the same experienced mason. The masonry units are hollow concrete block having a nominal compressive strength of 1800 psi based on the gross area. The mortar is proportioned as a Type S. The walls have nominal heights and thicknesses of 64 in. and 8 in., respectively. Three different wall lengths are used: 48 in., 80 in., and 96 in. The walls are tested in the NBS Tri-directional Testing Facility using fixed ended boundary conditions at the top and bottom of the walls. Lateral in-plane displacements are applied at the top of the wall while maintaining a constant compressive axial (vertical) stress. The vertical compressive stress is varied for each of the different wall lengths. The test results indicate a relatively weak effect of aspect ratio on the shear stress at diagonal cracking for aspect ratios less than or equal to 1 and a nearly linear relationship between maximum shear stresses and vertical compressive stresses.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

Aspect ratio; compression; concrete block; masonry; shear; strength; structural testing; walls.

13. AVAILABILITY

[XX] Unlimited

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