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The Development of an Improved Test for Evaluating the Racking Resistance of Wall Panels

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The Development of an Improved Test for Evaluating the Racking Resistance of Wall Panels

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SI Conversion Units

In view of the present accepted practice in this country for building technology, common U.S. units of measurement have been used throughout this publication. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measures, which gave official status to the metric SI system of units in 1960, appropriate conversion factors have been provided in the table below. The reader interested in making further use of the coherent system of SI units is referred to:

NBS SP 330, 1972 Edition, "The International System of Units"

ASTM E380-75/IEEE Std. 268-1976 ASTM/IEEE Standard Metric Practice

Table of Conversion Factors to Metric (S.I.) Units

Physical Quantity	To convert from	to	multiply by
Length	inch	meter	$2.54^* \times 10^{-2}$
	foot	m	$3.048^* \times 10^{-1}$
Area	$inch^2$	m^2	$6.4516^* \times 10^{-4}$
	$foot^2$	m^2	9.290×10^{-2}
Volume	$inch^3$	m^3	1.639×10^{-5}
	$foot^3$	m^3	2.832×10^{-2}
Temperature	Fahrenheit	Celsius	$t_C = (t_F-32)/1.8$
Temperature difference	Fahrenheit	Kelvin	$\Delta t_K = (\Delta t_F)/1.8$
Pressure	inch Hg (60F)	$newton/m^2$	3.377×10^3
Mass	lbm	kg	4.536×10^{-1}
Mass/unit area	lbm/ft^2	kg/m^2	4.882
Moisture content rate	$lbm/ft^2 week$	$kg/m^2 s$	8.073×10^{-6}
Density	lbm/ft^3	kg/m^3	1.602×10
Thermal conductivity	$Btu/hr \cdot ft^2 \cdot (°F/inch)$	$\frac{W}{mK}$	1.442×10^{-1}
U-value	$Btu/hr \cdot ft^2 \cdot °F$	$\frac{W}{m^2K}$	5.678
Thermal resistance	$°F/(Btu/hr \cdot ft^2)$	$K/(W/m^2)$	1.761×10^{-1}
Heat flow	$Btu/hr \cdot ft^2$	W/m^2	3.155

*Exact value; others are rounded to four digits.

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by

C.W.C. Yancey

Abstract

An experimental investigation of the primary factors involved in the laboratory testing of prototype wall panels, under simulated wind-induced racking loads, is reported. The objective of the investigation was to recommend a static racking test method, generally applicable to a variety of wall construction types, that features realistic boundary and loading conditions. Initially, a literature survey was conducted for the purpose of evaluating the test methods which have been, or are being employed in determining the resistance of wall panels to static racking loads. In the experimental program, 17 exploratory tests were conducted on a sample comprised of two types of wall panel construction. The 8 ft by 8 ft steel-frame and wood-frame panels were subjected to a combination of vertical and horizontal loading and their resulting deformation behavior was systematically monitored. Modifications to the testing procedure and to the boundary condition at the top of the panels were introduced as the experiments progressed. Detailed descriptions of the laboratory procedures used are presented. As the tests were developmental in nature and not intended for performance evaluation of the types of construction, selected results are presented. A static racking test method, applicable to traditional and innovative wall construction was derived as a result of the laboratory study and the literature survey. The principal new features of the proposed standard method are: (a) the application of distributed vertical loading, (b) the capability of testing panels of various height-to- width ratios and (c) the provision of top and bottom boundary conditions which do not force unrealistic modes of failure.

Keywords: Lateral loads; loading rate; racking; test method; wall panels; walls; vertical loads.

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1. INTRODUCTION

1.1 Background - This study was conducted as a part of an applied research program sponsored by the Office of Policy Development and Research of the U.S. Department of Housing and Urban Development (HUD), for the purpose of developing improved structural test methods for evaluating the performance of housing components. The need for a test method development program was identified during evaluation testing that was conducted at NBS and other laboratories during HUD's demonstration housing program, Operation BREAKTHROUGH. It became apparent to some of the evaluators that several of the standard methods of testing the structural performance of building components contained features that were not compatible with the more innovative types of building constructions. Problems were encountered particularly with testing the thin, lightweight, stressed-skin types of construction. Based on the needs identified by the structural evaluations, HUD sponsored this project to study the principal features of several test methods with the objective of recommending structural test methods that are generally applicable to both traditional and innovative building materials and configurations. As an initial step in the program, a comprehensive survey of the literature relating to structural test methods used in evaluating walls, floors, roofs and complete buildings was conducted. Also, a written survey was conducted among the membership of ASTM Committee E-6, On Performance of Building Constructions, to help in identifying test method areas in need of basic research. A state-of-the-art report, Building Science Series (BSS) 58 [1][1/], was published as a result of the literature survey and of the written questionnaire. The information obtained from this initial effort provided the basis for several specific recommendations on fundamental studies needed to develop improved standard test methods. One of the recommendations focused on the need for some laboratory investigation of the section of the existing ASTM Standard E72 that pertains to racking testing.

1.2 Objective - The objective of this investigation was to develop an improved laboratory method of testing wall prototypes for their resistance to in-plane, shear (i.e., racking) forces representative of those induced by wind pressure. As it was intended that the derived racking test method would be recommended for adoption as a national voluntary standard, two limitations were placed on the investigation: (1) the recommended test method must be generally applicable to traditional wall construction and to innovative wall construction, and (2) the recommended test method must be simple so that it can be accommodated by most testing facilities. The objective was first approached by identifying the principal factors to be tested and then studying them experimentally.

[1/] Numbers in brackets refer to literature references listed in Section 7.

1.3 Scope - The investigation began with a critical evaluation of the methods described in the literature for testing the in-plane shear resistance of specimens of walls and wall segments. In addition to the ASTM Standard E72 [2], the study included those methods which essentially are modifications of the E72 method and those methods which constitute alternative approaches to the standard. Among the factors considered for comparative purposes were: (1) the restraint at the boundaries (i.e., the edges) of the specimen, (2) the applicability of the method to a wide range of wall construction types and (3) the presence of unrealistic restraint which tended to prevent the mechanism of failure most likely to occur in the erected wall assembly. After weighing the advantages and disadvantages of the various existing methods and considering the merits of several new concepts, a pilot racking test arrangement - consisting of a combination of horizontal and vertical, axial loading - was designed. A series of exploratory laboratory tests were then performed to evaluate the effectiveness of the testing arrangement in fulfilling the objectives of a full-scale laboratory racking test.

Two types of wall panels, 8 ft wide by 8 ft high (2.4 m by 2.4 m), were selected for the test sample. The panels were constructed as described below:

(1) light-gage steel framing covered with a sheet of gypsum wallboard on one face, and a sheet of insulating fiberboard on the other face.

(2) wood framing covered with a sheet of gypsum wallboard on one face and plywood on the other face.

The steel-frame panels were of proprietary design and they were purchased commercially. The wood-frame panels were assembled in the laboratory with the use of commercially available, lumber, plywood, gypsum wallboard and nails.

2. LITERATURE SURVEY

To assess the state-of-the-art with respect to racking and diagonal tension resistance tests on wall panels, a literature survey of racking test methods was conducted. The sources of information included performance test reports, technical papers, research reports and pertinent ASTM Standard Test Methods. The survey was confined to literature published in the United States between 1937 and the present.

In the literature reviewed, a majority of the tests were performed on either masonry wall panels or wood-frame wall panels, reflecting the prevalence of these types of wall construction in the United States. Further, they were acceptance-type tests conducted in accordance with ASTM Standard E72 [2] or with slight modification thereof. The advantages and disadvantages of various loading procedures and of different boundary restraints were discussed briefly in only a few of the reports. The fundamental problem of developing a suitable method of testing and evaluating the racking resistance of frame wall construction was addressed by only one research report [3]. A majority of the test material surveyed related to the testing of nominally square (e.g., 8 ft (2.4 m) by 8 ft (2.4 m) or 4 ft (1.2 m) by 4 ft (1.2 m)) panels whose orientation was in the vertical position. However, the literature indicates that several test programs have been undertaken in which the test specimens were oriented in the horizontal position [4], [5].

Schematic diagrams of some of the loading methods and boundary conditions documented in the literature are presented in figures 2.1 through 2.12. The oustanding features of each test setup are noted on the drawings for comparative purposes. A synopsis of test programs which utilized each of the 11 setups will be presented in the following paragraphs. The reference to specific tests or research programs is not intended to imply that the use of a particular test setup or procedure has been confined to the cases that are cited.

2.1 ASTM Standard E72-74 [2] - The test setup illustrated in figure 2.1 is the presently accepted standard racking test for wall panels. In the literature it was noted that an overwhelming majority of the reported racking tests have been conducted on a variety of wall construction types using this procedure. This method, featuring static, horizontal loading, was first adopted by ASTM as a Tentative Standard in 1947, after having been developed and published by the National Bureau of Standards and the U.S. Forest Products Laboratory during the 1930's. It was adopted as an ASTM Standard Method in 1954. Over the course of the ensuing 21 years, ASTM E72 has periodically undergone revisions. Nevertheless, the latest revised version (1974) is substantially the same as its 1947 predecessor. The procedure is applicable to the testing of complete wall assemblies or to the evaluation of the resistance contributed by sheathing materials (e.g., plywood and insulating fiberboard) that are attached to a standard 8 ft by 8 ft (2.4 m by 2.4 m) wood frame.

The HUD Minimum Property Standards [6] require the use of the ASTM E72 racking test to prove compliance with the requirements for adequate bracing of frame walls. In assessing the racking resistance of the sheathing materials, in either a dry or a wet condition, the method specifies that the specimens be subjected to a horizontal racking force (denoted as H in figure 2.1); this force is to be transmitted to the specimen by applying a compressive force to the end of a nominal 4 by 4 timber (see fig. 2.1) which is firmly bolted to the double top plates of the "standard" frame. The studs and plate elements comprising the standard frame are nominal 2 x 4 lumber. Displacement gages are so positioned to enable the determination of the net shear deflection traversed by the top of the panel. Deflection measurements are made upon reaching designated increments of loading and again after the removal of these loads. Residual deflections are reported as well as the net deflections associated with the increments of loading.

A hold-down assembly, formed by two threaded rods is required, as shown schematically in figure 2.1, to overcome the tendency of the loaded edge of the panel to tilt as the load is applied. It is noteworthy that this hold-down feature has been criticized by some evaluators for a number of years [1], [3]. An opinion has been expressed by several of the critical group that the presence of the hold-down introduces unrealistic external forces onto the panel and creates indeterminate stress and strain distributions within the test specimens. Furthermore, for some types of construction, this localized hold-down causes a different mode of failure than would be exhibited in a less restrained panel.

The bottom of the specimen is attached to a timber (steel as an alternative) plate that in turn is rigidly attached to the base of the loading frame or to the laboratory floor. The purpose of the stop shown in the lower right hand corner of figure 2.1 is to prevent sliding of the specimens as the racking force is increased.

Another feature of this method that has been criticized in the literature is the stiffening effect caused by the timbers at the top and bottom of the panel [1]. It has been suggested that the presence of the timbers artificially restrains the bending of the top and bottom plates of the panels, thereby resulting in an apparently stiffer panel. The literature does not indicate that this criticism has been substantiated by comparative tests.

In relation to the objective of developing a more widely applicable racking test method, the racking test experience gained during Operation BREAKTHROUGH indicates that the ASTM E72 test setup is, in general, not suitable for testing thin (e.g., $\leq$ 4 in(0.10 m)), pre-assembled, sandwich panels. The recommended means of attaching the bottom of the test specimens to the reaction frame and of connecting the load distribution beam (i.e., timber) to the top are incompatible with the end details of many types of sandwich panels. In addition, the hold-down assembly, which was described above, introduces undesirable concentrated forces to one corner of the test panels.

2.2 Eight by Eight Diagonal Compression Loading - As part of a research program aimed at determining the effect of mortar properties on the strength of masonry walls [7], a number of masonry wall panels were tested for racking resistance. Hollow concrete block walls and brick and block composite walls were loaded to failure. All the specimens measured 8 ft by 8 ft (2.4 m by 2.4 m), with a nominal thickness of 8 in (0.20 m). The loading apparatus, as depicted in figure 2.2, was in the form of a yoke consisting of two steel side bars, one on each side of the wall, spanning diagonally across the wall and connected at the ends to steel shoes. The upper end of the yoke was fitted with a hydraulic jack which was connected to a hand-operated pump. The load was transferred from the jack to the upper loading shoe by a dynamometer force link. Displacements in a directions parallel to the length of the wall were measured near the top and bottom of one end of the wall.

Applying a compressive load across a diagonal of the test panel is a very effective procedure for testing masonry wall panels in that it causes a diagonal crack failure mechanism, which is typical of this type of construction. When the panel is tested in a vertical position as illustrated in figure 2.2, the diagonal compression loading procedure can be considered to be a modification of the ASTM E72 Standard, with the added feature of being self-equilibrating. That is, the resolution of the diagonal load into vertical and horizontal components yields a loading system that is in static equilibrium. No external vertical force is necessary to hold down the corner that is subjected to the racking force.

2.3 Modified ASTM E72-68 - A modified version of the ASTM Standard E72 test setup discussed in section 2.1 is described in figure 2.3. It can be seen from the figure that there are no tie rods, as required by E72, to restrain uplift of the heel of the wall. The vertical reaction normally taken by the tie rods is taken by a hydraulic jack. The horizontal load is applied in the manner specified for the ASTM standard. This loading arrangement has been applied by NBS for the evaluation of 8 ft by 8 ft (2.4 m by 2.4 m) composite brick and block wall panels. The horizontal loading was applied to six nominal 12-in (0.30-m) thick walls through a steel shoe (see upper left corner in figure 2.3) that was set in high strength plaster. The vertical reaction was taken by a 100-ton (890-kN) capacity hydraulic jack. The reinforced concrete footings on which the walls were constructed were prestressed into position against the reaction frame and set in high strength plaster.

Scrivener [8] has also reported on the use of this loading arrangement for testing 12 reinforced, concrete-hollow-masonry walls. The static racking loads were applied to specimens 8 ft-8 in (2.6 m) high, 8 ft (2.4 m) long and 6 in (0.15 m) thick. Vertical load was applied to the loading shoe (see figure 2.3) which was just sufficient to statically balance the moment caused about the toe of the wall by the racking load, for each increment of racking load. Sixty-ton (534-kN) hydraulic jacks were used for applying both the vertical and horizontal loading. The geometry of the setup was such that the ratio of horizontal to vertical load was 0.9.

Although no reason was given for the use of a hydraulic jack hold-down instead of the dual tension rods described in section 2.1, it is suspected that the relative ease with which the vertical load could be pre-set and monitored were the determining factors in selecting the former. No critique was found in the literature pertaining to the relative merits of these two alternate means of applying the hold-down force. The results of racking tests that were performed during Operation BREAKTHROUGH on a relatively flexible polyester sandwich panel system indicated that localized vertical deformation was caused at the loaded corner by the use of the vertical hydraulic ram. This type of localized deformation behavior was not reported in other BREAKTHROUGH racking tests, performed on the same system, but with the use of tension hold-down rods. This fact not withstanding, there is not sufficient comparative information available to logically deduce which hold-down system is more acceptable.

2.4 NBS Test Method - This method was developed at NBS [9] with the intention of simulating service conditions for a wall with racking forces applied. A total of 51 masonry walls were tested in this way. Eight-inch hollow block walls and 4-inch brick walls of three different sets of dimensions were tested in the program. The wall dimensions were: (1) 8 ft by 8 ft (2.4 m by 2.4 m), (2) 4 ft by 8 ft (1.2 m by 2.4 m) and (3) 4 ft by 4 ft (1.2 m by 1.2 m).

As depicted in figure 2.4, a uniform vertical load was applied to the top of the wall panel and held constant during the test. The vertical load was applied along the centerline of the wall by 30-ton (267-kN) capacity hydraulic jacks spaced 12 in (0.30 m) apart. An incremental horizontal load was applied along the top edge of the wall until failure occurred. The horizontal loads were applied to a 2-in (0.05 m) thick by 8-in (0.20-m) wide steel plate, that extended along the entire length of the wall, by two 100-ton (890 kN) capacity hydraulic jacks.

Prior to the application of any vertical or horizontal load, the reinforced concrete footings, on which the walls were constructed, were "snugged up" against a steel plate located at the reaction end of the setup. This preliminary step was done to eliminate horizontal movement of the footings during the tests and it was accomplished by applying a 25-kip (111.2-kN) horizontal load directly onto the footing. To obtain uniform bearing of the footings against the reaction plate, they were set in high strength plaster. After the plaster set, the vertical compressive load was applied. The changes in length along the two principal diagonals were measured during the test with electromechanical gages.

2.5 Proposed Revised ASTM Standard Method - Currently (July 1975) a task group of ASTM Committee E-6 is preparing a proposed revision to the existing E72 Standard Method described in section 2.1. The revised procedure is intended to evaluate the static shear strength of a typical section of a framed shear wall (i.e., with framing members such as studs and top and bottom plates) under simulated load conditions. Also, the procedure is intended to provide a determination of the shear stiffness of the wall panel structure and of the connectors used to assemble and anchor the panel. The basis for the development of the proposed standard racking method was provided by a preceding proposed ASTM Standard cantilever test method for evaluating the shear strength and stiffness of framed floor and roof diaphragms. Most of the test experience gained with this test method has been in the area of diaphragm testing of floor and roof systems. As illustrated in figure 2.5, the shear wall assembly is assumed to act as a cantilevered plate girder. The top and bottom plate members are analogous to the flanges of a girder. The vertical framing and the sheathing are to act integrally in a manner analogous to the web of the girder. Upon the application of the horizontal load, H, the setup is designed to respond by having the web of the wall assembly resist all the shear force. The cantilever bending moment is assumed to be resisted solely by the flange members (i.e., the top and bottom plates).

The test method requires that vertical deflections be measured near the bottom of the panel on both the loaded (v_1) and unloaded (v_2) edges (see fig. 2.5). The total horizontal displacements near the top of the unloaded edge (u_1) are measured as well as the horizontal displacement near the bottom of the loaded edge u_2. The total horizontal displacement is analytically decomposed into its bending and shear components. By isolating the shear component it is possible to establish an approximate measure of the shear stiffness of the wall panel. Note in figure 2.5 that the hold-down rods that are required in the present ASTM E72 method have been eliminated for this setup. Instead, an uplift anchor "typical of the actual construction" is required. This feature is considered an improvement over ASTM E72 in light of the criticism discussed in section 2.1. The bottom of the frame is to be attached to a rigid base with anchorage connections that simulate those in the actual structure.

This test method improves on several of the alleged shortcomings of ASTM E72: (1) The elimination of an unknown external force makes it possible to apply some fundamental principles of engineering analyses to the test results. (2) The cantilever beam test setup allows for testing a wider range of panel aspect ratios (height/width) without concern for the geometry of the setup. That is, static equilibrium does not have to be satisfied by the use of an external vertical force, whose magnitude may have to be large. A large magnitude concentrated force can cause unrealistic stress and deformation effects in many cases.

This test method is intended for the evaluation of framed wall construction and, as such, the test setup is not applicable to sandwich panel construction. While the test procedure is applicable to sandwich panels, the means of applying horizontal load to the panel and the anchorage connections specified at the bottom of the test panel require some modification to account for the differences in construction details associated with sandwich panels.

2.6 Four by Four Diagonal Compression Loading - The test setup illustrated in figure 2.6 has been used extensively in masonry wall research and has been documented in the literature by Blume [10]. The Structural Clay Products Institute (SCPI) (now Brick Institute of America) [11], and NBS [9]. In a research program aimed at obtaining reliable data pertaining to the diagonal tension performance of reinforced, grouted, brick masonry wall panels, Blume selected this test method as being the most appropriate. The objective was to load the 4 ft by 4 ft (1.2 m by 1.2 m) brick panels in such a manner as to reproduce the diagonal tension crack pattern common to all types of brittle wall elements that have been damaged during major earthquakes. After studying several alternative methods of test, Blume concluded that the method of applying a compressive load at diagonally opposite corners, and at an angle of 45° with the bed joints, held the most advantages. It was concluded that this procedure would result in a more deterministic stress analysis, in addition to yielding more reliable results and allowing close control for test comparisons. It is recalled that in section 2.1 the problem of indeterminate internal stress distribution was identified as a shortcoming of ASTM E72. The advantage of experimentally effecting a determinate stress pattern lies with the possibility of using the test results in an engineering design and analysis process.

In each of the three methods referenced, the load was transmitted to the specimen at each load corner through a steel loading shoe (see figure 2.6) set in high strength plaster. To apply the load, Blume used a combination of three 100-ton (890-kN) hydraulic jacks. The loading jacks were suspended from a heavy steel testing frame that was anchored to the laboratory floor. In the NBS test program four 4 ft by 4 ft (1.2 m by 1.2 m) brick wall panels were tested using an identical setup. The source of the diagonal compressive loading was the head of a 600,000-lb (267-kN) capacity hydraulic testing machine. In the SCPI program, twenty-one 4 ft by 4 ft (1.2 m by 1.2 m) masonry wall specimens were tested by the diagonal tension test method. Both solid and heavy duty hollow brick units of nominal 6-in and 8-in thickness were used in constructing the specimens. The square specimens were tested in a steel frame with a 600,000-lb (267-kN) hydraulic jacks. The specimens were loaded through steel loading shoes.

In evaluating the utility of this test method, it is important to note that in all three test cases documented above, the diagonal compression loading setup was used on mansonry panels to effect a specific failure mechanism (i.e., diagonal tension cracking). Further, by orienting the panel in the test fixture so that the load is applied at a 45° angle to the bed joints, it ensures that the line of failure will closely simulate the crack pattern that has been observed for brittle wall segments. Thus, the method seems quite appropriate for the limited application cited. In fact, this method of test has been standardized by ASTM, for the determination of the diagonal tension capacity of masonry assemblages (ASTM E519-74) [12].

2.7 Diagonal Compression with Uniform Vertical Loading - Twelve 4 ft by 4 ft (1.2 m by 1.2 m) brick wall panels were tested at NBS [13] in the manner described by figure 2.7. As was the case for the method discussed in section 2.6, the objective was to cause failure by propagating a crack along the loaded diagonal. In this manner, a measure of the diagonal tension capacity of the specimens could be determined. In addition to the compressive loading applied along a diagonal, the wall panels were subjected to a uniform compressive load applied perpendicular to the top and bottom edges (equivalent to a "vertical load"). The "vertical load" was maintained during the application of the diagonal compressive load. The uniform "vertical load" was applied to the top edge by three 100-ton (890-kN) hydraulic jacks which were pin-connected to a yoke-type reaction frame. The jack loads were transferred to the top through three steel bearing beam sections, each 12 in (0.30 m) long. The reactive force was transmitted to the bottom edge through three identical beam sections. The bearing beams were installed so as to be free to translate relative to the top and bottom edges of the panels without applying undesirable friction forces into the specimens. Thus, the "vertical loading" was applied without developing lateral restraint as the panels underwent racking deformation. The important difference between this test procedure and that described in section 2.6 was the simulation of the dead and live gravity loads that can be attributed to the floors above that of the test panel. The diagonal compressive load was applied in the manner of the NBS tests described in Section 2.6.

2.8 Diagonal Loading on Masonry Piers - The test setup illustrated in figure 2.8 was used by Schneider [14] for investigating the shear resistance of reinforced concrete masonry piers. The report of this investigation was the only one found in the literature survey that presented information obtained from a study conducted under field conditions. While the behavior of full-sized masonry piers when subjected to horizontal forces was of primary interest, the interaction of the piers with surrounding spandrels was also studied. To fulfill the test objectives, two types of panels were tested: (1) The "fully restrained" piers were bound by masonry spandrels above and below as seen in figure 2.8; (2) The "cantilever" piers were tested without the use of a top spandrel member.

Several shear panel test methods were considered prior to the investigation; among them were the ASTM E72 method and the internal hold-down setup illustrated in figure 2.9. The stated requirement for the desirable loading method was that it should simulate the load acting on the free body of a pier removed from a multi-story shear wall. The hypothetical free body to be simulated consisted of a pier restrained at top and bottom by spandrels. The spandrels were loaded at diagonally opposed corners with a pair of force vectors, one vertical and one horizontal, as is depicted schematically in figure 2.10. It was therefore concluded that the most realistic representation of the force pattern in an actual wall could be effected by a diagonal load frame. Hence, the panels were tested in a simple diagonal load frame with a 300,000-lb (138-kN) capacity. The frame consisted of upper and lower steel bearing blocks, from which were extended tension rods on each side of the wall. The fully restrained piers were tested as shown in figure 2.8, while the testing of the cantilever piers required the use of a wide-flange steel beam at the top of the pier (in the absence of the top spandrel beam) to accommodate the upper bearing block. A 100-ton (890-kN) hydraulic jack was placed between the upper bearing block and the loading head to apply the diagonal loading. In some tests the piers were also subjected to an externally applied axial load in addition to the diagonal load. As depicted in figure 2.8, the axial load was applied by two self-contained hydraulic jacks whose bearing plate was positioned directly over the pier. A pair of vertical tension rods on each side of the wall extended from the loading head of this system to embedded bearing plates below the pier, thus permitting the application of a vertical load of known magnitude. It is interesting to note that this test method was employed only after its validity had been confirmed with the aid of photoelastic analyses of several plastic models.

2.9 Diagonal Compression in Horizontal Plane - While most of the racking tests have been performed on panels positioned in the vertical plane, several reports document tests in which the panels were placed in the horizontal plane. Generally, the horizontal orientation is selected as a matter of convenience to the testing or research facility. Furthermore, this arrangement is usually associated with the testing of relatively light-weight types of wall construction, such as wood frame and light-gage, metal-frame walls. In one research program concerned with the racking resistance of frame wall construction [3], test panels, positioned in the horizontal plane, were subjected to compression along one diagonal. A schematic drawing of the test setup is shown in figure 2.11.

The researchers recommended this test method as an alternate to ASTM Standard E72, after they had critically evaluated the ASTM Standard method. They concluded that the major shortcomings of the standard method (see section 2.1 for a discussion of several alleged shortcomings) could be eliminated by the diagonal compression loading approach. For example, the top and bottom timbers would be eliminated, thereby removing the alleged unrealistic restraint of the top and bottom plates. Furthermore, it was felt that the indeterminate effects of anchor bolts and hold-down rods on the internal stresses and strains would be eliminated. The fact that the panels would be tested in the horizontal plane with a relatively simple loading frame would preclude the need for a large frame which must react the racking load at heights of 8 to 9 ft (2.4 m to 2.7 m) above the laboratory floor. In their test method development program, pilot tests were conducted to determine the feasibility of the proposed diagonal compression test setup. Panels of three different sizes were tested 8 ft by 8 ft (2.4 m by 2.4 m), 4 ft by 8 ft (1.2 m by 2.4 m) and 2 ft by 8 ft (0.6 m by 2.4 m). Duplicate panels were tested by the ASTM Standard E72. The change in length along the unloaded diagonal was measured by a single dial gage.

The diagonal loading was produced by a hydraulic jack which caused a tension force in two round steel bars. The tensile force in the bars caused a compressive force to be transmitted to the opposite corners of the panels through steel angles. The capacity of the loading assembly was not mentioned, but the test data indicated that the maximum load applied was 2300 lb (10.2 kN).

2.10 Horizontal Diagonal Tests With Compressive Edge Loading - During 1965 and 1966, NBS carried out a multi-disciplinary study of the performance characteristics of exterior wall systems for one-and two-family residences [4]. The structural evaluation phase of the comprehensive program was concerned with measuring the strength and stiffness of seven types of load-bearing walls. Among the various tests performed was the racking of 8 ft by 8 ft wall (2.4 m by 2.4 m) panels which were representative of 5 of the 7 selected wall types. The wall panels, complete with interior and exterior finish materials, were tested in the horizontal plane. Figure 2.12 illustrates the principal features of the loading method. Structural data on the other two wall types were obtained from reports of two previous test programs [7], [15].

The diagonal compressive load was applied with the use of a loading yoke. The yoke consisted of two tension rods - one on each side of the panel - which extended between loading shoes located at diagonally opposite corners. The source of the load was a hydraulic jack which was positioned in line with rods at one corner of the panels. The edge loading apparatus consisted of a series of springs and tie-bar yokes suitable for applying and maintaining up to 2000 lb (8.9 kN) compressive load. Five equally-spaced edge loading assemblies were used in each test. In accordance with prescribed test procedure, the edge loading - of predetermined magnitudes - was applied to the panels before the application of diagonal loading was begun. The edge loading was maintained at a constant magnitude throughout the test sequence. The diagonal compressive load was increased incrementally until failure of the wall assemblies occurred. The incremental loading procedure used, essentially conformed to that recommended by the then current edition of ASTM Standard E72, except for the loading rate. Instead of using the strain rate of 0.20 inches per minute (0.08 millimeters per second), recommended in ASTM E72 for tests on nailed wood constructions, the loading rate used varied from about 10 to 20 kips per minute (741.4 to 1482.7 newtons per second). The researcher concluded that the recommended rate was inconvenient for some type of construction and that it was difficult to determine and maintain. The author concluded, on the basis of this study, that the diagonal racking test is as satisfactory as the ASTM E72 method for evaluating wall panels. This conclusion was strengthened by referencing some photo-elastic studies that indicated similar stress distribution patterns for both methods. While the diagonal compression test procedure is easier to perform for some types of constructions, several problems must be considered: (1) the diagonal load causes unrealistically high bearing stresses at the loaded corners and (2) the diagonal test is run with all four edges unrestrained, thereby providing no simulation of the wall's connection to floor and ceiling members.

2.11 Horizontal Version of ASTM E72 Method - Figure 2.13 shows a test setup that essentially conforms to ASTM Standard E72 except that the panels are tested in a horizontal plane. The National Association of Home Builders (NAHB) Research Foundation [5] has utilized this arrangement in a number of racking tests of exterior and interior frame wall panels. The fact that the organization's research facility has the loading frame embedded into the concrete floor slab makes the horizontal setup a logical choice. It is noted schematically in figure 2.13 that NAHB also modified the standard method to the extent of replacing the tension rod hold-down with a reaction roller bearing. The purpose of the rollers is to allow the top of the panel to translate in the direction of loading without restraint being provided by the hold-down. As is the case in any of the horizontal setups, the test panels must be supported underneath by roller-bearing supports. The NAHB research report reviewed in this literature survey documented the results of comparative tests which were performed to quantify the relative racking strengths and stiffnesses of a variety of exterior and interior frame wall panels. The report did not include an evaluation of the applicability of the test method.

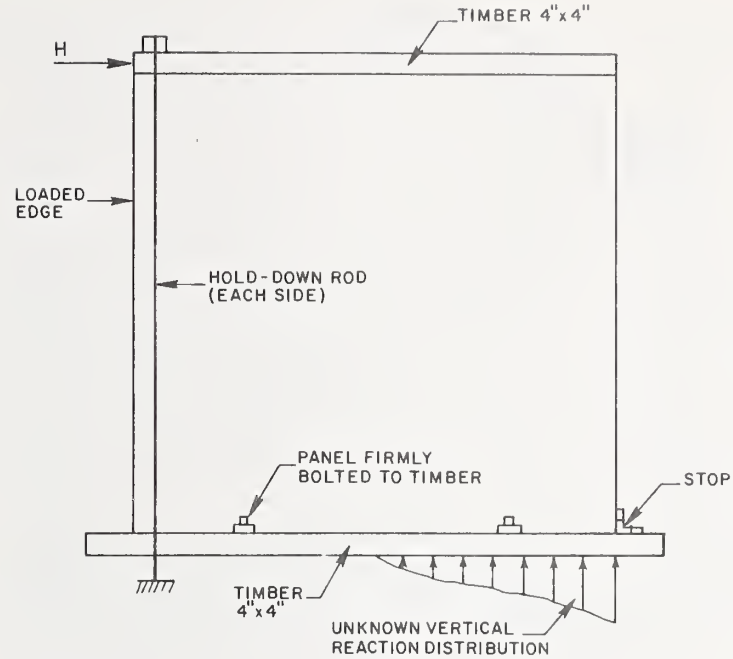


Figure 2.1 - ASTM Standard Method E72-74 [2].

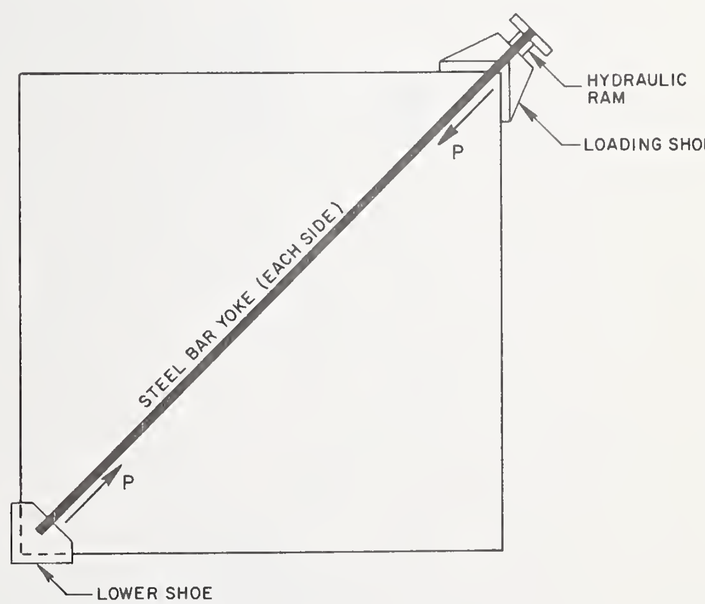


Figure 2.2 - Eight by eight diagonal compression loading.

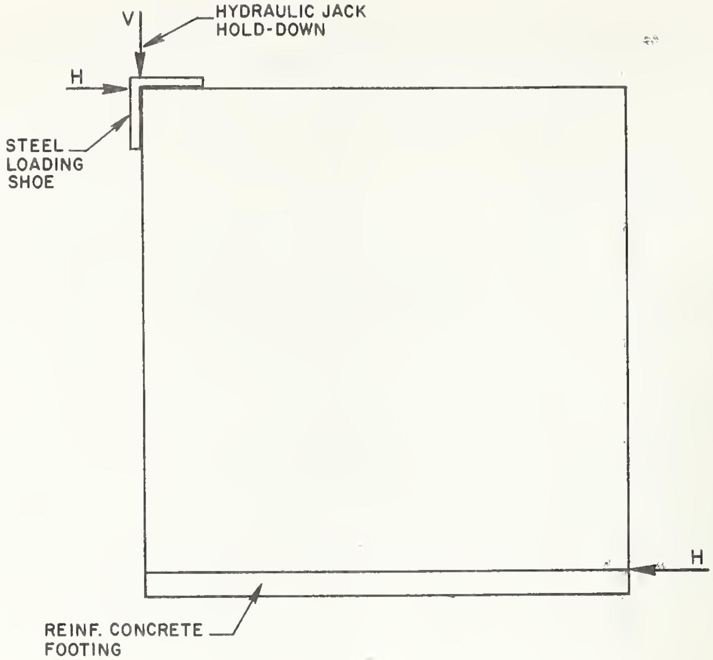


Figure 2.3 - Modified ASTM E72 method.

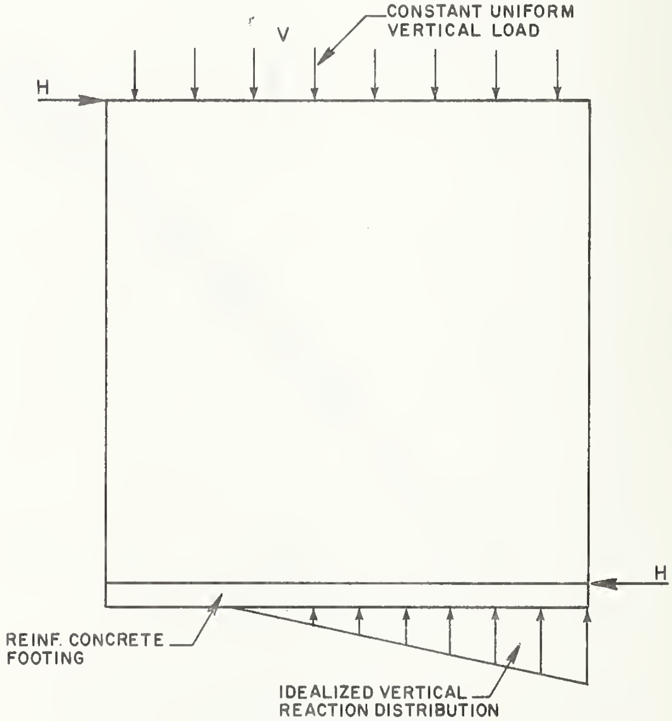


Figure 2.4 - NBS test method.

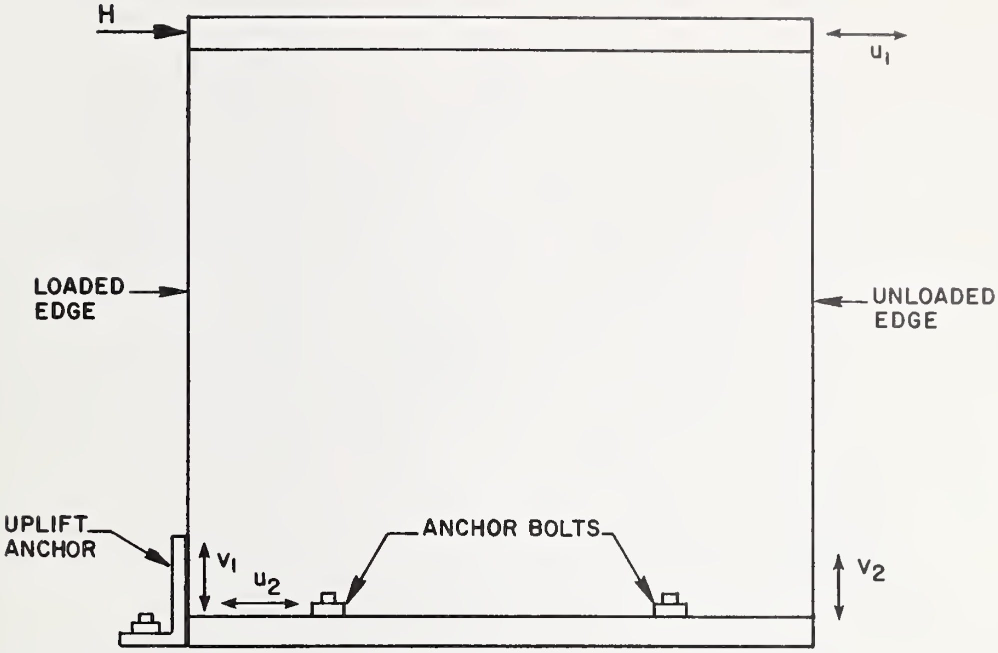


Figure 2.5 - Proposed revised ASTM standard.

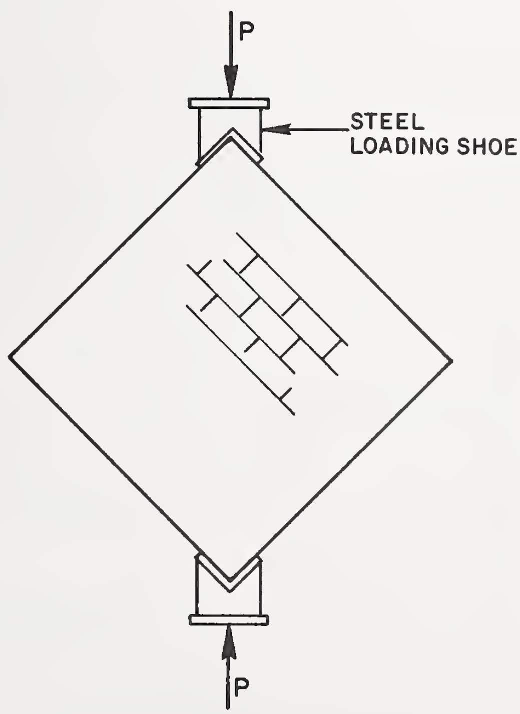


Figure 2.6 - Four by four diagonal compression loading.

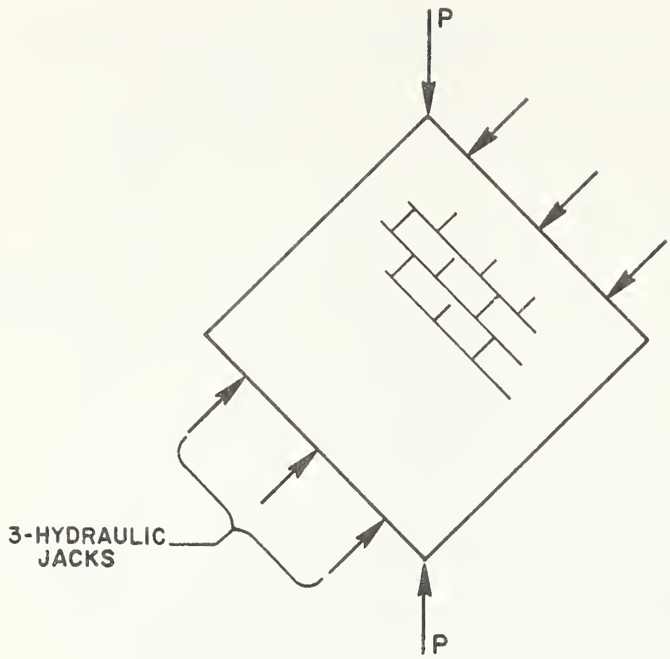


Figure 2.7 - Diagonal compression with uniform edge loading.

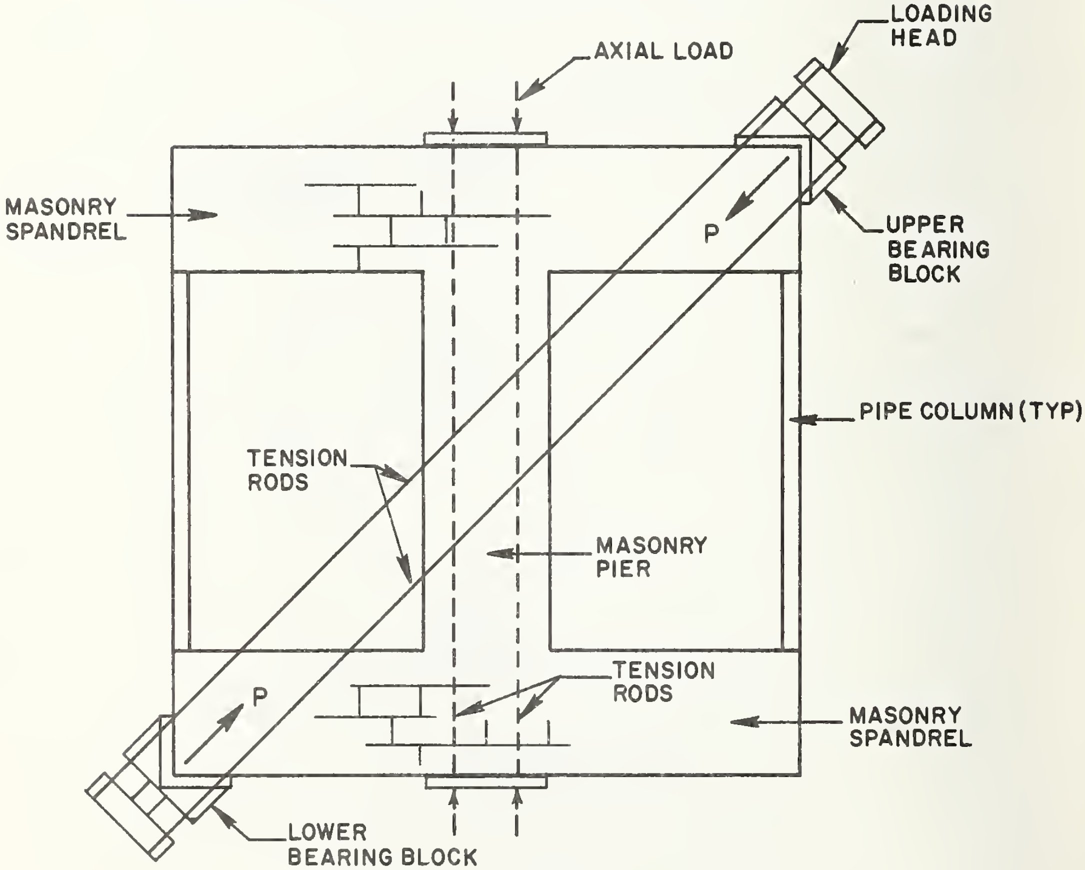


Figure 2.8 - Diagonal loading on masonry piers.

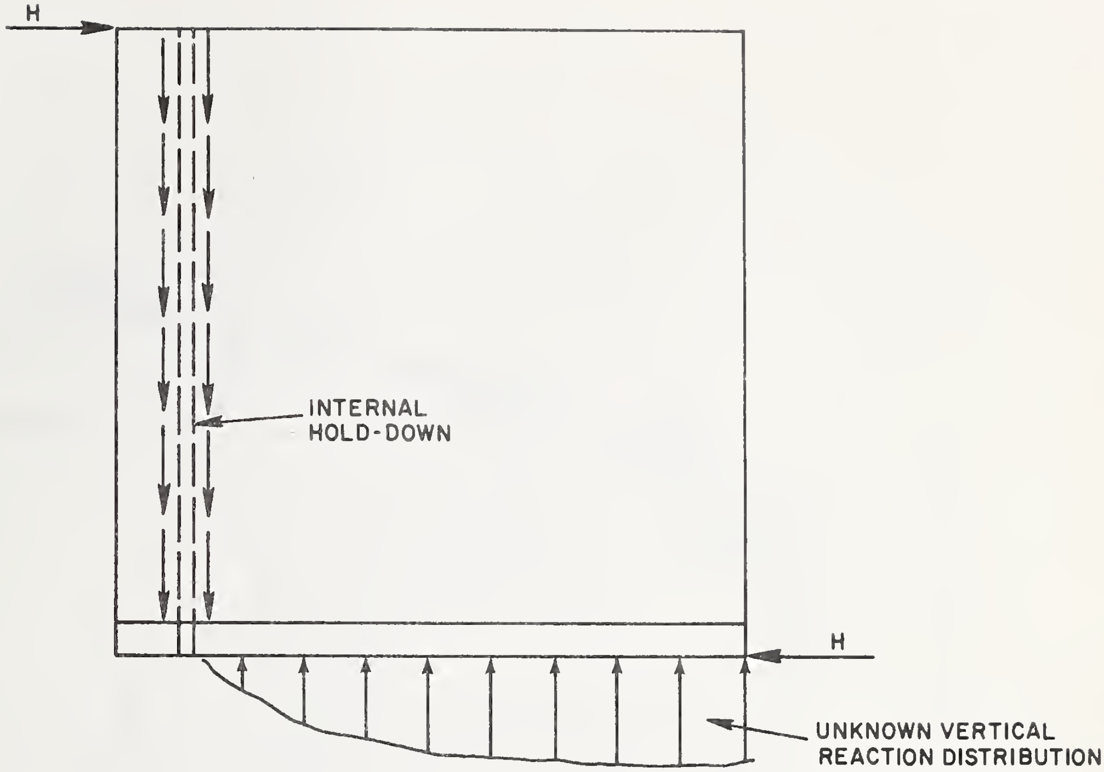


Figure 2.9 - Standard racking with internal hold-down.

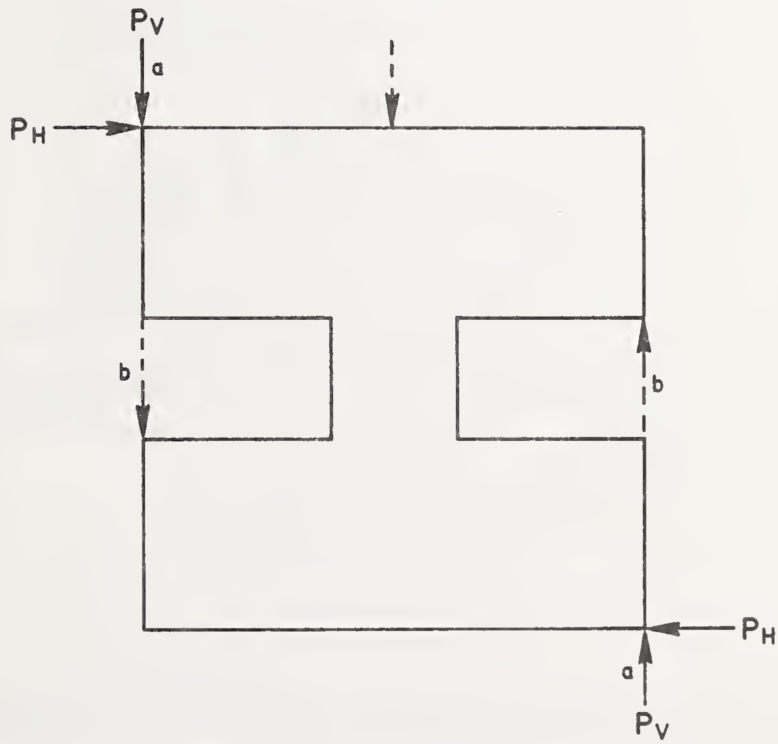


Figure 2.10 - Free body diagram of pier from masonry shear wall.

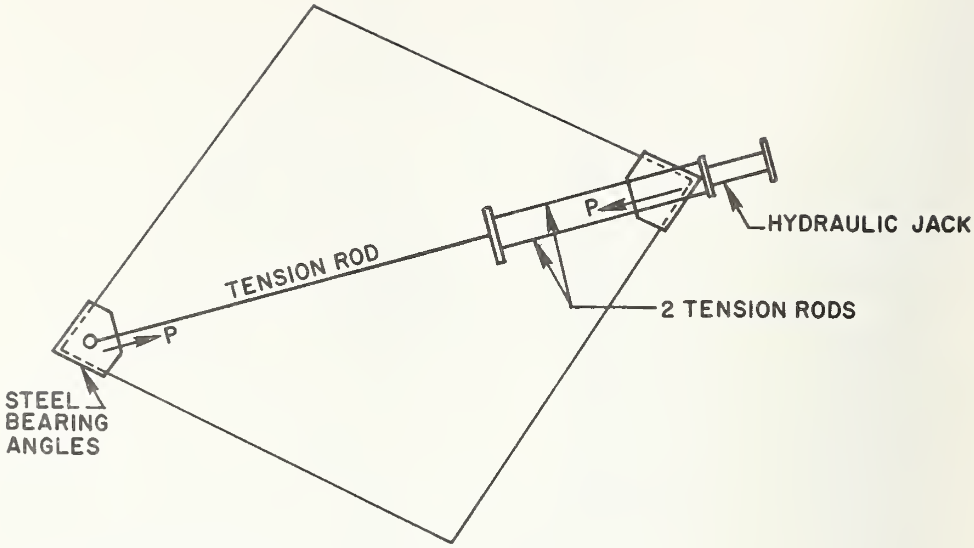


Figure 2.11 - Diagonal compression in horizontal plane.

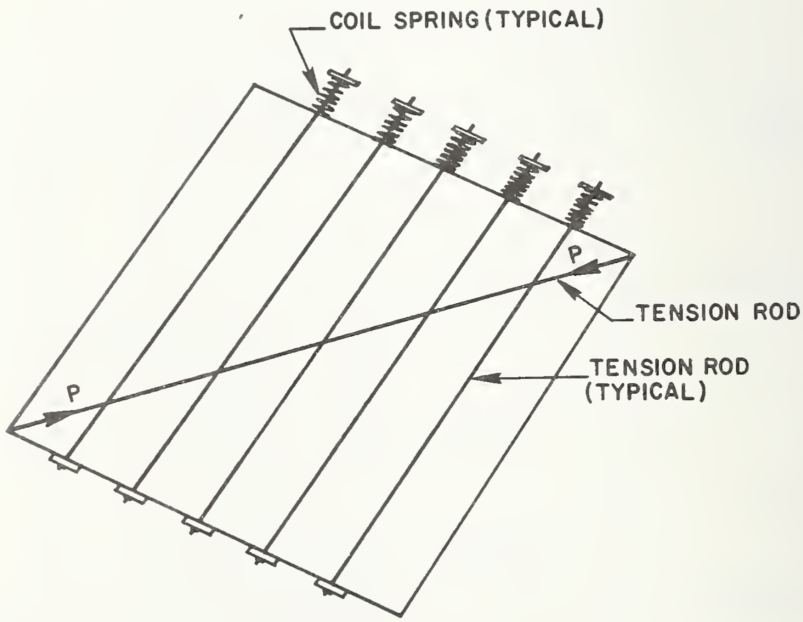


Figure 2.12 - Horizontal diagonal test with compressive edge loading.

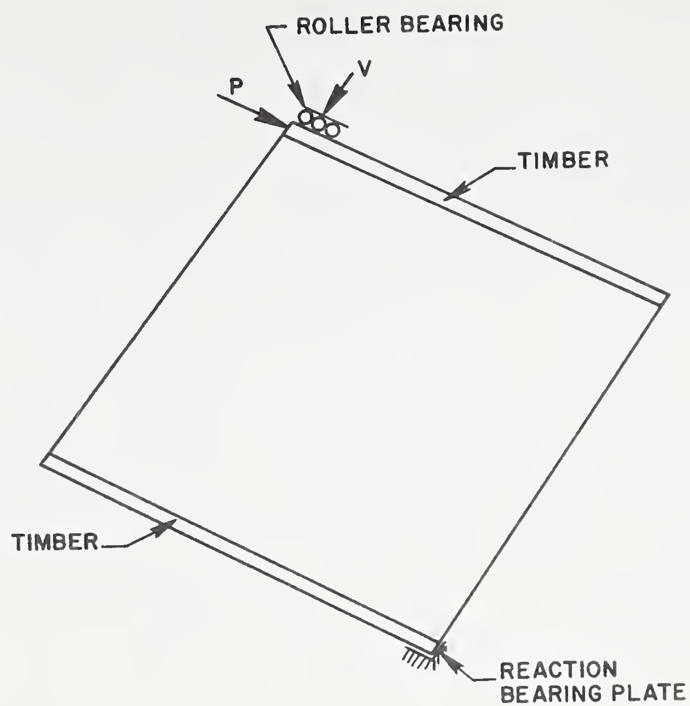


Figure 2.13 - Horizontal version of ASTM E72 method.

3. LABORATORY TESTS

Seventeen static racking tests were conducted on wall specimens constructed as described in paragraphs 3.1.1 and 3.1.2. A detailed description of the test specimens and the prevailing conditions for each test are given in table 1. In each test, the racking load was applied by a hydraulic jack and the resulting deformations were measured at several locations with electromechanical deflection gages. For monitoring the deformation response of the specimens, visual observation and an x-y recorder were used.

3.1 Description of Specimens - Wall panel specimens representative of steel-frame and wood-frame wall construction were used in conducting the laboratory experiments. Seven test sequences were performed on a single 8 ft by 8 ft (2.4 m by 2.4 m) proprietary steel-frame panel while the remaining ten tests were performed with the use of five wood-frame panels. The steel-frame panel was obtained commercially and the wood-frame panels were assembled in the laboratory with commercially available materials.

3.1.1 Light-Gage Steel-Frame Construction - The 8 ft by 8 ft (2.4 m by 2.4 m) specimen (see figure 3.1) was assembled by joining two prefabricated 4 ft by 8 ft (1.2m by 2.4m) panels whose z-shaped frame members were made of 18-gauge galvanized steel. The vertical framing of each panel consisted of three z-shaped studs, spaced on 2-ft (0.6-m) centers; the top and bottom ends of the studs were each connected to a single z-shaped horizontal member. The cross-section of each framing member consisted of a 3 5/8 in (92.1 mm) web, one flange 1 1/2 in (38.1 mm) wide and the other flange 1 1/8 in (28.6 mm) wide. Both flanges of the studs were extended at the ends to form steel tabs. The tabs were pre-drilled to allow single-nail-fastening of the studs to the nominal 2 by 4 wood top and bottom plates that were used in assembling the 8-ft (2.4-m) wide test panel. Pointed barbs, punch-formed on one flange of each stud, were used to clinch a 4 ft by 8 ft by 1/2 in (1.2 m by 2.4 m by 12.7 mm) sheet of asphalt-impregnated insulating fiberboard. This face was specified as a typical exterior sheathing for the wall assembly. The opposite face (interior) consisted of a 4 ft by 8 ft by 1/2 in (1.2 m by 2.4 m by 12.7 mm) sheet of gypsum wallboard. This facing was fastened to the steel frame by one plastic rivet at each corner and by an adhesive that was applied to the interior flange of all frame members. To assemble the 8-ft (2.4-m) wide test specimen, two 4-ft (1.2-m) wide panels were butted together with a single dowel, located at approximately mid-height, being used for positioning and alignment. Then the top plate was installed by placing an 8-ft (2.4 m) length of 2 by 4 lumber flat against pre-drilled tabs described above. In order to facilitate anchorage of the panel to the base of test frames, two 1/2-in (12.7-mm) diameter, 3 1/4-in (82.4-mm) long, hex-head bolts were inserted into the wood plate prior to its attachment to the steel framing. To accommodate the anchor bolts, a 1/2-in (12.7-mm) diameter hole was drilled 12 in (0.30 m) from each and the hole was counterbored to a 3 1/4-in (82.4-mm) diameter. The depth of counterbore was just enough to accept a flat, 3 1/4-in (82.4-mm) diameter washer and the head of the anchor bolt. Wood putty was used as a filler around the head of the bolt. As an added precaution against slippage of the bolt head, a finishing nail was driven through a pre-drilled hole in the bolt-head.

3.1.2 Wood-Frame Construction - The 8 ft by 8 ft (2.4 m by 2.4 m) wood-frame specimens were fabricated in the laboratory with the use of commercially available building materials. All framing members were prepared from nominal 2 by 4 Construction-grade, Hem-Fir lumber. The vertical framing members were spaced 16 in (0.41 m) o.c. (see figure 3.2). Double 2 by 4 studs were used at each vertical edge of the panel. The horizontal framing consisted of double top plates and a single bottom plate. The lower top plate and the bottom plate were connected to the studs by end-nailing 2-16d common nails per stud. The upper top plate was faced-nailed to the lower top plate with 10d common nails at 16 in (0.41 m) o.c. A 1-in (25.4-mm) thick wood spacer was placed between the corner studs at third points. The studs were nailed together at each spacer with 4-16d common nails. In order to provide anchorage for the wall panels, a 1/2-in (12.7-mm) diameter hole was drilled through the bottom plate, at a distance of 12 in (0.30 m) from each end. As it was intended to insert a 1/2-in anchor bolt from the underside of the specimens, a nut-washer-block assembly (see figure 3.2) was positioned atop the bottom plate immediately above the pre-drilled hole. The wood block was glued and toe nailed to the bottom plate. This attachment procedure was repeated at the second pre-drilled hole. The exterior sheathing consisted of a single 1/2-in (12.7-mm) thick layer of plywood (3 ply). Two 4 ft by 8 ft (1.2 m by 2.4 m) sheets were applied vertically and fastened to the framing with 6d common nails. The nails were spaced at 6-in (0.15-m) centers along the top and bottom plates and the outermost studs and at 12-in (0.30-m) centers along the intermediate studs. The interior facing consisted of a single 1/2-in (12.7-mm) thick layer of gypsum wallboard. Two 4-ft by 8-ft sheets were used, with one sheet being cut along an 8-ft edge into two pieces, 16 in (0.41 m) wide and 32 in (0.81 m) wide respectively. The wallboard was applied vertically and fastened to the framing with 6d common nails, spaced at 6 in (0.15 m) o.c. The overall thickness of the specimens was 4 1/2 in (0.11 m).

3.2 Testing Frame and Load Application

3.2.1 Testing Frame - All racking tests were performed within an adjustable assembly consisting of beam and column members that were bolt-connected. Figure 3.3 illustrates a typical test setup and provides details pertaining to dimensions and frame member sizes. The 12-in (0.30-m) deep box beam, having a 15-ft (4.6-m) span length, was supported on each end by spreader beams which spanned between two nominal 8-in (0.20-m) wide-flange column members. The column base plates were anchored to the laboratory tie-down floor by 1 1/2-in anchor bolts. It is noted in figure 3.3 that the wall panels were bolted to the web of a nominal 8-in (0.20-m) wide-flange member which was in turn bolted to the tie-down floor at four locations with 1 1/2-in anchor bolts. This reaction beam provided resistance to horizontal shear force and to the uplift force acting at the heel of the wall specimen. To prevent local buckling of the web of the reaction beam, 3/8-in (9.5-mm) thick stiffener plates were welded to the web along the length of the beam at 12-in (0.30-m) centers.

3.2.2 Load Application - In all tests except the first one conducted on the steel-frame panel, the test loading consisted of a combination of vertical, in-plane, line loading and horizontal, in-plane loading applied near the top of the wall panel. The horizontal load was applied by a single 30-ton (267-kN), hydraulic jack. There were two alternate methods used for applying the vertical loads. In the first method, the loads were applied by four hydraulic jacks of the same design and capacity as the horizontal jack. The four jacks reacted against the nominal 12-in (0.30-m) deep box beam in a manner illustrated in figure 3.3. Two independent hydraulic systems were employed to activate and control the loading jacks: (1) The horizontal jack was activated by a variable-speed electric-motor-driven hydraulic pump whose output flow characteristics were controlled by several manually-operated control valves. Figure 3.4 presents a schematic diagram of this hydraulic loading system. (2) The four vertical jacks were operated from a single manifold located on the output side of a compressed-air-driven, hydraulic pump. The use of the four hydraulic jacks for vertical loading is shown in figure 3.5.

The alternate method of applying vertical loads involved the use of four "saddle-type" dead weight assemblies that replaced the four hydraulic jacks. The three photographs comprising figure 3.6 illustrate the principal details of this dead weight loading system. The magnitude of loading was increased to the desired level by adding equal numbers of lead brick, at 27 lb (120.1 N) per brick, to each "stirrup" of each assembly.

To achieve a transfer of the vertical and horizontal loads to the specimen, a nominal 6-in (0.15-m) deep, 9-ft (2.74-m) long, steel channel was attached to the 2 x 4 top plate of the specimen by 3/8-in lag bolts spaced at 12-in (0.30-m) centers. As is indicated in figure 3.3, a closed section was formed at the ends of the channel by welding a 6 1/2 by 4 by 3/4 in (0.17 by 0.10 by 0.02 m) steel plate to the channel. It was through this plate that the horizontal force was transferred to the loading channel. A channel section was selected over a solid timber section because a channel will provide for alternate attachment when the test specimens represent a type of wall construction which does not use wood framing members along the top edge. A channel can be satisfactorily attached to a particular specimen by using either its web or the flanges for fastening.

The bearing detail for the vertical jacks went through several modifications as the need for improvement was identified. The nature of the bearing detail changes consisted of replacing the bearing materials as well as altering the configuration of previously used materials. Figure 3.7 illustrates the five bearing conditions that were employed during the testing program. The three photographs in figure 3.8 show several of the bearing assemblies at various stages of laboratory testing.

3.3 Instrumentation and Measurements - The instrumentation used in this experimental program consisted of electromechanical sensors, a processor-controlled data acquisition system and various supplementary test equipment. Figure 3.9 shows a schematic of the instruments and data acquisition system.

3.3.1 Load Measurement - For measurement of loads, a full-bridge, strain gage-type load cell was attached to each hydraulic jack. All load cells used in the test program had a full range of 30 tons (267 kN).

3.3.2 Deflection Measurement - To measure the deflection of the test specimens and the deflections at several locations on the tests frame, linear variable differential transformers (LVDT's) were used. The total number of LVDT's used for this purpose, ranged from 8 to 10; the exact number of LVDT's used for each test is indicated in table 1. Depending on the location - hence the expected magnitude of displacement - of the sensor, the full scale range of the LVDT's was either $\pm$ 0.1 in (2.5 mm), $\pm$ 1 in (25 mm) or $\pm$ 3 in (76 mm). LVDT readouts were accurate to within $\pm$ 0.5%. Figure 3.10 shows the relative location of the seven LVDT's that were either attached to the specimen or located on the reaction frame adjacent to the specimen for all tests. LVDT 7 was supported by a floor-mounted frame and it measured the total horizontal displacement at the end of the load-distribution channel. LVDT 12 measured relative slip between the top plates and the load-distribution channel. Figure 3.11 is a closeup view of LVDT's 7 and 12. LVDT 8 was oriented in the vertical direction and attached to the 2 x 4 bottom plate. It measured the total uplift of the wall at the bottom of the loaded edge (heel). LVDT 9 measured the vertical separation between the end stud and the bottom plate. LVDT 10 measured the horizontal translation of the bottom plate with respect to the reaction beam an elevation close to the bottom. LVDT's 11 and 13 were attached to the reaction beam to measure its contribution to horizontal translation and vertical lifting respectively. One to three additional LVDT's were located near the top of the reaction frame to measure slip between the bolted members.

3.3.3 Recording of Data - All load cells and deflection gages (LVDT's) were calibrated before the testing was initiated. The output from all load and deflection transducers was automatically scanned, recorded and printed with the use of the mini-computer-controlled data acquisition system described schematically in figure 3.9. At each designated load increment, the voltage output from each load and deflection channel was scanned, indicated on the digital voltmeter and recorded by a magnetic tape recorder. Hard copy output was obtained in the form of teletype printout at certain designated increments. The data recorded on magnetic tape were subsequently processed by computer which converted the voltages into the appropriate engineering units of load and displacement.

3.4 Test Procedure - The seventeen tests were performed in the sequence presented in table 1. Except for test number 1, the 8 ft by 8 ft (2.4 m by 2.4 m) specimens were subjected to distributed, constant magnitude vertical loading and concentrated, incrementally increasing horizontal loading. Without the vertical loading, the steel-frame panel (test # 1) was first tested as an 8-ft (2.4-m) high cantilever. The horizontal loading was applied in approximately 400-lbf (1.78-kN) increments with the deflection and load measurements being recorded immediately upon reaching a specified level of loading (i.e., 400 lbf, 800 lbf, etc). The loading in test 1 was discontinued after reaching the 800-lbf (3.56-kN) level due to the excessive rigid body rotation of the specimen.

The same steel frame panel was employed in test 2. However the loading procedure was modified to incorporate the application of vertical loading. The loading sequence was comprised of two stages: (1) the vertical load was gradually applied until the predetermined magnitude was reached and (2) the horizontal load was applied in the manner described for test 1. For applying the vertical load, four hydraulic jacks, spaced at 2-ft (0.61-m) centers were used. The specified load magnitude was 500 lbf/ft (7.30 kN/m) or equivalently 100 lbf/ram (4.45 kN/ram). The test was halted after 7 increments of horizontal load, having reached a magnitude of 2750 lbf (12.33 kN).

Tests 3 through 7 were also performed on specimen number 1, using the above described procedure. During these experiments, the bearing condition for both the vertical and horizontal loading was modified several times. A description of these modifications was presented in figure 3.7.

Beginning with test 8, the racking tests were performed on 8 ft by 8 ft (2.4 m by 2.4 m) wood-frame panels. Specimen #2 was used for tests 8 through 13. See figure 3.2 for a description of a typical wood-frame panel. The loading procedure for test 8 was identical to that for test 2, described above. Beginning with test 9, the magnitude of the vertical loading was changed for each test to observe the effect of different magnitudes on the deformation behavior of the specimen. The range of vertical loading (refer to table 1) was 375 lbf/ft (5.47 kN/m) to 750 lbf/ft (10.95 kN/m). It was on test 12 that the four dead load assemblies (see figure 3.6) were first employed. The four saddle-type assemblies - each weighing 47 lb (209 N) - were located at the identical positions of their hydraulic jack counterparts. The vertical load was applied gradually by stacking the 27-lb (120-N) lead bricks onto the metal stirrups. The nominal magnitude of vertical loading applied during tests 12 and 13 was 500 lbf/ft (7.30 kN/m) and 625 lbf/ft (9.2 kN/m) respectively.

For the sake of comparing the deformation behavior observed during tests 12 and 13 with that exhibited by specimens with no loading history the next two tests (tests 14 and 15) were performed on new wood-frame panels (specimens 3 and 4). Specimen #3 was subjected to a vertical loading of 500 lbf/ft (7.30 kN/m), while 625 lbf/ft (9.12 kN/m) was applied to specimen # 4. During tests 14 and 15, the horizontal loading was applied at the approximate rate of 400 lbf/min (29.7 kN/sec). This rate was achieved with the aid of a stopwatch. In the 13 previous tests no record was kept of the loading rate, but it was deduced from a comparison of total test times that the previous rates were lower than 400 lbf/min (29.7 kN/sec).

Test 16 was performed on a wood-frame panel (specimen #5) which had no loading history. The hydraulic loading system was employed for vertical load application; the constant magnitude was 500 lbf/ft (7.30 kN/m). The rate of horizontal load was approximately 400 lbf/min (29.7 kN/sec).

Because of the 400 lbf/min (29.7 kN/sec) rate of loading was somewhat arbitrary, it was decided that test 17 would be performed at a faster rate to see if there was any appreciable difference in the apparent stiffnesses of the wood-frame panels. The loading rate was increased to 800 lbf/min (59.3 kN/sec) for this test. The loading sequence for test 17 was as follows: (1) the vertical load was applied by the dead weight assembly to the level of 500 lbf/ft (7.30 kN/m), (2) the horizontal loading was increased to the first increment, 400 lbf (1.78 kN), and the load and deflection readings were recorded immediately thereafter, (3) the horizontal load was then maintained for a period of 5 minutes and all readings were recorded at the end of the 5-minute hold period, (4) the horizontal load was released to zero and another set of readings were recorded, (5) the horizontal load was increased to the magnitude of two increments (i.e., 800 lbf or 3.59 kN) and the intermediate steps 2, 3 and 4, were repeated. This step-by-step procedure was performed for 7 increments of loading and testing was halted when the horizontal load reached a magnitude of 2875 lbf (12.78 kN).

Table 1 - Summary of racking test experiments.

TEST NUMBER	TEST DESCRIPTION	SPECIMEN DESCRIPTION	VERTICAL LOAD lbf/ft (kN/m)	NUMBER OF LVDT's	MAX. HORIZONTAL TEST LOAD lbf(kN)
1	SPECIMEN #1 Experiment #1	STEEL-FRAME	NONE	8	789 (3.51)
2	SPECIMEN #1 Exper. #2	" "	500 (7.30)	9	2750 (12.23)
3	SPECIMEN #1 Exper. #3	" "	" "	9	2800 (12.45)
4	SPECIMEN #1 Exper. #4	" "	" "	9	3275 (14.57)
5	SPECIMEN #1 Exper. #5	" "	" "	9	2825 (12.57)
6	SPECIMEN #1 Exper. #6	" "	" "	9	3225 (14.35)
7	SPECIMEN #1 Exper. #7	" "	" "	9	3175 (14.12)
8	SPECIMEN #2 Exper. #1	WOOD-FRAME	500 (7.30)	9	3225 (14.35)
9	SPECIMEN #2 Exper. #2	" "	750 (10.95)	10	3150 (14.01)
10	SPECIMEN #2 Exper. #3	" "	375 (5.47)	10	3200 (14.23)
11	SPECIMEN #2 Exper. #4	" "	625 (9.12)	10	3125 (13.90)
12	SPECIMEN #2 Exper. #5	" "	500 (7.30)1/	10	3175 (14.12)
13	SPECIMEN #2 Exper. #6	" "	625 (9.12)1/	10	3225 (14.35)
14	SPECIMEN #3	WOOD-FRAME	500 (7.30)1/	10	3225 (14.35)
15	SPECIMEN #4	WOOD-FRAME	625 (9.12)1/	10	4025 (17.90)
16	SPECIMEN #5	WOOD-FRAME	500 (7.30)	10	4340 (19.31)
17	SPECIMEN #6	WOOD-FRAME	500 (7.30)1/	10	2875 (12.79)

1/ *Dead weight in the form of lead bricks was used instead of hydraulic jacks.*

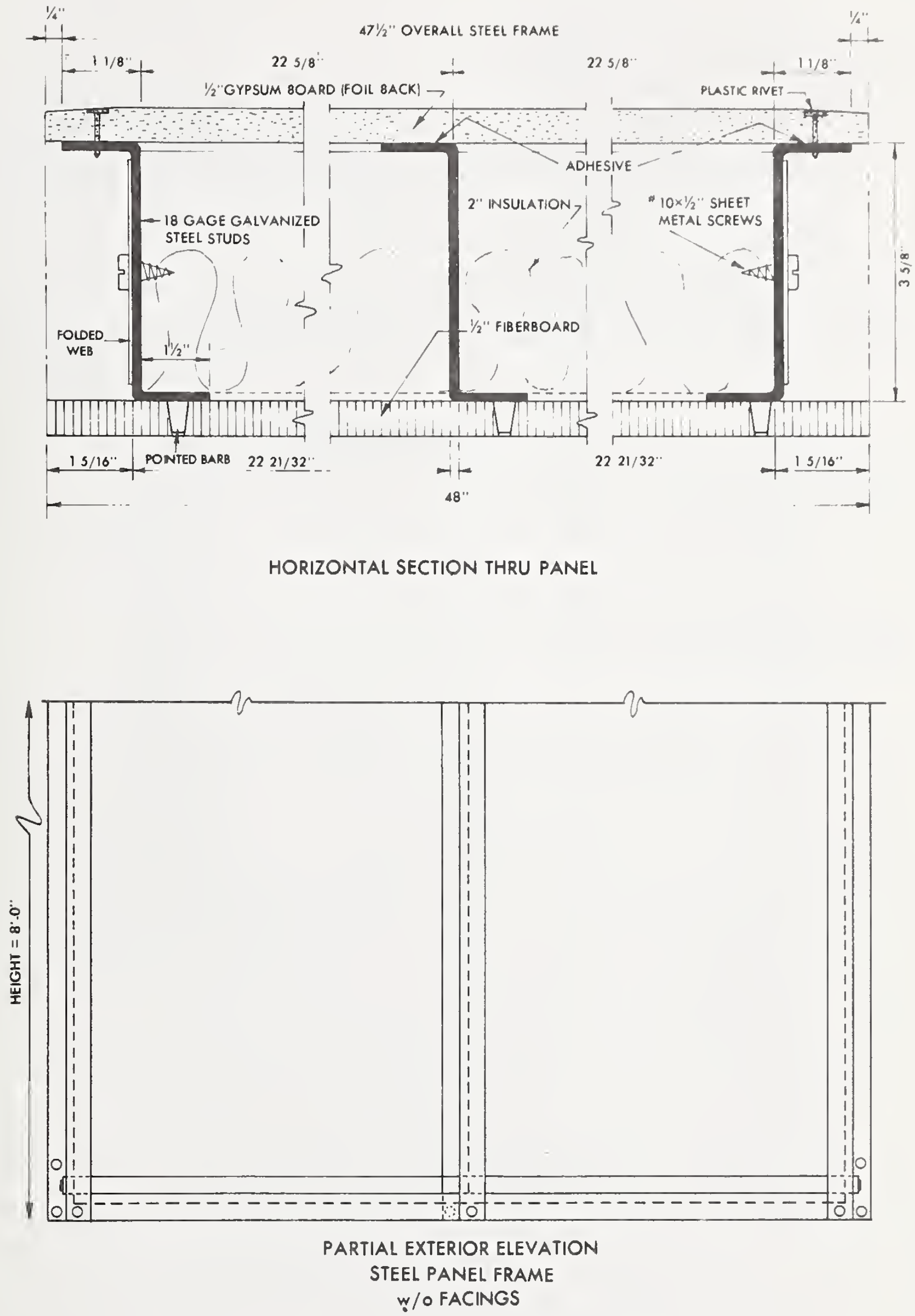


Figure 3.1 - Details of steel-frame test panel.

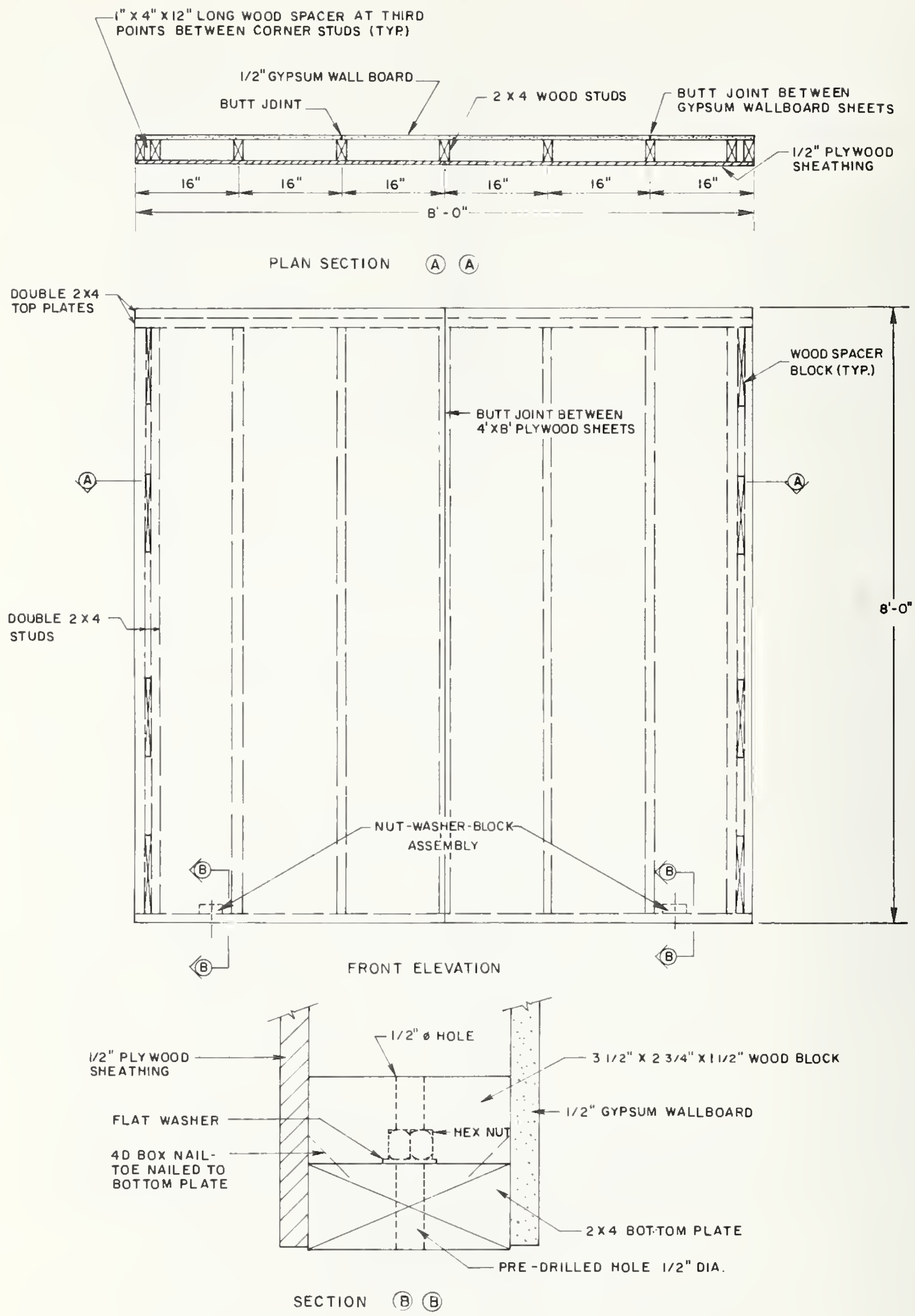


Figure 3.2 - Details of wood-frame test panel.

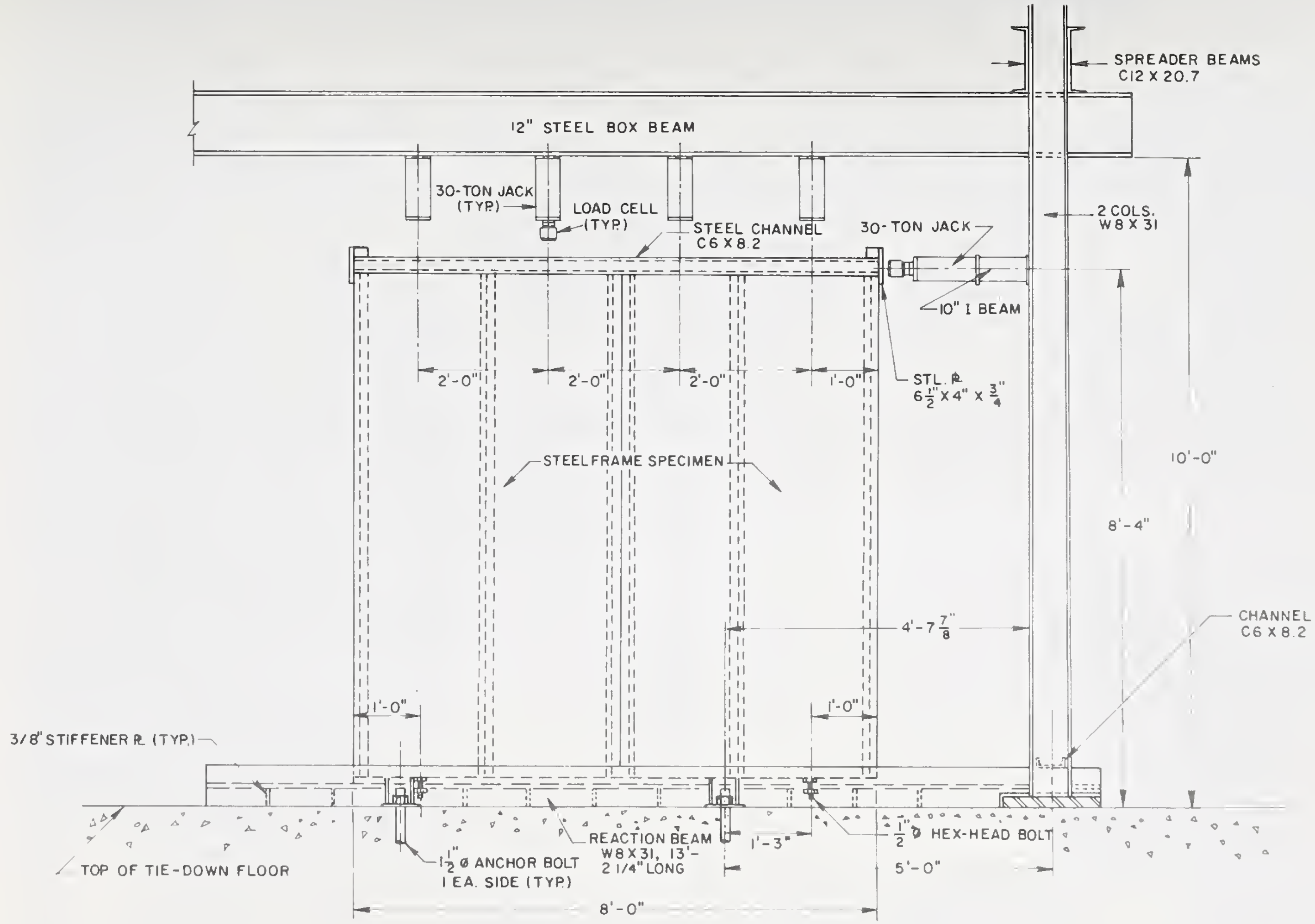


Figure 3.3 - Partial view of test frame with wall specimen in test position.

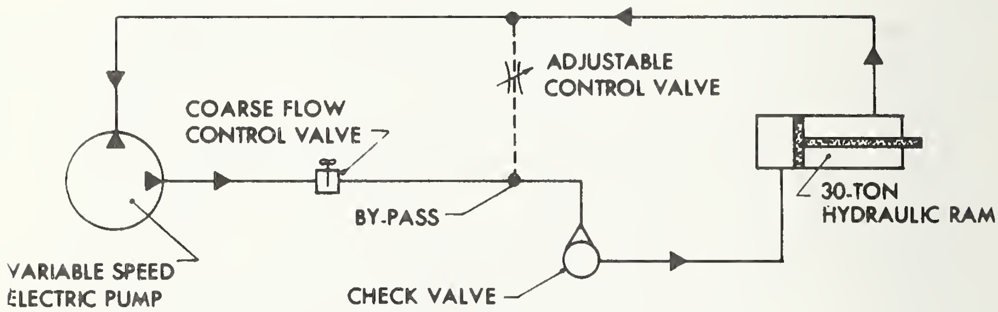


Figure 3.4 - Schematic of horizontal load hydraulic system.

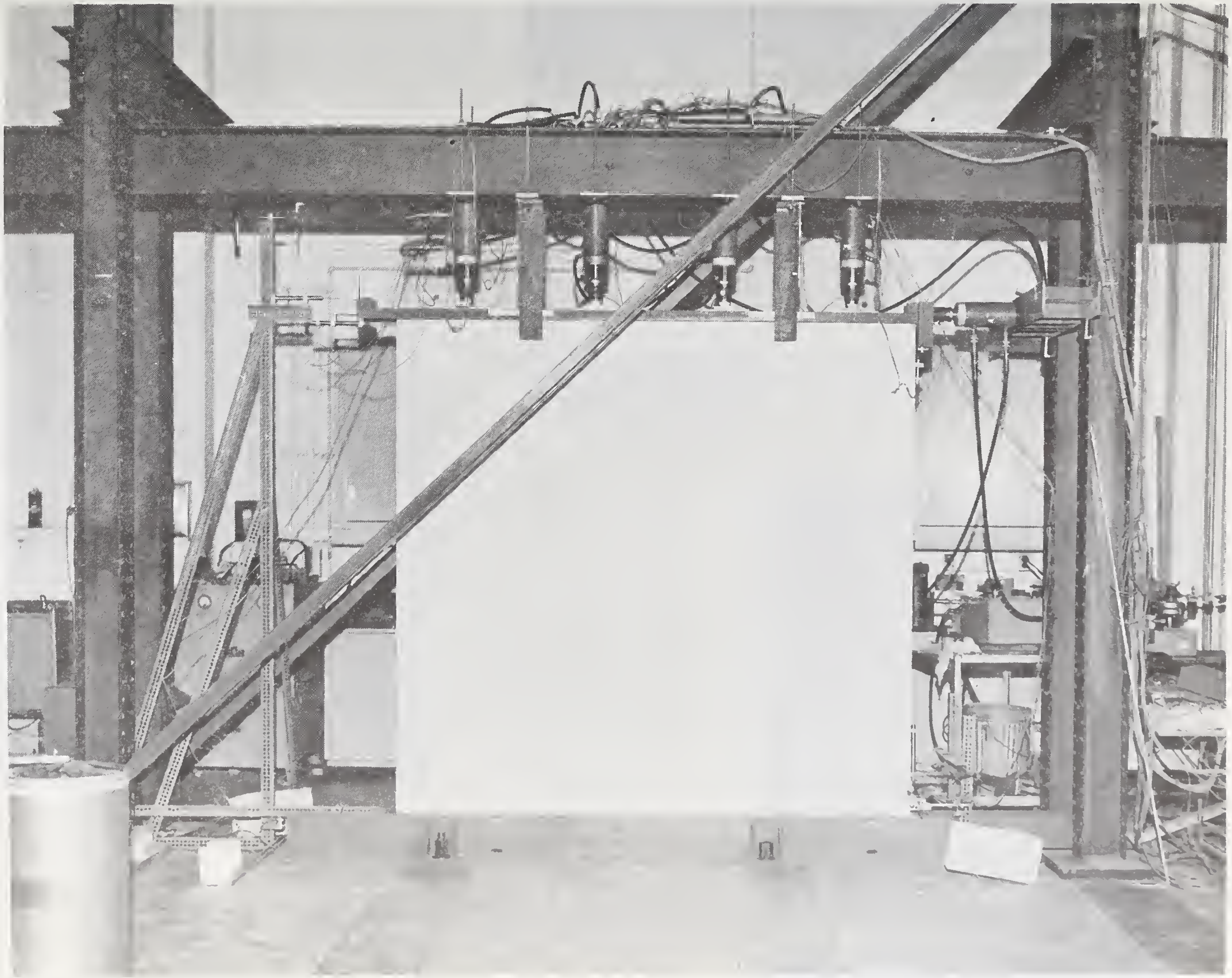
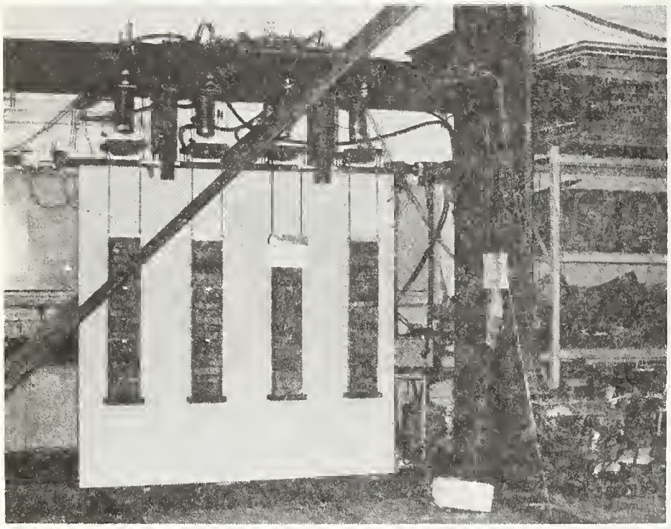
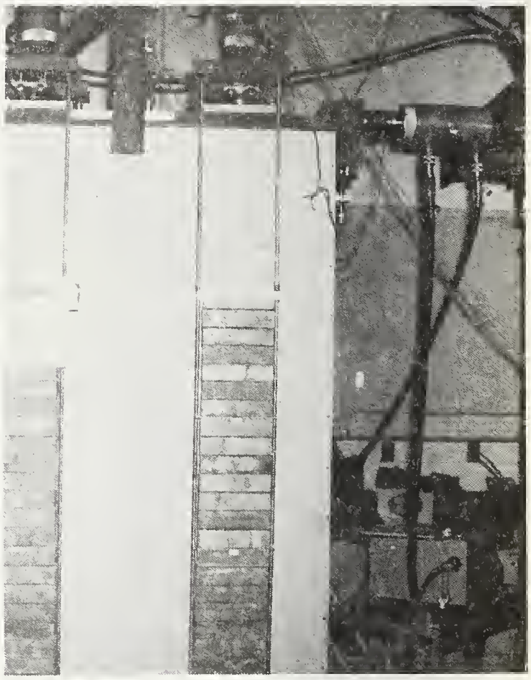


Figure 3.5 - Photograph showing hydraulic jacks used for vertical loading.

(a) Side view of the four assemblies.



(b) Close-up of two of the saddle-type assemblies.



(c) View at top edge of the loaded specimen.

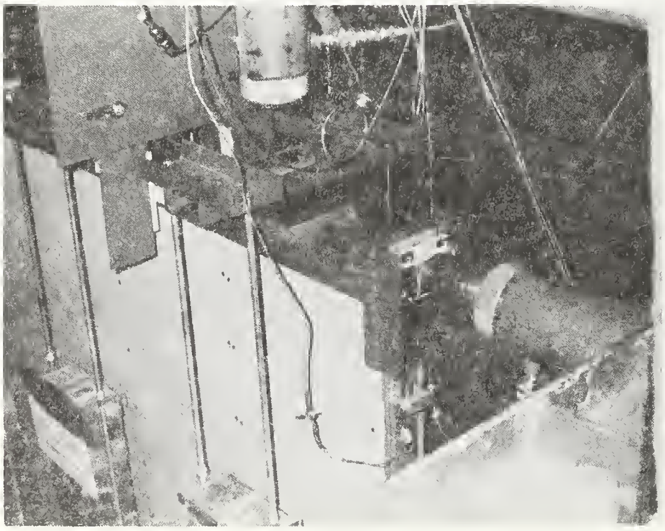


Figure 3.6 - Photographic description of dead weight vertical loading assemblies.

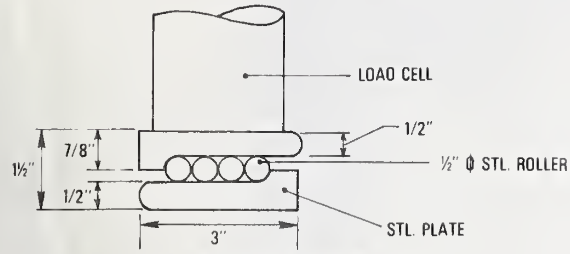
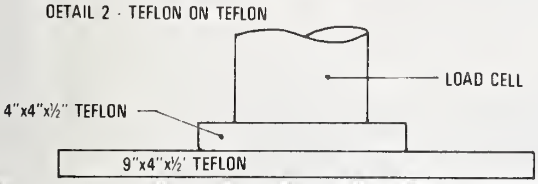
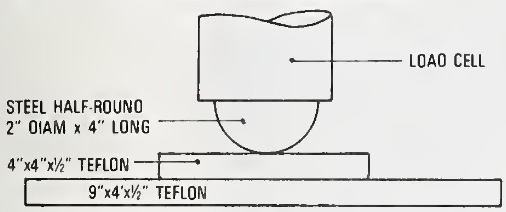
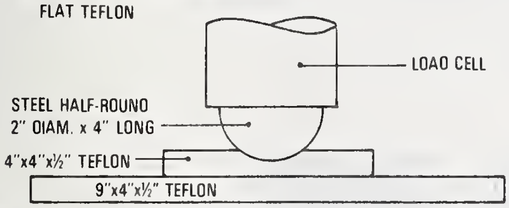
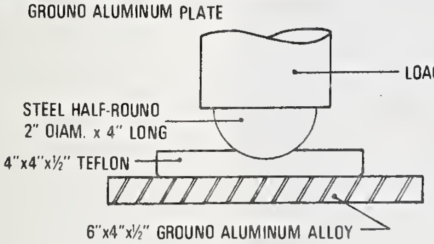
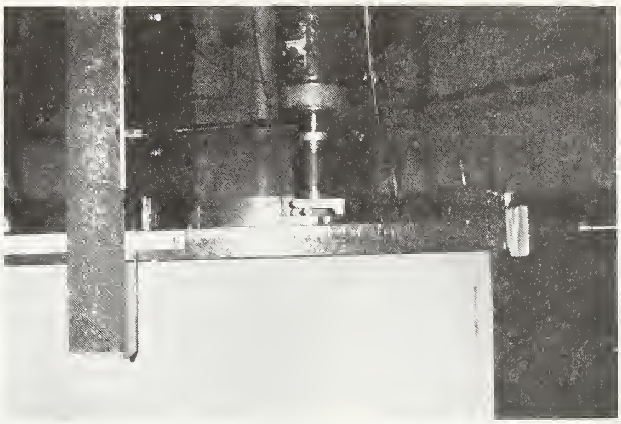
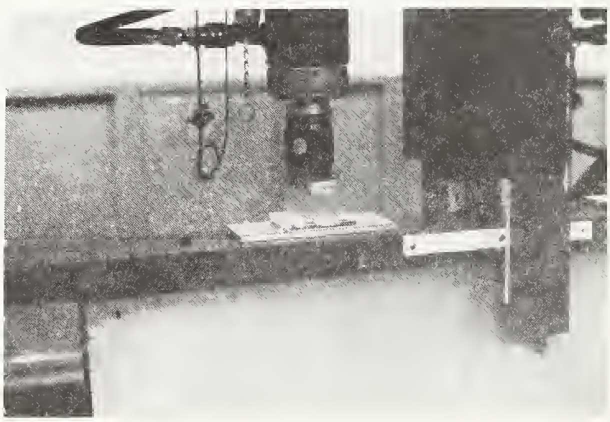
BEARING DETAIL	TEST NUMBERS	REMARKS
DETAIL 1 - STL. ROLLER-STL. PLATE ASSEMBLY 	1 thru 3	1. Exhibited low friction characteristics. 2. Unable to satisfactorily accommodate the rigid body rotation of the specimen. 3. Has limited translation capability.
DETAIL 2 - TEFLON ON TEFLON 	4	1. Coefficient of friction (μ) is unknown for teflon on teflon. 2. Translation capability was improved. 3. Lack of accommodation of rigid body rotation.
DETAIL 3 - STL. HALF-ROUND WITH TEFLON ON TEFLON 	5	1. Improved rotation capability achieved, but point bearing caused gouging of teflon. 2. Relative motion occurred between teflon pads, but μ still unknown. 3. Good translation capability.
DETAIL 4 - STL. HALF-ROUND, GROOVED TEFLON, FLAT TEFLON 	6	1. Distributed bearing obtained by grooving upper teflon pad. 2. Frictional characteristics between teflon pads need improving because of start-stop action.
DETAIL 5 - STL. HALF-ROUND, GROOVED TEFLON GROUND ALUMINUM PLATE 	7 thru 17	1. Acceptable rotation capability. 2. Good translation range. 3. Distributed bearing. 4. Relatively low friction characteristics at aluminum/teflon interface.

Figure 3.7 - The five bearing conditions used for vertical loading.



(a) Condition 1

(b) Condition 1



(c) Condition 5

Figure 3.8 - Several bearing conditions used during testing.

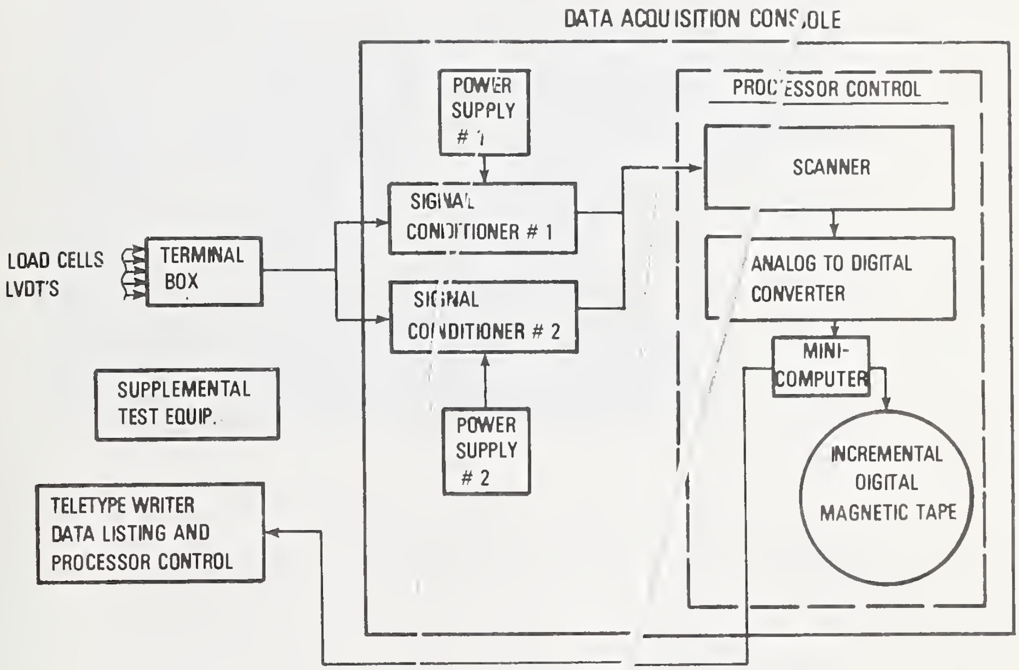


Figure 3.9 - Schematic of data acquisition system.

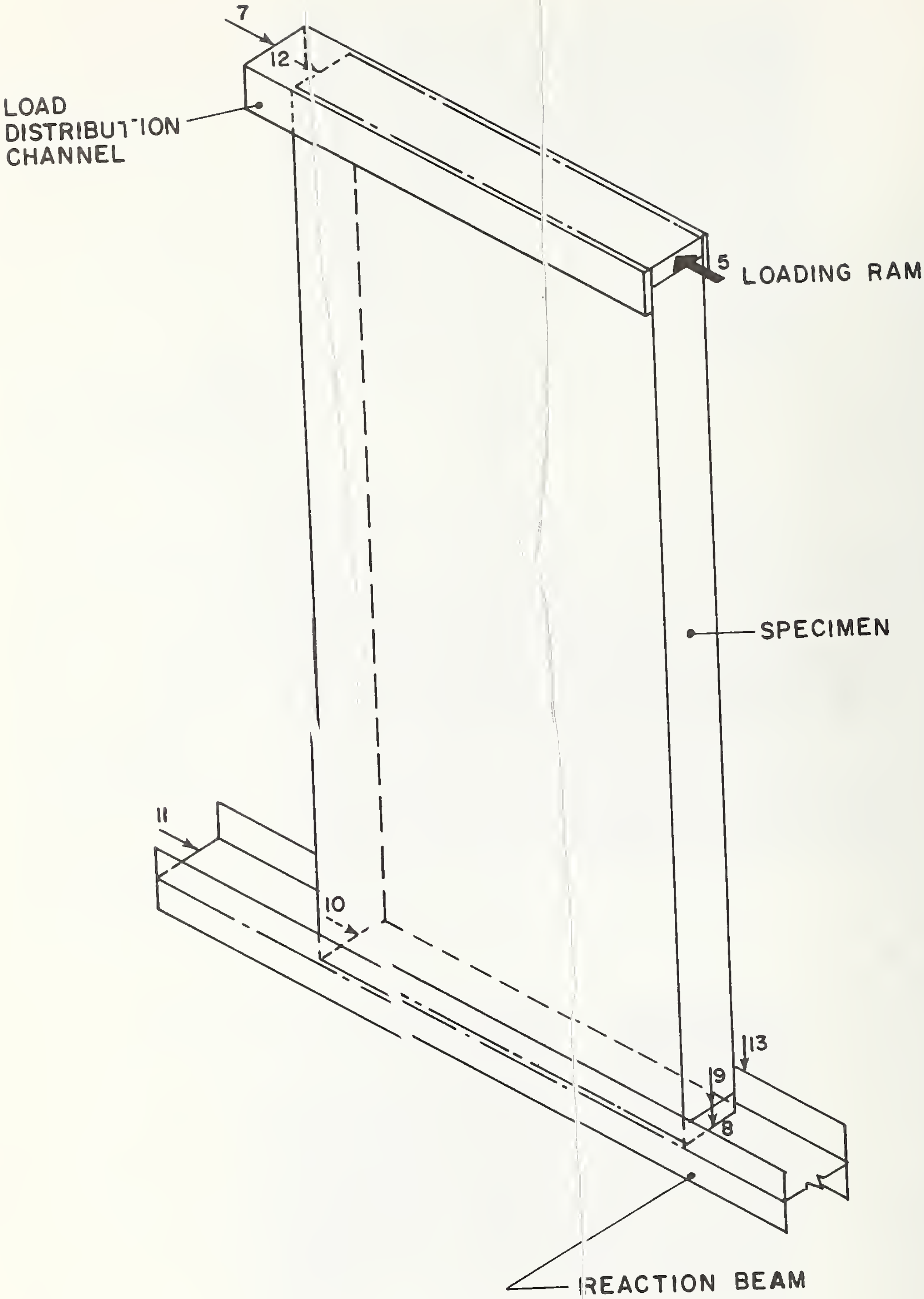


Figure 3.10 - Relative locations of seven LVDT's.

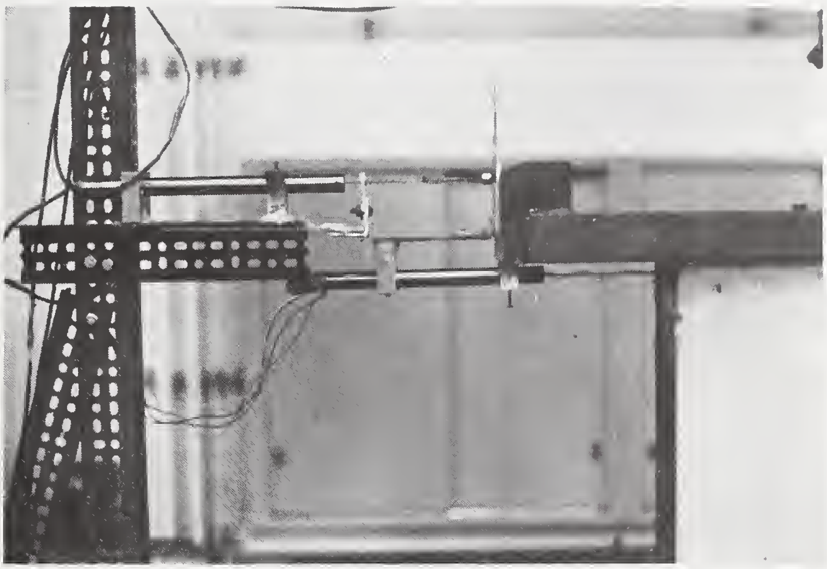


Figure 3.11 - Closeup view of LVDT's 7 and 12.

4. DISCUSSION OF RESULTS

Both quantitative and qualitative results were obtained from the laboratory testing of typical wall panel prototypes. The quantitative results were in the form of load and deflection measurements which were recorded at the load increments cited in section 3.4. The qualitative information resulted from observing the behavior of the specimens, the reaction frame, the electromechanical deflection gages and the bearing assemblies during testing. Noting that the purpose of these tests was to assess the applicability of the pilot test method, the quantitative data are important to this investigation to the extent that they have implications for the stated purpose. In the discussion that follows, these data will be presented only when they serve to emphasize a relevant point.

4.1 Behavior of the Panels - The modes of failure of the steel-frame and wood-frame panels were similar. From the standpoint of racking resistance, the weakest link in both types of construction was the nail connection between the stud nearest the horizontal load and the 2 x 4 wood bottom plate (i.e., at the heel of the panel). With the application of the vertical loading, the specimens were compressed, thus increasing the contact pressure between the bottom plate and the laboratory floor. As the horizontal load was increased the overturning tendency reduced the contact pressure at the heel of the panel. At some point in the loading cycle, the entire panel uplifted from the laboratory floor. The uplift action was opposed by the imposed vertical loading, the panel's self weight and the 1/2-in anchor bolt located a foot away from the heel of the panel. With increasing horizontal load, a separation appeared between several studs and the bottom plate. In the case of the wood-frame panels, the end-nail connections between the studs and the bottom plate were loosened as the nails were withdrawn. During the tests conducted on the steel-frame panel the nails which were inserted through the pre-drilled steel tabs on the studs (see section 3.1 for description) into the 2 x 4 bottom plate were partially pulled up through the bottom plate. This separation, which was greatest at the heel, permitted the panel to undergo substantial rigid body rotation under increasing horizontal load. Once the separation occurred, the clinching action of the nearby anchor bolt (located 12 in or 0.30 m from the end of the wall), along with a reduced uplift force, caused the end of the 2 x 4 bottom plate to relax and return to its initial position of contact with the laboratory floor. The tabulated data obtained from test 16 is presented in table 2 as typical test printout. The deformation behavior described above can be inferred from observing the data in columns marked 4, 5, 7, 8 and 9. A graphical description, based on the same data, is presented in figure 4.1. Columns marked 4 and 5 present the vertical and horizontal load information respectively. Columns marked 7, 8 and 9 were generated by the deflection gages of the same numbers and whose locations are illustrated in figure 3.9. Note that the deflections of increasing negative sign in columns 8 and 9 reflect panel compression as the vertical loading (col. 4) was increased to the designated level of 1000 lb (4.5 kN) per jack. As the horizontal load (col. 5) was increased there was gradual sign reversal associated with the vertical deflections (8 and 9) until at approximately 2400 lb (10.7 kN) the heel of the panel lifted from the laboratory floor. At the 4000 lbf (17.8 kN) level the panel's superstructure (i.e., studs, sheathing and top plates) separated from the bottom plate. Upon reaching the maximum recorded load of approximately 4300 lbf (19.1 kN), the separation increased as the bottom plate returned toward the laboratory floor while the superstructure underwent rigid body rotation. A comparison of cols. 7 and 9 for scan 17, after the horizontal load had dropped off somewhat, indicates that the ratio of the readings of LVDT 9 to LVDT 7 is about 74%. The significance of this ratio is that it reflects the portion of the total horizontal deflection, measured at the top of the wall, which is attributed to rigid body rotation. Similar patterns of the deformation were noted in the other test runs as well. It is necessary to correct for the effects of rigid body rotation when there is only interest in assessing the in-plane shear resistance of the sheathing and studs. For example, in the case of the deflection gages used in this investigation, the readings from LVDT 9 can be used to determine the horizontal translation due to rigid body rotation. To determine the magnitude of the deflection measured by LVDT 7 that is due to shear deformation, the results from LVDT 9 must be subtracted from the LVDT 7 reading.

4.2 Resistance of Reaction Beam - It was intended that the wide-flange reaction beam be held stationary during the application of horizontal load. To measure the effectiveness of the four 1 1/2-in anchor bolts at resisting sliding and uplift motion, deflection gages 11 and 13 (see fig. 3.9) were mounted on the beam with reference to the laboratory floor. A review of the test data indicates that the maximum horizontal movement, as measured by gage 11, was 0.01 in (0.25 mm) and the maximum uplift deflection was less than 0.001 in (0.025 mm). The maximum horizontal movement occurred during test 14. Subsequently to test 14, the anchor bolts were re-tightened with the result that the maximum horizontal movement was reduced to less than 0.001 in (0.025 mm). In light of the insignificant amount of movement of the reaction beam, it was not necessary to adjust the total horizontal deflection as measured by LVDT 7.

4.3 The Effect of Loading Rate on Deflections - As was previously mentioned, only specimen #6 (test 17) was loaded at the relatively high rate of 800 lbf/min (59.3 N/sec); the remainder of the specimens were loaded at rates not in excess of 400 lbf/min (29.7 N/sec). The higher rate was approaching the maximum practical rate that could be achieved with the loading system used. The objective was to establish if there was any apparent increase in stiffness attributable to the higher loading rate. Because of the variables of method of load application and magnitude of vertical loading there are not substantial data available on which to base a conclusive answer. However, a graphical comparison (figure 4.2) of the results of test 14 with those of test 17 - which had a loading rate twice that used in test 14 - shows no apparent difference in the stiffness of the two specimens up to the load level at which rigid body rotation was incipient.

4.4 The Effect of Holding Period - In test 17 (see section 3.4) a 5-minute period of load maintenance ("holding period") for each designated increment of horizontal loading was introduced. The length of the holding period was based upon an adopted amendment of ASTM Standard E72-74, Conducting Strength Tests of Panels for Building Construction [2]. There are five reasons cited for the 5-minute application of constant-level increment loads. The reason of particular interest to this investigation is quoted as follows:

> "To observe any time-dependent deformation or load redistribution or both, and to record accurately the load level when time-dependent deformation starts, at the divergence of the immediate and delayed load-deformation curves. This load level may, under certain conditions, have an important bearing on the design load."

The results from test 17 did not indicate any time-dependent deformation of specimen #6 over the horizontal load range of 0 to 2875 lbf (0 to 12.98 kN). It was at this load level that the panel's superstructure underwent considerable rigid-body rotation. Table 3 presents some results from test 17. The deflections measured by LVDT's 7 and 9 are tabulated for the 5-minute holding period as well as for the recording period immediately following the arrival at the designated racking load.

4.5 The Effect of Vertical Load Magnitude on Lateral Stiffness of the Panels - Realizing that the magnitude of vertical loading is dependent on such factors as the type of construction and the spatial framing characteristics of the building, it was decided that the magnitude of vertical loading would be varied for this test program. The range of loading, 375-750 lbf/ft(5.47-10.95 kN/m), was established as typical of the gravity loading transmitted to a bearing wall in low-rise residential and light commercical buildings. In general, the horizontal deflection measured at the top of a wall panel subjected to a racking force consists of five components: (1) shear deformation of the panel, (2) flexural deformation of the panel due to cantilever action, (3) internal mechanical slip, (4) rigid body rotation of the panel, and (5) movement of the anchorage system. As was reported in section 4.2, the movement of the anchorage system was negligible in all 17 tests. Further, it can be shown with calculations that the expected flexural deformation component is relatively small for the wall panel types tested. While the effect of vertical loading on shear deformation and internal slip has not been established in general, it is reasonable to hypothesize that a specimen's resistance to rigid body rotation would be increased with an increase in magnitude of vertical loading. To test this hypothesis, four load-deflection curves generated by the deflection measurements from LVDT 9 (see fig. 3.9) were plotted as shown in figure 4.3. All of the data for these plots were generated from tests performed on specimen #2. Furthermore, the vertical loading for each of the tests was applied by hydraulic jacks. While not providing conclusive evidence, these curves do tend to support the hypothesis.

4.6 Dead Weight Application Versus Hydraulic Jack Application - Seven load-deflection curves are presented in figure 4.4 to provide a basis for making a quantitative comparison between the two means of applying vertical loading. The abscissa of these curves measures the total horizontal displacement at the top of the wall panel as obtained from LVDT 7. The curves are plotted for vertical load magnitudes of 500 lbf/ft (7.30 kN/m) and 625 lbf/ft (9.12 kN/m). The relative positions of curves of equal vertical load magnitude, but with differing means of load application, suggest that the use of hydraulic jacks will result in an apparently higher stiffness. A sufficiently large number of identical specimens would have to be tested to substantiate this observation. The need for a larger number of tests is further borne out by the anomalous position of the curve for test 16. Although test 16 was conducted with the same vertical loading as used in tests 8 and 12, the results from test 16 indicate greater stiffness and higher strength. This inconsistency is thought to be caused by the inherent variability of the properties of the product. Nevertheless, there is a trade-off to consider when deciding which loading method to employ. The use of hydraulic jacks makes it necessary to operate two hydraulic systems simultaneously when performing the racking test with combined vertical and horizontal loads. On the other hand, the use of dead weight, in the form of bricks, introduces the cumbersome task of stacking and unstacking the loading material in order to affect the desired load level. A notable advantage in using dead weight is that the magnitude of vertical loading remains constant throughout the range of horizontal loading. By contrast, the vertical hydraulic jacks necessitated constant vigilance of a digital voltmeter to establish when adjustment of the control valves was needed as the horizontal load was increased. It is acknowledged that a load maintaining device can be used to eliminate the problem of fluctuating load. But, the solution does call for the addition of a piece of relatively expensive equipment. A typical fluctuation in vertical loading across the four hydraulic jacks can be surmised by observing columns marked 1, 2, 3, and 4 in table 2. These columns give the magnitude of vertical loading at the four load positions. For wall panel tests in which there is considerable uplift resulting from the racking load, the stroke of the hydraulic jacks must be adjusted to accommodate the rotation of the top edge of the panel. For example, in the four vertical jack arrangement used in this investigation, the piston of the jack nearest the horizontal load (see fig. 3.3) was forced to retract more (as much as 1 1/4 in (31.7 mm)) than that of the furthest jack. To prevent an increase in the hydraulic pressure it was necessary for the operator to bleed off some of the oil. Of course, the dead weight assembly necessitated no such stroke and pressure adjustments as the racking loads increased.

4.7 Assessment of the Use of Electromechanical Deflection Gages - The use of electromechanical deflection gages (LVDT's) was not based primarily on an accuracy of measurement requirement. Rather, the number of channels of deflection data and the need for immediate, simultaneous, readout dictated the use of this instrumentation. Also, the desire to monitor the panel's behavior continuously via an x-y plotter warranted their use. It should be noted that testing had progressed through test 3 before the gages were adjusted to accommodate motion transverse to the longitudinal axis of gages 7, 8 and 9. As is shown schematically in figure 4.5, the LVDT is a uniaxial measuring gage. The rotation of the panel - following uplift at the heel - caused considerable movement transverse to the intended measuring direction of these gages, resulting in some bending of the LVDT cores. This problem was compounded by the fact that the sensing "bullet" that was attached to the core had to positively contact the respective reference plates (which were attached to the specimen) to measure the panel's movement throughout the loading and unloading cycle. This positive contact was produced by using either a coiled spring which encircled the stem of the sensor (see fig. 4.5) or a rubber band which was wrapped around the bullet and the adjacent reference plate. The presence of the springs or the rubber bands caused pressure to be imparted to the metal plates. The pressure in turn caused a friction force in the direction perpendicular to the longitudinal axis of the LVDT. When a panel's superstructure rotated as a rigid body, the tendency for the metal plates to move relative to the sensing bullet nose was restrained by the friction force. The force, acting at the tip of the bullet, increased with increasing horizontal load and eventually was sufficient to induce bending deflection in the core. The problem was solved by attaching a thin pad of teflon to the face of the metal plates, thus creating a much smoother surface of contact for the sensing bullet.

4.8 The Development of an Acceptable Bearing Detail - Five different bearing details were used in conjunction with the vertical hydraulic jacks. Figure 3.7 gives a schematic description of the various details. In addition, fig. 3.7 shows which bearing conditions were used for the tests that involved vertical hydraulic jacks. It should be noted that the bearing detail for the horizontal jack was changed concurrently with a change in the detail for the vertical jacks. For the details shown in fig. 3.7 four identical sets of hardware were used for the four vertical jacks.

The rationale for modifying the various bearing details was directly influenced by the deformation behavior exhibited by the test specimens used in this investigation. The tendency of these systems to exhibit substantial rigid body rotation under racking load formed the basis for two of the three requirements comprising the criteria against which the bearing details were judged. The three requirements were as follows: (1) that the bearing hardware be able to accommodate the rigid-body rotation; (2) that the bearing hardware function while the top of the walls underwent relatively large lateral translation and (3) that the bearing hardware offer relatively low frictional resistance to the lateral translation that would result from the racking load. The third requirement would be applicable regardless of the deformation behavior of the test specimen.

The bearing detail modifications were made on the basis of a qualitative assessment of their performance vis-a-vis the previously mentioned criteria. In connection with the low friction requirements, some measurements of the relative motion of the parts of the bearing detail were made. These measurements were not documented, but rather served to indicate at what horizontal load level there was perceivable movement at the top of the wall. The comments listed in fig. 3.7 reflect the subjective judgement of the investigators with respect to the performance of the particular detail. Initially, a steel roller-steel plate assembly (Detail 1 in fig. 3.7) was selected on the basis of its satisfactory use in previous racking tests. Four 1/2-in rollers were sandwiched between two haunched steel plates. The top plate of the sandwich was mechanically attached to the load cell and the jack through the use of a threaded rod which passed through the hole in their respective centers. The bottom plate rested directly on the web of the nominal 6-in (0.15-m) loading channel. Hence, relative horizontal movement between the top of the wall panel and the four vertical jacks could be accommodated. While this assembly apparently satisfied the requirement of low frictional resistance, its limited translation capability and its inability to accommodate the rigid body rotation - associated with the tendency to overturn of the specimen led to the decision to change the bearing detail. As relative horizontal movement occurred between the top and bottom plates, support for the steel rollers was lost. Consequently, several rollers dropped out, reducing the bearing area. Also, because the top plate was stationary while the bottom plate rotated with the top of the wall, the assembly tended to come apart. The first change occurred after test 3.

The translation capability was improved by using two pads of 1/2in (12.7-mm) thick teflon as shown by Detail 2 in fig. 3.7. However, the second assembly did not satisfy the requirement for rotation accommodation and the coefficient of friction for the teflon pads was unknown. It was observed that relative horizontal motion was occurring, but a quantitative evaluation of the friction coefficient was not attempted.

After completing test 4, it was decided to change the detail to address the requirement of rotation accommodation while maintaining the increased translation capability introduced in Detail 2. To accomplish this objective, a steel half-round was attached to each of the four hydraulic jacks. This hardware (see Detail 3, fig. 3.7) created a roller effect as the wall panel rotated. The half round was mechanically attached to the load cell and the loading jack and it therefore remained stationary as the teflon pads followed the rotation of the wall panel. The improvement in rotation accommodation not withstanding, this condition introduced an undesirable point bearing of the steel half-round on the top teflon pad. The effect of the point bearing was to gouge the teflon, thereby introducing additional resistance to the horizontal movement.

The gouging problem associated with Detail 3 was eliminated, following test 5, by machine-grooving the teflon pad to the same radius of curvature as that of the half-round. The mating curved surfaces were observed to function acceptably at all load levels. With the requirements of adequate translation and rotation accommodation fulfilled, the need for low frictional resistance to horizontal load was further addressed. The final change occurred after the completion of test 6.

The best solution to the low frictional resistance requirement was found in the replacement of the 9-in (0.23-m) long bottom teflon pad (see Details 2, 3 & 4 in fig. 3.7) with a plate of ground aluminum alloy. The surface finish of the plate was measured, within ± 10% accuracy, to be 8 microinches (0.20 microns). While no data were obtained to establish the coefficient of friction for the teflon-aluminum interface for the test load magnitudes of 750, 1000 and 1250 lbf (3.34, 4.45 and 5.56 kN) some data published by the Polychemicals Department of E.I. DuPont De Nemours & Co., Inc., was studied to establish the order of magnitude. From a DuPont Engineering and Design Data publication it was found that for FEP resin teflon on Elastuff A-2 steel having a surface finish of 5 to 6 microinches (0.13 to 0.15 microns) rms, typical values for static coefficient of friction are as follows: (1) 0.1 at 15 lbf (66.7 N), (2) 0.028) at 300 lbf (1.33 kN), (3) 0.024 at 1000 lbf (4.45 kN) and (4) 0.018 at 2000 lbf (8.90 kN). These values are approximate in that they were scaled from a test curve. Note that the coefficient of friction decreases with increasing load. Having achieved the desired low friction characteristics, along with good rotation capability, distributed bearing and acceptable translation capability, Detail 5 was accepted as the recommended solution for the vertical load bearing problem, and it was used for the last ten tests. While there are no comparative figures offered to support the conclusion, it was judged - on the basis of the qualitative observations made during these investigations - that the coefficient of friction for the teflon-aluminum interface was significantly lower than that for the teflon-teflon interface.

Table 2 - Typical test printout - test 16.

```
***TEST IDENTIFICATION - 8X8 WALL RACKING TEST SPECIMEN 5 WOOD FRAME 1000LBS VR40
***TEST DATE - FEB 7,1975

***SUB2***PRINTOUT OF LOAD CHANNEL VS. OTHER CHANNELS***

THE CHANNEL DESCRIPTIONS ARE:
        5 - LOAD CELL HORIZ. #41
        1 - LOAD CELL E1  P6
        2 - LOAD CELL PH-2
        3 - LOAD CELL P4
        4 - LOAD CELL  W4  #3
        6 - LVDT TOP FRAME I CHAN. HORIZ. MOVEMENT
        7 - LVDT TOP WALL U CHAN. HORIZ. MOVEMENT
        8 - LVDT WEST BOT 2X4 VERT. MOVEMENT
        9 - LVDT WEST BOT.  SIDE 2X4 VERT. MOVEMENT

THE UNITS OF THE CHANNEL DATA ARE:
        5 - KIPS
        1 - KIPS
        2 - KIPS
        3 - KIPS
        4 - KIPS
        6 - INCHES
        7 - INCHES
        8 - INCHES
        9 - INCHES
```

CHANNEL SCAN	5	1	2	3	4	6	7	8	9
1	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
2	-.0175	-.2383	-.2291	-.2526	-.2302	.0000	.0020	-.0043	-.0032
3	-.0148	-.4856	-.4744	-.4654	-.4832	.0000	.0058	-.0102	-.0096
4	-.0309	-.7883	-.7558	-.7798	-.7959	.0000	.0067	-.0135	-.0157
5	-.0027	-1.0098	-.9956	-1.0090	-1.0247	.0001	.0076	-.0154	-.0183
6	.4274	-.9544	-.9769	-.9898	-1.0147	-.0001	.0198	-.0145	-.0174
7	.7983	-.9145	-.9487	-1.0008	-1.0545	-.0019	.0270	-.0133	-.0163
8	1.1841	-.9390	-.9487	-.9610	-1.1071	-.0039	.0423	-.0116	-.0146
9	1.6545	-.9222	-.9635	-.9980	-1.1185	-.0058	.0583	-.0093	-.0125
10	2.0026	-.8771	-.9527	-.9774	-1.1569	-.0074	.0708	-.0070	-.0104
11	2.3869	-.9544	-.9648	-.9857	-1.2691	-.0123	.1122	.0020	-.0021
12	2.8157	-.9145	-.9527	-1.0172	-1.0687	-.0166	.1623	.0173	.0121
13	3.1960	-.8166	-1.0318	-1.0008	-1.0631	-.0205	.2295	.0493	.0418
14	3.5898	-.7908	-1.0251	-1.0134	-1.0744	-.0256	.3088	.0874	.0766
15	4.0105	-.9140	-1.0130	-1.0186	-1.0730	-.0297	.4013	.1385	.1288
16	4.3398	-1.0201	-1.1886	-1.1490	-1.2237	-.0333	.8563	.0478	.5014
17	3.9540	-1.0227	-1.0144	-.9349	-1.0716	-.0333	1.6503	.0093	1.2211
18	-.0394	-.9969	-.9809	-1.0049	-.9863	-.0038	.2302	-.0128	.0178
19	-.0067	.0013	.0000	.0014	-.0099	-.0048	.1798	-.0062	.0209

Table 3 - Selected results from test 17.

Racking Load kips (kN)	Time[1] min	Total Horizontal Deflection - LVDT 7 in (mm)	Vertical Separation at Heel - LVDT 9 in (mm)
0.386 (1.717)	0	0.037 (0.94)	0.005 (0.13)
0.388 (1.726)	5	0.037 (0.94)	0.005 (0.13)
0.778 (3.461)	0	0.089 (2.26)	0.015 (0.38)
0.778 (3.461)	5	0.093 (2.36)	0.015 (0.38)
1.172 (5.213)	0	0.142 (3.61)	0.031 (0.79)
1.159 (5.155)	5	0.147 (3.73)	0.031 (0.79)
1.597 (7.104)	0	0.199 (5.05)	0.051 (1.30)
1.620 (7.206)	5	0.207 (5.26)	0.054 (1.37)
2.097 (9.328)	0	0.275 (6.99)	0.087 (2.21)
2.060 (9.163)	5	0.277 (7.04)	0.087 (2.21)
2.394 (10.649)	0	0.332 (8.43)	0.115 (2.92)
2.357 (10.484)	5	0.332 (8.43)	0.115 (2.92)
2.700 (12.010)	0	0.427[2] (10.85)	0.178 (4.52)
2.673 (11.890)	5	0.545[2] (13.84)	0.279 (7.09)
2.867 (12.753)	0	1.426 (36.22)	1.052 (26.72)
2.792 (12.419)	5	1.427 (36.25)	1.053 (26.75)

Note 1: Data recorded immediately upon reaching the designated load level is identified by a zero (0) in this column. Readings obtained after the 5-min holding period will have a 5 shown in this column.

Note 2: The nearly 30% increase in the deflection as measured by LVDT 7, at this load level, was also indicated by the other LVDT readings. However, no explanation was uncovered for this apparent deviation from typical behavior.

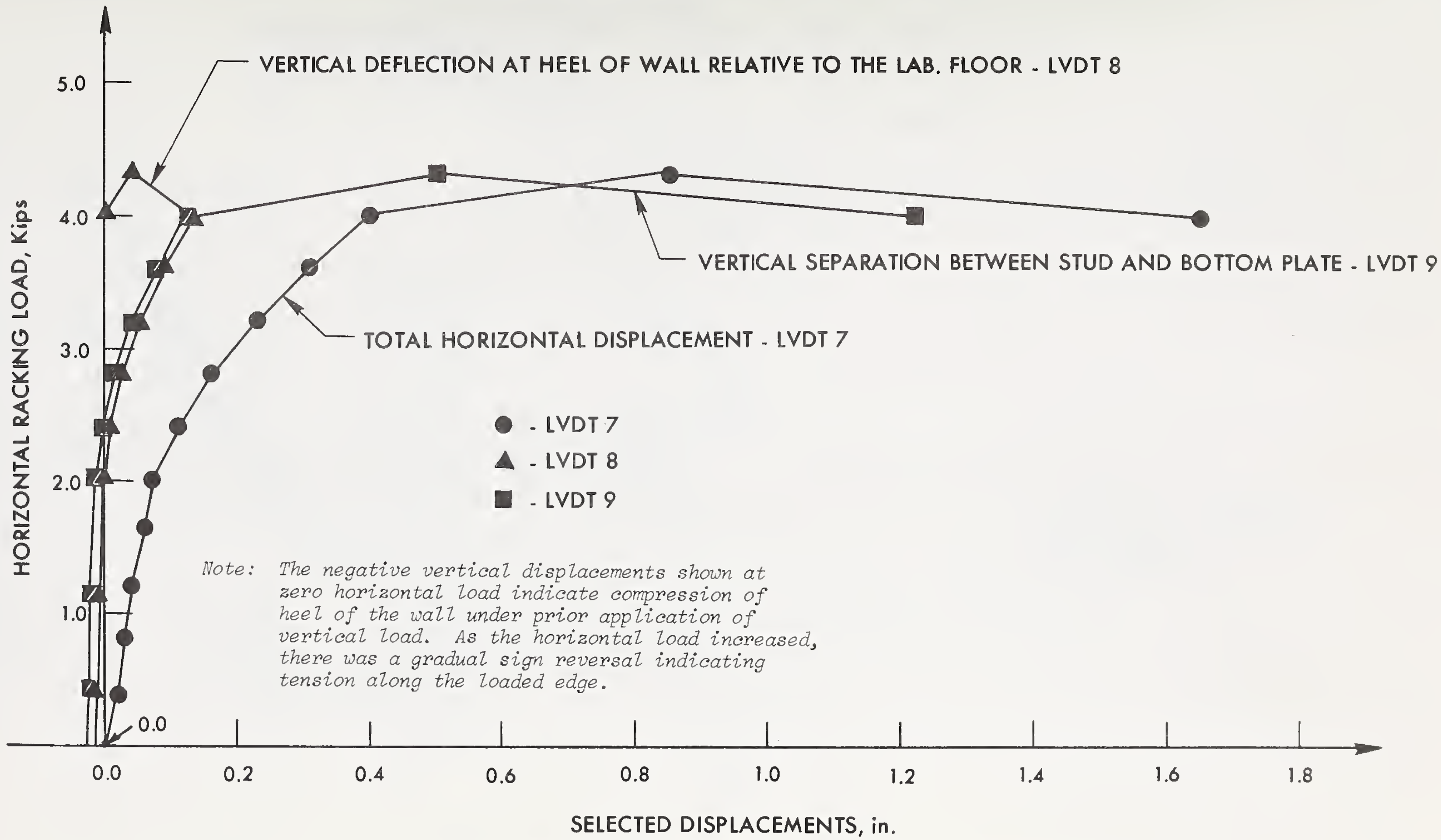


Figure 4.1 - Racking load versus selected displacements showing specimen response.

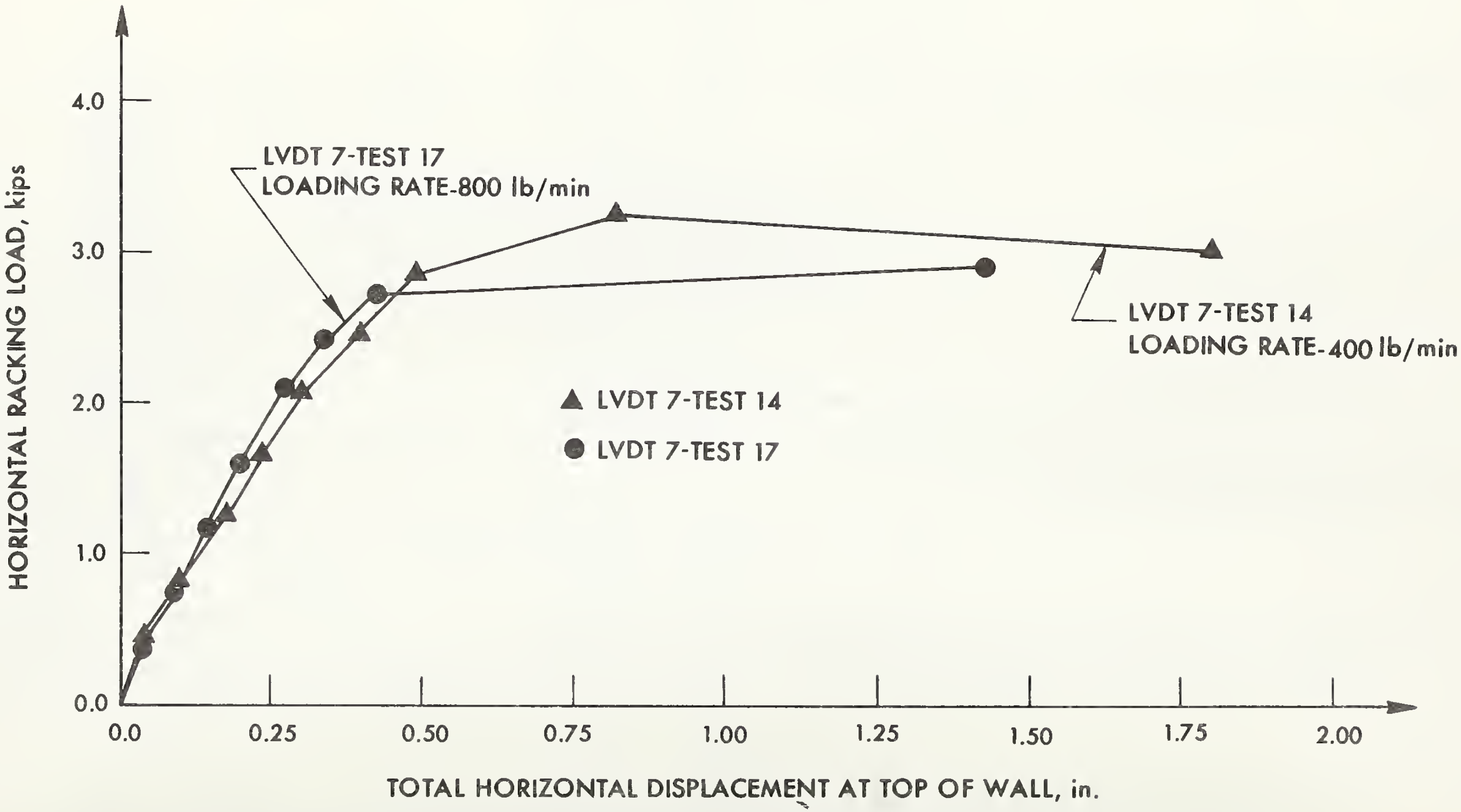


Figure 4.2 - Racking load versus total horizontal displacement for tests with different loading rates.

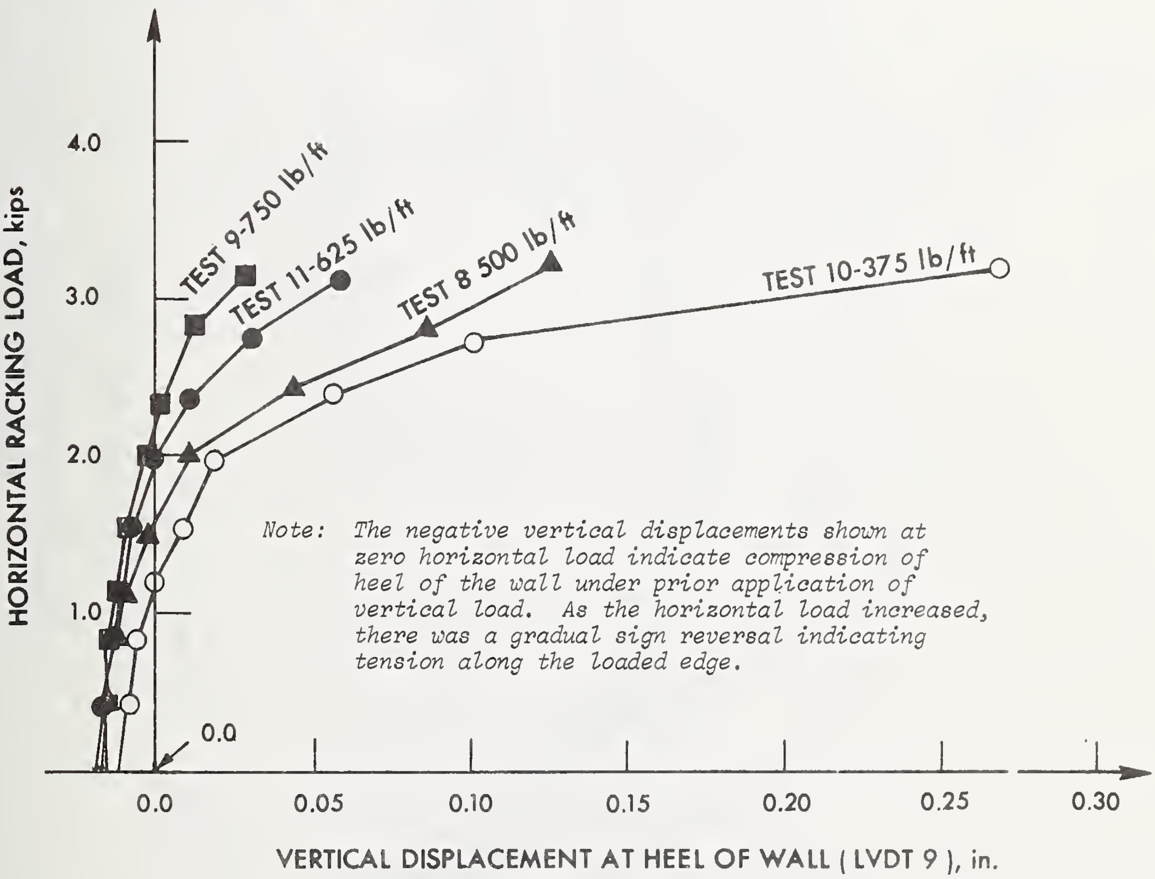
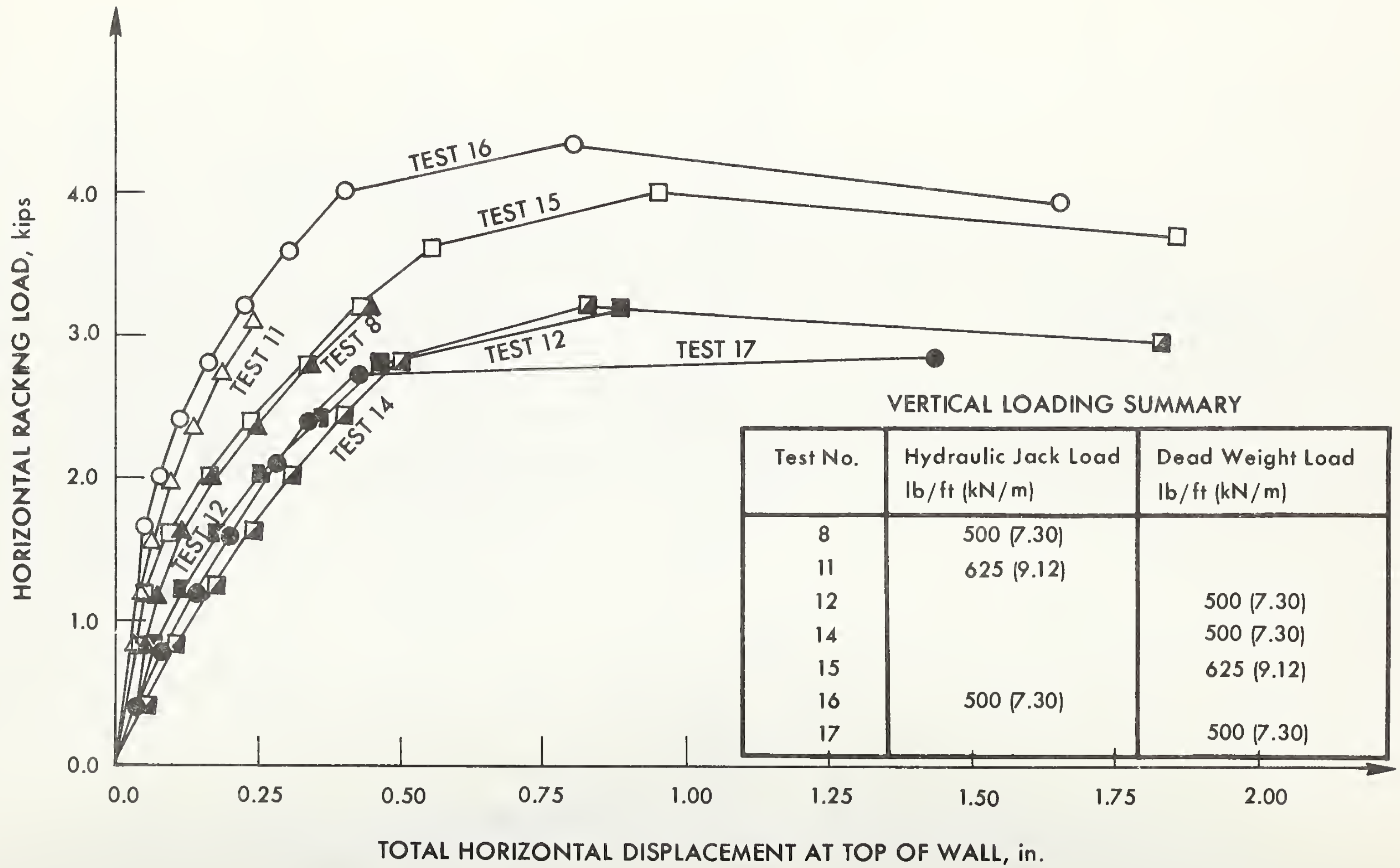


Figure 4.3 - Racking load versus total horizontal displacement for varying vertical load.



VERTICAL LOADING SUMMARY

Test No.	Hydraulic Jack Load lb/ft (kN/m)	Dead Weight Load lb/ft (kN/m)
8	500 (7.30)	
11	625 (9.12)	
12		500 (7.30)
14		500 (7.30)
15		625 (9.12)
16	500 (7.30)	
17		500 (7.30)

Figure 4.4 - Dead weight vertical load results versus hydraulic jack vertical load results.

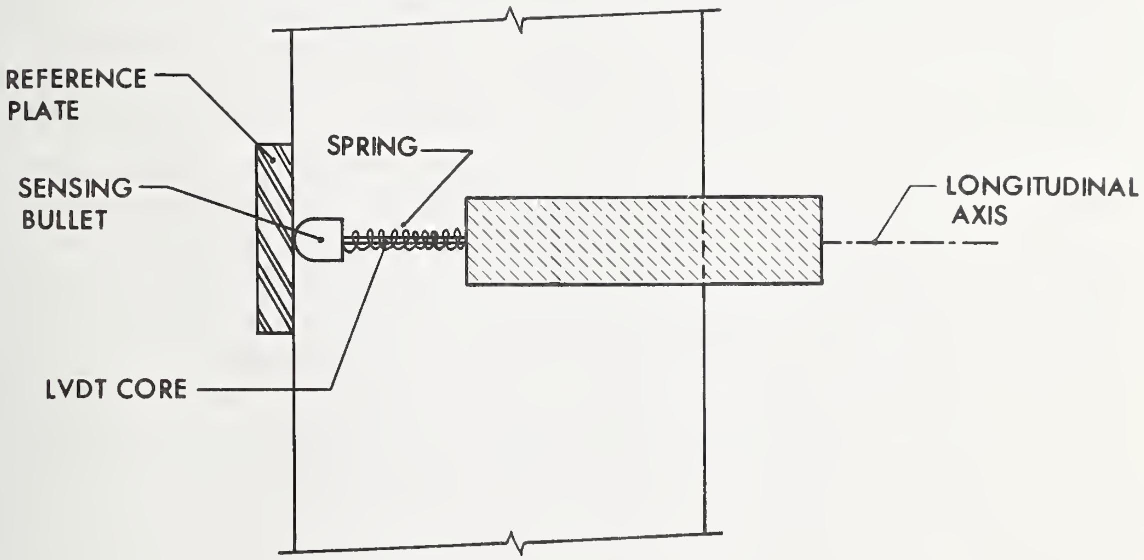


Figure 4.5 - Schematic of a typical LVDT.

5. SUMMARY AND CONCLUSIONS

5.1 Summary - An experimental investigation of the primary factors involved in the laboratory testing of prototype wall panels under simulated wind-induced racking loads was reported herein. Preliminary to establishing the test parameters that warranted investigation, a critical evaluation of the methods described in the literature for testing the in-plane shear resistance of wall and wall segment specimens was conducted. In addition, an ASTM task group that was concerned with the deficiencies in the existing racking test method in ASTM Standard E72-74 was consulted for its assessment of immediate research needs. Several test factors which were of common concern were identified as a result of consulting the task group and surveying the literature. The approach used in developing the proposed racking test method was to hypothesize a test setup and test procedure and then to perform a number of trial runs on typical wall panels to converge to a final test procedure for recommendation.

Seventeen static, racking tests were conducted on two types of wall panels in the laboratory. In all tests except the first one, the wall panels were first subjected to a distributed vertical loading, the magnitude of which was maintained nominally constant once the desired load level was reached. The vertical load, ranging from 375 lbf/ft (5.47 kN/m) to 750 lbf/ft (10.95 kN/m), was applied by using either hydraulic jacks or deadweight assemblies. Then a horizontal racking force was incrementally applied, by the use of a single hydraulic jack, to an upper corner of the 8 ft by 8 ft (2.4 m by 2.4 m) specimens. The resulting horizontal and vertical deflections at key locations were measured by uniaxial, electromechanical gages. The load and deflection data were automatically recorded on an electronic data acquisition system. Hard copy printout was obtained from a teletype console while in-test monitoring of deformation response was achieved by observing a load-deflection curve drawn by an x-y plotter. As the tests were developmental in nature and not intended to evaluate the relative resistance capacity of construction types, only selected results were presented herein.

A proposed standard method of testing for racking resistance was written according to the format recommended for ASTM Standard Methods and it is presented in the Appendix of this report. The proposed method describes recommended apparatus and a systematic procedure for obtaining performance data from representative wall specimens. Although the laboratory tests used only 8 ft by 8 ft (2.4 m by 2.4 m) specimens, the recommended procedure is generally applicable to wall segments and to entire walls of various height-to-width ratios. The principal new features of the test method are: (1) the application of vertical loading to simulate imposed gravity loading in the actual structure; (2) the provision of boundary conditions at the bottom of the wall which do not force unrealistic modes of failure; and (3) the use of a test setup which allows for the testing of panels of a variety of height-to-width ratios.

5.2 Conclusions - Some of the conclusions drawn on the basis of the literature survey and laboratory investigation have been transformed into recommendations which were incorporated into the proposed standard method, (see the Appendix). In light of the fact that the test program did not include a wide range of construction types and the effects of such test factors as loading rate and holding period were not studied comprehensively, the following enumerated opinions are presented as tentative conclusions.

(1) The proposed standard method, in common with the existing ASTM Standard racking test method and practically all the other methods mentioned in the literature, essentially measures load resistance and deformation behavior under monotonic loading. The weakness in this approach stems from the apparent lack of a rational way to correlate the racking test results with the actual performance of the corresponding walls or wall segments in service. Unless the failures during service conditions are certain to result from chance overloads, any statement pertaining to the acceptability of the construction under repeated service loads must be based on an empirical relationship between previous static racking tests and successful service performance.

(2) In order to advance the state-of-the-art with respect to racking resistance testing, future analytical and experimental studies should be directed at defining component interaction of various building constructions and at establishing realistic service loadings. Once progress is made in these fundamental research areas, test method development can conceivably advance to a standard methodology with realistic loading and boundary simulations, the results from which can be correlated with actual service behavior.

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Mrs. D. Borkman and Miss J. Reinhold, Clerk-Typists, performed the typing of the several drafts of this report.

Messrs. L. Payton and M. Glover, Engineering Technicians, erected the test frame, installed test hardware and prepared the test specimens.

Mr. J. Owen, Electronic Technician, executed the instrumenting of the specimens and operated the data acquisition equipment during testing.

Mr. M. Lemay, Engineering Technician, performed most of the fabrication and machine work.

Messrs. R. Williams, Physicist and F. Rankin, Supervisory Engineering Technician, supervised the instrumentation-data acquisition activity and the laboratory fabrication, erection and specimen preparation activity, respectively.

Mr. L. Cattaneo, Structural Research Engineer, designed most of the test fixtures, participated in the execution of the laboratory testing and performed various advisory functions during the preparation of the proposed test method and of this report.

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APPENDIX

PROPOSED STANDARD METHOD OF TEST FOR RESISTANCE OF PROTOTYPE SHEAR WALL PANELS SUBJECTED TO RACKING LOADS

Introduction

In general, building codes and construction regulations do not state specific requirements for racking nor do they specify quantitative limitations for racking deflection. This absence of code requirements is attributable to the relatively small number of buildings which have failed in a racking mode and to the lack of reliable correlation between the loss of building serviceability and associated racking deflection. Nevertheless, there are a significant number of occasions that dictate the execution of laboratory racking tests on wall panel specimens. For example, a building regulatory body may call for performance test results before approving the use of some innovative material or building system. Also, a building component manufacturer may wish to compare the racking resistance of his product with that of traditionally accepted wall constructions. It is the purpose of this test method to provide a systematic procedure for obtaining performance data from representative wall specimens.

A.1 Scope

A.1.1 A procedure for measuring and monitoring the in-plane shear force resistance and deformation response of prototype wall panels is presented. The gradually applied test loads are intended to simulate the horizontal force (generated by wind pressure acting on walls oriented at right angles to the shear wall) transmitted to the shear wall by horizontal space dividers such as floors and roofs and the vertical loads contributed by the construction above the actual shear wall.

A.1.2 The procedure and apparatus are applicable to wall segments and to entire walls of various height-to-width ratios.

A.1.3 It is intended that the test method be applicable to a wide range of wall construction types, including frame construction and stressed-skin construction. However, the apparatus and procedure do not apply to masonry and concrete wall construction.

A.1.4 This racking test procedure can be performed on unaged specimens (i.e., with no history of loading and environmental aging) as well as on specimens that have undergone natural or simulated aging.

A.1.5 In general, the load and deflection results obtained by this method **will not provide** the sole basis for predicting the performance of actual shear walls throughout their service life. However, design weaknesses should be revealed, comparative performance data can be obtained and characteristic deformation patterns and modes of failure can be determined through this static loading procedure.

A.2 Summary of Method

In this method, a wall panel specimen, representative of a wall segment or of an entire continuous wall in a building, is subjected to a combination of in-plane vertical loading and a concentrated horizontal racking load. The vertical test loading is distributed along the top of the wall panel specimen in a manner representative of the gravity live and dead loads contributed by the components (e.g., roof and upper-story floors) located above the wall in the actual structures. The vertical test load may be applied by using hydraulic equipment such as jacks or by using fixtures containing dead weight. The concentrated horizontal load is applied close to the top edge of the wall specimen in a manner representative of the resultant horizontal wind force transmitted by a floor or roof diaphragm to the top of the shear wall in the actual structure. First, the vertical loading is maintained constant while the horizontal load is applied in a single excursion, monotonic, incremental manner until a specified load level or deflection level is reached. The magnitudes of the vertical and horizontal loads are monitored throughout the test and measurements are recorded at selected test intervals. Horizontal and vertical displacements are measured in a logical pattern to ensure that the deformation behavior of the wall specimen is adequately described. The displacement measurements are recorded concurrently with the corresponding measurements of load magnitudes.

A.3 Significance

A.3.1 The degree of correlation between the results obtained from testing an isolated wall panel specimen and the complex interaction of the acutal wall or wall segment with the other building components has not been satisfactorily established. Therefore, the laboratory test results should be construed as supportive data useful to the overall evaluation process.

A.3.2 This test method is suitable for supplying a manufacturer of building components, a designer, or a builder with useful design, research, and development information pertaining to the deformation behavior, potential weaknesses, degree of overdesign, if any, and the relative resistance of a particular wall assembly design. Such information would also be useful to building regulatory officials. In this sense, the method is best construed as serving the purpose of either a rating test or a research and development test.

A.3.3 In light of the fact that the method involves a static loading condition, it is suitable for evaluating simulated wind force effects rather than the dynamic effects associated with earthquake phenomena.

A.3.4 As only a small number of tests will generally be conducted on prototype wall panels, the interpretation of results should duly consider the variablity of the properties of the construction materials and of the workmanship.

A.3.5 When tests are performed on new specimens (i.e., with no loading and aging history) the performance evaluation should consider the potential degradation attributable to time-related effects (such as creep and environmental aging).

A.4 Apparatus

The apparatus should conform to the detailed requirements prescribed in the following paragraphs.

A.4.1 Tests should be performed within a reaction frame whose lateral and vertical stiffnesses are at least one hundred times greater than the respective stiffnesses anticipated for the wall specimens. Figure A.1 shows a recommended test setup with hydraulic jack loading systems for both the horizontal and vertical loading. Alternatively, figure A.2 illustrates the use of a system of dead weight pendulums for applying the vertical loading. To simulate the transmission of the horizontal force from a connecting diaphragm, a steel channel is attached to the top edge of the test panel. For framed wall panels and stressed-skin panels, a nominal 6-in deep channel is recommended. To support the bottom edge of the specimen, a steel, wide-flange section is recommended.

A.4.2 The vertical hydraulic jacks may be actuated by either a power assisted or manually operated pump. The horizontal hydraulic jack shall be actuated by a pump capable of applying pressure at controlled rates.

A.4.3 The vertical hydraulic jacks or the deadweight assemblies shall be spaced along the entire width of the specimen to produce the effect of a uniformly distributed vertical loading.

A.4.4 A force link should be attached to each hydraulic jack to measure the magnitude of applied load. The force links should be positively attached to their respective jacks to accommodate the translation of the wall relative to the stationary jacks.

A.4.5 A minimum of four deflection gages should be mounted on a specimen to measure discrete displacements. These deflection gages should be electromechanical to afford continuous and autographic monitoring by an x-y plotting machine. The minimum gages shall be mounted in the locations shown in the schematic diagram denoted as figure A.3.

A.4.6 It is recommended that the wall panels be tested in the vertical position. However, if the test facility is such that racking tests must be conducted with the specimen in a horizontal position, provision should be made for applying the simulated in-plane, gravity loading, and for preventing out-of-plane deflections of the specimen.

A.4.7 Low friction lateral support shall be provided along the top edge of the specimen, and at intermediate heights on the specimen to prevent out-of-plane deflection. For this purpose it is recommended that one of the following be used: steel rollers, ball bearings immersed in a grease matrix or a teflon-polished metal interface.

A.4.8 In many instances test specimens are likely to undergo rigid body rotation and/or to respond with a relatively large horizontal translation. The load-bearing assembly used to transmit vertical and horizontal jack loading to the specimens must accommodate these deformations. For example, the vertical and horizontal load-bearing assemblies should have acceptable rotational capability and be capable of accommodating translations of at least 3 in (76 mm). In addition, the assemblies should provide low frictional resistance to sliding and effect uniformly-distributed bearing. The bearing assembly detailed in figure A.4 is recommended for fulfilling these requirements. However, alternative bearing assemblies that satisfy the performance requirements are permitted.

A.5 Safety Precautions

A.5.1 All components of the hydraulic loading systems, such as jacks and load cells, should be interfastened, suspended from, or otherwise connected to the reaction frame so that they are adequately supported in the absence of the wall specimen in its test position. The load-distribution member and the reaction beam may be connected to the specimen.

A.5.2 Caution should be exercised to prevent injuries to personnel and damage to test equipment as a result of unexpected catastrophic release of strain energy accumulated during testing.

A.6 Test Specimens

A.6.1 Wall panel specimens should be representative of the materials, details and workmanship to be used in the wall construction intended for service. The height of the specimens should equal the height of the wall in actual use. The width of wall segments representing field-built walls should be a whole number multiple of the center-to-center spacing of the vertical loadbearing frame members or of other similar repeated design details. The width of prefabricated wall segment specimens (such as stressed-skin panels) shall be at least two times the width of the basic modular panels. In no case shall the wall panel specimens be less than one story-height in height and 8 ft (2.4 m) in width.

A.6.2 Racking tests should be conducted on a sample of at least five identically prepared wall specimens.

Note 1: The number of specimens selected is dependent on the variability of the material properties and of the workmanship.

A.6.3 During preparation of the specimens, careful consideration should be given to the type and location of anchorage that is specified for the wall assembly. In some cases, it may be necessary to insert or attach part of the anchorage hardware to the wall panel specimens during specimen preparation. Otherwise, proper simulation of the anchorage may not be possible because of inaccessibility to the inside of the wall.

A.7 Conditioning

A.7.1 All specimens should undergo an identical systematic atmospheric conditioning procedure prior to testing to ensure a uniformity of temperature and relative humidity exposure and that a common equilibrium moisture content is attained. Both un-aged specimens and specimens subjected to some form of aging (i.e., field aging or accelerated aging) should reach the same set of temperature and moisture content conditions prior to test.

A.8 Procedure

The procedure is summarized as follows:

The in-plane vertical loading should be applied first, using one of the test setups recommended in section A.4, or an equivalent setup. Once the specified magnitude of simulated gravity loading has been reached, the horizontal loading should be applied to the specimen in increments. The size of the loading increments should be chosen so that no greater than 1/10 of the estimated horizontal test load is applied during each increment.

A.8.1 The first set of data is obtained by recording the readings of the load and deflection gages prior to the application of any test loading. These zero load readings will serve as reference points for all subsequent measurements.

A.8.2 The vertical test load should be applied gradually (i.e., so as not to constitute an impact load) until the specified load magnitude is attained. While maintaining this vertical loading, a second set of load and deflection readings should be recorded. The vertical load should be maintained constant during the subsequent application of horizontal loading.

A.8.3 The horizontal load should then be applied continuously, during successive increments in a manner that effects, as nearly as possible, a uniform rate of deformation (See Note 2.) In the absence of loading rate guidelines substantiated by satisfactory test experience, it is recommended that the rate of loading during each increment not exceed 500 lbf/min (37 N/sec).

Note 2: Effecting a uniform rate of deformation within the test increments may not be synonymous with applying load at a uniform rate. For those types of construction that exhibit a nonlinear load-deformation relationship, it will be necessary to vary the loading rate in order to approach the requirement of uniform deformation rate.

A.8.4 The horizontal load should be applied in increments selected in accordance with paragraph A.8. The sequence of horizontal loading is as follows: The load is increased from zero to the first increment and a set of load and deflection recordings is made. Unless otherwise specified the load should then be decreased to the zero load level and measurements recorded again. The load should be continuously increased to two increments and a set of measurements recorded. Then the load is decreased to the zero load level and measurements recorded. This sequence of loading should be repeated for three increments, four increments, etc., until either a specified limit state (e.g., failure) or a predetermined magnitude of test load is reached. This maximum horizontal loading should then be released, allowing the load to decrease to the zero load level. There, a set of measurements should be recorded. Finally, the vertical load should be decreased to its zero load level and a set of load and deflection measurements recorded. The vertical and horizontal load and the deflection measurements should be recorded in accordance with paragraph A.8.5.

A.8.5 Load and measurements should be recorded upon reaching the end of the specified increment of loading. Having maintained the load at the specified magnitude for a 5 minute period, load and deformation measurements should again be recorded. When the loading is decreased, the load and deformation measurements should be recorded instantaneously upon reaching the zero load level. After a recovery period of 5 minutes, the set of readings should again be recorded. The schematic load-time plot in figure A.5 illustrated the loading and unloading cycle with the recording points denoted by dots.

A.9 Calculations of Results

A.9.1 The value of the distributed vertical load is to be calculated (and expressed) as the sum of the loads measured at individual loading points divided by the width of the test specimen.

A.9.2 The distributed horizontal load value at any load increment is to be calculated by dividing the measured concentrated load value by the width of the test specimen.

A.9.3 The net horizontal deflection undergone by the top of the wall specimen, relative to its bottom, is to be calculated in two steps:

(1) The horizontal translation resulting from the rigid-body rotation of the specimen is subtracted from the total horizontal deflection measurement obtained from deflection gage [1] (see figure A.3). Symbolically, this difference can be expressed as

$$\Delta H1 = \Delta_1 - \frac{H}{W}(\Delta_3 - \Delta_4)$$

where, Δ_1, Δ_3, Δ_4 are the deflections (with the sign convention shown in figure A.3) measured by gages 1, 3 and 4 respectively. H is the height of the wall panel and W is the width of the wall panel in the direction of the horizontal load.

(2) The difference obtained in Step (1) is reduced by the total horizontal translation measured at the bottom of the specimen.

$$\Delta H = \Delta H1 - \Delta_2$$

A.9.4 Additional calculation of test results should be performed by the following procedure:

a. Obtain results in accordance with paragraphs A.9.2 and A.9.3 for a given test parameter X_i (such as, maximum load, maximum horizontal deflection, deflection at a specific load level or residual deflection) from at least 5 specimens: X_1, X_2, X_3, X_4, X_5, . . X_n.

b. Calculate the sample average for the test parameter by:

$$\overline{X} = \frac{1}{n} \sum_{i=1}^{n} X_i$$

c. Calculate the sample estimate of the standard deviation:

$$s = \sqrt{\sum_{i=1}^{n} \frac{(\overline{X} - X_i)^2}{n-1}}$$

d. Establish one-sided tolerance limits to satisfy the degree of confidence that is desired in making a performance prediction. General formulation of the tolerance limit statement: The probability is γ (e.g., 0.95) that at least a proportion P (e.g., 0.90) of a population of wall assemblies will exhibit a performance parameter (e.g., percent of deflection recovery) greater than $\overline{X}$ - ks. In this formulation, $\overline{X}$ is the sample mean and s is the sample estimate of the standard deviation based on a sample size of n, ($n \geq 5$). The appropriate value of the multiplier k is obtained from a table of factors for one-sided tolerance limits for normal distribution, (e.g. see "Handbook of Experimental Statistics," Handbook 91, Nat'l. Bureau of Standards, Aug. 1963).

A.10 Report

A.10.1 The report should include the following:

A.10.1.1 Dates of the tests and of the report.

A.10.1.2 Statement that the tests were conducted in accordance with these methods. Deviations from these methods shall be described.

A.10.1.3 Identification of the sample specimens, including manufacturer, source, physical description, detailed engineering drawings, photographs and other pertinent information.

A.10.1.4 Detailed information of test set-up including engineering drawings and photographs to make possible the duplication of the test set-up by others.

A.10.1.5 Description (in addition to photographs) and interpretation of mode of failure, provided the test was performed to the point of failure of the specimens.

A.10.1.6 Horizontal load-displacement graphs or other (if applicable) graphic test progress records such as stress-strain curves. The displacement co-ordinate should be presented in terms of total horizontal displacement, net horizontal displacement and residual horizontal displacement.

A.10.1.7 Tables of test results (for various parameters such as maximum load, maximum deflection at allowable load, etc.) including sample average, sample estimate of standard deviation and tolerance limits calculated for stated confidence level (cf. A.9.4.d).

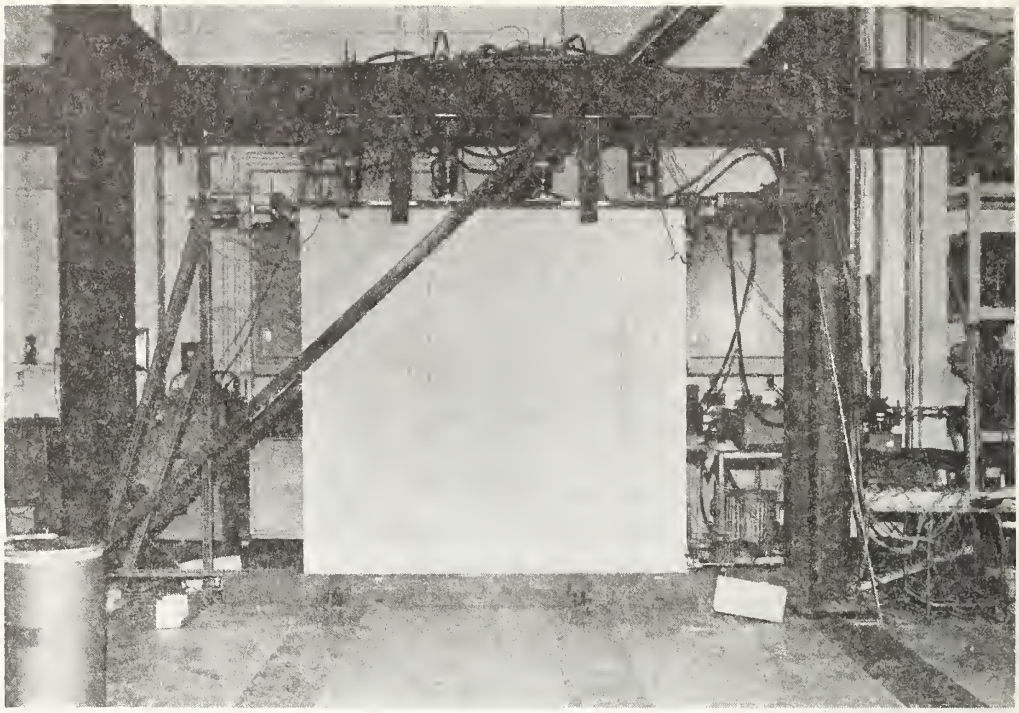


Figure A.1 - Recommended test setup with dual hydraulic loading systems.

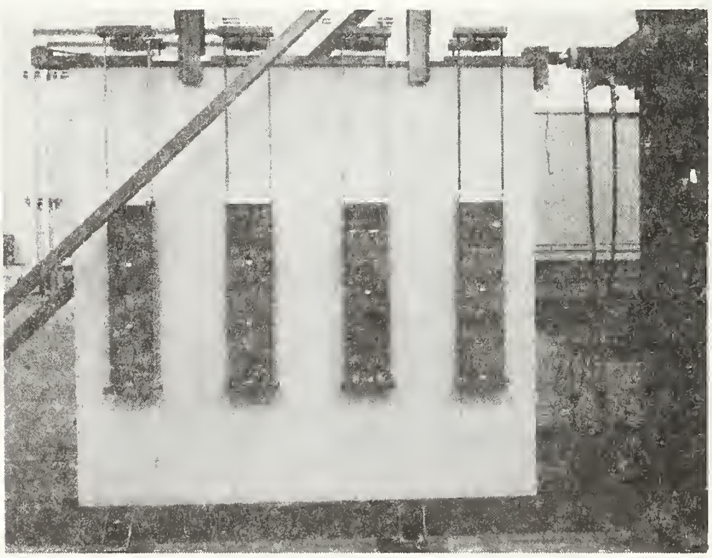
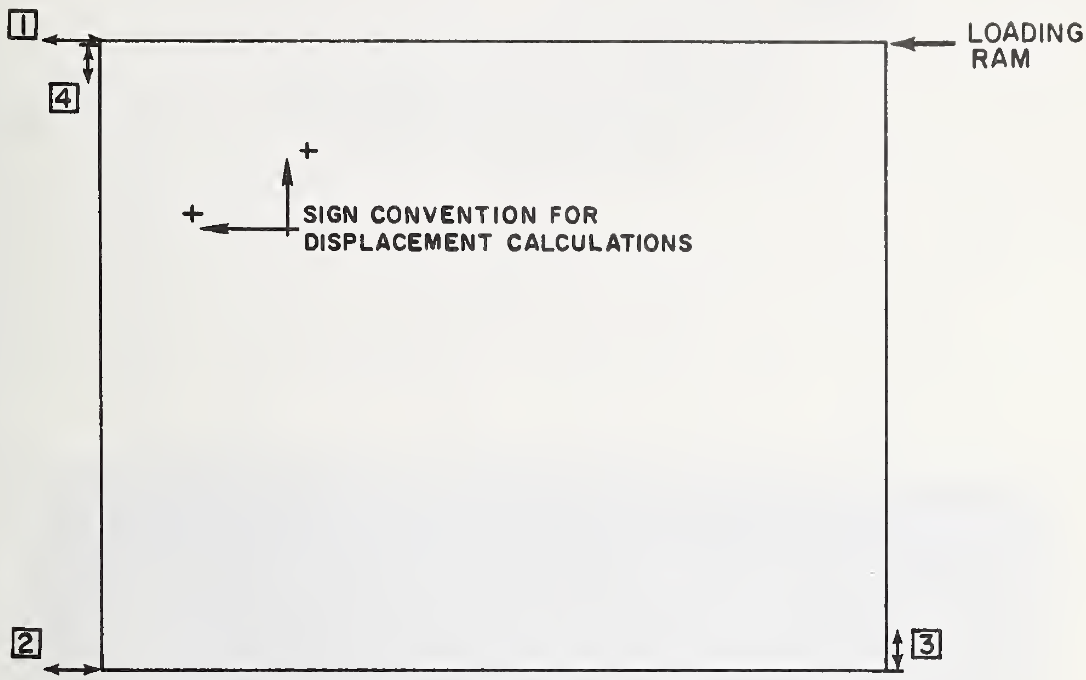


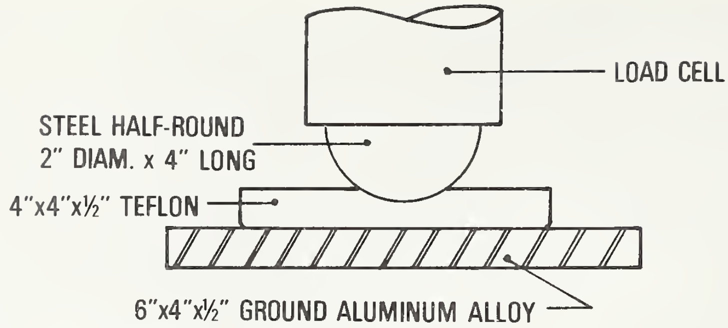
Figure A.2 - Alternate test setup with dead weight vertical loading assembly.



FOOTNOTES:

1. DISPLACEMENT GAGE LOCATION :
2. THESE MINIMUM DISPLACEMENT GAGES ARE INTENDED TO MEASURE DISCRETE DEFLECTIONS OF THE SPECIMENS RELATIVE TO A STATIONARY REFERENCE.
3. THE MEASUREMENTS OBTAINED FROM GAGE 2 WILL HAVE TO BE MODIFIED IN THE EVENT OF SIGNIFICANT SLIDING OF THE REACTION BEAM.

Figure A.3 Schematic of minimun deflection gage requirements.



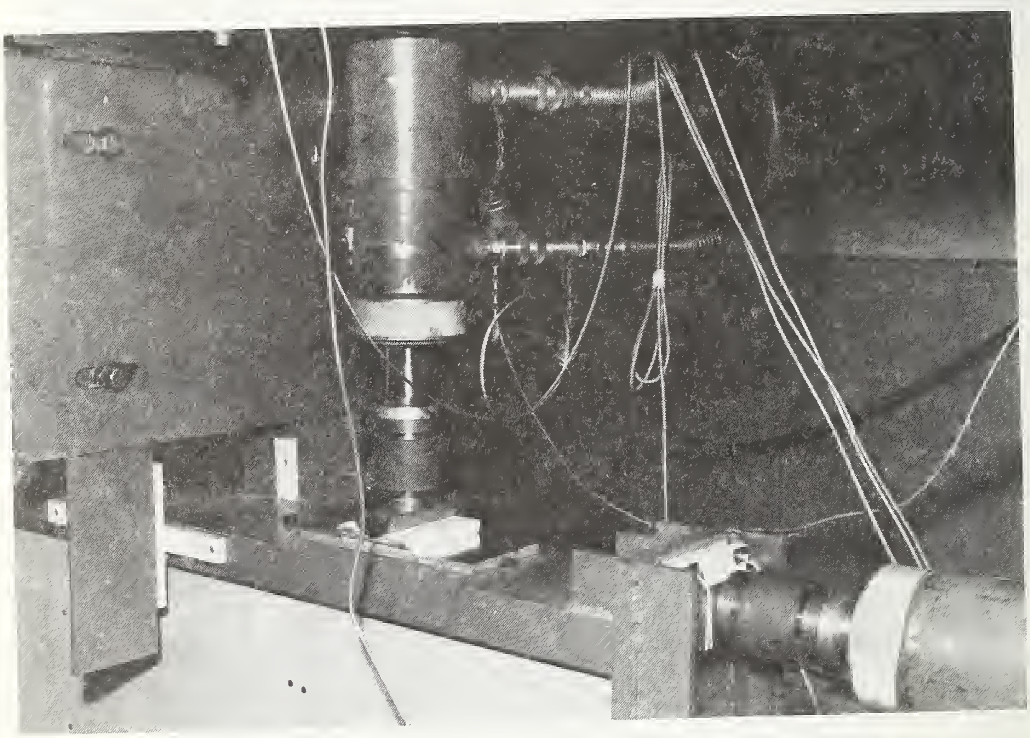


Figure A.4 - Details of recommended bearing assembly.

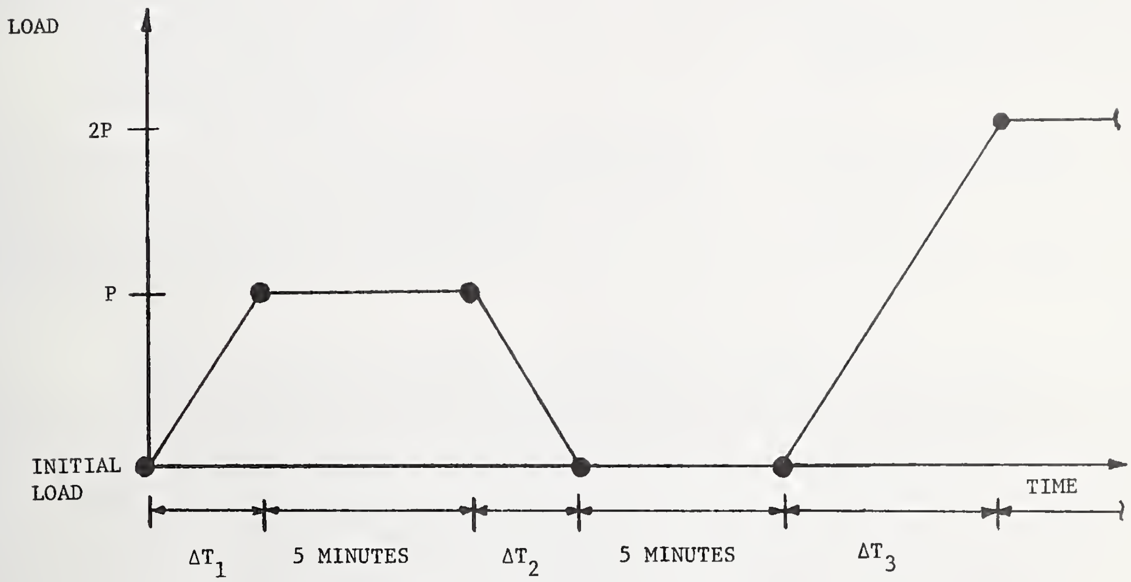


Figure A.5 - Load-time schematic diagram.

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15. SUPPLEMENTARY NOTES

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)* An experimental investigation of the primary factors involved in the laboratory testing of prototype wall panels, under simulated wind-induced racking loads, is reported. The objective of the investigation was to recommend a static racking test method, generally applicable to a variety of wall construction types, that features realistic boundary and loading conditions. Initially, a literature survey was conducted for the purpose of evaluating the test methods which have been, or are being employed in determining the resistance of wall panels to static racking loads. In the experimental program, 17 exploratory tests were conducted on a sample comprised of two types of wall panel construction. The 8 ft by 8 ft steel-frame and wood-frame panels were subjected to a combination of vertical and horizontal loading and their resulting deformation behavior was systematically monitored. Modifications to the testing procedure and to the boundary condition at the top of the panels were introduced as the experiments progressed. Detailed descriptions of the laboratory procedures used are presented. As the tests were developmental in nature and not intended for performance evaluation of the types of construction, selected results are presented. A static racking test method, applicable to traditional and innovative wall construction was derived as a result of the laboratory study and the literature survey. The principal new features of the proposed standard method are: (a) the application of distributed vertical loading, (b) the capability of testing panels of various height-to- width ratios and (c) the provision of top and bottom boundary conditions which do not force unrealistic modes of failure.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Lateral loads; loading rate; racking; test method; wall panels; walls; vertical loads.

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