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NBSIR 73-121

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C. W. Yancey and N. F. Somes

Center for Building Technology
Institute for Applied Technology
National Bureau of Standards
Washington, D. C. 20234

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Final Report

Prepared for
Office of Research and Technology
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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary

NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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Notation

The following notation is applicable for the entirety of this report:

Service Loads (psf)

D = dead load

E = earthquake load

L = live load

W = wind load

Deflections (inches)

dh = horizontal drift

dv = vertical net deflection

dvr = residual vertical net deflection

Dvr = residual vertical gross deflection

Lengths (inches)

h = height above either finished grade (ground outside the building) or the interface between the building system and separately-built basement, whichever is higher.

l = length of member

SI Conversion Units

In view of present accepted practice in this country in this technological area, common US units of measurement have been used throughout this paper. In recognition of the position of the United States as a signatory to the General Conference on Weights and Measurements which have official status to the metric SI system of units in 1960, we assist readers interested in making use of the coherent system of SI units by giving conversion factors applicable to US units used in this paper.

Length

1 in = 0.0254* meter

1 ft - 0.3048* meter

Area

1 in^2 = 6.4516* x 10^{-4} $meter^2$

1 ft^2 = 9.2903 x 10^{-2} $meter^2$

Force

1 lb (lbf) = 4.448 newton

1 kip = 4448 newton

Pressure, Stress

1 psi = 6895 newton/$meter^2$

1 psf = 47.88 newton/$meter^2$

Moment

1 kip-in = 113.0 newton-meter

Temperature C° = 5/9 (Temperature °F - 32)

*Exact value

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1. Introduction

This paper reports the results of tests to determine the structural strength and stiffness characteristics of a wood framed volumetric housing module. The series of structural tests was performed subsequent to a series of tests relating to transportation by rail. The entire test program was conducted in conjunction with the HUD-sponsored industrial housing program, Operation BREAKTHROUGH. An integral part of the transportation study was the shipment of the module, over 850 miles of rail track, from its point of manufacture to the National Bureau of Standards (NBS) Structures Laboratory at Gaithersburg, Maryland. This report refers to the transportation only inasmuch as it concerns the module, and, in particular, its condition at the start of the structural tests. The total sequence of the tests closely simulated the experience of an actual module as it undergoes manufacture, transportation, erection, and in-service loading.

The concept of fabricating volumetric modules in a factory and assembling them on the housing site to form complete dwelling units is one that is growing in popularity within the building industry. Such modules can have a width and length ranging up to 12 ft and 60 ft, respectively, while their height is approximately 10 ft. The feasibility of this concept hinges on the economics of transporting the units from a central point of manufacture to distant construction sites.

Of the many factors to be considered in regard to transportation, its effect on the subsequent performance of the module, as a component of the living unit, is of primary concern. Cost considerations require damage incurred during regular rail shipment to be held to a minimum. For the system in question, transportation was particularly critical since the initial production of modules would have to withstand rail shipment for a distance exceeding 2000 miles. An experimental shipment was therefore conceived, using a full-scale prototype module of a configuration considered to be most critical for transportation.

2. Test Structure

2.1 Housing System

The housing system represented in this study is characterized by wood framed modules joined into clusters at the building site to form units. The isometric view presented in figure 2.1, illustrates three such townhouses, arranged in a staggered pattern. The exterior envelope and the interior partitions are common throughout the system and are described in paragraph 2.3.

As structural integrals, modular units such as the test specimen are connected in various arrangements to resist gravity live loads, environmental forces (i.e., earthquake, snow and wind forces) and occupant loads (i.e. impact). The arrangement utilized in this system is a four-module combination which results in a two-story house.

2.2 The Selected Module

The interface between adjacent modular units provides a natural boundary in the selection of a test specimen. The full-scale module selected for the transportation study and the subsequent structural testing is designated as a second-story front unit. The bold outline in figure 2.1 denotes the boundary of the test module in relation to the remaining three segments. Although its selection was predicated upon choosing a module critical for transportation, the construction of the module was thought to be representative of the system in general.

As erected in the laboratory, the module was 59 ft-4 1/2 in long x 11 ft-9 1/2 in wide x 15 ft-7 1/2 in high.

As shown in the floor plan, figure 2.2, the module consisted of two distinctly different portions. One portion enclosed three bedrooms and was 40 ft-1 1/2 in long. The other, a 19 ft-3 in-long living room space was a triangular prism without any floor framing. Its function in the actual housing system is to provide a "cathedral ceiling" above the first floor living room.

2.3 Fabrication Details

It should be noted that the module, being a prototype, was hand-built by the manufacturer according to his then-current plans and specifications. As the housing system was undergoing a multi-stage structural evaluation of the plans, specifications and calculations, these documents were necessarily mutable. Therefore, it should not be construed that the following details of the module were indicative of the final construction details of the housing system.

The roofing consisted of wind-resistant shingles, of Underwriters Laboratories, Inc. Class C, one layer of asphalt-saturated felt underlayment (ASTM Specification D226, 15 lb type) and a roof sheathing of plywood DFPA grade-trademarked "Standard with exterior glue" 1/2-in thick. The 4 ft x 8 ft plywood sheets were oriented so that the face grain ran parallel to the span of the roof rafters. The shingles were stapled to the plywood with 16 ga staples, with 3/4-inch legs. The rafters supporting the roofing surface were 2 x 6[1/] members of Douglas Fir, Construction Grade, spaced, 24 inches on centers (o.c.). The entire roof system of the test module was hinged along the top plate of the front wall to reduce the height of the shipping envelope; in its shipping position,

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[1/] As subsequently used throughout this report, size descriptions such as 2 x 6 refer to nominal timber dimensions in inches, in accordance with U. S. Product Standard PS 20-70, American Softwood Lumber Standard, Department of Commerce, Washington, D. C.

the plane of the roof was horizontal. In the laboratory, the roof was rotated about the hinge until its plane made an angle of 36° with the horizontal. The rafters were then braced near the peak of the roof by 2 x 4 strut members which were attached to the top plate of the rear wall by hinge connections. The struts were positioned at an angle of 54° with the horizontal and hence intersected the rafters at right angles.

The ceiling surface consisted of one layer of 1/2-inch gypsum wallboard (ASTM Specification C36-68). [1][2/] The supporting ceiling joists were 2 x 4's of Douglas Fir, Construction Grade spaced 16" o.c. The wallboard was attached to the joists with a bead of an elastomeric adhesive and 6d nails, spaced at 16 in o.c. along the perimeter and 24 in o.c. at intermediate members. The rim joists were double 2 x 6's while the header beams were single 2 x 6 members.

All vertical framing members were 2 x 4 Douglas Fir studs, spaced at 16 in o.c. The party wall between the middle and south bedrooms (see figure 2.2) was of double stud construction, with each line of framing separated by a 1/2-inch air space. Single 2 x 4 members formed the top and sole plates for all vertical framing.

The exterior surfaces of the walls were respectively finished to be consistent with the position of the module in the actual townhouse layout. The front wall was covered with a single layer of 7/16-inch hardboard siding backed by a layer of 1/2-inch fire-retardant gypsum sheathing (ASTM C79-69). [2] The hardboard sheets were applied vertically with 4d S499D nails, spaced at 16 in o.c. along the perimeter and at intermediate studs. One x two battens were used at each vertical joint as well as at intermediate studs.

2/ Numbers in brackets indicate references at the end of the report.

The rear wall, functioning as an interface between two adjacent modules in the actual structure, was sheathed with 3/8-inch plywood grade-marked "Standard". The plywood sheets were attached to the studs with 6d tee nails, spaced at 6 inches o.c. along the perimeter and at 12 inches o.c. along intermediate members. Contiguous end walls of modules, such as the north wall of the prototype module (see figure 2.2), were covered with a double layer of 1/2-inch, Type "X" gypsum wallboard (ASTM C36). The siding on the south wall of the module was identical to that attached to the front wall. The wall section in figure 2.3 shows the details of a typical exterior bearing wall in the two-story building. The materials and construction details specified for the roof, ceiling and front wall of the module are illustrated in this figure.

All partition wall surfaces, except at the party wall between the middle and south bedrooms, consisted of a single layer of 1/2-inch gypsum wallboard (ASTM C36). The party wall serves as a fire barrier and, therefore, a double layer of 1/2-inch, Type "X" gypsum wallboard was used to cover each side of the wall. The interior surface of all exterior walls consisted of a single layer of 1/2-inch, Type "X" gypsum wallboard (ASTM C36). All interior and exterior gypsum wallboard was attached with 4d S499D nails along with an application of an elastomeric adhesive. A nail spacing of 16 inches o.c. was used throughout.

The principal components of the floor were plywood sub-flooring-underlayment and 2 x 8 wood joists. The plywood was 5/8 in grade-trademarked "Underlayment with exterior glue," Group I. The plywood sheets were oriented with the face grain parallel to the span of the joists and they were secured by nailing. Eight-penny common nails were spaced at 6 in o.c. along the perimeter and at 10 in o.c. over intermediate supports. The joists were designated as Construction Grade Douglas Fir and their clear span measured 11 ft-3 1/2 in. Conventional 16-inch joist spacing was used. Both the rim joists and header beams were double members, consisting of a 2 x 10 nailed to a 2 x 12, the 2 x 10 being outermost.

Wall-to-wall nylon carpet, with foam padding, was installed in the factory in all three bedrooms. Pre-assembled push-out bay window assemblies were installed in the laboratory in the north and middle bedrooms according to the plans (see figures 2.1 and 2.2). Bi-fold metal doors in closet openings were installed at the factory.

2.4 Condition of the Module Before Testing

The module was visually inspected for damage or other evidence of structural distress, upon its arrival at the laboratory. All cracks in wallboard and other forms of local damage were systematically documented. Prior to lifting and transporting from the factory, reference points had been established on the interior and exterior wall surfaces and linear measurements were made between the reference points. These measurements were repeated in the laboratory, so as to determine any dimensional changes in the module caused by the handling and shipping operations.

It was observed that the interior surfaces incurred two types of damage as a result of lifting and transportation: The first type was hairline cracking on the surface of the gypsum wallboard. These fine cracks were located mostly near doorways, closet openings and window frames. There was no apparent damage to the structural framing associated with this cracking. In the second type, the wallboard tape, applied to the joint between two adjacent panels of wallboard, was torn at several locations, reflecting relative motion between the panels. Most of the tearing occurred along the horizontal joint formed by intersecting ceiling and wall panels. The most significant tear was noted at the junction between the ceiling and the south wall of the south bedroom. At this location, the tape was split, revealing a 1/4-in wide separation, between the wall and the ceiling, that extended along the joint for 12 inches.

All of the damage was readily repairable by conventional surface treatment, prior to structural testing. The damaged tape joints were repaired by re-taping and applying a joint compound. The surface cracks in the gypsum were repaired by application of joint compound. It should be noted that no nail popping was observed on any of the surfaces. Furthermore, the exterior showed no significant damage.

The differences between the two sets of dimensional measurements, previously noted, were determined and the results have been tabulated in Appendix A. As indicated on table A.3, the magnitude of dimensional change ranges from -5/16 in to +7/8 in. It is important to note that there was no visible sign of distress associated with these extreme values. Assuming a normal distribution of the dimensional change, it is found that approximately 68 per cent of the changes fell between +1/8 in and -1/8 in.

2.5 Support Assembly

In its test position, the module was seated upon a wood base, which was anchored to the laboratory test floor. To simulate the joint between the first and second story modules in the actual structure, the perimeter beam for the support assembly was chosen to match that specified for the first-floor ceiling in the townhouse.

As shown in figure 2.4, the base consisted of 2 x 8 cross beams, spaced at 4 ft-0 in o.c. and nailed to the perimeter beam. Detail "A" shows the perimeter beam as a 2 x 8 face-jointed to the inside of a 2 x 10. The beam was notched at 10-ft intervals to accommodate the horizontal leg of a 5 in x 4 in x 1/2 in steel angle. The vertical leg of the angle was welded to two 5-inch channels, that were arranged back-to-back and spaced far enough apart to accommodate a 1 1/2-inch tie-down bolt. The bolt effected the necessary anchorage to the laboratory test floor. A typical tie-down assembly is described in detail "A" of figure 2.4. The orientation of the module in relation to the support assembly can be determined by referring to the notation "Front" and "Rear" on figures 2.2 and 2.4.

Due to length limitations on the laboratory tie-down floor, approximately one-fifth of the module extended outside the laboratory. Most of the living room space was enclosed by a temporary shelter and was secured to a temporary concrete slab with five angle tie-downs. A typical angle tie-down is described in detail "B" of figure 2.4. Four 16d common nails were used to attach the angle to the face of the perimeter beam while a 3/4-inch diameter masonry anchor bolt secured the horizontal leg to the concrete slab.

3. Objectives and Scope

The general objective of the series of six tests was to quantify some of the structural characteristics of the wood framed module which were not conducive to analysis and to supplement these data with visual observations. Specific objectives for the respective tests are cited in the paragraphs that follow.

In the following chronological sequence of tests, the racking tests were designed so that each test would be more critical to the structural integrity of the module than the one that preceded it.

3.1 Service Life Racking - Test 1

3.1.1 Objective

To determine the stiffness of the module with respect to lateral load and to estimate the drift, at the second-floor level in the actual building when it is subjected to wind forces.

3.1.2 Scope

The module was subjected to static concentrated loads simulating wind forces normal to the front face of the building and the resulting horizontal and vertical deflections of selected points were measured. No attempt was made to consider variations of loading distribution or the module's response as a function of time.

3.2 Transient Floor Vibrations - Test 2

3.2.1 Objective

To determine the damping behavior of the floor when subjected to vibrations of relatively short duration, such as those induced by human activities.

3.2.2 Scope

This test recorded the decay of the amplitude of floor displacement, with time, following a single impulse excitation.

The same procedure was performed for each of four combinations of the point of delivery of impulse and the point of measurement of displacement. This was done in order to observe the difference in readings resulting from varying the combination. The floor in the largest room, the north bedroom, was selected for testing and its location is shown in figure 3.1.

3.3 Sustained Floor Load - Test 3

3.3.1 Objective

To determine the deflection of the floor, at critical locations, both under a uniformly distributed load and subsequent to its removal.

3.3.2 Scope

This was a two-day test performed on the south bedroom floor, the location of which is shown in figure 3.2. Since the floor construction was identical in all three rooms, it was considered necessary to test only one floor.

Following this test, the triangular-shaped living room space was completely severed from the bedroom portion and all further testing was conducted on the remaining 40-ft - 1 1/2 in long module. It was concluded that this alteration would result in a closer representation of lower-story construction in the actual building.

3.4 Repeated Racking - Test 4

3.4.1 Objective

To document any detectable decrease in serviceability and to determine if a reduction in lateral stiffness resulted upon the module being subjected to repeated applications of lateral loading.

3.4.2 Scope

One thousands cycles of simulated wind force were applied at right angles to the front face of the module. Horizontal and vertical deflections of selected points were measured. Qualitative assessment of the structure's response was accomplished by visually examining those areas identified as potential points of distress.

3.5 Reversals of Racking - Test 5

3.5.1 Objective

To describe qualitatively the extent of distress and damage to all visible connections and exposed components as the module was subjected to loading that, in magnitude, corresponded to earthquake design provisions in the Uniform Building Code [3].

3.5.2 Scope

Five cycles of reversed lateral load were applied at right angles to the front face of the module. The structure was visually examined for evidence of distress or failure at the conclusion of testing.

3.6 Racking to Capacity - Test 6

3.6.1 Objective

To quantify the maximum lateral load which the module could withstand.

3.6.2 Scope

Static lateral force was applied in increasing magnitude, at right angles to the front face of the module until failure occurred. Deflection data were periodically recorded and the module was visually examined for signs of distress and damage.

4. Test Setup and Instrumentation

4.1 Service Life Racking - Test 1

The five 10-ton hydraulic rams schematically located in figure 4.1, were actuated through a dual manifold system. Rams 1, 2 and 5 were branched from one manifold, while rams 3 and 4 were connected to a second line. In order to measure the magnitude of force in the hydraulic systems, a load cell was attached to one ram in each system. Hydraulic pressure, corresponding to a particular jacking force, was monitored visually from two single-channel strain indicator boxes. A pressure transducer located in each manifold provided the electrical input to the indicator boxes. The centerline of each ram was measured to be 9 ft-9 in above the laboratory test floor.

The rams were attached to reaction frames constructed of rolled steel sections. The principal parts of a typical frame consisted of a wide-flange column, 10 ft high, and a diagonal member consisting of two angles placed back-to-back. The column was braced at mid-height by the diagonal member and both elements were bolted to the laboratory floor. The design capacity of each frame was 10 kip applied horizonally at the top of column. Several reaction frames are shown in figure 4.10.

A total of 40 linear variable differential transducers (LVDTs) was used to measure displacement of the module. The relative location of 28 of the transducers is shown in figures 4.2 and 4.3. The isometric view in figure 4.2 locates the 14 horizontal and 5 vertical transducers along the rear of the module. An input signal was supplied to two X-Y recorders by LVDTs no. 5 and 17. Thus, the combined signals of the load cells and LVDTs enabled a load-deflection curve to be plotted for all cycles of loading.

Nine LVDTs were attached to the front of the module (see figure 4.3). Several dial gages with a range of ± 1 inch and graduated to 0.001 inch were employed along the front to provide a check against the LVDT recordings.

One face of two shear wall panels was instrumented with 6 LVDTs. Schematic drawings of the rectangles formed by the transducers are shown in figure 4.4 against the background of the two wall panels, Plane 1 and Plane 3. Transducers 23 through 34 measured wall racking deformation. Figure 4.5 shows the detail of a typical support of LVDTs positioned along the rear of the module.

Calibration of load cells, pressure transducers and deflection transducers was performed prior to all racking tests. All data for this test, as well as most of the data for the remaining racking tests, was acquired through the use of a computer-controlled automatic scanner and a digital voltmeter. The capability of the system was 200 channels. The voltmeter readings were recorded for the designated load levels, on magnetic tape and also on a teletype console printout. The entire array of data acquisition equipment is illustrated in figure 4.6. The output data, as recorded on tape, was later converted to engineering units and the results were printed in tabular and graphical form by an electronic computer.

4.2 Transient Floor Vibration - Test 2

The test arrangement, as shown in figure 4.7, consisted of a weighted leather bag, a bag-release mechanism, a tripod for support and a linear variable differential transducer (LVDT) for deflection measurement.

Lead shot was placed in the bag to increase its weight to 25 lb. It was established that the potential energy of the bag (weight of bag times height of drop) of 75 ft-lb was sufficient to induce a measurable excitation of wood-joist floors. Consequently, the bag was suspended 3 ft above the finished floor.

The LVDT had a gage length of $\pm$ 1.0 in and was calibrated to measure increments of $\pm$ 0.0001 in. A beam of adjustable length, to which the LVDT was attached, is shown in the background of figure 4.7. The beam spanned approximately 15 ft-6 in between the north and south walls of the North Bedroom. To insure that the response of the LVDT was in phase with that of the floor at the point of observation, the plunger was secured to the surface of the plywood underlayment-subfloor. An oscillograph, equipped with a galvanometer of 600 Hz response, was used to record the LVDT output. A trace of the floor response was printed on oscillograph recording paper.

4.3 Sustained Floor Load - Test 3

A total of five instruments were used to measure deflection. Two were LVDTs and the remaining three were dial gages. Four of these instruments are visible in figure 4.8.

The LVDTs were of $\pm$ 1 inch gage length and were calibrated to read increments of $\pm$ 0.0001 in. The dial gages had a range of $\pm$ 1 inch and were graduated 0.001 inch. A strip-chart recorder continuously recorded the output of the LVDTs, while the dial gages were read periodically with the aid of a telescope mounted on a tripod. The support beam, partially shown in figure 4.8, served as the base for the deflection readings.

4.4 Repeated Racking - Test 4

Two 10-kip electro-servo hydraulic rams (2 and 3), shown in figure 4.9, were located approximately equal distance from the ends of the 40 ft - 1 1/2 in module. The reaction frames employed in Test 1 were also used for this test. The entire test setup is shown in figure 4.10. The load amplitude and frequency, and the cyclic function were automatically controlled by the servo-controlled console shown in the foreground. The number of cycles of loading to be applied in a given test interval was preset and a counter indicated when the total number of designated cycles had been completed.

The centerline of the rams was 9'-9" above the laboratory floor. Each of the 10-kip rams was equipped with a load cell, one of which can be seen in the closeup of figure 4.11.

The deflection gages employed for Test 1 were retained for this cyclic loading test, with the exception of LVDTs 14, 15 and 16. These LVDTs were previously attached to the portion of module that was severed. One LVDT was attached to each spreader beam spanning between the reaction frames in order to monitor the deflection of the beam at the point of application of the load.

The input provided by the deflection gages and the ram load cells were monitored and recorded through the use of the same computer-controlled automatic scanner and digital voltmeter discussed earlier. The voltmeter readings at 50-cycle intervals were recorded on magnetic tape and teletype console printout.

4.5 Reversals of Racking - Test 5

The same basic testing arrangement was used for Test 5 as was used for Test 4. The two 10-kip electro-servo hydraulic rams remained in the same location along the front of the 40 ft-1 1/2 in module. In order to transmit a tensile force at the eave line, three 1/2-inch diameter threaded rods were extended through the module to connector plates attached to the front and rear faces. Two of the tension rods are visible in the left foreground of figure 4.11. The load amplitude and frequency, and cyclic function were automatically controlled by the servo-controlled console shown in figure 4.10.

The centerline of the rams was 9 ft - 9 in above the laboratory floor. All of the LVDTs employed in Test 4 were used for monitoring deflection.

4.6 Racking to Capacity - Test 6

As indicated schematically in figure 4.9, four loading rams were employed in this test. Rams 1 and 4, both 10-ton manually-operated hydraulic actuators, were positioned at the ends of the test structure. The two 10-kip electro-servo hydraulic rams, 2 and 3, were located approximately equidistant from the ends. The centerline of each ram was 9 ft - 9 in above the laboratory floor.

A 5-kip load cell was attached to each of the 10-ton rams and a digital voltmeter was connected to one of the load cells to monitor the load application. A servo-controlled console controlled the load application of the two electro-servo hydraulic rams.

The X-Y recorders provided a plot of load versus deflection for all stages of loading. LVDTs 5 and 8 were wired to supply the input for the deflection coordinate. The 10 kip load cells attached to rams 2 and 3 were linked to the X-Y recorders to provide the data for the load coordinate.

After each succeeding increment of loading, all 43 channels of data input was recorded through the use of a digital voltmeter and a computer-controlled automatic scanner. A magnetic tape recording was obtained in addition to a teletype printout.

5. Load Program

5.1 Service Life Racking - Test 1

Concentrated loads in five locations were applied to the front face of the module at the eave line. The positions of the loading rams were selected to simulate the racking effect of a uniform wind pressure distribution along the length of the front face. The normalized pressure distribution diagram shown in figure 5.1 was included to show the deviation from the ideal of unit pressure. The maximum deviation occurred at the living room end and amounted to 6 percent.

The first loading of the test simulated the shear force that, in the actual structure, is transmitted to the top of the second story transverse walls. To allow for the resistance provided by the adjacent module in the actual structure, the simulated wind force, in this and in subsequent racking tests, was taken to be one-half of the wind drag force calculated for the actual structure.

The second loading simulated the shear force that in the actual structure is transmitted to the top of the lower story transverse walls. The effect of the vertical load contributed by a second-story module on the response of the module acting as a first-story unit was not simulated during the the second loading. Table 5.1 summarizes the magnitude of the ram loads for successive increments of equivalent wind pressure.

5.2 Transient Floor Vibration - Test 2

An impact load was applied to the floor as a result of releasing the 25-lb bag from the head of the tripod at a height of 3 ft. The bag-release mechanism was operated from outside the test room in order to eliminate any damping effects that may have been provided by test personnel.

Two impacts were delivered for each of the four combinations, of the point of delivery of impulse and the point of measurement of displacement, to observe the reproducibility of the results. A displacement versus time trace of the floor response was recorded on photo-sensitive oscillograph paper.

5.3 Sustained Floor Load - Test 3

The uniform loading was effected by placing two layers of sand bags over the 11 ft-0 in x 9 ft-7 in floor area. A total of eighty bags was used, the individual weights of which ranged from 78 lb to 82 lb. The average weight of the lot was found to be 80 lb. The total weight superimposed on the floor was 6,400 lb, resulting in a uniform pressure of 61 psf. The dead weight of the floor assembly was calculated for the components as specified, to be 10 psf. Therefore, the actual total gravity load was 71 psf.

The specified factored load combination for the test was 1.5L + 1.2D. The values used for the dead weight and the design live load (i.e. 1D and 1L respectively) were as follows:

1D = 10 psf
*1L = 30 psf (bedroom in a single-family dwelling)

Using these design load values, the total load required for testing was 57 psf. This magnitude of loading amounts to 85 percent of the floor's required capacity. By comparing

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* Adoped from the FHA Minimum Property Standards, "Structural Design Data," Appendix A, par, C-2 Floor Loads, Table 1 [4].

the actual test load with the specified load value, it is seen that a 24.5 percent greater load was applied than was required.

Vertical deflection of five points was recorded immediately after the full load was applied and several times during the subsequent 24 hours. The ability of the floor to return to its initial position was quantified by recording the deflection at the same points, upon unloading the floor. Measurements were obtained immediately after the load was removed and at several intervals during the subsequent 24 hours.

5.4 Repeated Racking - Test 4

Concentrated loads were applied at the eave line of the front face of the module at two locations. These loads varied with time in accordance with a half-sine wave. This test involved 1000 cycles of loading from 1D to (1D + 0.5W). The magnitude of the horizontal forces was determined by considering the contributory area shown in figure 5.3b, minus the 19 ft-3 in long living room space which had been severed from the remaining bedroom portion. The loading used was considered capable of closely representing the loading experience of the actual structure during its service life. The design wind pressure (i.e. 1W) was taken to be 20 psf.

The 1000 cycles of loading were applied automatically by the hydraulic rams and the load control was preset such that 50 cycles of loading would be applied at a frequency of 1 Hz. The maximum amplitude of loading during each cycle was 2.5 kips per ram. Twenty blocks of these 50 cycles of loading were required to complete the test loading. In addition, there were two manually-controlled cycles of loading, one preceding the first 50-cycle block and one following the 1000th cycle. The entire sequence of loading is shown schematically in figure 5.2. The manually controlled cycles are denoted as "static" cycles in the figure. Note that the abscissa is intermittently labeled with a letter to establish the terminals of the 50-cycle blocks, as well as the points of zero and peak load for the static cycles. The horizontal and vertical displacements of selected points were measured at the terminals of the 50-cycle blocks and residual deflection measurements were obtained 24 hours after the 1,000th cycle.

5.5 Reversals of Racking - Test 5

The application of 5 cycles of lateral load, reversing from +1E to -1E, was intended to provide a simulation of the fatigue experience that the structure could undergo during a major earthquake. Since there is no known requirement for deflection limitation of a structure subjected to such loading, the main consideration was the effect on the visible joints in the test structure and the change in stiffness of the structure.

The magnitude of the test load was calculated in accordance with the seismic provisions for two-story structures in the 1967 edition of the Uniform Building Code.[3] The weight calculation was based upon a two-story, wood-frame structure 40 ft-1 1/2 in long x 12 ft wide.

A sinusoidal forcing function was applied to the front of the test module The frequency of the forcing function was varied to observe any resulting differences in the characteristics of response. The three selected frequencies were 0.1 Hz, 0.5 Hz and 0.75 Hz.

5.6 Racking to Capacity - Test 6

It was discovered in Test 1 that no measurable increase in residual deflection occurred after three cycles of loading had been applied. In order to effect this "shake-down" condition prior to beginning the test, three cycles of loading were performed by ram nos. 2 and 3. Figure 4.9 shows the location of the rams. The peak load in each cycle was approximately 100 lb per ram. Zero load readings were obtained before and after the three cycles.

The racking test was begun with a load of 500 lb on each of rams 2 and 3 and 250 lb on each of rams 1 and 4. This 2:1 ratio was maintained throughout the test in order to effect uniform load distribution. The structure was then subjected to monotonic loading and horizontal deflection at two points was recorded using two X-Y recorders. Loads on rams 2 and 3 were generally increased in increments of 500 lb except that in the early stages of the test the load level was increased directly from 1000 lb per ram to 2000 lb per ram. At the predetermined load levels, interior and exterior surfaces were examined for signs of distress. Closet doors and the three exterior windows were also checked for malfunction.

6. Results

Four tests involved racking response and two tests were concerned with floor performance. Generally, the data acquired from the four racking tests had to be transformed to engineering units through the use of an electronic computer. In the case of tests 1 and 6, curves relating applied load to resulting deflection (i.e. P-Δ curves) were subsequently plotted automatically for all deflection transducer channels. As a means of confirming the reliability of the readout from the automatic data acquisition equipment, X - Y recorders plotted P-Δ curves for the response at two critical locations. A secondary check was accomplished by using the readings of six mechanical dial gages at various locations along the front of the test structure.

6.1 Service Life Racking - Test 1

A series of curves of applied load versus net horizontal displacement are presented in figures A.3 through A.12.

The values on the abscissa were obtained by calculating the difference between the horizontal deflection at the top of the rear wall and that at the top of the support assembly. No attempt has been made to separate the gross horizontal deflection at a point into its three components, i.e. deflection due to 1.) rigid body rotation, 2.) curvature and 3.) racking.

Five curves depicting the lateral displacement profile are shown in figure 6.1. These curves, corresponding to equivalent wind pressures of 13.19, 26.38, 35.50, 41.96 and 47.63 psf, illustrate the deformation behavior of the test module relative to its original position.

6.2 Transient Floor Vibration - Test 2

The response of the test floor to the impact loading is presented in figures 6.2 through 6.5 in the form of deflection amplitude versus time curves. There were two trials for each of the four setups (see right side of figure 6.2 and 6.3) and hence there are eight traces presented.

The response for the first trial within a given setup is denoted by the number 2 followed by a single letter (i.e. 2A). The second trial for the same setup is identified by the number 2 followed by two letters (i.e. 2AA). In all cases, the positive side of the trace corresponds to the downward motion of the floor.

It should be noted that in three of the four test setups the initial amplitude trace is truncated rather than possessing a vertex similar to the remaining amplitudes. This anomaly was due to the limited output of the amplifier in the oscillograph recorder. The positive half of the first cycle has been extrapolated by dashed lines to indicate the probable initial amplitude.

6.3 Sustained Floor Load - Test 3

The deflections recorded by a LVDT placed at the center of the south bedroom are presented in figure 6.6, where they are compared with results obtained by a dial gage. A second LVDT was located 8 inches south of the one depicted schematically in figure 6.6 and the two plots of deflection versus time were identical. The lengths of time required by the loading and unloading operations are presented for completeness. Since the load was neither applied nor removed in a strictly regulated manner, it is doubtful that the relationship between deflection and time was linear. Consequently, dashed lines are used to join points corresponding to the beginning and the end of these two operations.

It should be noted that within each 24-hour observation period, there were approximately 15 hours during which no data was obtained from the dial gages. Consequently, dial gage readings are concentrated near the ends of the creep and recovery periods. In the case of the LVDT output, however, the recording of data was continuous.

6.4 Repeated Racking - Test 4

The output from all LVDT's and from both load cells was recorded at the terminal points of the 50-cycle blocks. These 21 data points are indicated by the letters C through W on figure 5.2. In the static cycles, data from all channels was recorded at the points indicated by the letters A, B, X and Y in figure 5.2. It should be noted that the data at points X and and Y was acquired 24 hours after the 1000th cycle was completed. By comparing the magnitude of the LVDT readings for the 20 data points, beginning at point D, with the reference reading obtained at point C, it was possible to determine the ability of the module to recover its original geometry. The comparison of the deformation response for five channels is presented in table 6.1. The LVDTs selected for presentation were located either at the top of the rear wall or at the joint between the module and the support assembly.

Visual examination of the interior and exterior of the module at each terminal point did not lead to the discovery of any new damage or distress.

6.5 Reversals of Racking - Test 5

The five reversals of lateral load did not cause any apparent structural damage to the test module or to the joint at its base. No new cracks were observed nor did any old cracks re-appear. The maximum amplitude of ram travel, as recorded by the strip chart recorder, was 0.15 inches in the direction of pull and 0.10 inches in the direction of push. These values of maximum amplitude were independent of the frequency of the forcing function. The peak lateral load was set on the control console at 4600 lb in each direction.

6.6 Racking to Capacity - Test 6

The deflection at each LVDT location was measured for each increment of load. Curves were generated by electronic computer to show the relationship between applied load and net horizontal defleciton along planes 1, 3 and 4. It was not possible to plot a curve for plane 2 because of a malfunction in LVDT 17. The abscissa for each of the three curves (figures 6.7 through 6.9) was obtained by subtracting the horizontal deflection at the top of the support assembly from that at the top of the rear wall. The magnitude of the force at ram 2 is plotted along the ordinate of each curve.

The testing was terminated when the bond was broken between the module base and the support assembly.

On the front side, the glue line failed in the vicinity of the tie-down assemblies; consequently, the module was vertically separated from, and laterally displaced relative to, the support assembly. Between the tie-down assemblies the entire module-support assembly was raised to the point that it lost contact with the laboratory floor. Also, there was horizontal splitting of the 2 x 10 perimeter beam adjacent to two of the interior tie-down assemblies along the front of the support assembly. These local failures were apparently caused by a combination of tension perpendicular to the grain and horizontal shear in the direction of the lateral force. The level at which the splitting occurred coincided with the top of the 2 x 8 perimeter beam shown in detail "A" of figure 2.4. These cracks were tapered over their approximately two-foot length, with the wider end being immediately adjacent to the tie-downs. Along the rear of the module, there was horizontal splitting of the header beam in the vicinity of the interior tie-down assemblies. The mode of failure was horizontal shear deformation. Furthermore, the two most critical LVDTs, 8 and 11 were compressed to the fullest extent of their range of 1 inch at the time the test was terminated.

7. Discussion of Results

The results of all the racking tests (Tests 1, 4, 5 & 6) are subject to the general qualification that an adhesive with unknown durability properties was used in some critical structural applications. It was not within the scope of this test program to evaluate the durability of the adhesive used, so it is not possible to draw any conclusions about its long-term performance from these tests.

7.1 Service Life Racking - Test 1

The total lateral force was interpreted as an equivalent wind pressure in accordance with ANSI Standard A58.1 - 1972

[5]. Since the entire two-story structure falls within one height zone, a uniform pressure was considered to act on the projected wall area. According to section 6.5.3.2.3 and table 6, of A58.1, it is recommended that a pressure coefficient of -0.7 be used normal to the leeward slope and -0.3 be used normal to the windward slope. By performing two coordinate transformations, the resultant horizontal force on the roof can be represented by a pressure coefficient of +0.4 applied normal to the vertical projection of the roof.

A comparison of columns (A) and (B) in table 5.1 will show that the ratio between them changes after the total lateral load value of 5150 lb. This change reflects the consideration of two cases of contributory area. Although the test module was designated as a second-story unit, it was concluded, after comparing the plans and details of the upper and lower-story units, that its lateral stiffness was reasonably representative of that of a lower-story unit. Thus, the first four lateral load tabulations in table 5.1, were designed to simulate the wind pressure acting on the contributory area whose profile is illustrated in figure 5.3a. The remaining five tabulations were assumed to simulate the wind pressure acting on a wall area extending from midheight of the lower story to the ridge of the roof. The profile of the area contributing to the second loading condition is shown in figure 5.3b.

In order to estimate the lateral stiffness of the two-story structure in its site assembled position, it is first necessary to determine the degree of correlation between the test module and the actual structure. It has been previously stated that the test module was a prototype of a second-story front unit in the proposed structure. The difference between the test module and the proposed structure is the detail of the support assembly. By comparing the details of the assembly as illustrated in figure 2.4 with those of the lower-story ceiling (see figure 2.3), it is seen that the edge members are identical. Otherwise, the ceiling diaphragm differs from the support assembly since there is a difference in size and spacing of the joists and an absence of gypsum wallboard from the latter. This particular qualification notwithstanding, it is still worthwhile to postulate a model that can be used to relate drift at the second floor level to static wind pressure acting normal to the longitudinal walls of the erected structure. The analogy is presented pictorially in figure 7.1. The top illustration refers to the data points associated with the vertical planes identified in figure 4.4. Total lateral load applied to the test structure is denoted as P while notations Δ_1, Δ_2, Δ_3, and Δ_4 refer to the horizontal planes in which lateral deflection was measured. In ascending order the levels are: 1.) the laboratory floor, 2.) the top of the support assembly, 3.) the floor of the module, and 4.) the ceiling of the module. In the bottom illustration, the four horizontal diaphragms present in the actual structure are labelled in ascending order. The total concentrated load apportioned to the respective levels is symbolized by the arrows on the left hand side of the sketch. The equations yielding the gross horizontal deflection at levels 1 through 3 are shown on the right side of the sketch with deflection at level 3 being referred to specifically as drift. A typical application of the model to data acquired for plane 3 is included in Appendix B. The resulting drift value was subsequently used as one of the coordinates to locate a point on the drift versus simulated wind pressure curve.

The result of plotting the derived drift as it varies with the simulated wind pressure is presented in figure 7.2. Three vertical planes, 2, 3 & 4, were selected for presentation as the data showed them to be the most critically affected by the test loading. The curves for planes 2 and 4 must be qualified in that all four contributing data points alluded to in the top sketch of figure 7.1 were not located along the rear of the test module. In the case of plane 2, the data for Δ_1 and Δ_2 was provided by LVDTs 39 and 38 respectively, both of which were located on the front and offset approximately 3 ft from plane 2. In order to provide values for Δ_2 along plane 4, the output from LVDT 22 was used. This transducer was also located on the front and offset 8 1/2 in from plane 4. The primary assumption underlying this improvisation is that the support assembly acted as a diaphragm subjected to in-plane flexure. Therefore, it can be reasonably assumed that the deflection measured at a point on the front of the assembly is the same as that occurring directly in line with that point on the rear.

It is also necessary to qualify the curve of drift versus simulated pressure for the fact that the effect of the vertical load provided by a second-story module was not simulated during the loading.

The dashed vertical line in figure 7.2 coincides with the conventionally accepted maximum allowable drift. This value, h/500, where h is the height as defined in the Notation section, is normally used in the design of medium and high-rise buildings, and is associated with a wind having a 50-year mean recurrence interval. Using the point of intersection of this line with the curve derived for plane 4, it is concluded that the maximum pressure at which the system would satisfy this drift limitation is 21 psf.

The diagonal transducers that were installed on the walls denoted as planes 1 and 3 (see figure 4.4) were expected to afford a correlation between the deformation measured at the wall surfaces and the lateral deflection measured at the ceiling level of the test module. However, the test data showed the change in length along the diagonals to be an order of magnitude less than the corresponding horizontal deflection. From this it is apparent that either the ceiling diaphragm did not transfer a significant amount of the lateral load to these two planes, or there was relative movement between the wall framing and the gypsum wallboard surface. Since compatibility must be satisfied between the ceiling diaphragm and the transverse walls, it is reasonable to conclude that resistance was provided by the transverse walls and that relative movement occurred between the framing and the surface.

Figure 6.1 shows a set of profiles for lateral deflection along the top of the rear wall. The five deflection transducers from which the data were obtained, are numbered and shown in their respective positions in the plan view at the top of the figure. The curve between successive points is approximated by straight lines. The shape of the profiles indicates that the ceiling assembly underwent in-plane deformation while transferring load to the shear walls. It is observed that the maximum measured lateral displacement occurred in planes 3 and 4.

It should be noted that the total wind drag applicable to the actual structure was divided by a factor of 2 to account for the stiffness provided by the second module. The construction details indicated that the two modules were bolted together near the top and bottom of their common wall with 3/8 inch diameter through bolts. This mechanical connection would presumably cause the two modules to deflect laterally in a compatible manner. Given two beams with identical properties, when one is placed upon the other, the given load is shared equally by the beams and the beams are compatible in deflection. In a similar manner, two identical modules bolted in the manner described above, could be expected to be compatible in deflection and to participate equally in resisting lateral forces. However, given that the transverse walls in the rear module may not be distributed the same as those in the front module, the distribution of the lateral deflection in the actual structure may differ from that shown in figure 6.1. This qualification to the profile curves is acknowledged.

There are ten curves presented in Appendix C, figures C.1 through C.10, which describe the measured net horizontal deflection in the five previously identified planes. Two plots are presented for each plane, one for each of the contributory areas (see figure 5.3) on which the ram loads were based. A study of figures C.1 through C.10 reveals a common behavior with respect to deflection. There was a residual deflection at the end of the first cycle of loading, but subsequent cycling to the same maximum load did not result in a substantial increase in this deflection. When the maximum load level was increased, there was likewise an increase in the residual deflection. Further cycling to the same peak load caused little increase in residual deflection. This behavior may be attributed to the removal of slackness in the connections. Once this slackness was removed, the system behaved in a reasonably elastic manner and the response was reproducible.

7.2 Transient Floor Vibration - Test 2

It is seen from figures 6.2 through 6.5 that the impact load was sufficient to create a measurable response in the floor assembly. This study was concerned with damped free vibration caused by a short-duration load and hence it is necessary to account for the period of response during which the forcing function was on the floor system. This effect is believed to be accounted for by neglecting the first cycle of response because it is judged that the duration of the load was no greater than the natural period of the subsystem. The gain in amplitude observed between the time of 0.35 and 0.4 seconds suggests that at this point the bag made a second contact with the floor. The range of the natural frequency derived from the response curves extends from 23 Hz to 26 Hz.

There was 50% success in reproducing the results of the first trial in the two-trial sets. Tests 2BB and 2DD correlated closely with the initial trials, 2B and 2D respectively. But the results of tests 2A and 2C were not reproduced during their sequels, 2AA and 2CC. In the latter two cases, there was evidence of the superposition of a response of lower frequency on the floor's response. One explanation for this occurrence is that the beam supporting the deflection transducer may have been vibrating slowly, caused by some secondary motion in the walls between which it spanned. This reasoning is supported by the fact that there is a measurable shift in the average deflection after 0.2 seconds in both of these trials. It should be noted that the support beam was attached to the surface of the walls by using rubber suction cups. It is conceivable that the beam could have slipped down the wall a short distance, due to vibration induced in the walls, before the cups were secured again.

In analyzing the damping characteristics of the floor, approximate decay envelopes can be drawn in six of the eight traces. It is meaningless to attempt to extend the envelope beyond the point where additional energy is introduced by the bag's second impact on the floor. Therefore, the useable portion of the deflection-time traces lies between the 2nd and 8th cycles. It can then be generally concluded that in all four test setups, the deflection amplitude in the 8th cycle of oscillation has decayed to about 20% of the amplitude of the 2nd cycle.

7.3 Sustained Floor Loading - Test 3

Examination of the test data shows that the maximum vertical deflection occurred beneath the LVDT (location shown in figure 6.6). The magnitude of deflection at this point, under full load, including the effect of creep, was 0.500 inches. The full load deflection beneath the dial gage (located 8 inches from the LVDT) was 0.431 inches or about 86 percent of maximum floor deflection.

The increase in deflection due to creep was found to be linear for both the instruments. Creep deflection amounted to 5.0 percent and 5.56 percent of the maximum deflection as measured respectively by the LVDT and the dial gage. In the removal of the superimposed load, was 81 and 91 percent respectively. These recovery percentages compare favorably with the American Concrete Institute's (ACI) criterion for evaluating the performance of concrete construction under static load. Section 20.4 of ACI Standard 318-71 [6] requires retesting of construction failing to show 75 percent recovery, 24 hours after load removal.

7.4 Repeated Racking - Test 4

The deflection data presented in Table 6.1 was chosen to be representative of the total amount of data obtained. It was found that the average final residual deflection was 10.4 percent (varied from 7.8 to 18.2 percent) of the maximum deflection due to the superimposed loading. Thus, the structure, after being subjected to 1000 cycles of simulated wind loading, recovered approximately 90 percent of the maximum deflection. These results must be qualified by the fact that the possibly-detrimental effects of aging and temperature changes on the adhesive joining the module to the support assembly were not allowed for.

7.5 Reversals of Racking - Test 5

Since there are no known criteria limiting the magnitude of the maximum deflection and the amount of recovery, the results of this racking test are qualitative. Although there was almost one order of magnitude difference between the highest and lowest frequencies used, the response of the structure appeared to be independent of the frequency. The fact that no cracking or other signs of distress were noted during the course of testing is an indication that structural distress probably did not occur.

7.6 Racking to Capacity - Test 6

As expected, the glue joint on the simulated windward side was the critical zone of weakness in the test assembly. This glue line was subjected to shear as well as direct forces. A tensile force was transmitted to the joint when the magnitude of uplift, caused by the overturning moment, was sufficient to exceed the gravity force inherent in the module. The dead load along the base of the windward wall was approximately 155 lb per foot. The geometry of the test configuration yields the following relationship:

$$V = \frac{h}{W} \times \frac{P}{L} = 0.019P$$

where:

V = the uniform vertical force attributed to uplift (lb/ft)
P = the total lateral force (lb)
h = the height of the point of application of P above the joint, 9.00 ft.
W = the width of the module, 11.67 ft.
L = the length of the longitudinal glue line, 40.125 ft

By assigning a value of 155 to V, it is seen that uplift is imminent when P equals 8072 lb. The maximum total force applied to the module was 16,920 lb. Once the ultimate stress of the adhesive was exceeded, the glue line failed and the module was separated from the support assembly. There were no direct tests performed to determine the glue line strength. The upward force was reacted by the tie-down assemblies and so the separation occurred adjacent to the supports. The lack of vertical restraint on the windward side made it possible for relative horizontal displacement to occur between the module and the support assembly.

It is observed on figures 6.7 through 6.9 that at the load level of 3500 lb there was an offset in the horizontal deflection with no apparent increase in loading. Since it is doubtful that a "strain hardening "behavior was exhibited by the wood-frame structure, it is concluded that the offset was attributed to the means of loading. It is recalled that two hydraulic systems were used in this test. The ordinate in the three figures represents the force applied by rams 2 and 3, which were controlled by an electronic console. Once the load level was set, the servo-mechanism would automatically adjust the system until that load is resisted. On the other hand, rams 1 and 4 were manually activated. Accordingly, there was a time lag for applying the end ram loads as well as for correcting any maladjustment that might arise. Therefore, if the load began to drop off or if the structure drifted away from the end rams, it would be necessary for the operator to jack the ram until the desired load was attained. Any additional movement of the LVDTs would appear on the plots with no apparent increase in the load that is shown on the ordinate.

8. Conclusions

A summary of the conclusions drawn from the six tests are listed below. All of the conclusions are subject to the pertinent qualifications mentioned in Section 7.

1. Notwithstanding the fact that for some evaluative tests the module represented a sample of one, its use was concluded to be a practicable means of accomplishing evaluation by physical testing.

2. Most of the test methods used were ad-hoc since no existing standard methods were applicable to the tests. In view of these shortcomings in test methodology, improved or new test methods must be developed.

3. Based on the analytical model used to condition the results, it is concluded that 21 psf is the maximum static wind pressure at which the system satifies conventional drift requirements as applied to medium and high-rise buildings.

4. When lateral wind load is simulated by concentrated forces acting in line with a horizontal diaphragm, the strains measured on the surface of the transverse walls are not compatible with the lateral deflection undergone by the diaphragm. The lack of correlation can probably be attributed to the relative motion between the wall framing and the gypsum wallboard.

5. For the range of lateral loads used to simulate service life phenomena, the test structure behaved elastically after the slack was removed. Accordingly, it is expected that repeated applications of a given loading sequence will yield highly reproducible results.

6. Using the results of six of the eight tests performed as a basis, it was concluded that the natural frequency of the test structure's floors lies between 23 and 26 Hz.

7. The percent of recovery, measured 24 hours after removal of the sustained floor loading was a minimum of 81 percent. This compares favorably with the 75 percent minimum recovery required by ACI Standard 318-71.

8. The structural integrity of the test module was preserved through 1000 cycles of simulated wind loading. This conclusion is substantiated by the fact that there was approximately 90 percent recovery of the maximum deflection.

9. The area of structural weakness for racking load resistance was within the glue joint between the test structure and the support assembly.

9. Acknowledgements

The authors acknowledge the contributions of the following NBS staff and laboratory personnel:

Frank A. Rankin, Supervisory Technician, was in charge of all laboratory handling, placement and dismantling of the test structure. He also supervised the erection of the reaction frames and the operation of mechanical equipment.

James Raines, Engineering Technician was responsible for the placement of the electronic instrumentation and the operation of the data acquisition equipment.

Randolph Williams, Physicist, was in charge of the advanced stages of the electronic data processing.

Charles Bulik, Electronics Engineer, was responsible for the coordination of the instrumentation and data acquisition activities.

Felix Y. Yokel, Structural Research Engineer, contributed many helpful suggestions and comments pertaining to the planning and execution of the test program and to the preparation of the report.

Lymus Payton, Edward Tuma, James Warfield and James Seiler, Technicians, participated in the handling, placement and testing of the test structure.

Cathy Glaze, Clerk Stenographer, performed the typing of the several drafts of this report.

The technical review and helpful suggestions contributed by Wayne C. Lewis, Research Specialist, Forest Products Laboratory, are gratefully acknowledged.

10. References

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[6] ACI Standard 318-71, American Concrete Institute, Building Code Requirements for Reinforced Concrete, 1971.

(A)	(B)	(C) =3(A) + 2(B)	(D)
Ram Jacking Force, lb		Total Lateral Force, lb	Equivalent Wind Pressure, psf
At Rams 1,2 & 5	At Rams 3 & 4		
192	355	1286	6.50
385	710	2575	13.19
577	1065	3861	19.78
770	1420	5150	26.38
1070	1860	6930	35.50
1270	2190	8180	41.96
1440	2490	9300	47.64
1620	2810	10480	53.69
1800	3140	11680	59.82

Table 5.1 - Test 1 (Ram forces and equivalent wind pressure)

(A)	(B)	(C) = 2(A) + 2(B)	(D)
Ram Jacking Force, lb		Total Lateral Force, lb	Equivalent Wind Pressure, psf
At Rams 1 & 4	At Rams 2 & 3		
250	500	1500	10.28
500	1000	3000	20.56
1000	2000	6000	41.12
1250	2500	7500	51.40
1500	3000	9000	61.68
1750	3500	10500	71.96
2000	4000	12000	82.24
2250	4500	13500	92.52
2500	5000	15000	102.80
2725	5450	16350	112.05
2820	5640	16920	115.95

Table 5.2 - Test 6 (Ram forces and equivalent wind pressure)

Run Number	Load (kips)	LVDT READINGS (inches) Channel Numbers				
		5	17	8	19	35
Static *	0.0	0.0	0.0	0.0	0.0	0.0
Static	2.49	0.055	0.088	0.114	0.072	0.051
Static	0.0	0.001	0.003	0.003	0.002	0.002
1 **	0.01	0.002	0.003	0.003	0.002	0.001
2	0.02	0.004	0.003	0.003	0.002	0.001
3	0.04	0.005	0.006	0.006	0.004	0.002
4	0.05	0.007	0.007	0.007	0.004	0.002
5	0.0	0.005	0.005	0.005	0.003	0.002
6	0.0	0.004	0.002	0.001	0.001	0.0
7	0.04	0.009	0.007	0.006	0.004	0.002
8	0.03	0.010	0.007	0.006	0.004	0.002
9	0.03	0.009	0.006	0.006	0.004	0.002
10	0.04	0.010	0.009	0.008	0.005	0.003
11	0.06	0.010	0.009	0.010	0.006	0.003
12	0.05	0.010	0.010	0.012	0.006	0.003
13	0.04	0.008	0.006	0.010	0.005	0.003
14	0.04	0.010	0.008	0.010	0.005	0.004
15	0.05	0.011	0.010	0.012	0.006	0.004
16	0.03	0.010	0.010	0.011	0.007	0.004
17	0.02	0.011	0.010	0.011	0.007	0.004
18	0.01	0.011	0.009	0.010	0.006	0.004
19	0.02	0.011	0.010	0.011	0.007	0.004
20	0.05	0.013	0.011	0.012	0.008	0.004
Static	2.50	0.051	0.098	0.121	0.076	0.054
Static	0.0	0.010	0.008	0.010	0.006	0.004

Table 6.1 - Repeated Racking Test Results

* The word "static" in the column headed Run Number refers to the zero and peak load readings recorded during the initial and final static cycles. See points A, B, C, X and Y in figure 5.2 on page 59.

** The numbers listed in the column headed Run Number refer to the terminals of the 50-cycle blocks of loading. For example, Run Number 1 on the table corresponds to terminal point D in figure 5.2 on page 59.

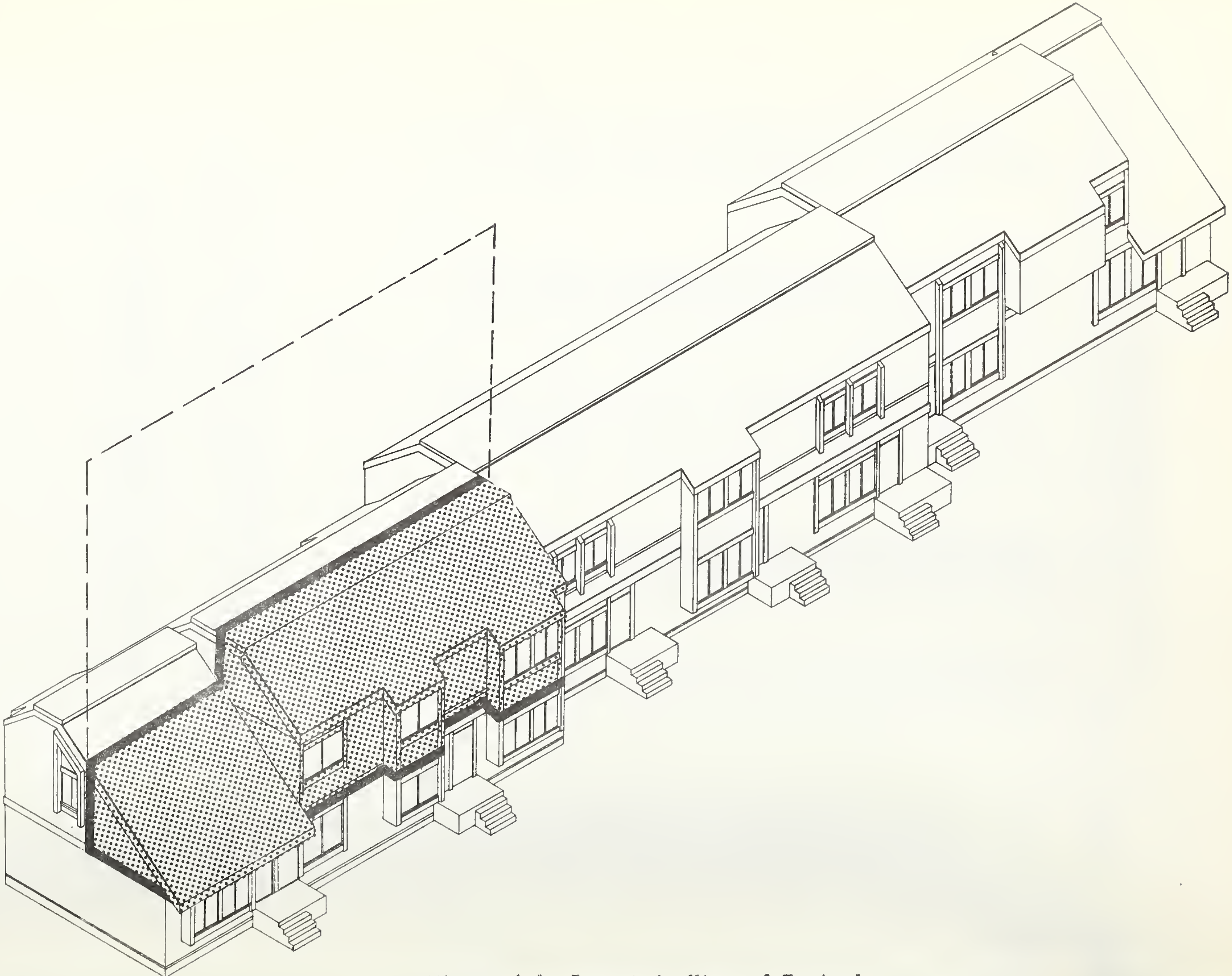


Figure 2.1 Isometric View of Typical Townhouse Cluster

NOTE 1: Living room space was severed following Test 3.

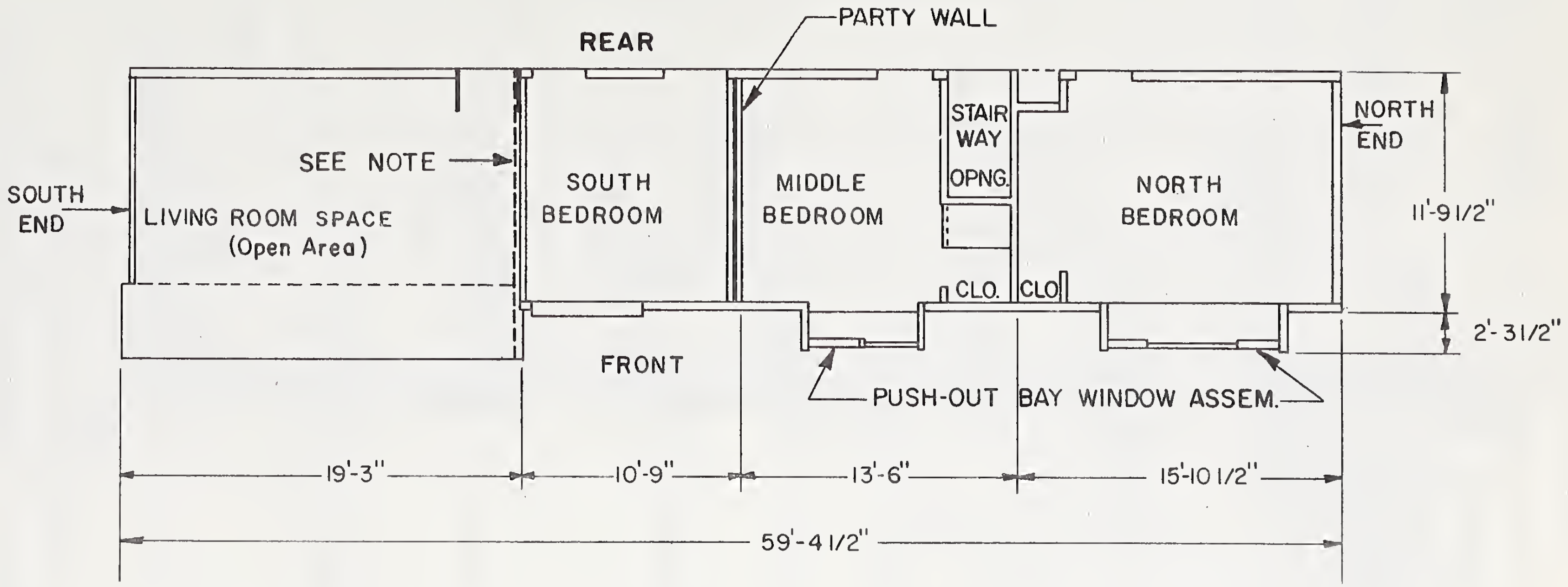
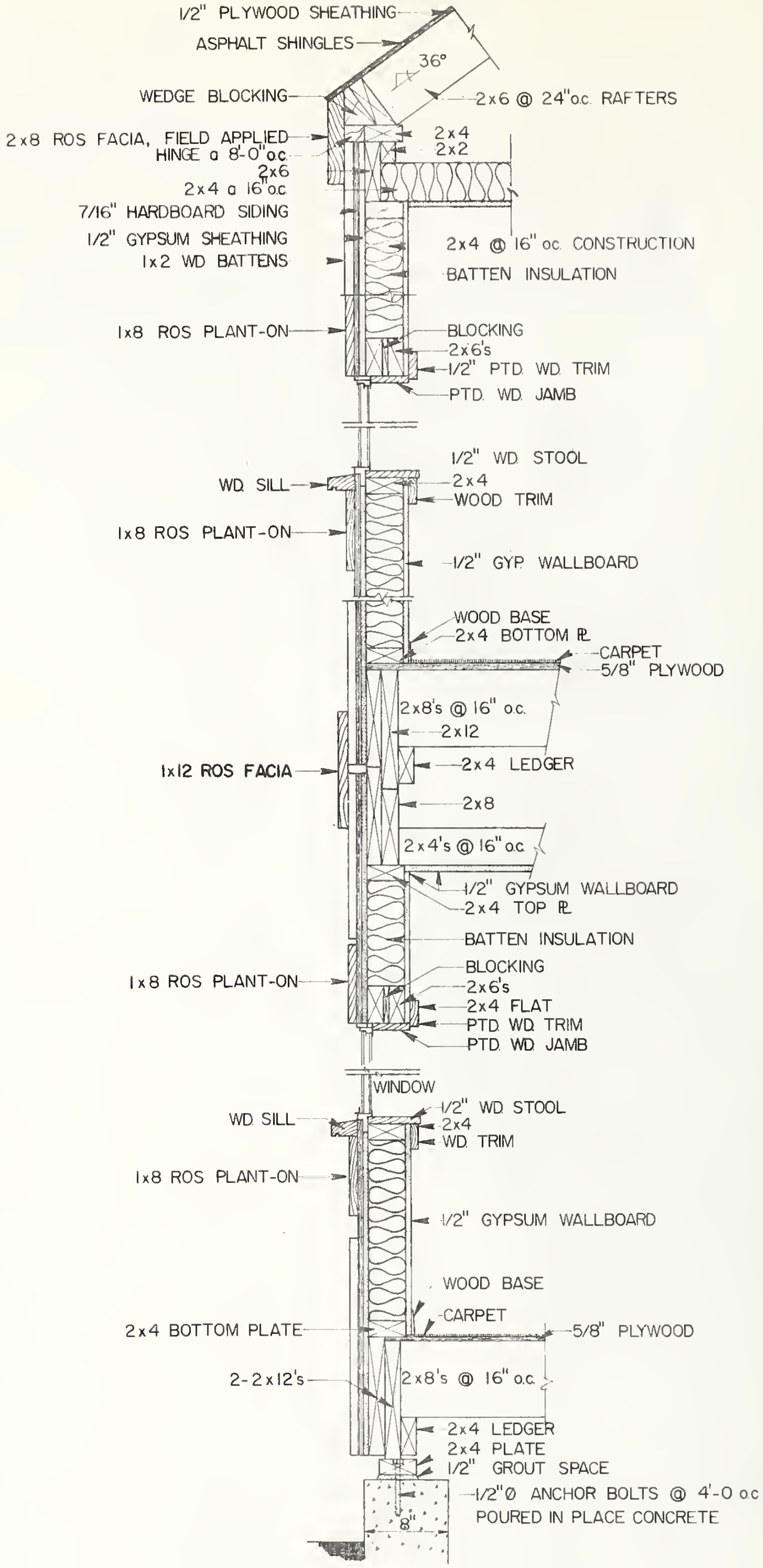


Figure 2.2 Module Floor Plan

NOTE 2: The push-out bay window assemblies were prefabricated and secured to the floor of the respective bedroom during shipment



SECTION THROUGH EXTERIOR BEARING WALL

Figure 2.3 Exterior Wall Section in Two-Story Structure

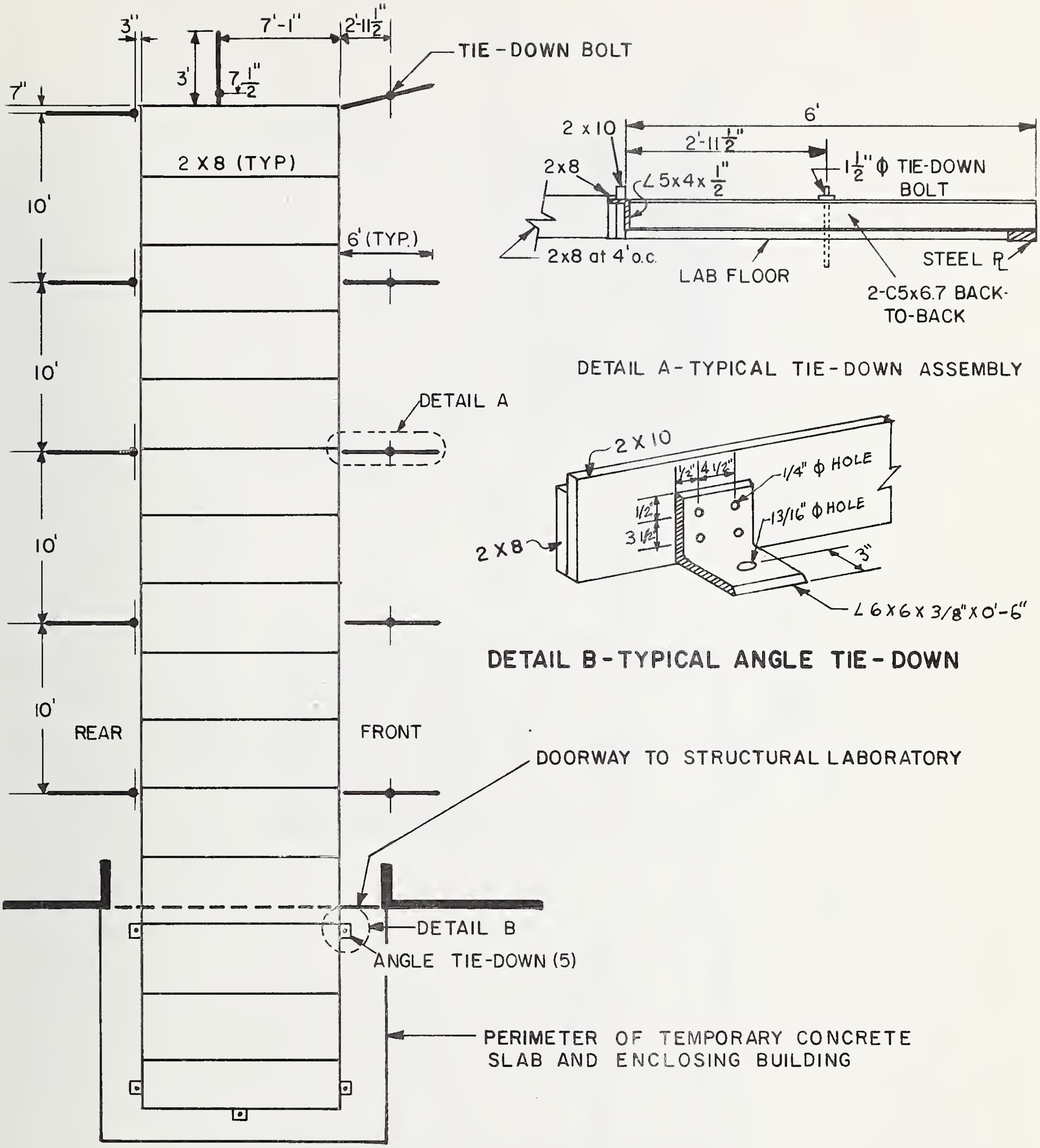


Figure 2.4 Plan and Details of Support Assembly

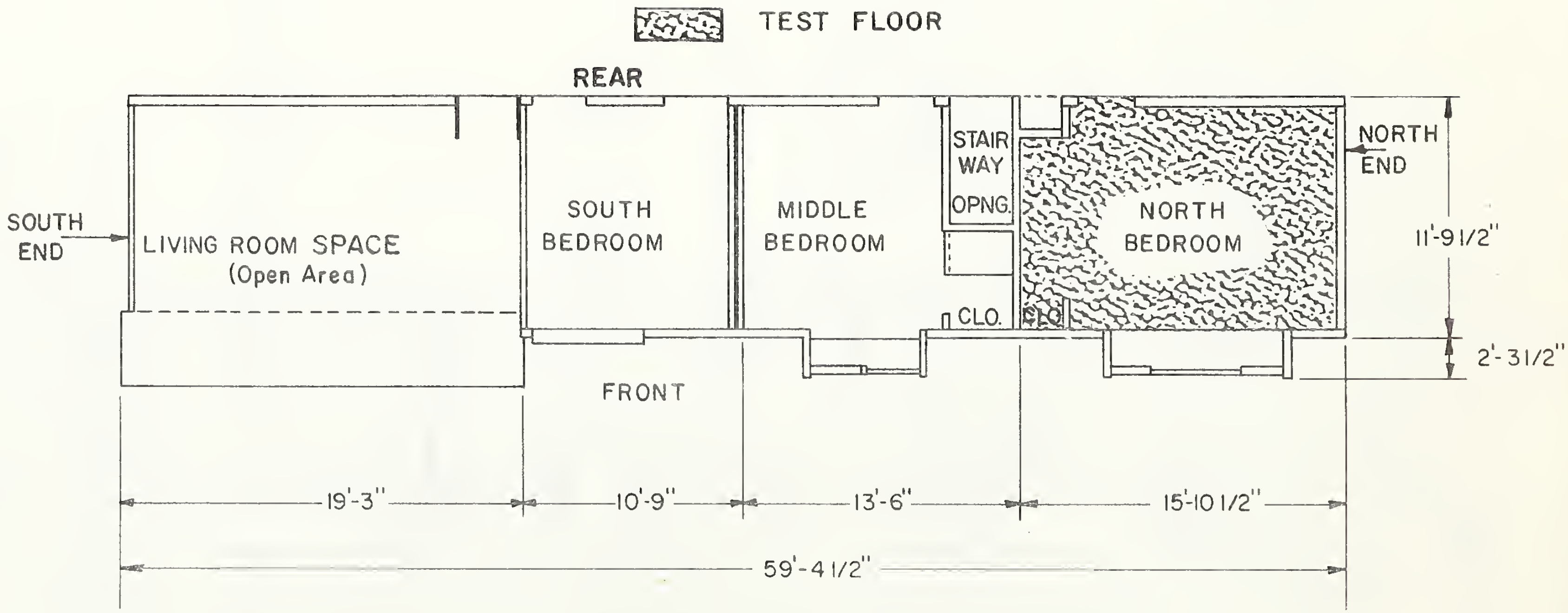


Figure 3.1 Test Floor for Transient Vibration - Test 2

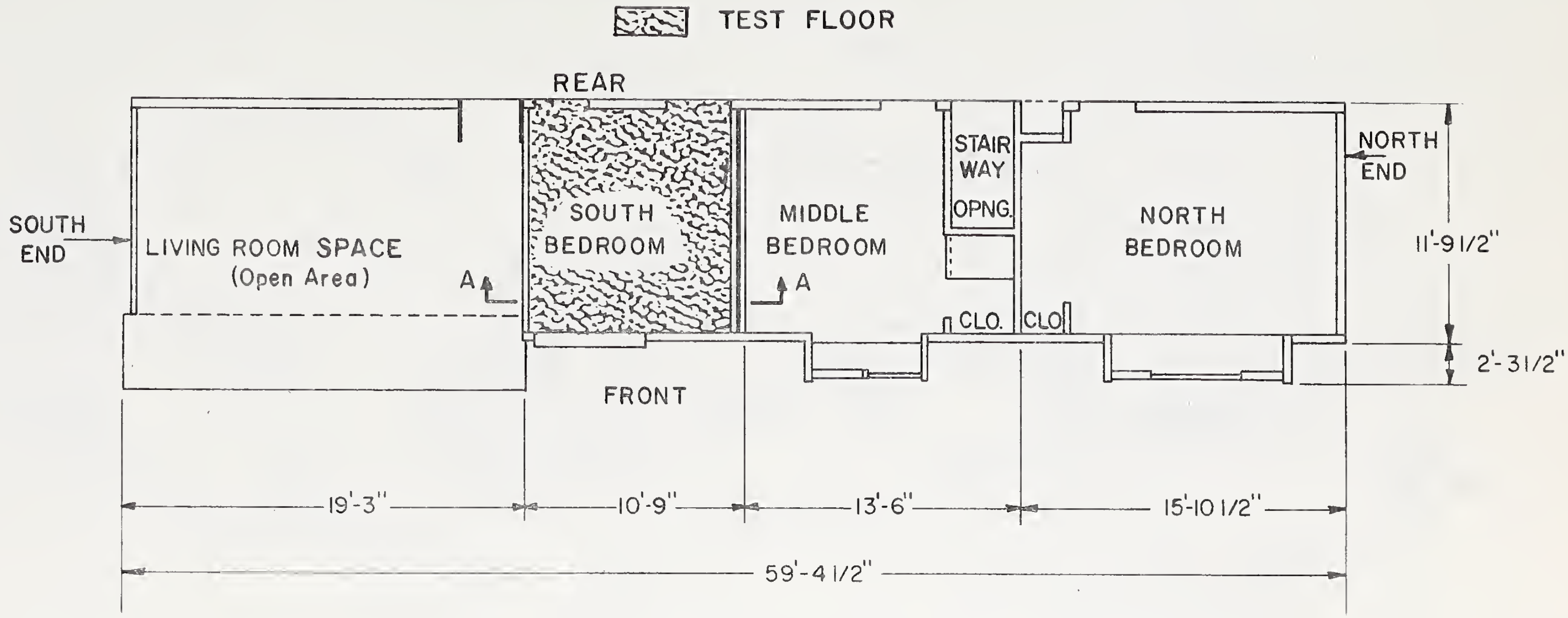


Figure 3.2 Test Floor For Sustained
Load- Test 3

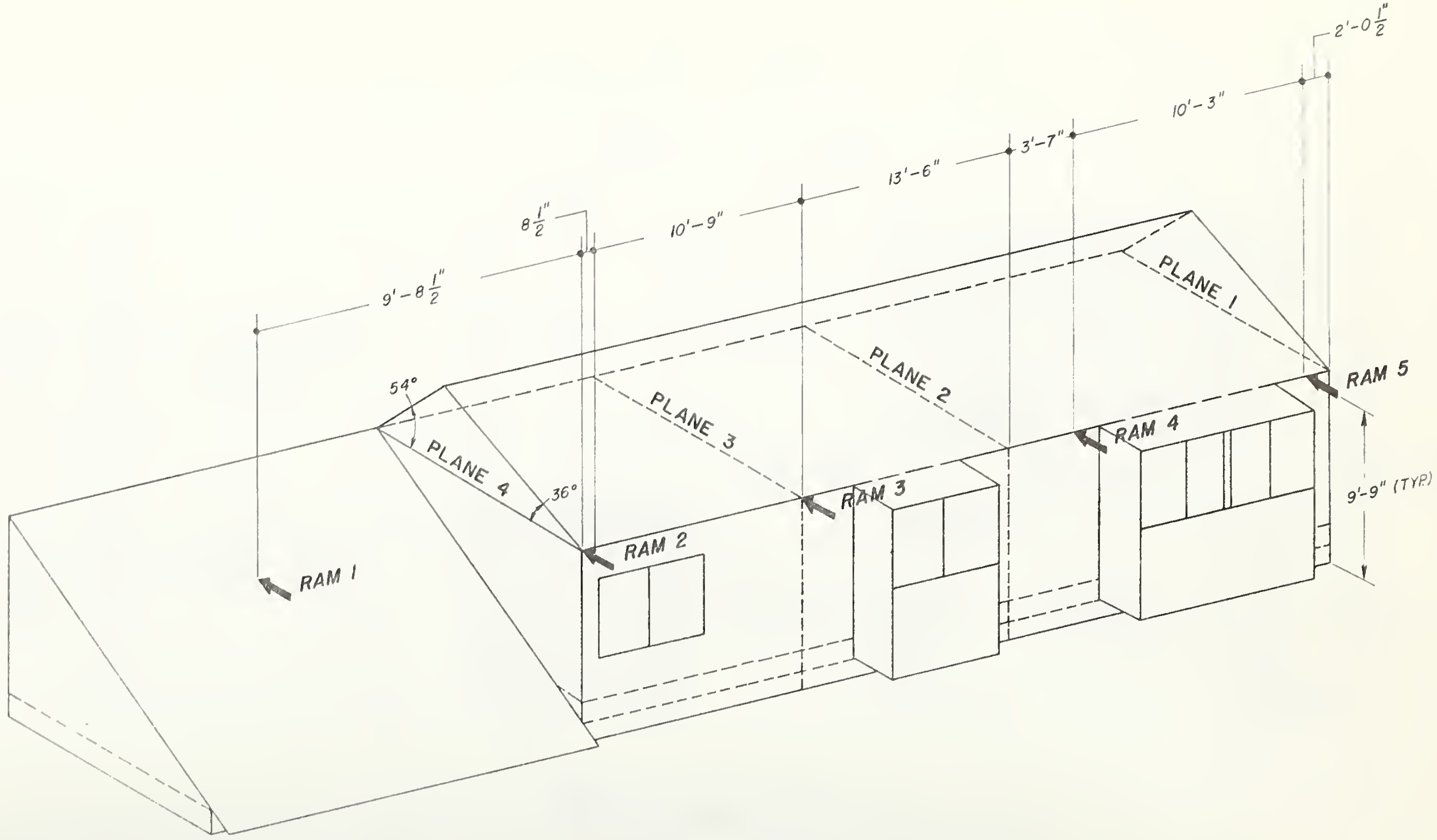


Figure 4.1 Ram Locations for Test 1

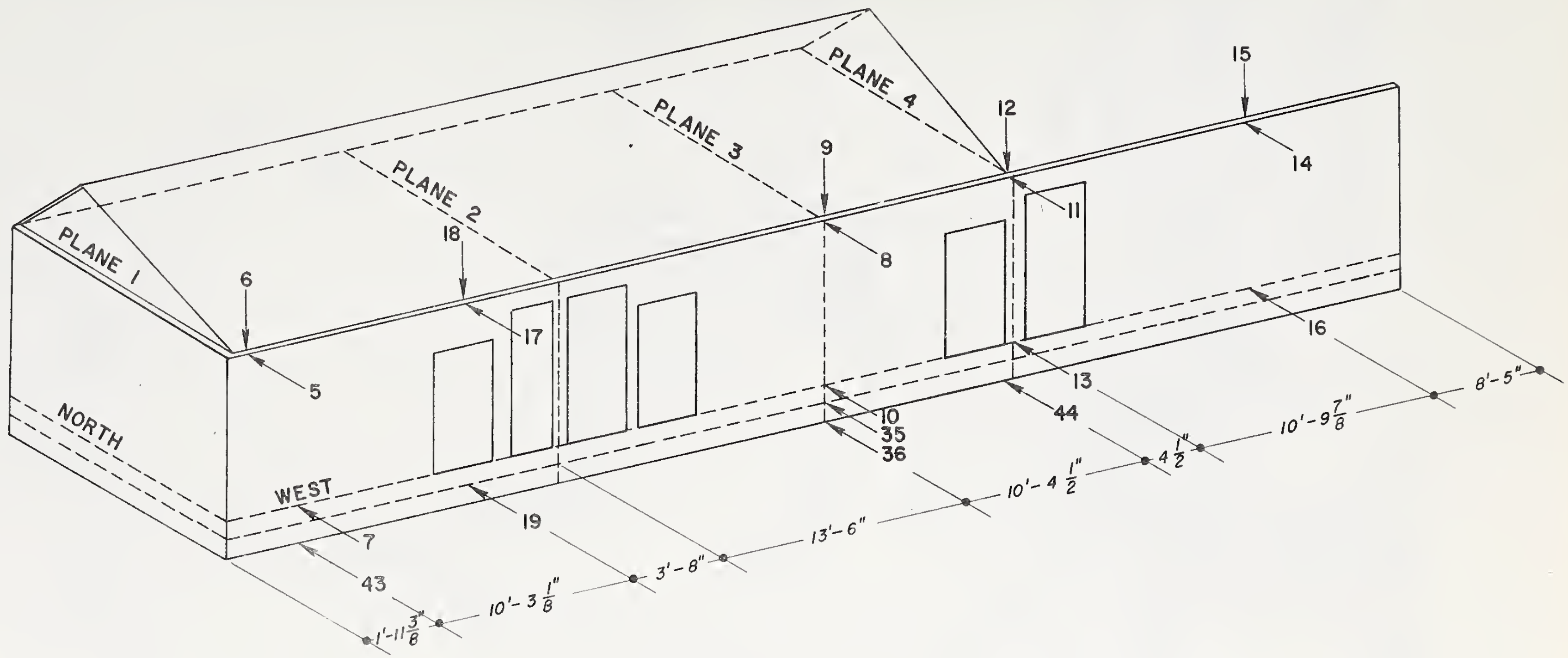


Figure 4.2 Exterior Instrumentation on the Rear - Test 1

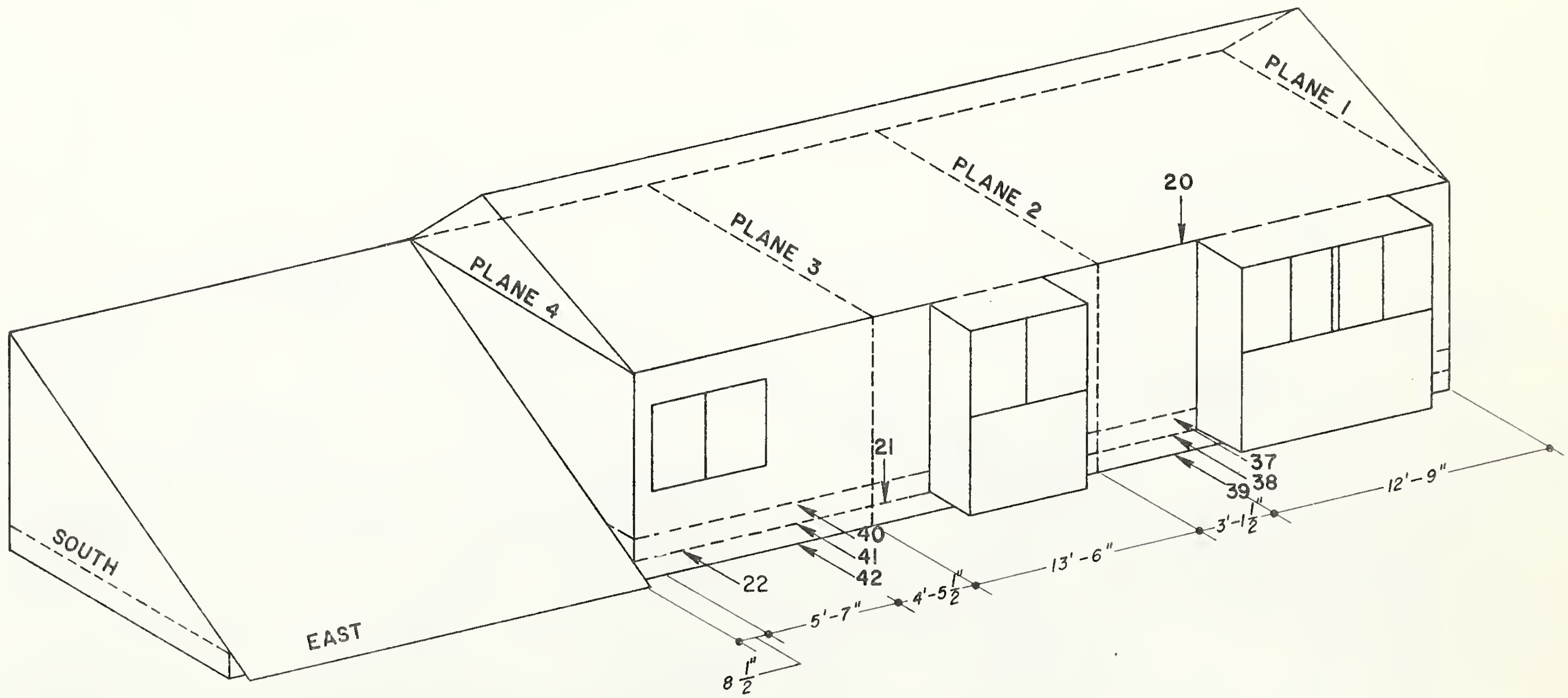


Figure 4.3 Exterior Instrumentation on the Front - Test 1

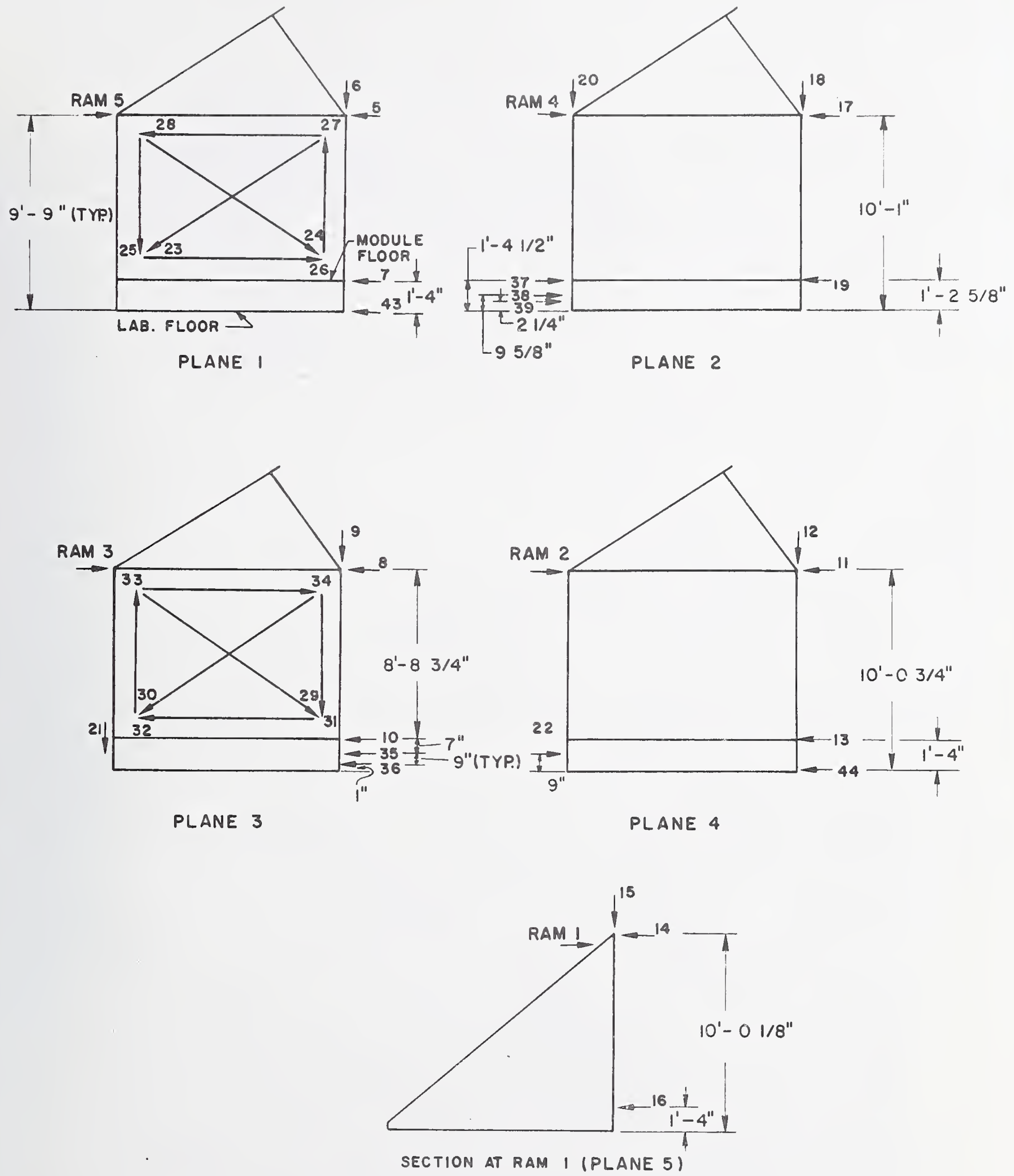


Figure 4.4 Cross Sections Showing Loading Rams and Instrumentation

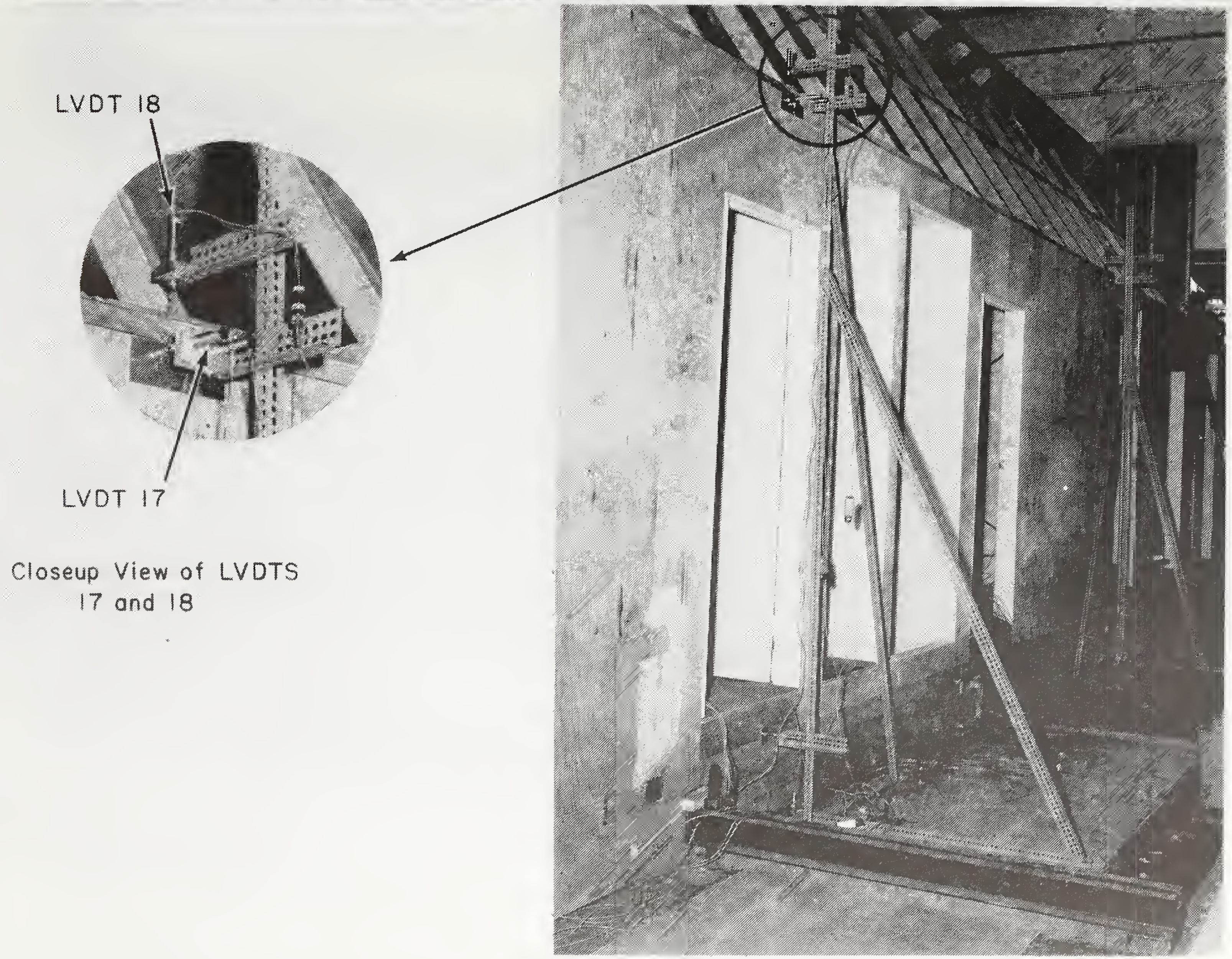


Figure 4.5 Typical Instrumentation Arrangement (Rear Wall)

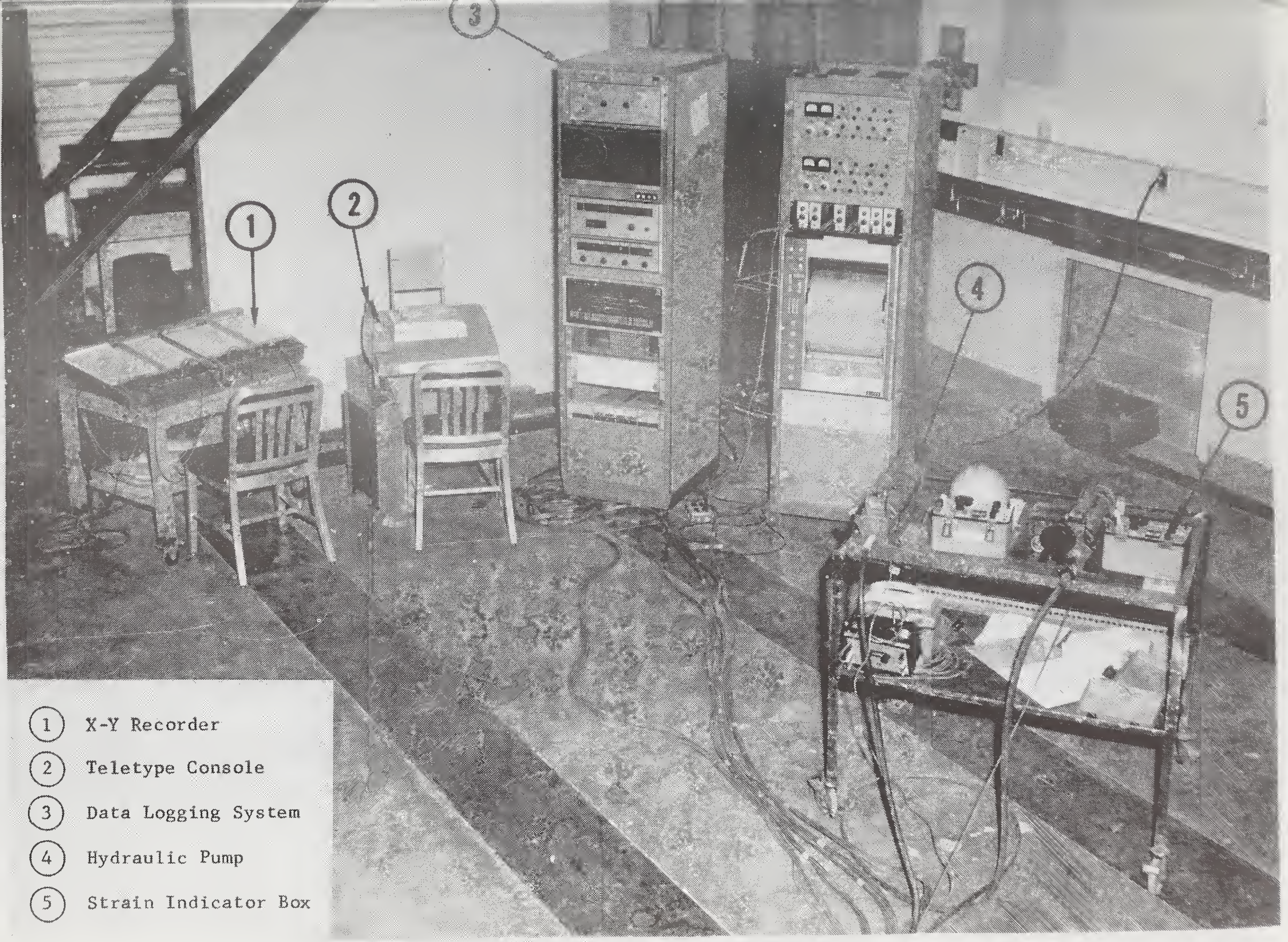


Figure 4.6 Data Acquisition Equipment and Hydraulic Pumps

Figure 4.7 Typical Setup for Transient Vibration Testing

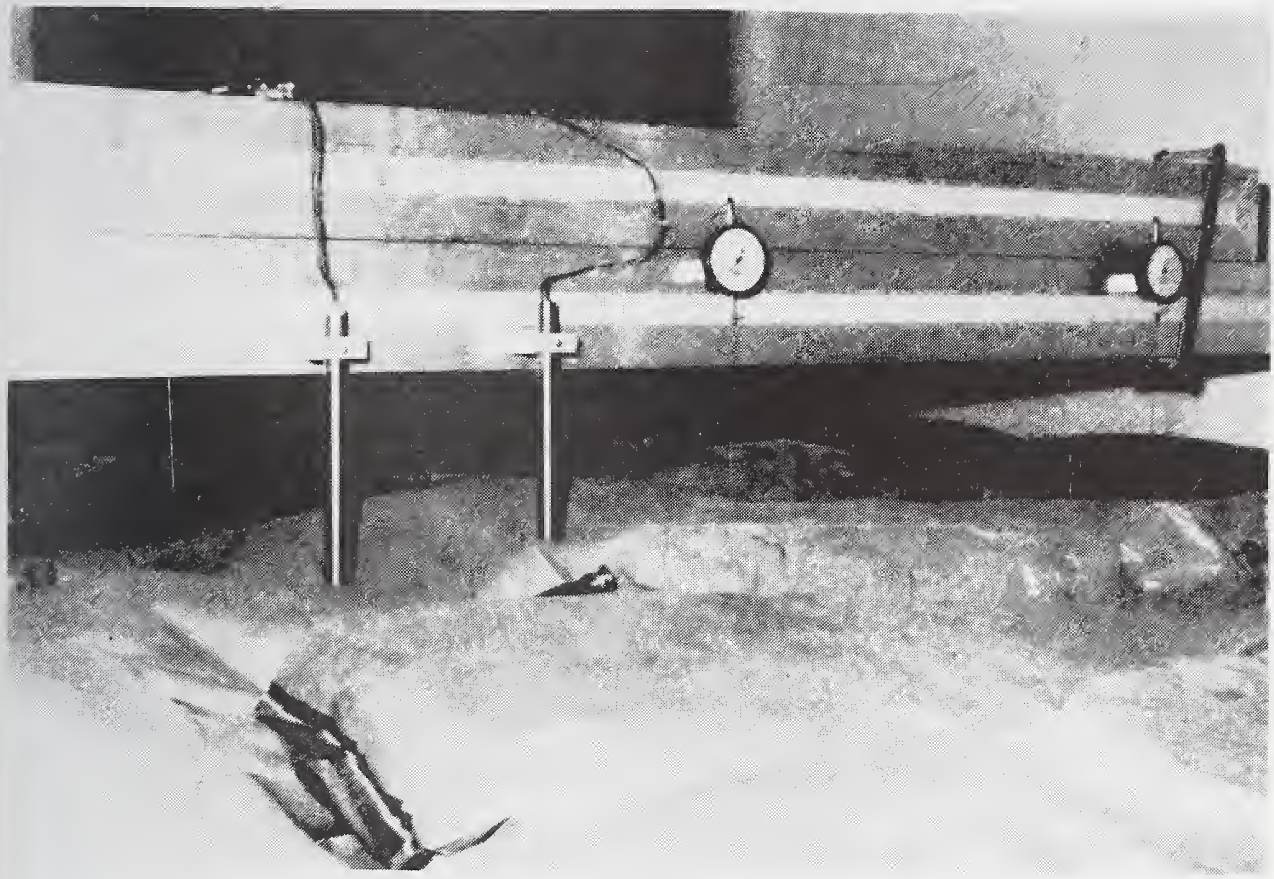


Figure 4.8 Partial View of Sustained Load Testing

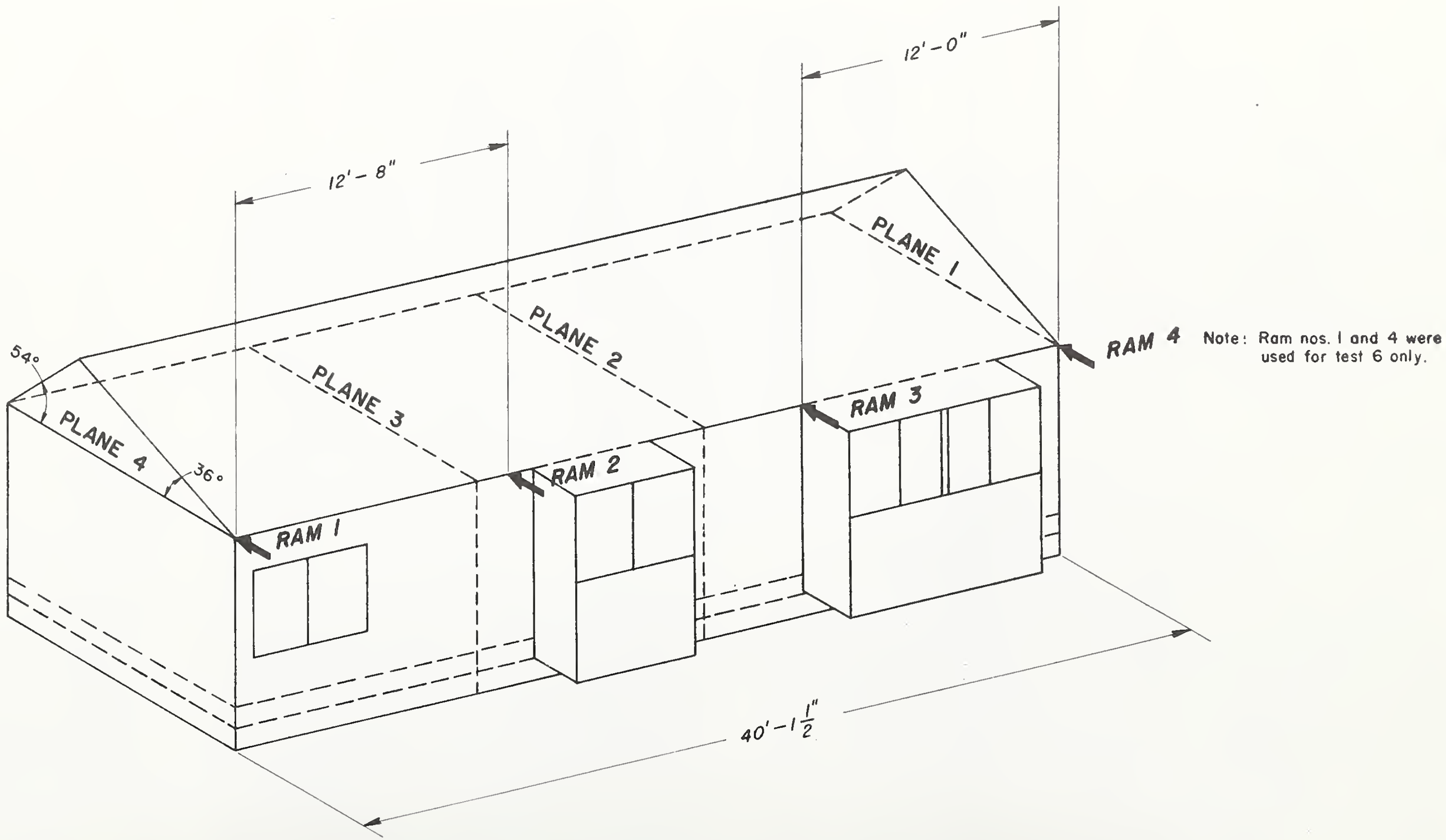


Figure 4.9 Ram Locations for Tests 4, 5 and 6

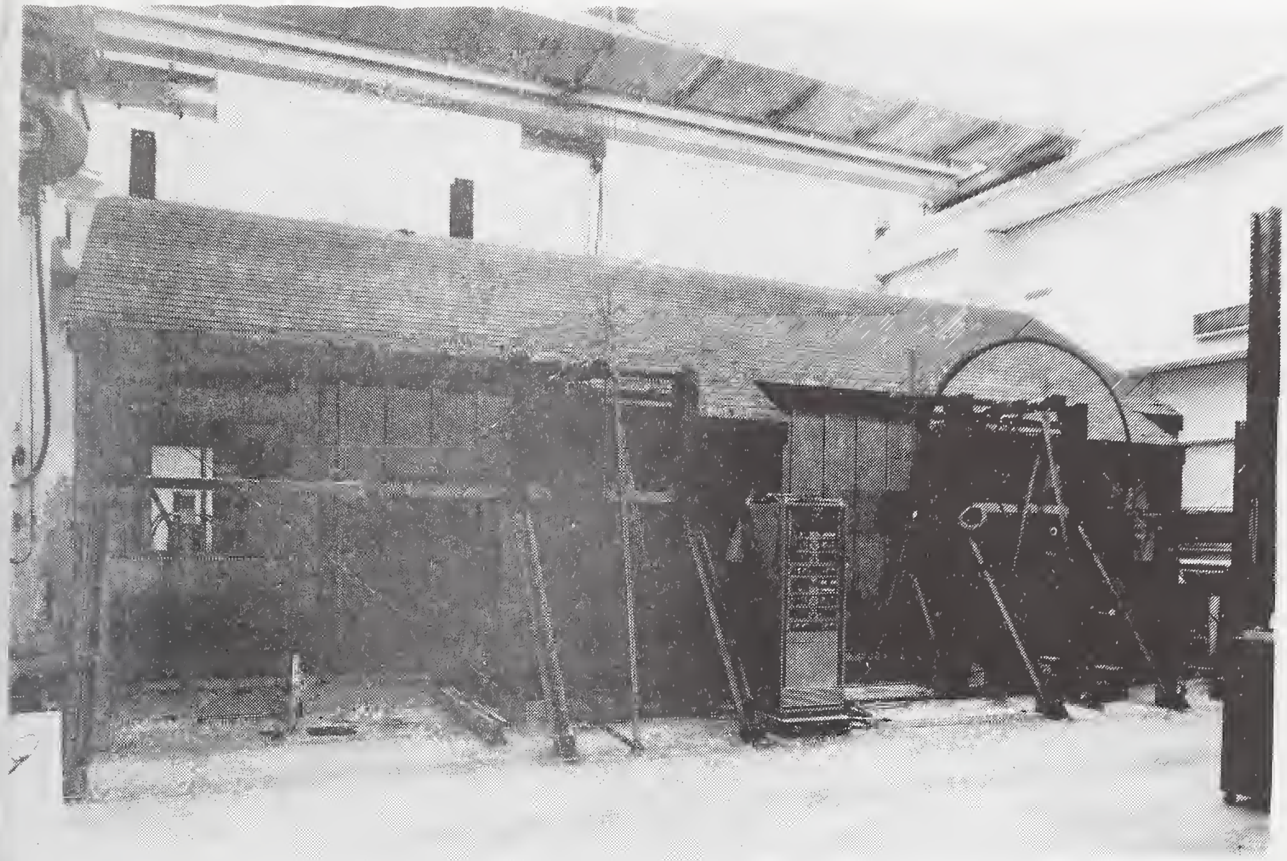


Figure 4.10 Test Setup for Repeated Racking

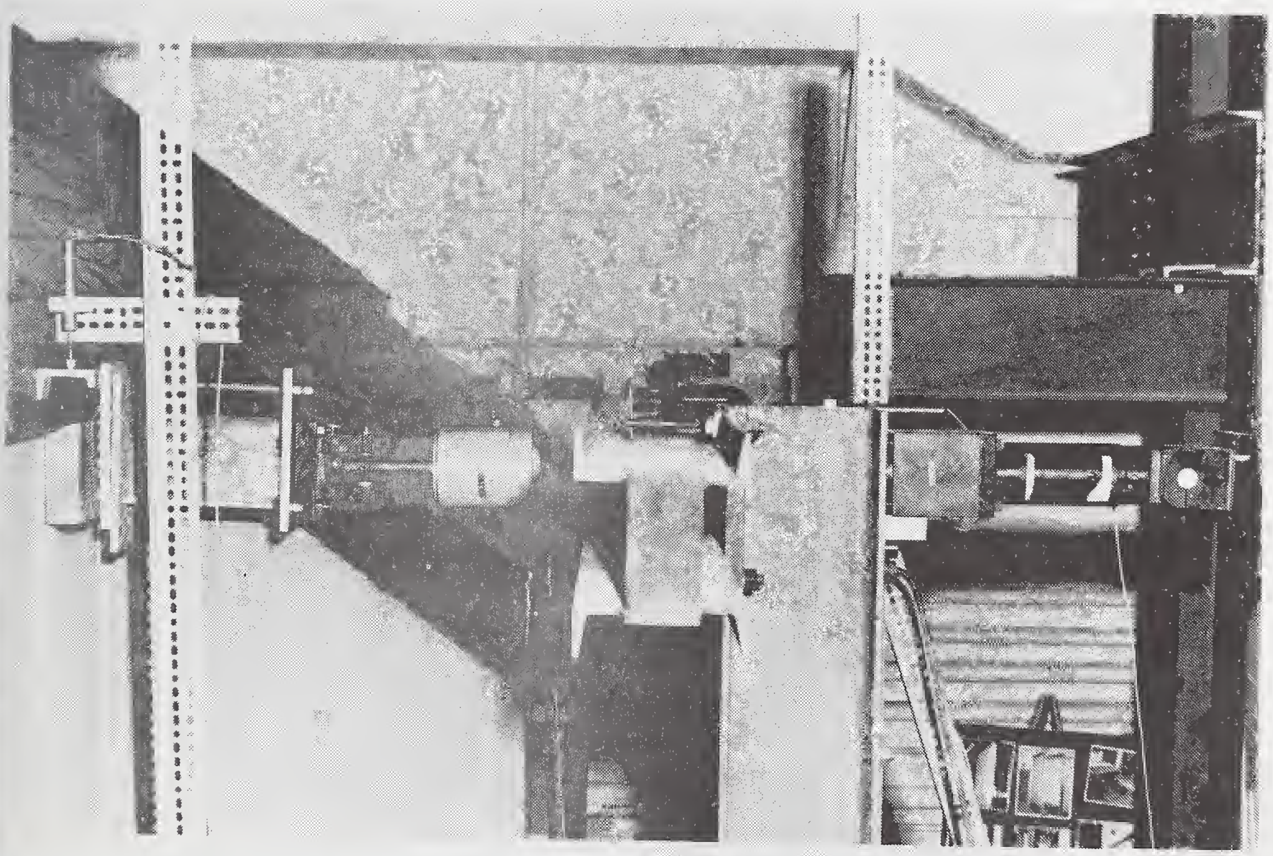


Figure 4.11 Closeup View of Ram in Region Shown in Figure 4.10

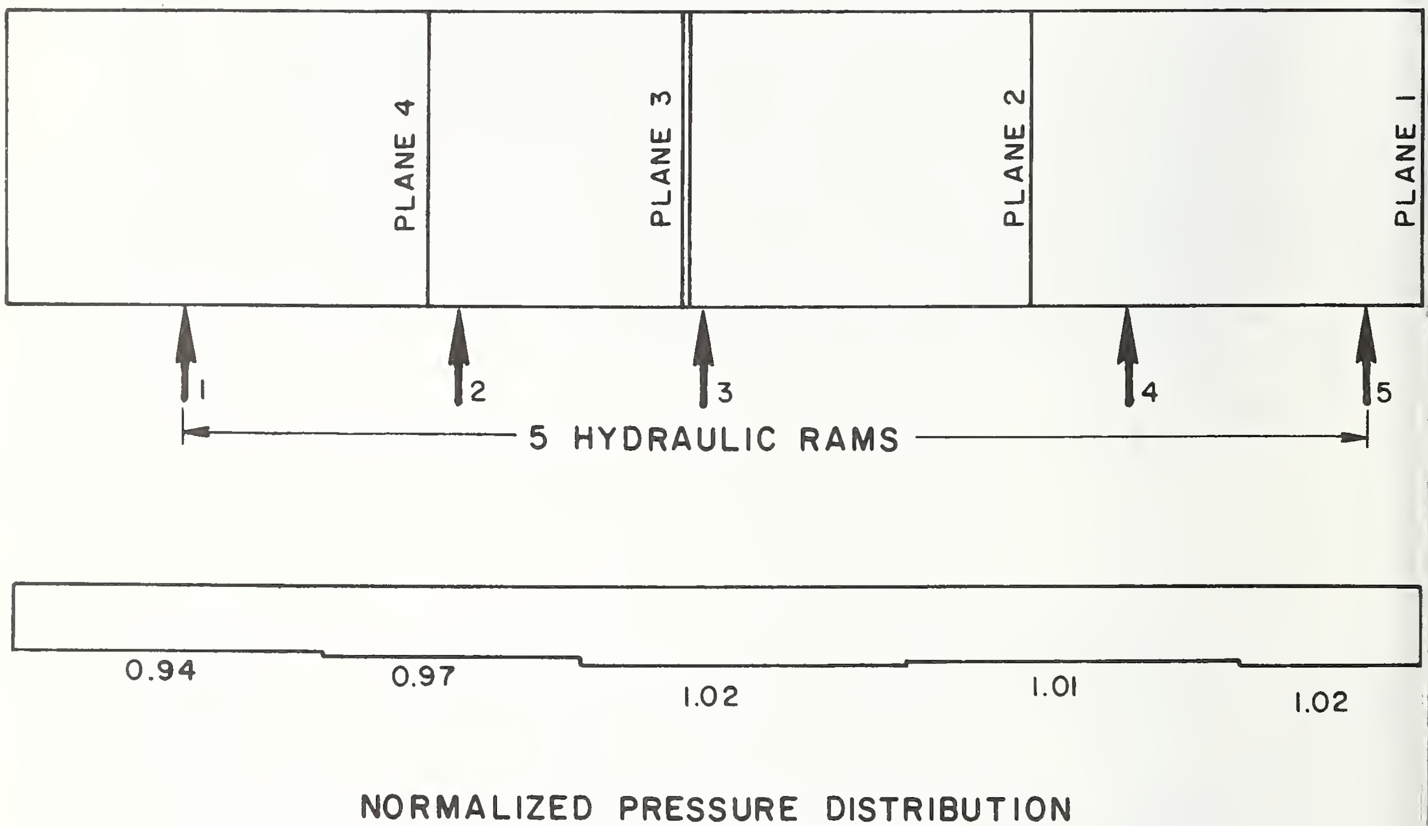


Figure 5.1 Pressure Distribution Effected by Loading Rams - Test 1

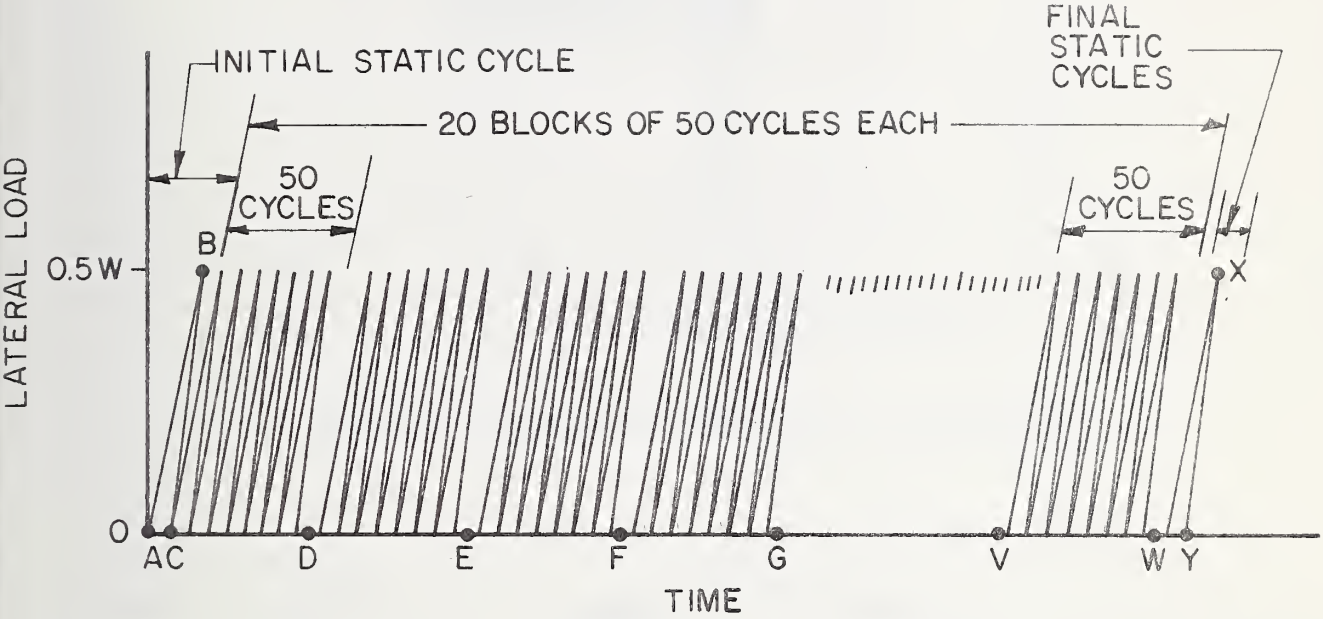


Figure 5.2 Loading Sequence for Test 4

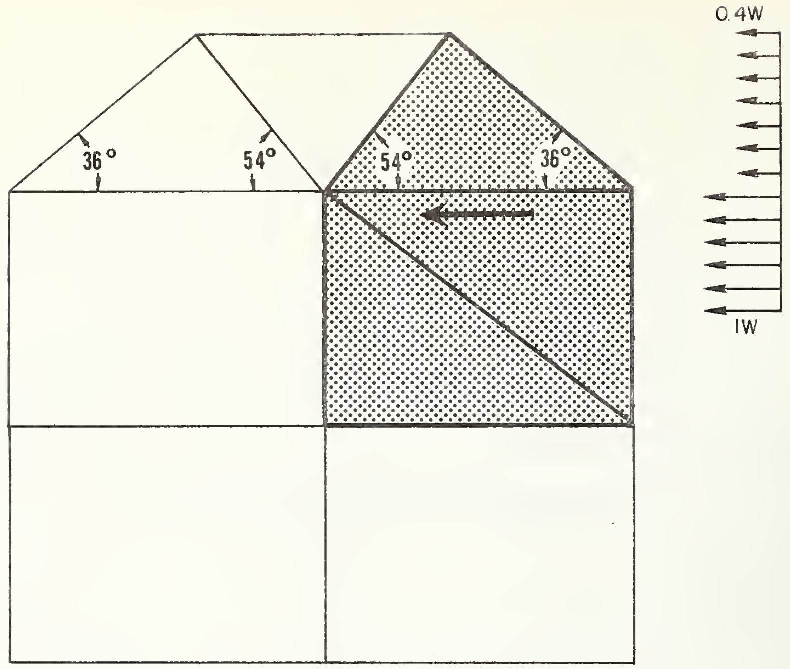


Figure. 5.3a Second Story

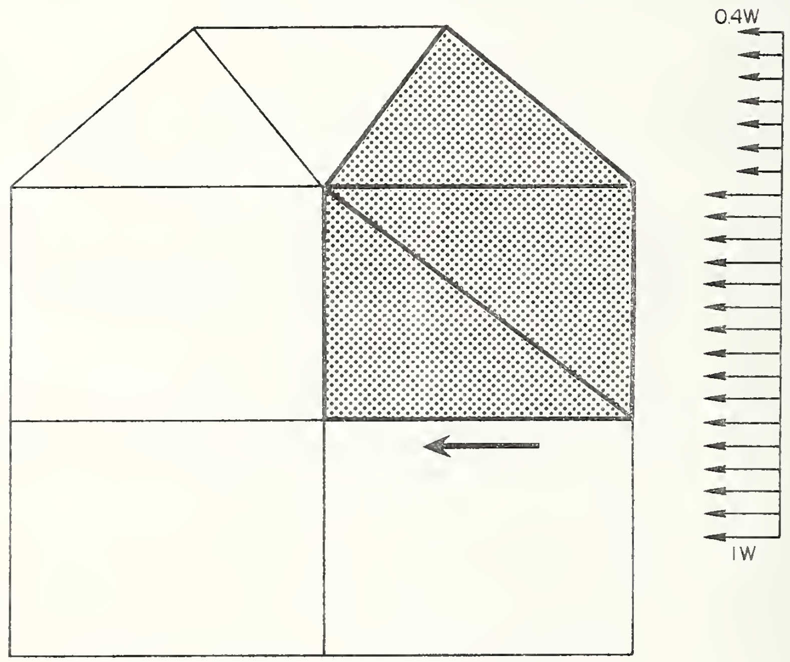
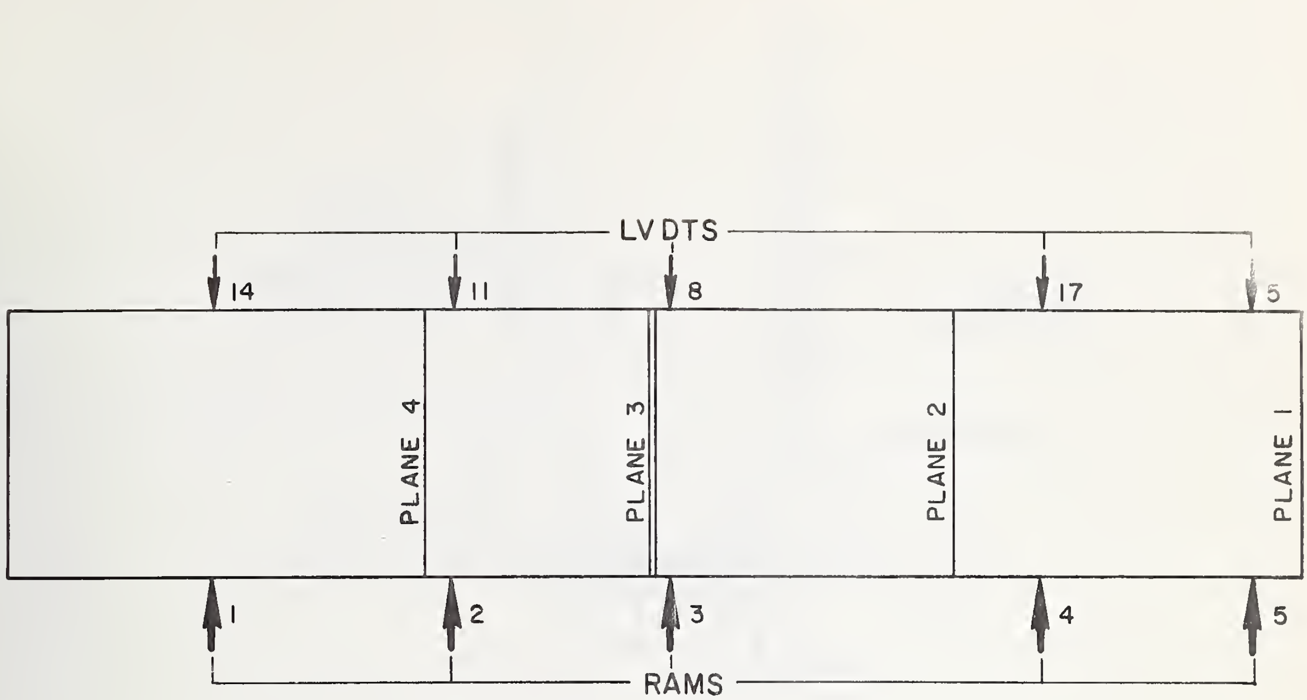
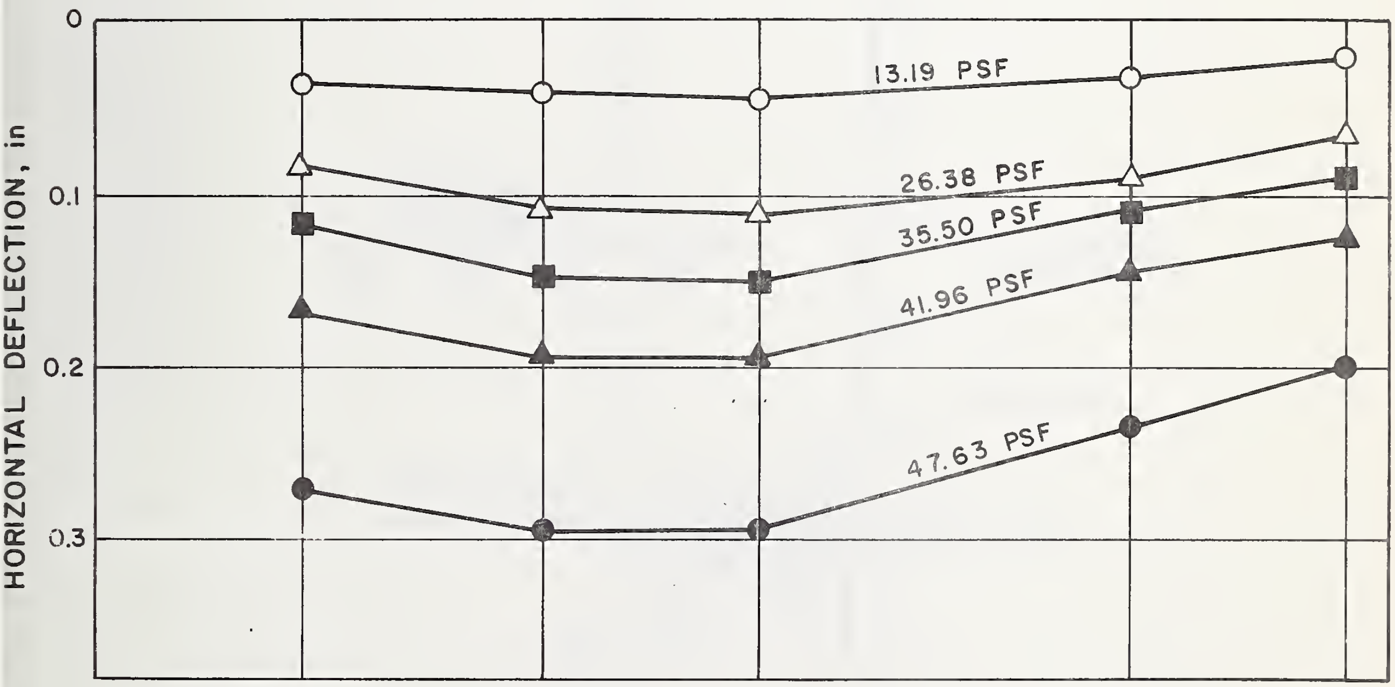


Figure. 5.3b First Story

Figure 5.3 Contributory Areas for Racking Loads in Test 1



PLAN OF RAMS AND HORIZONTAL TRANSDUCERS



LATERAL DISPLACEMENT PROFILE ALONG TOP REAR OF MODULE

Figure 6.1 Profile of the Lateral Displacement for Varying Simulated Wind Pressures - Test 1

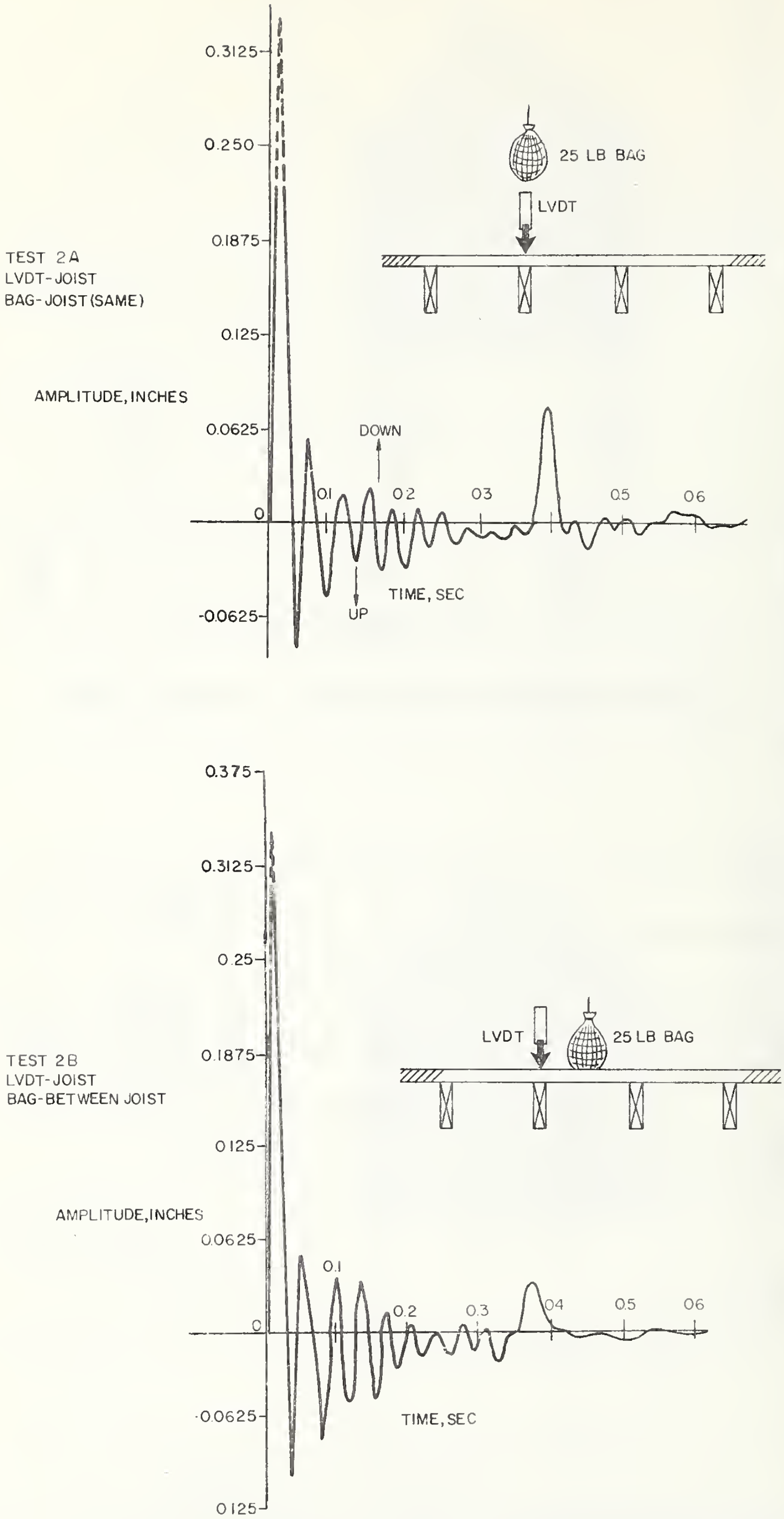
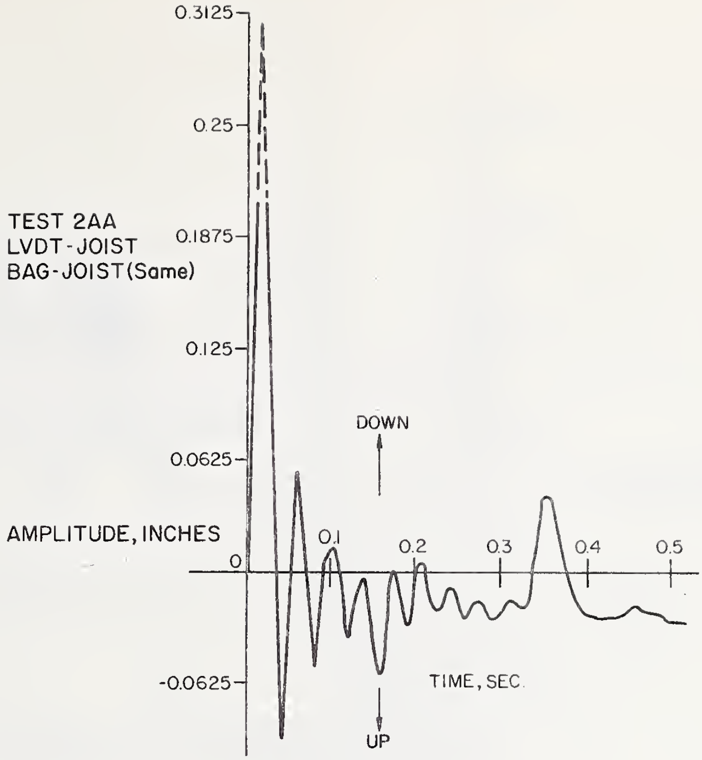


Figure 6.2 Deflection versus Time Traces for Tests 2A and 2B



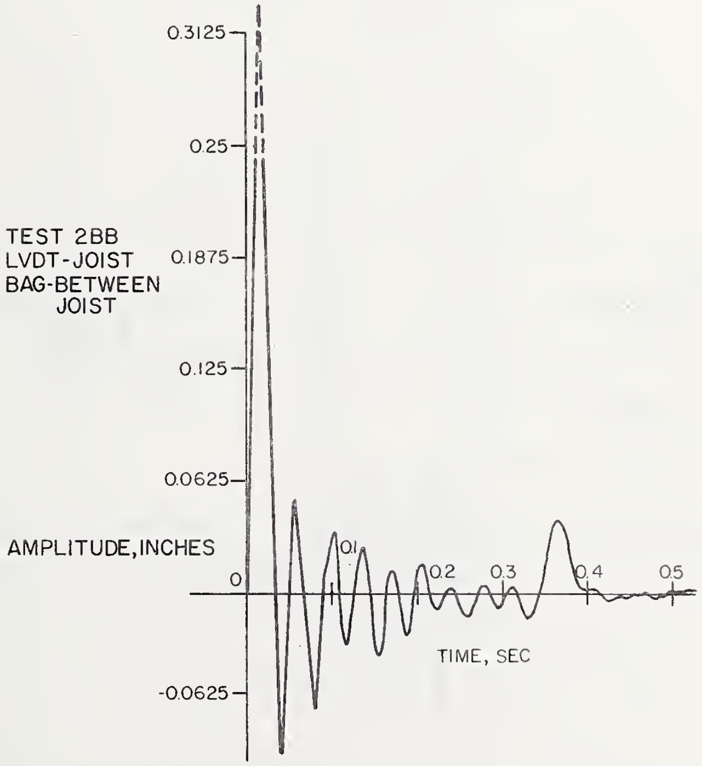
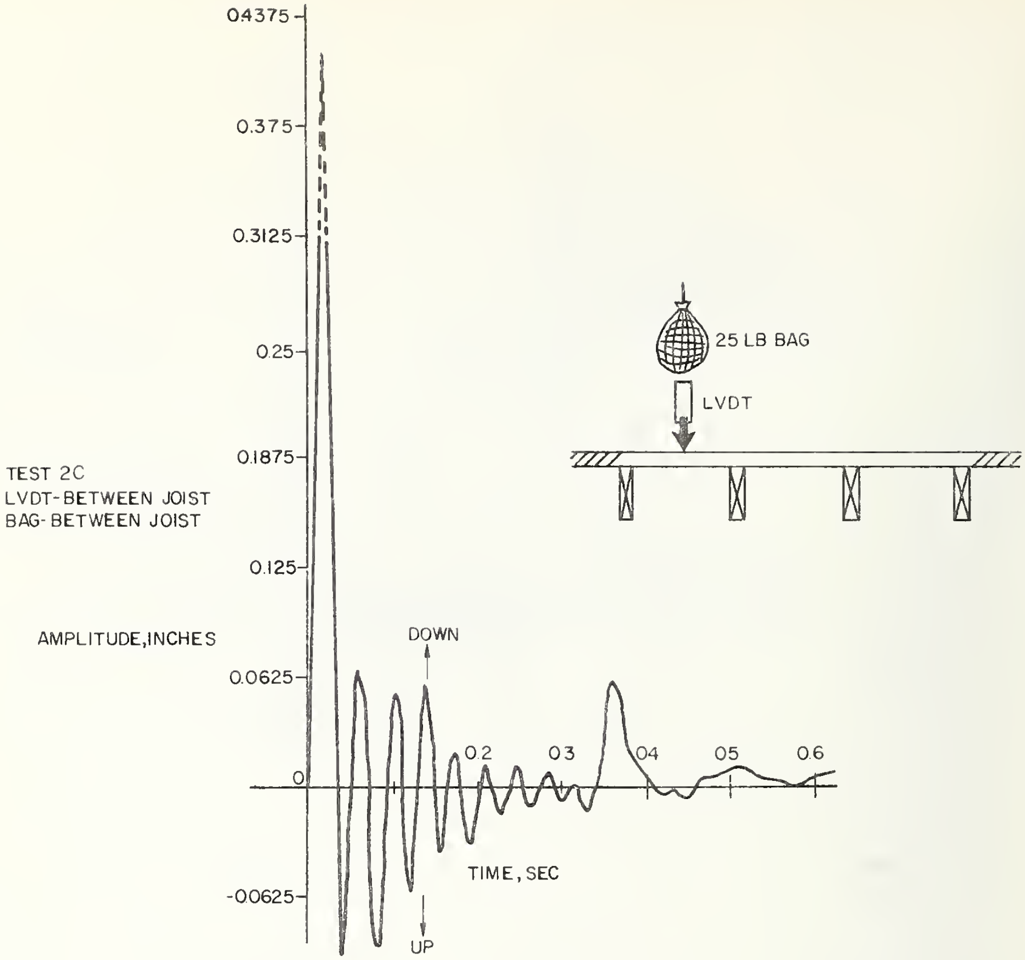


Figure 6.3 Deflection versus Time Traces for Tests 2AA and 2BB



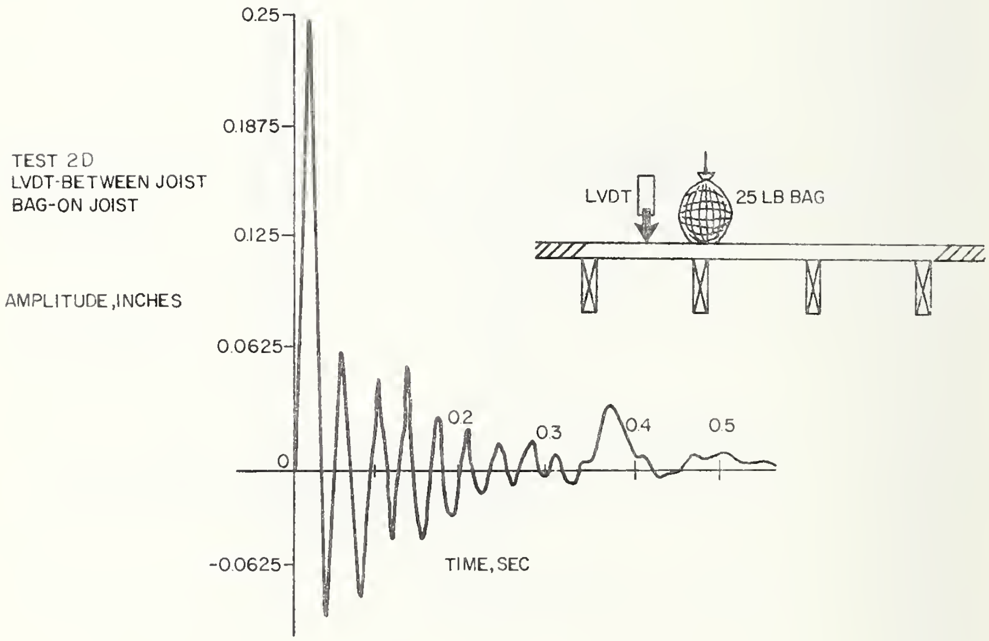
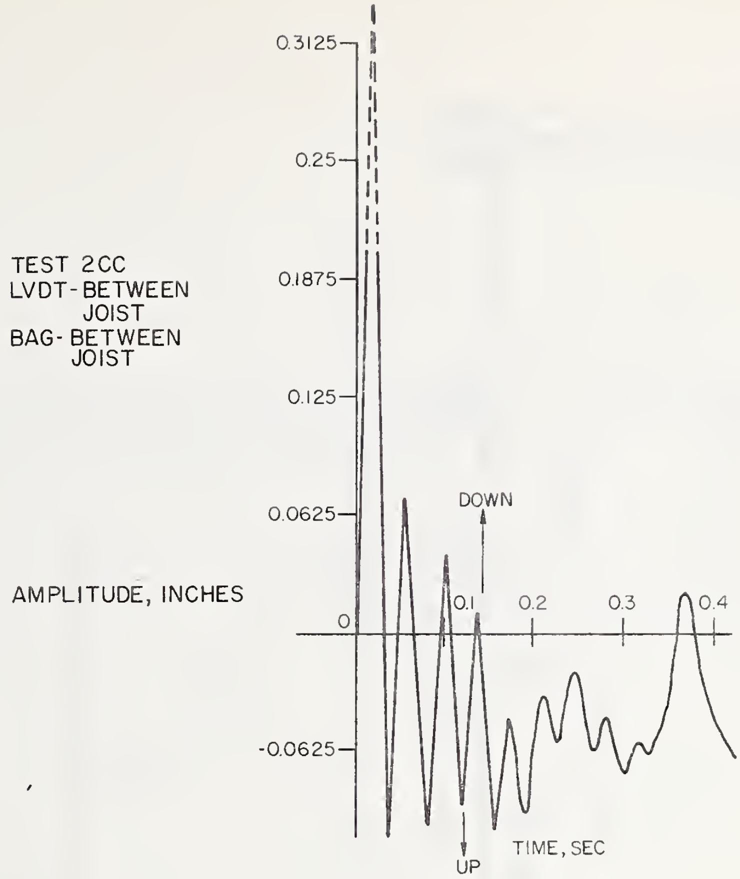


Figure 6.4 Deflection versus Time Traces for Tests 2C and 2D



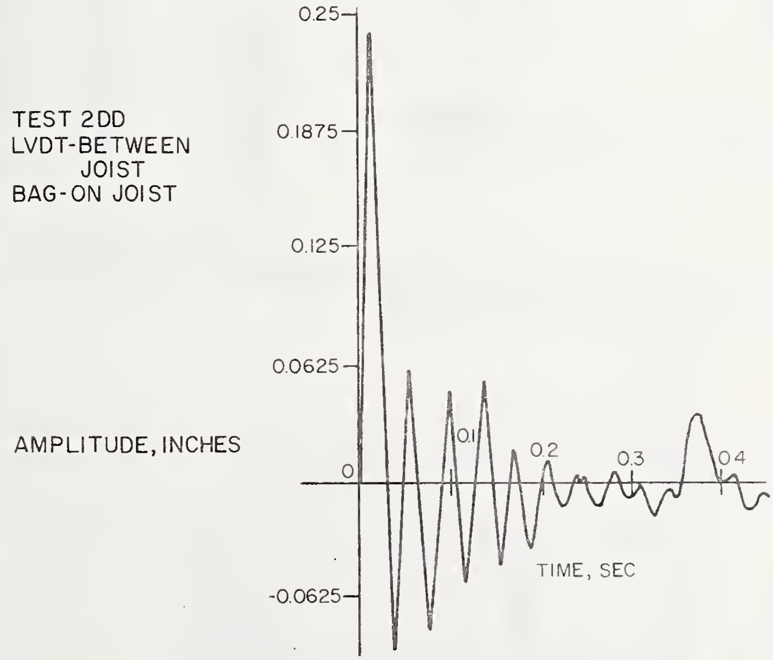


Figure 6.5 Deflection versus Time Traces for Tests 2CC and 2DD

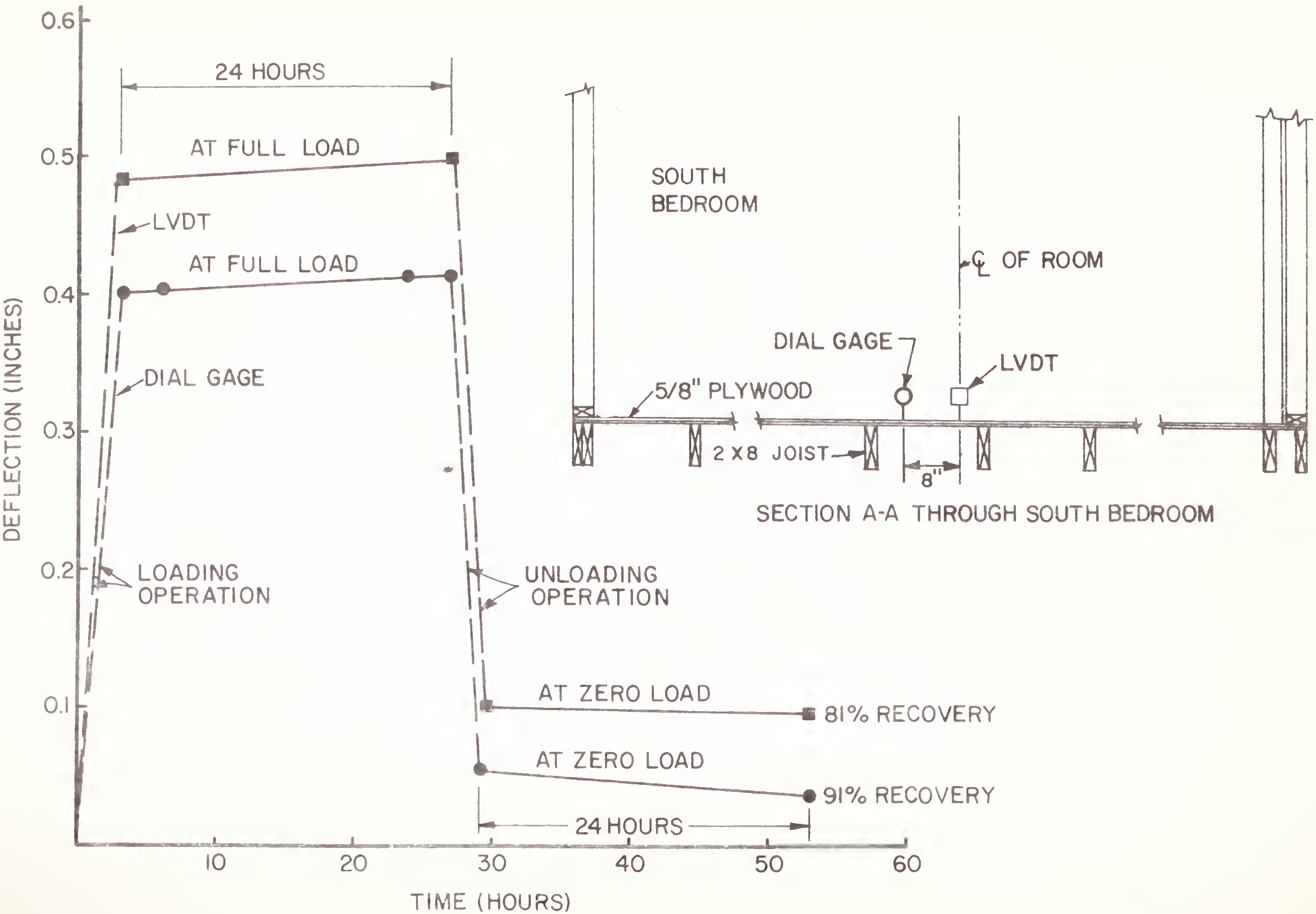


Figure 6.6 Graphical History of Floor Deflection Due to Sustained Loading - Test 3

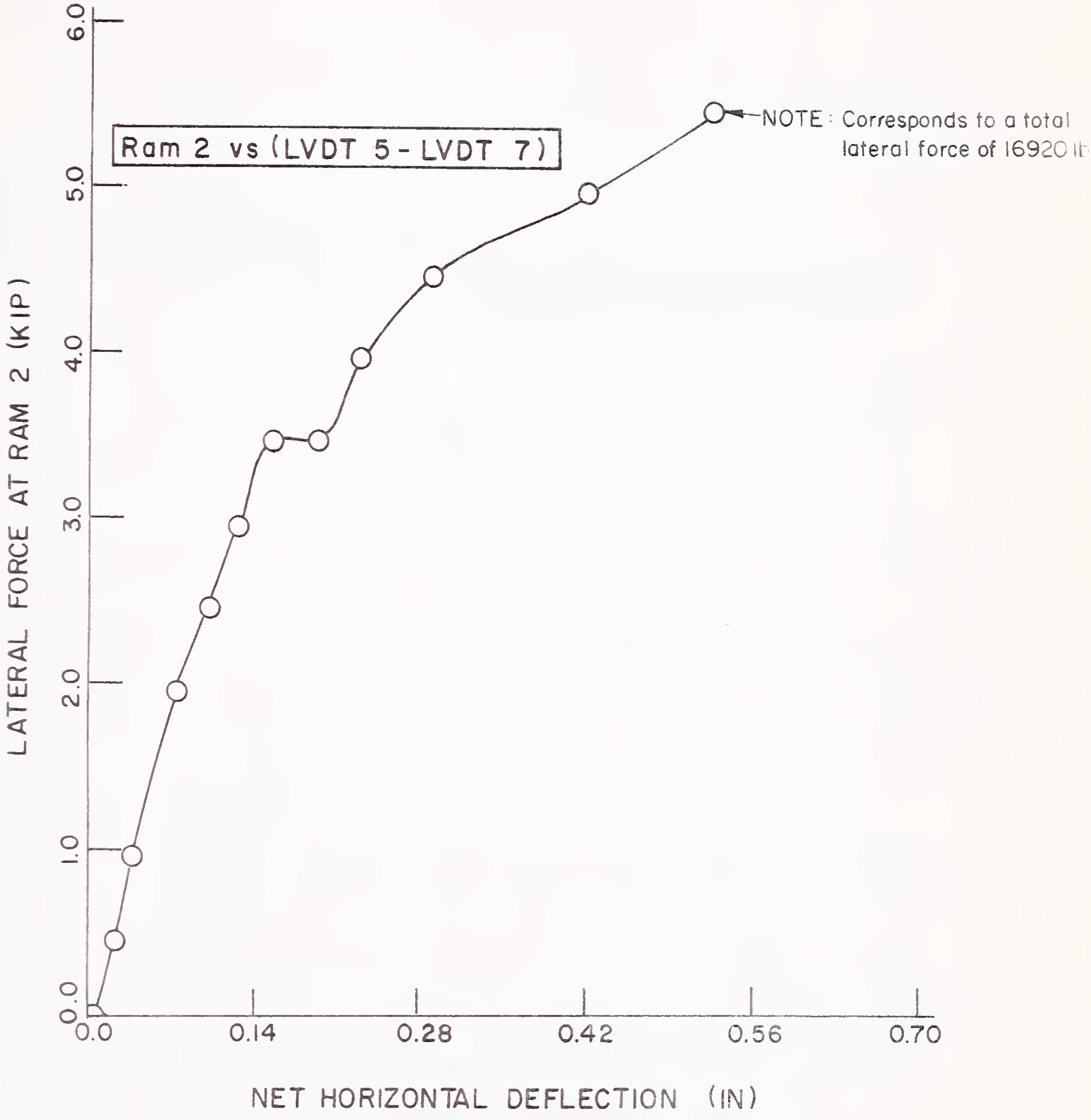


Figure 6.7 Lateral Force at Ram 2 versus Net Horizontal Deflection Along Plane 1 - Test 6

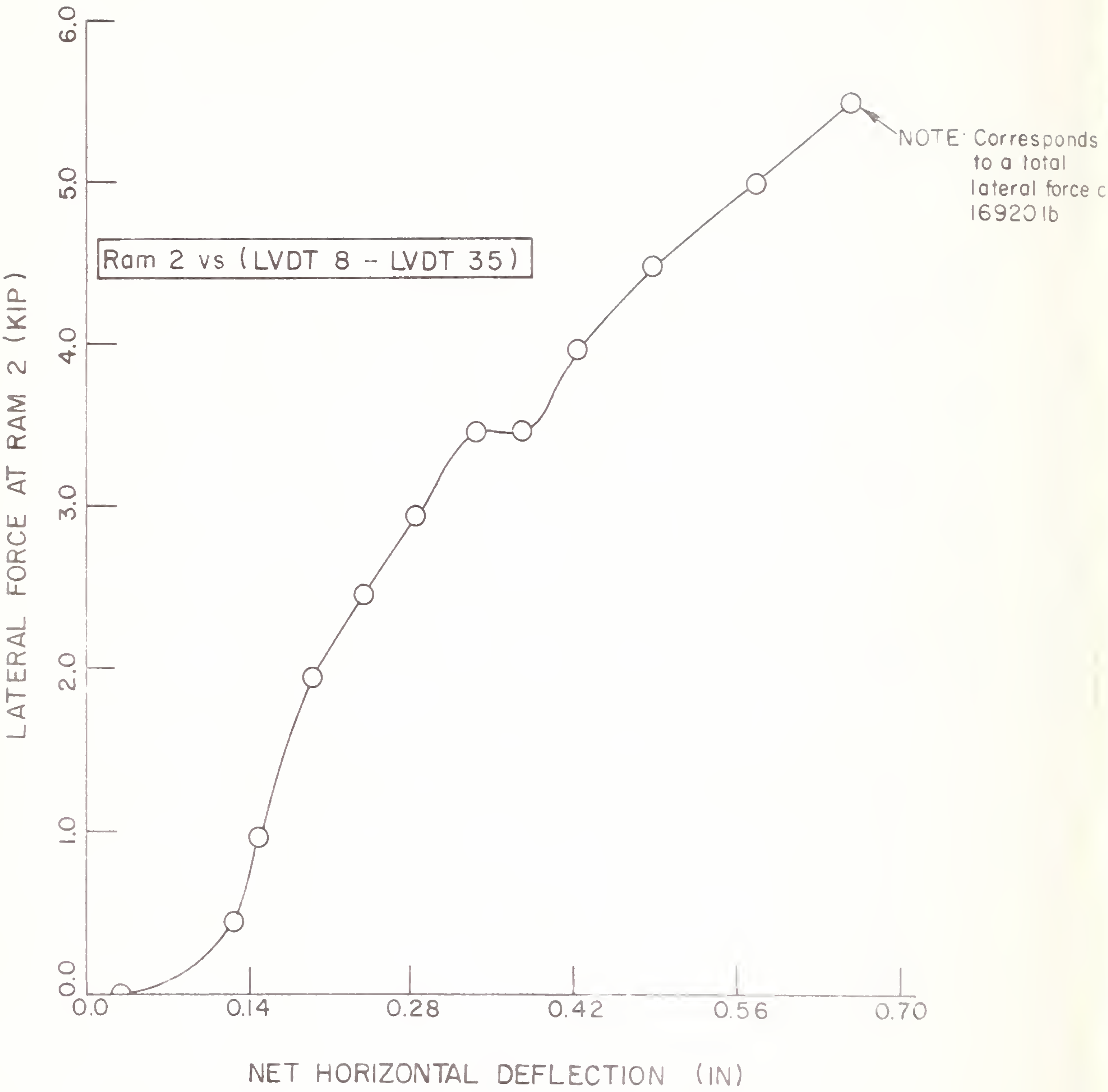


Figure 6.8 Lateral Force At Ram 2 versus Net Horizontal Deflection Along Plane 3 - Test 6

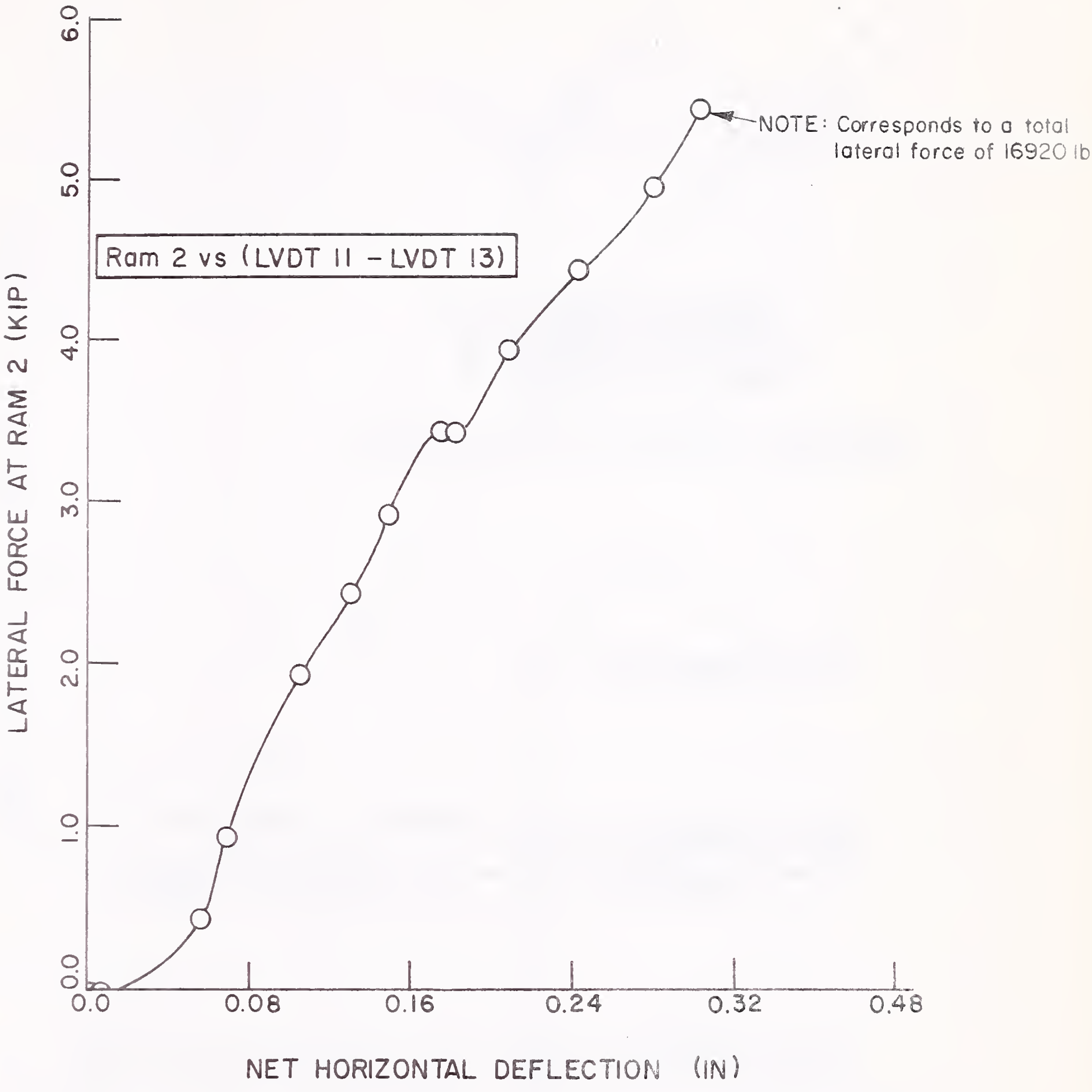


Figure 6.9 Lateral Force at Ram 2 versus Net Horizontal Deflection Along Plane 4 - Test 6

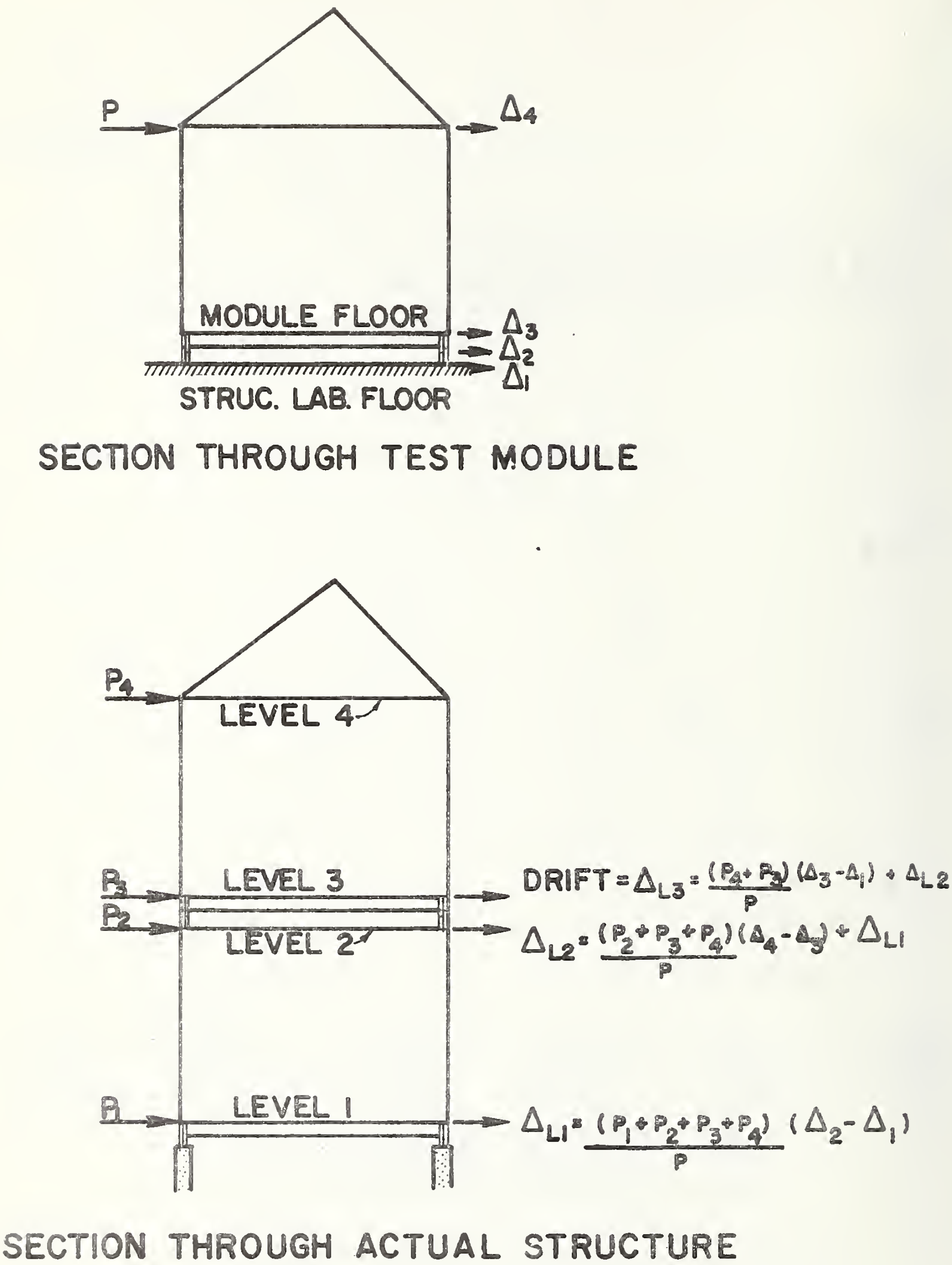


Figure 7.1 Analytical Model for Drift Derivation - Test 1

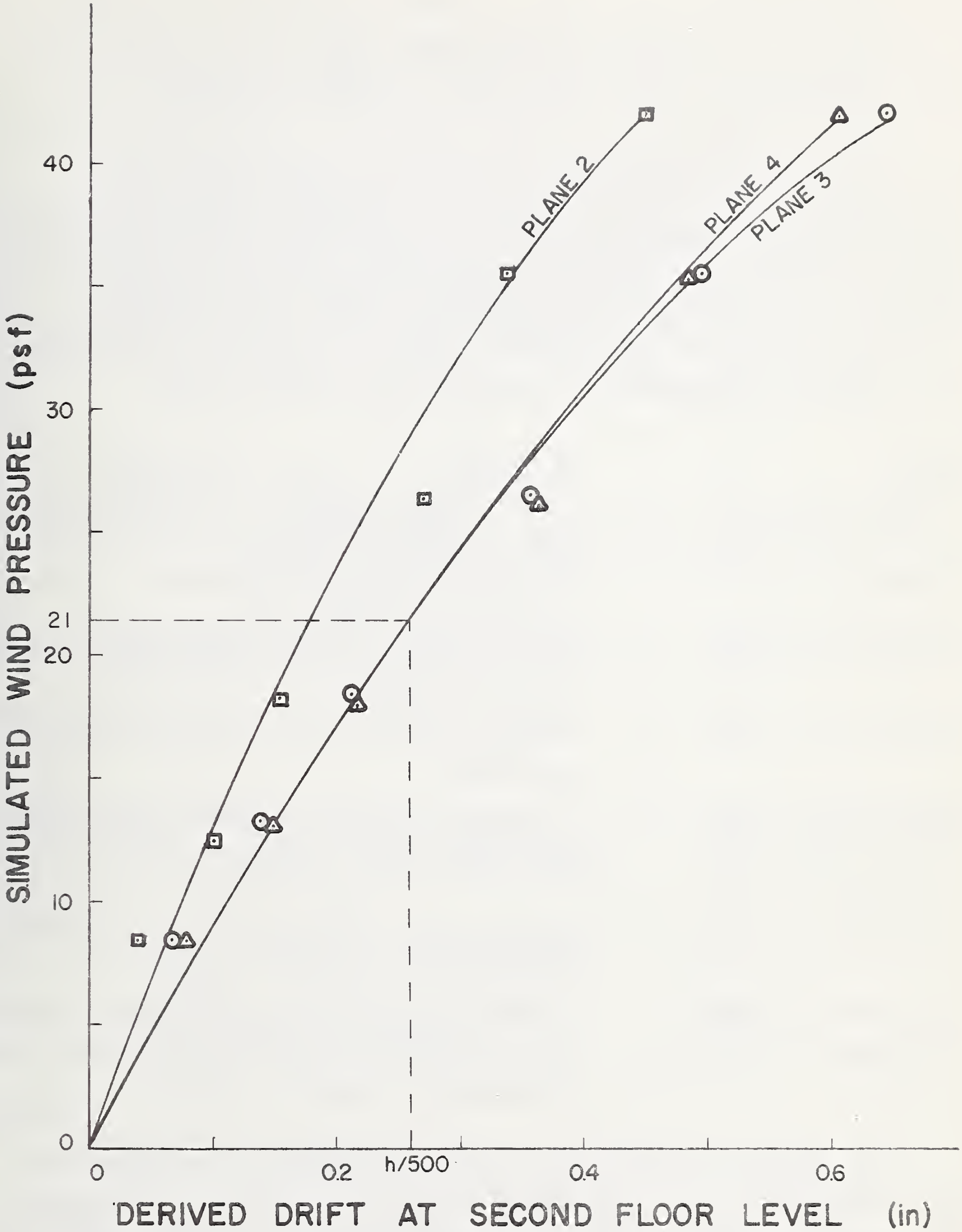


Figure 7.2 Wind Pressure versus Derived Drift Curves - Test 1

RECORD OF CRACK FORMATION ON INTERIOR SURFACES

The following record described the cracking patterns observed on the interior surfaces of the test module for the entire history of lifting and shipping, prior to structural testing. In order for the reader to relate the observed cracking to one of the several events, a capsule history of the handling operations is provided in tabular form.

Date	Activity
January 13, 1971	Trial crane lift by the producer in the assembly plant
January 14, 1971	Module lifted from assembly base onto a flatbed trailer
January 14, 1971	Short trip by truck from assembly plant to rail siding
January 14, 1971	Module lifted from trailer to 89'-6" rail car
January 15, 1971	A series of five railroad hump tests
January 20, 1971 - February 14, 1971	850-mile rail trip from Michigan to NBS
February 16, 1971	Crane lift from rail car to a flatbed trailer
February 16, 1971	1-mile truck ride to structures laboratory
February 16, 1971	Module lifted from flatbed trailer to laboratory support assembly

It should be noted that the description of a given crack--once identified--is considered to be unchanged for subsequent activities unless it is specifically noted. The four room areas of the module are assigned numbers from I to IV. The Living

Room Space is assigned the number I, the South Bedroom is labeled Room II, the Middle Bedroom is labeled Room III and Room IV is the North Bedroom. The four walls of any given room area are labeled XF, XR, XS, XN, where X is a number from I to IV. The second symbol refers to the orientation of the wall in relation to the floor plan in figure 2.2. The symbols F and R refer to the front and rear walls, respectively; the south wall is denoted by S and the north wall is denoted by N. Thus, a designation such as IIF refers to the front wall of the South Bedroom.

Date: January 14, 1971

Module Status: a) Module resting on flatbed trailer at rail siding, b) Module resting on rail car prior to Bump Tests

Note: Observations were recorded for Status a) above and then checked for Status b).

Room Number: II

Crack #1

Location: On wall IIF, 11 1/4 in to the left of the lower edge of the window frame.

Description of Crack:

Type: Vertical surface crack

Length: 15 1/4 in

Max. Width: 0.011 in

Crack #2

No data was recorded.

Crack #3

Location: On wall IIF, beginning just below left edge of window frame.

Description of Crack:

Type: Vertical, hairline crack

Length: 15 in

Max. Width: Not measurable

Crack #4

Location: On wall IIF between bottom of window sill and electrical outlet.

Description of Crack:

Type: Vertical, hairline crack

Length: 10 in

Max. Width: Not measurable

Crack #5

Location: At intersection between the ceiling and wall IIL. Crack begins at wall IIR.

Description of Crack:

Type: Horizontal crack in the tape at the joint.

Length: 12 7/8 in

Max. Width: 0.216 in

Crack #6

Location: On wall IIF, 10 7/8 in to the left of the window frame.

Description of Crack:

Type: Vertical, hairline crack

Length: 3 1/4 in

Max. Width: Not measurable

Crack #7

Location: At the corner formed by walls IIF and IIS, beginning at the top of the base board and extending upward to bottom of window sill.

Description of Crack:

Type: Vertical tear in the tape joint

Length: No data recorded

Max. Width: 0.060 in

Date: January 15, 1971

Module Status: Module resting on rail car prior to Bump Tests

Note: Module's interior was scrutinized prior to lifting from trailer to rail car, but no data was recorded due to the time element. However, it was generally observed that all the cracks documented below were previously observed when the module was resting on the trailer.

Room Number: III

Crack #1

Location: On wall IIIF, immediately to the right of the header above the push-out bay window.

Description of Crack:

Type: Horizontal, hairline crack

Length: 3 in

Max. Width: Not measurable

Crack #2

Location: On wall IIIF, extending the entire length between the right hand corner of the push-out window frame and the top of the baseboard.

Description of Crack:

Type: Vertical, hairline crack

Length: Approximately 20 in (not measured)

Max. Width: Not measurable

Crack #3

Location: On wall IIIF, at about the middle of the window frame; extending from the head of the push-out bay window to the ceiling.

Description of Crack:

Type: Vertical, hairline crack

Length: Approximately 16 in (not measured)

Max. Width: Not measurable

Crack #4

Location: On wall IIIF, extending from the left edge of the header over the push-out bay window to the ceiling.

Description of Crack:

Type: Vertical, hairline crack

Length: Approximately 16 in (not measured)

Max. Width: Not measurable

Crack #5

Location: On wall IIIF, extending from the left hand corner of the window sill (push-out bay window).

Description of Crack:

Type: Diagonal, hairline crack

Length: 5 1/2 in

Max. Width: not measurable

Crack #6

Location: At the joint between wall IIIN and the ceiling. Crack begins 5 1/2 in south of the closet (see figure 2.2).

Description of Crack:

Type: Horizontal crack in the tape joint

Length: 21 in

Max. Width: Data not recorded

Date: January 15, 1971

Module Status: Module resting on the rail car prior to Bump Tests

Note: Module's interior was scrutinized prior to the lift from the trailer to the rail car, but no data was recorded. However, it was generally observed that all the cracks documented below were previously observed when the module was resting on the trailer.

Room Number: IV

All cracks were located on wall IVF.

Crack #1

Location: At right edge of the header above the push-out bay window.

Description of Crack:

Type: Vertical, hairline crack

Length: 3 in

Max. Width: Not measurable

Crack #2

Location: Located within the right 1/3 of the push-out bay window, immediately above the header. Crack extended full length between the header and the ceiling.

Description of Crack:

Type: Vertical, hairline crack

Length: Approximately 16 in (not measured)

Max. Width: Not measurable

Crack #3

Location: Directly above the center of the push-out window, extending from the header to the ceiling.

Description of Crack:

Type: Vertical, hairline crack

Length: Approximately 16 in (not measured)

Max. Width: Not measurable

Crack #4

Location: Above the header of the push-out window; the center of the crack was located 4 ft to the south of the left side of the window frame.

Description of Crack:

Type: Vertical, hairline crack

Length: 4 in

Max. Width: Not measurable

Crack #5

Location: Projecting from directly above the left edge of the window header.

Description of Crack:

Type: Vertical, hairline crack

Length: 2 in

Max. Width: Not measurable

Crack #6

Location: Situated between the bottom of the window sill and the electrical outlet.

Description of Crack:

Type: Vertical, hairline crack

Length: 7 in

Max. Width: Not measurable

Crack #7

Location: Situated between the electrical outlet and the top of the baseboard.

Description of Crack:

Type: Vertical, hairline crack

Length: 4 3/4 in

Max. Width: Not measurable

Date: January 15, 1971

Module Status: Module resting on rail car subsequent to the 5th (i.e. the last) Bump Test

Room Number: II

Crack #5

Location: Previously given.

Description of Crack:

Same as before

Length: No change

Max. Width: Crack closed to the point that width was no longer measurable

Crack #8

Location: On wall IIS, 1 in below the ceiling

Description of Crack:

Type: Horizontal, hairline crack

Length: Approximately 72 in

Max. Width: Not measurable

Date: Febraury 17, 1971

Module Status: Module resting on the laboratory support assembly after final lifting

Room Number: I

Crack #1

Location: On wall IS at the joint between the ceiling and the wall. The crack projected from a point approximately midway down the sloping roof line.

Description of Crack:

Type: Diagonal crack in the tape, following the slope of the roof.

Length: 7 in

Max. Width: Not measurable

Crack #2

Location: On wall IS, beginning at the ceiling line and projecting downward. The topmost point of the crack was located 1 ft-10 in from wall IF (actually no wall here, but rather an eave).

Description of Crack:

Type: Diagonal, hairline crack

Length: 12 in

Max. Width: Not measurable

Crack #3

Location: On wall IS, immediately adjacent to wall IF, near the bottom of the wall.

Description of Crack: Half-moon crack in the gypsum wall board. Width of crack was not measurable.

Room Number: II

Note: The following cracks were all observed on wall IIR.

Crack #9

Location: At the upper left corner of the door jamb which is adjacent to the Living Room Space (see figure 2.2).

80

Description of Crack:

Type: Vertical surface crack

Length: 12 1/2 in

Max. Width: 3/64 in

Crack #10

Location: At the joint between wall IIR and the ceiling, near the corner formed by wall IIS.

Description of Crack:

Type: Horizontal tear in the tape joint.

Length: 28 in

Max. Width: No data recorded

Crack #11

Location: Projecting from the end of Crack #10.

Description of Crack:

Type: Vertical, hairline crack

Length: 3 1/4 in

Max. Width: Not measurable

Crack #12

Location: To the north of the door jamb nearest the Living Room Space.

Description of Crack:

Type: Vertical, hairline crack

Length: 11 1/2 in

Max. Width: 1/64 in

Crack #13

Location: At the joint between the wall and ceiling about midway between walls IIN and IIS.

Description of Crack:

Type: Horizontal, hairline crack in the joint.

Length: 37 in

Max. Width: Not measurable

Note: The following cracks were all observed on wall IIF and their width was not measurable.

Crack #14

Location: Around window frame.

Description of Crack:

Type: Vertical, hairline crack

Length: 4 1/4 in

Crack #15

Location: Above window frame at the ceiling line.

Description of Crack:

Type: Horizontal, hairline crack in the tape joint

Length: 9 1/2 in

Crack #16

Location: At the corner formed by walls IIF and IIS, beginning just above the end of Crack #7.

Description of Crack:

Type: Vertical tear in the tape joint

Length: 23 1/2 in

Crack #17

Data is too incomprehensible to report

Crack #18

Location: At the corner formed by walls IIF and IIS, near the ceiling.

Description of Crack:

Type: Vertical, hairline crack in the tape joint.

Length: 2 1/2 in

Room Number: III

Crack #7

Location: On wall IIIR, at left edge of the door jamb.

Description of Crack:

Type: Vertical, hairline crack

Length: 9 1/2 in

Max. Width: Not measurable

Crack #8

Location: Along the joint between wall IIIR and the ceiling, beginning 1 1/2 in from wall IIIS.

Description of Crack:

Type: Horizontal tear in the tape joint, barely visible in some places.

Length: 12 1/2 in

Max. Width: Not measurable

Crack #9

Location: Inside the closet at the joint between the ceiling and the walls.

Description of Crack: Hairline crack in the tape, extending completely around the perimeter of the closet. The width was not measurable.

Room Number: IV

Crack #8

Location: Center of the crack was 2 in below the ceiling on wall IVN; crack began 4'-6" from wall corner formed by wall IVR.

Description of Crack:

Type: Horizontal, hairline crack

Length: 48 in

Max. Width: Not measurable

Crack #9

Location: On wall IVN, beginning 1 in below the ceiling.

Description of Crack:

Type: Vertical, hairline crack

Length: 3 in

Max. Width: Not measurable

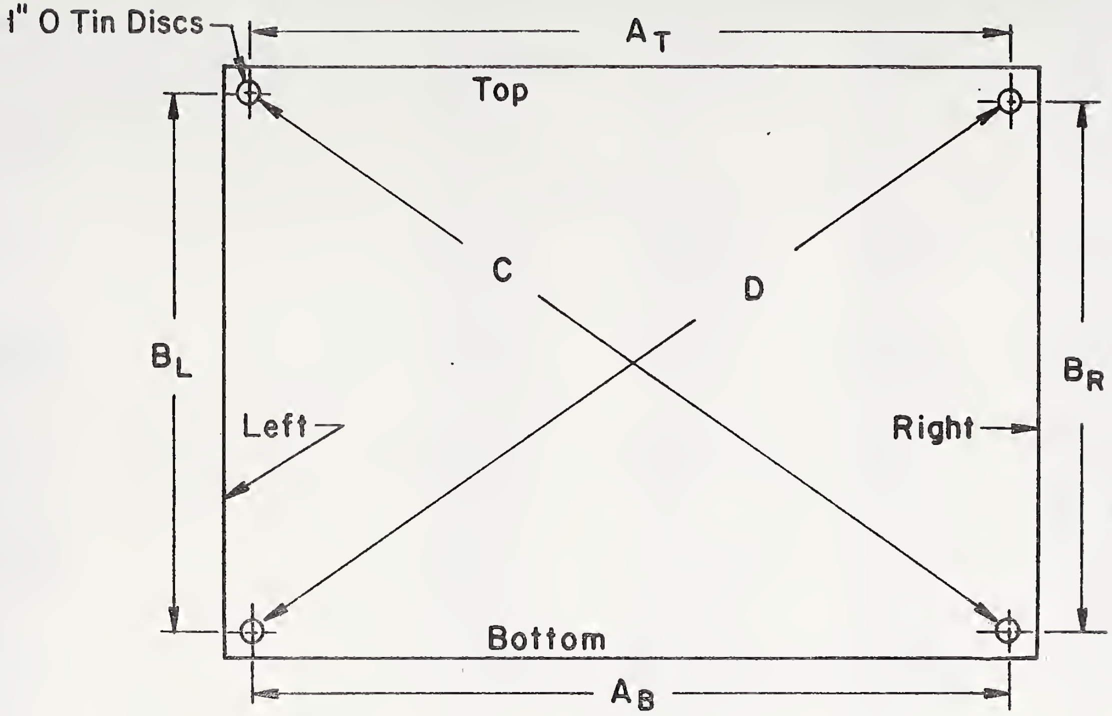


Figure A.1 Typical Set of Linear Measurements

Date of Recording - January 12, 1971
Status of Module - Module Standing on Assembly Base Prior to Initial Lifting
Temperature = 32°F

Location of Measurement	DISTANCE BETWEEN TARGETS (inches)					
	A_T**	A_B	B_L	B_R	C	D
Interior						
South Bedroom						
Front Wall	109 7/8	109 1/8	85	86	138 3/4	138 15/16
Rear Wall	No significant wall area existing			--	--	--
South Wall	127 3/16	126 15/16	86 3/16	86 1/16	153 5/8	153 3/8
North Wall	126 5/16	126 1/8	85 3/4	85 11/16	152 1/2	152 1/2
Middle Bedroom						
Front Wall	110 3/8	110 1/16	85 1/2	85 3/4	139 1/16	140 1/16
Rear Wall	73 1/8	74	85 5/8	85 11/16	112 15/16	112 13/16
South Wall	127 3/8	127	86	86 1/8	153 13/16	153 1/4
North Wall	127 1/2	127 1/4	85 3/4	85 3/4	153 5/8	153 3/4
North Bedroom						
Front Wall	150 1/4	150 3/4	86 7/8	86 15/16	174 3/4	173 3/4
Rear Wall	115 1/16	114 15/16	87	87 5/16	144 1/2	144 1/4
South Wall	127 11/16	127 5/16	86 3/4	86 3/4	154 3/16	154 5/16
North Wall	127 5/8	128 5/16	87	87 1/4	154 5/16	155 3/8
Exterior						
Front Elevation	476 5/8*	477*	100 7/16	100 5/16	487 7/16*	487 3/16*
Rear Elevation (North Span)	464 5/8*	464 5/8*	87	86 7/8	472 7/16*	472 15/16*
Rear Elevation (South Span)	222 3/16*	223 11/16*	86 7/8	86 1/4	239 5/16*	226 5/8*
North Elevation	116 3/8	116 1/16	87 5/8	87 5/8	145 9/16	145 7/16

* Actual measurements were corrected for temperature differential

** See figure A.1 for an illustration of the symbols in this table

Table A.1 - Initial Linear Measurements

Date of Recording - February 16, 1971
Status of Module - Module Standing on Support Assembly Prior to Testing
Temperature - 68°F

Location of Measurement	DISTANCE BETWEEN TARGETS (inches)					
	A_T	A_B	B_L	B_R	C	D
Interior						
South Bedroom						
Front Wall	109 15/16	109 1/8	85	85 11/16	138 3/4	139 1/16
Rear Wall	No significant wall area existing			--	--	--
South Wall	127 1/4	126 15/16	85 7/8	86	153 5/8	153 1/4
North Wall	126 1/4	126 1/8	85 3/4	85 9/16	152 5/8	152 5/8
Middle Bedroom						
Front Wall	110 5/16	110	85 1/2	85 11/16	139 5/16	139 15/16
Rear Wall	73 1/16	74 7/8	85 5/8	85 11/16	113 3/16	112 13/16
South Wall	127 7/16	127	85 13/16	86 1/8	153 15/16	153 3/8
North Wall	127 1/2	127 5/16	86	85 11/16	153 5/8	153 3/4
North Bedroom						
Front Wall	150 1/4	150 3/4	86 13/16	86 15/16	173 3/4	173 7/8
Rear Wall	115 1/16	114 7/8	87	87 3/8	144 5/8	144 3/8
South Wall	127 3/4	127 5/16	86 11/16	86 5/8	154 3/16	154 5/16
North Wall	127 3/4	128 5/16	87 1/16	87 1/4	154 5/16	155 3/8
Exterior						
Front Elevation	476 1/2	476 7/8	100 7/16	100 3/16	487 3/16	487 1/16
Rear Elevation (North Span)	464 5/8	464 3/8	86 5/8	86 7/8	472 5/16	472 13/16
Rear Elevation (South Span)	222 1/4	223 9/16	86 7/8	86 1/8	239 3/8	226 11/16
North Elevation	116 3/8	116 1/16	87 5/8	87 1/2	145 9/16	145 7/16

Table A.2 - Second Record of Linear Measurements

Location of Measurement	DIMENSIONAL CHANGES (in)					
	A_T	A_B	B_L	B_R	C	D
Interior						
South Bedroom						
Front Wall	+1/16	NC**	NC	-5/16	NC	+1/8
Rear Wall	No significant wall area existing			--	--	--
South Wall	+1/16	NC	-5/16	-1/16	NC	-1/8
North Wall	-1/16	NC	NC	-1/8	+1/8	+1/8
Middle Bedroom						
Front Wall	-1/16	-1/16	NC	-1/16	+1/4	-1/8
Rear Wall	-1/16	+7/8	NC	NC	+1/4	NC
South Wall	+1/16	NC	-3/16	NC	+1/8	+1/8
North Wall	NC	+1/16	+1/4	-1/16	NC	NC
North Bedroom						
Front Wall	NC	NC	-1/16	NC	NC	+1/8
Rear Wall	NC	-1/16	NC	+1/16	+1/8	+1/8
South Wall	+1/16	NC	-1/16	-1/8	NC	NC
North Wall	+1/8	NC	+1/16	NC	NC	NC
Exterior						
Front Elevation	-1/8	-1/8	NC	-1/8	-1/4	-1/8
Rear Elevation (North Span)	NC	-1/4	-3/8	NC	-1/8	-1/8
Rear Elevation (South Span)	+1/16	-1/8	NC	-1/8	+1/16	+1/16
North Elevation	NC	NC	NC	-1/8	NC	NC

** NC = Zero Change

Table A.3 - Difference Between Measurements Tabulated in Tables A.1 and A.2

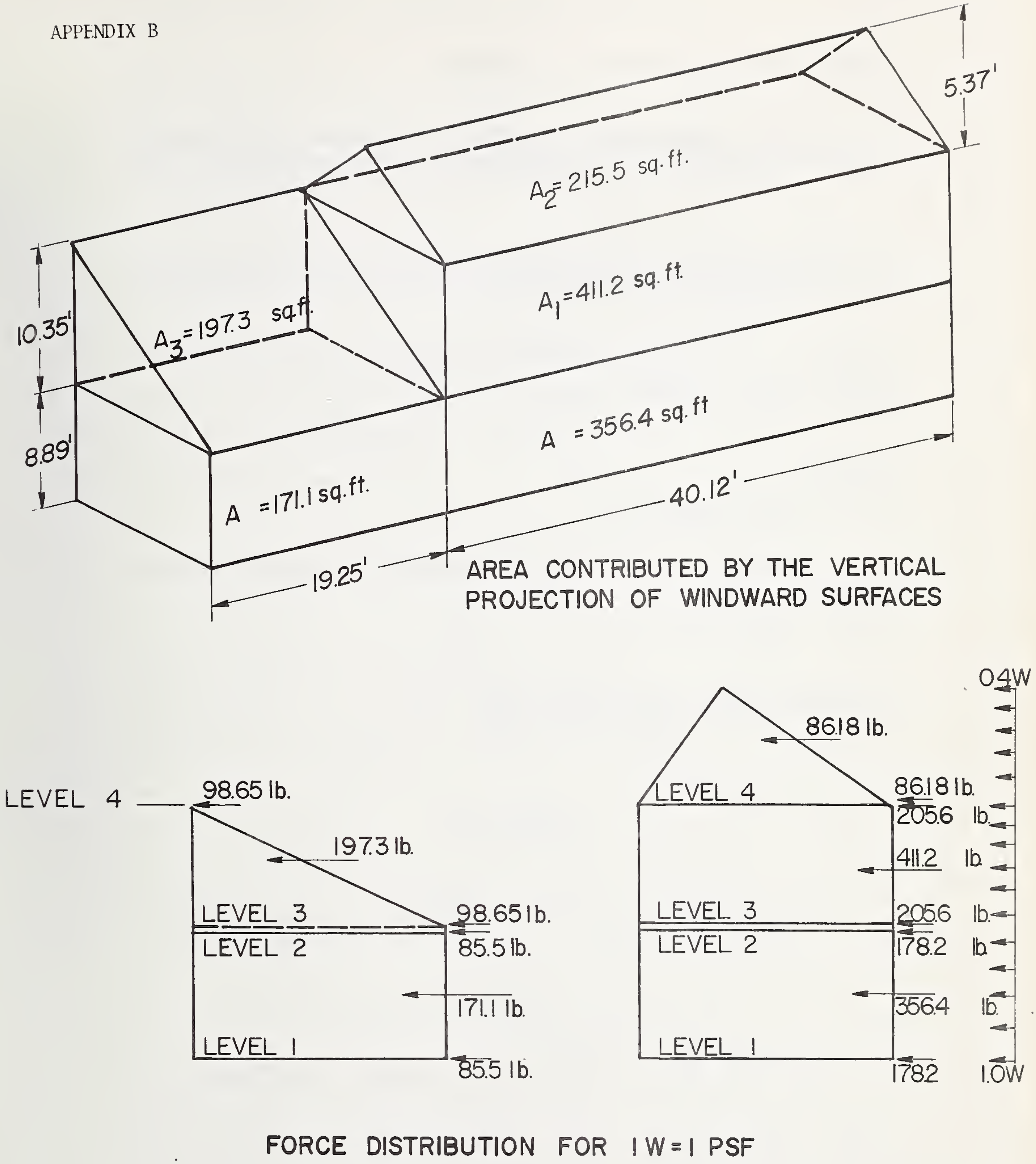


Figure B.1 Lateral Force Distribution on Actual Structure Due to Design Wind Pressure

SUMMATION OF FORCES FOR 1 psf PRESSURE

The following computations represent the summation of horizontal forces at the four levels shown in figure B.1 , for a pressure of 1 psf.

<u>Level 4</u>

205.63 + 86.18 + 98.65 = 390.43 lb.

<u>Level 3</u>

98.65 + 205.6 + 304.25 lb.

<u>Level 2</u>

85.55 + 178.2 = 263.75 lb.

<u>Level 1</u>

85.55 + 178.2 = 263.75 lb.

Total Horizontal Force = 1222.18 lb.

A TYPICAL APPLICATION OF THE DRIFT MODEL TO TEST DATA

Total Applied Lateral Load, $P \doteq 5150$ lb.

Equivalent Wind Pressure, $1W = \frac{5150}{3904.6} \times 20 = 26.378$ psf

One-Half Wind Pressure = 26.378/2 = 13.189 psf

CONCENTRATED FORCES AT DESCENDING LEVELS OF THE ACTUAL STRUCTURE

Level 4, $P_4 = 13.189 \times 390.43 = 5150$ lb.

Level 3, $P_3 = 13.189 \times 304.25 = 4013$ lb.

Level 2, $P_2 = 13.189 \times 263.75 = 3479$ lb.

Level 1 $P_1 = 3479$ lb.

CUMULATIVE FORCES AT DESCENDING LEVELS OF THE ACTUAL STRUCTURE

Level 3, $P_4 + P_3 = 5150 + 4013 = 9163$ lb.

Level 2, $P_4 + P_3 + P_2 = 9163 + 3479 = 12642$ lb.

Level 1, $P_4 + P_3 + P_2 + P_1 = 12642 + 3479 = 16121$ lb.

LOAD RATIOS

1. $\frac{16121}{5150} = 3.1304$ 2. $\frac{12642}{5150} = 2.4547$ 3. $\frac{9163}{5150} = 1.7793$

PLANE 3

LVDT Readings (in)	Differences (in)	Load Ratio	Factored Δ_s (in)	Cumulative Λ_s (in)
$\delta_8 = 0.110 = \Delta_4$	$\Delta_2 - \Delta_1 = 0.044$	3.1304	0.1377	$0.1377 - \Delta_{L1}$
$\delta_{10} = 0.062 = \Delta_3$	$\Delta_4 - \Delta_3 = 0.048$	2.4547	0.1178	$0.2555 - \Delta_{L2}$
$\delta_{35} = 0.049 = \Delta_2$	$\Delta_3 - \Delta_1 = 0.057$	1.7793	0.1014	$0.3569 - \Delta_{L3}$
$\delta_{36} = 0.005 = \Delta_1$				

DRIFT $= \Delta_{L3} = 0.3569$ in.

$\Delta/h = 0.3569/130 = 1/364$

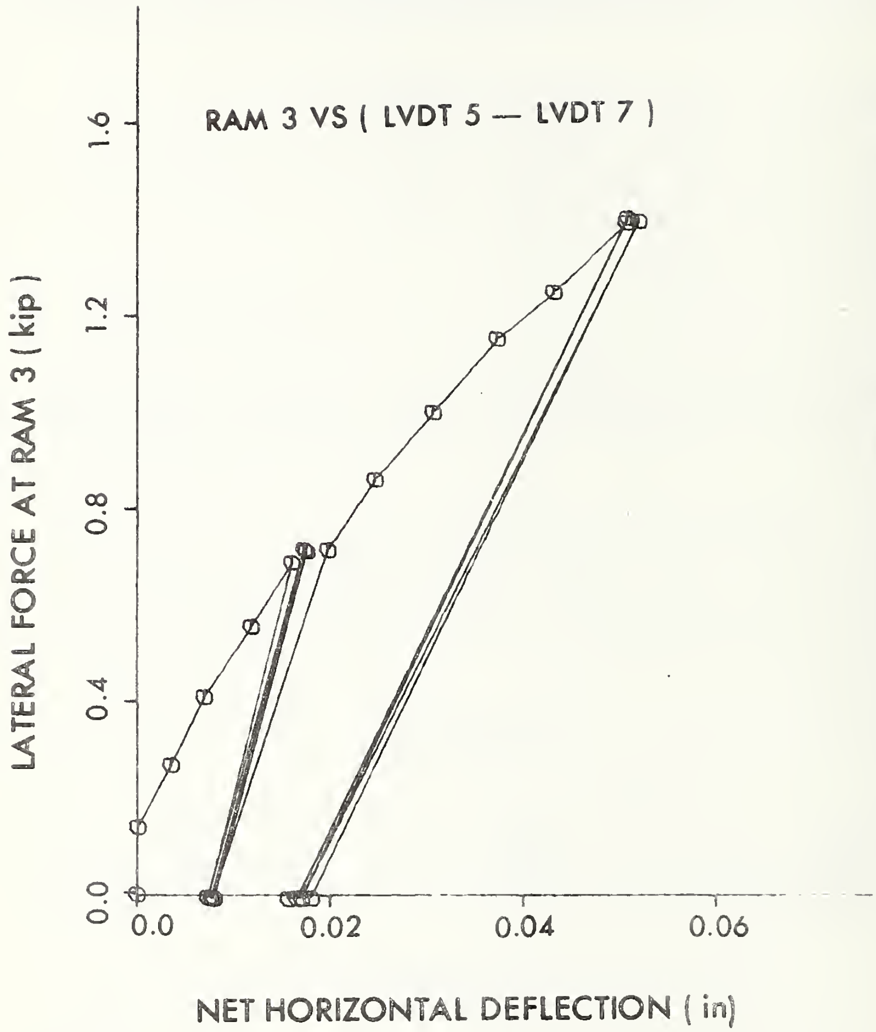


Figure C.1 Force at Ram 3 versus Deflection Along Plane 1 for Profile Shown in Figure 5.3a - Test 1

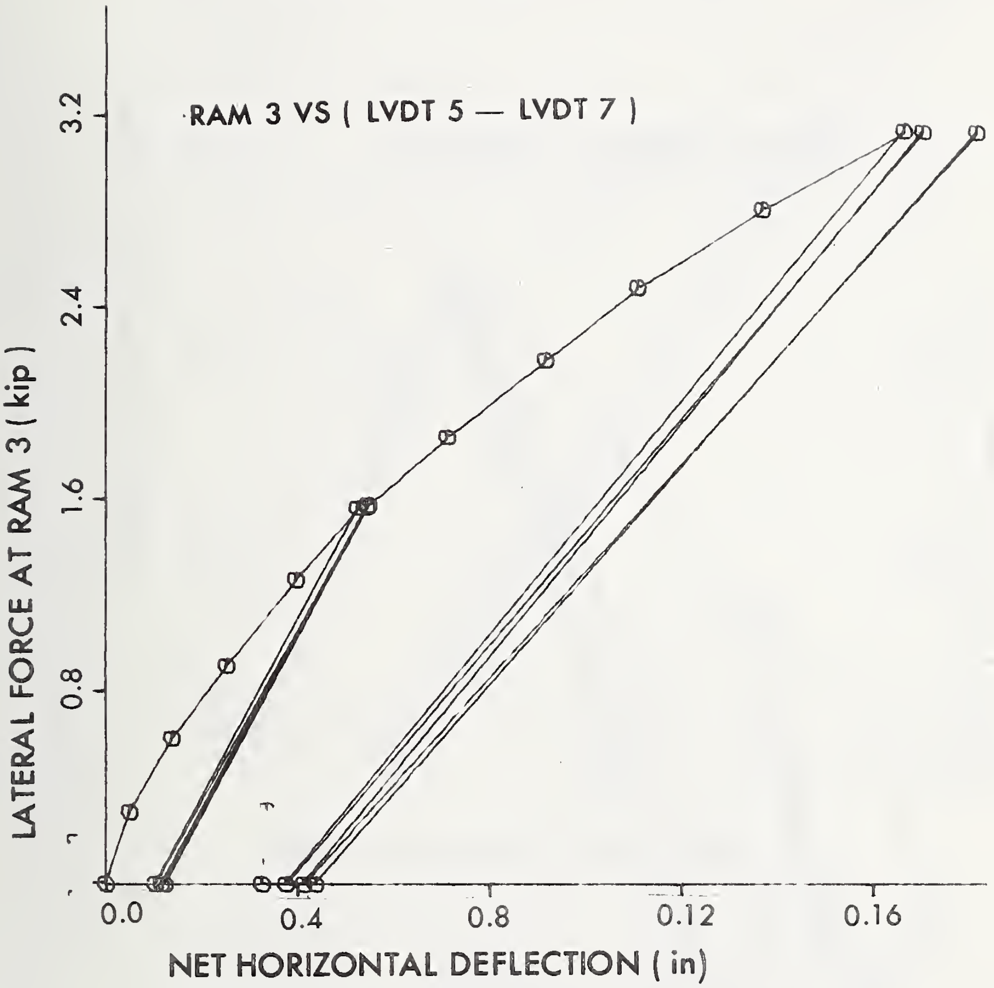


Figure C.2 Force at Ram 3 versus Deflection Along Plane 1 for Profile Shown in Figure 5.3b - Test 1

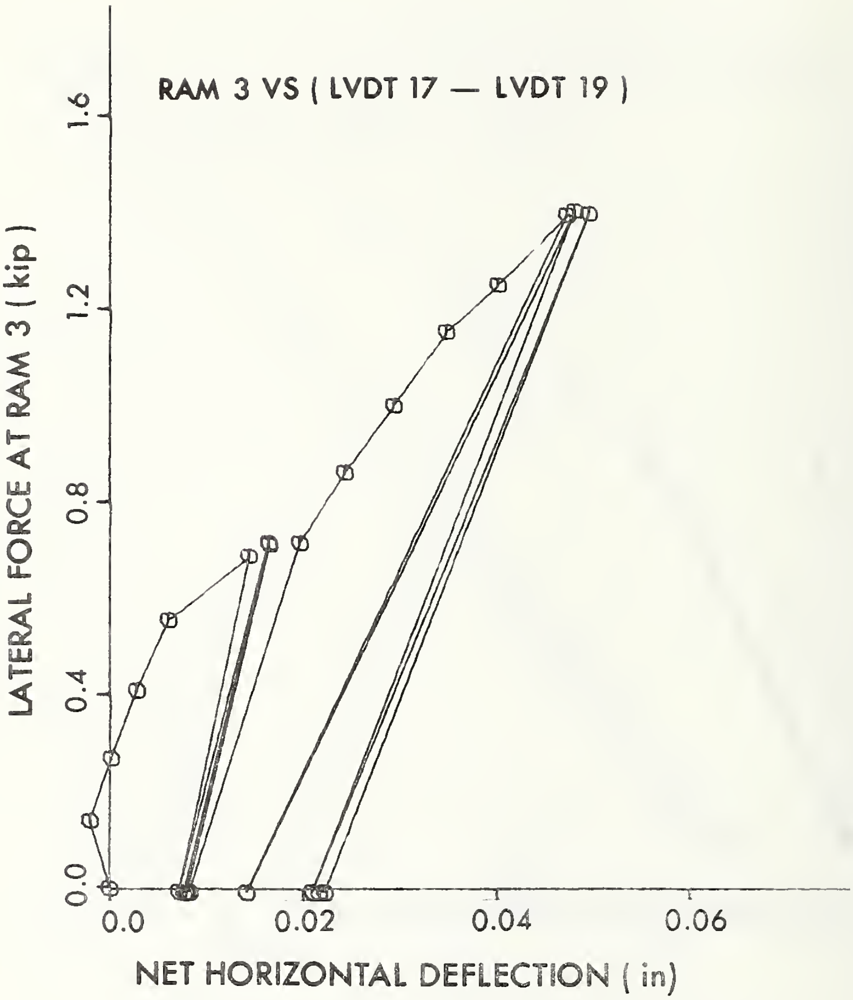


Figure C.3 Force at Ram 3 versus Deflection Along Plane 2 for Profile Shown in Figure 5.3a - Test 1

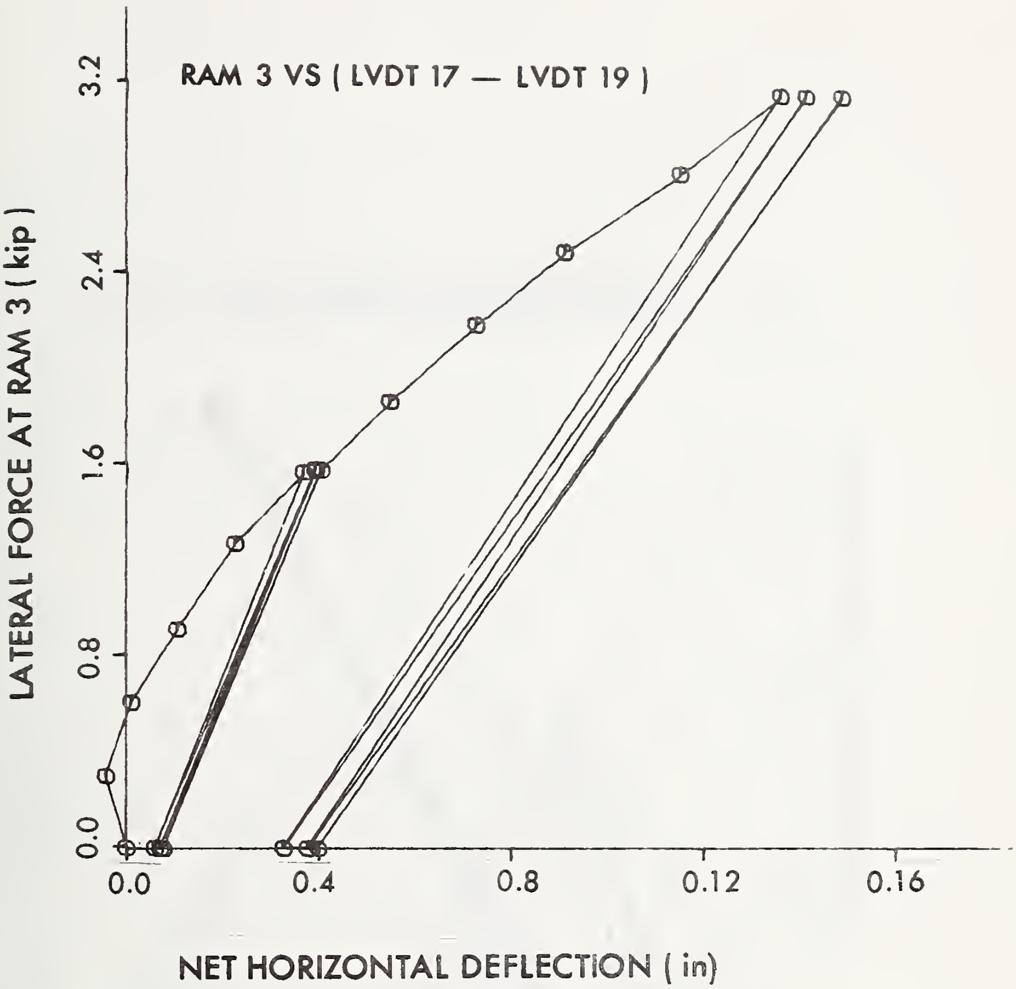


Figure C.4 Force at Ram 3 versus Deflection Along Plane 2 for Profile Shown in Figure 5.3b - Test 1

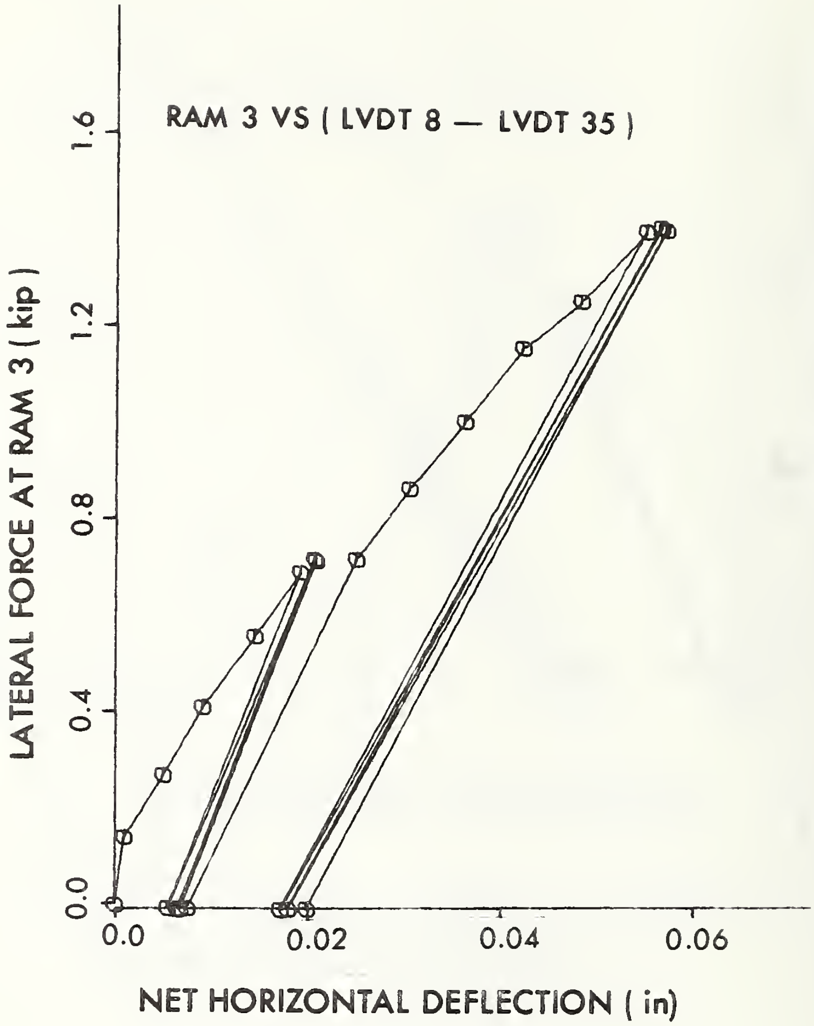


Figure C.5 Force at Ram 3 versus Deflection Along Plane 3 for Profile Shown in Figure 5.3a - Test 1

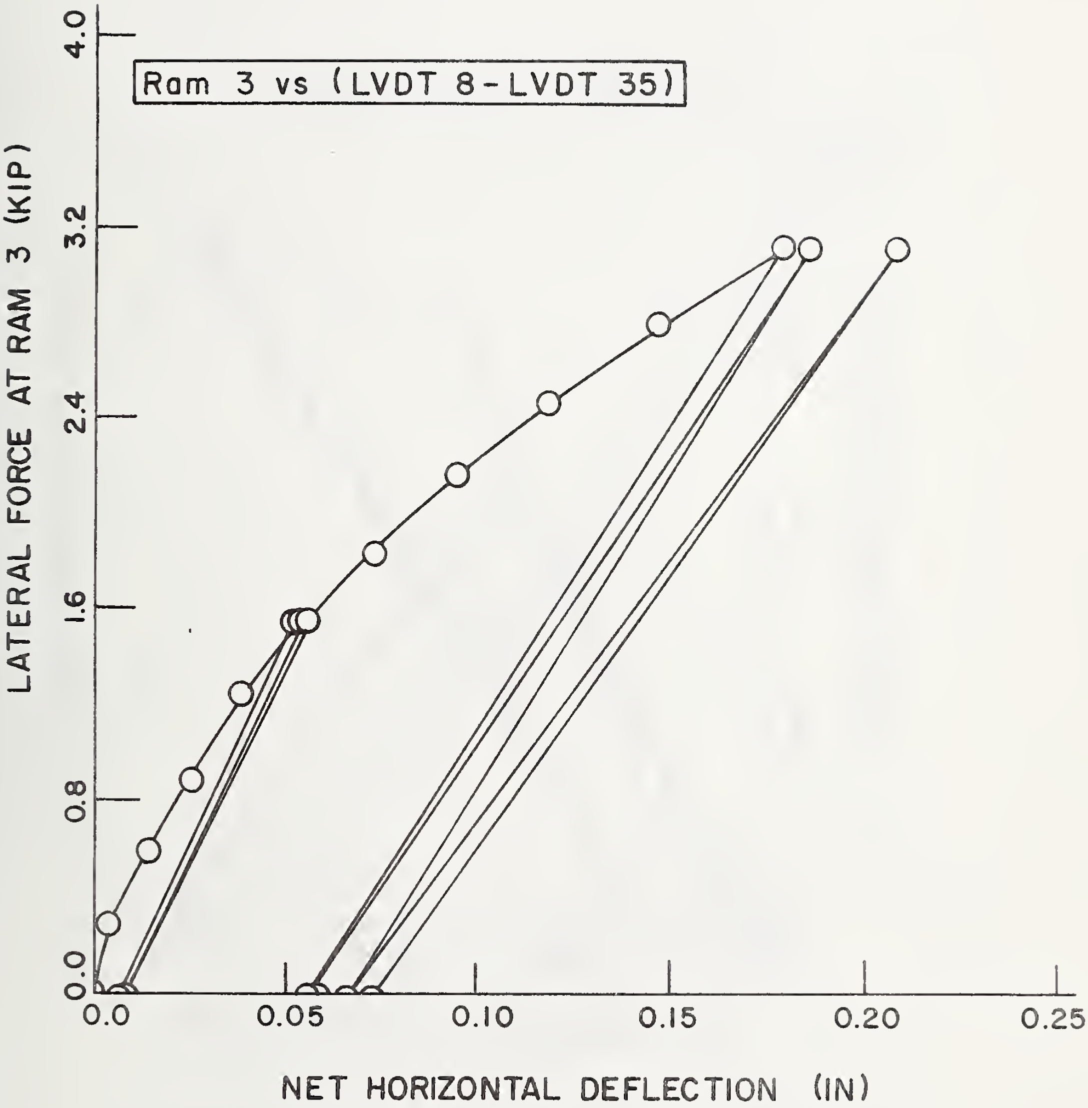


Figure C.6 Force at Ram 3 versus Deflection Along Plane 3 for Profile Shown in Figure 5.3b - Test 1

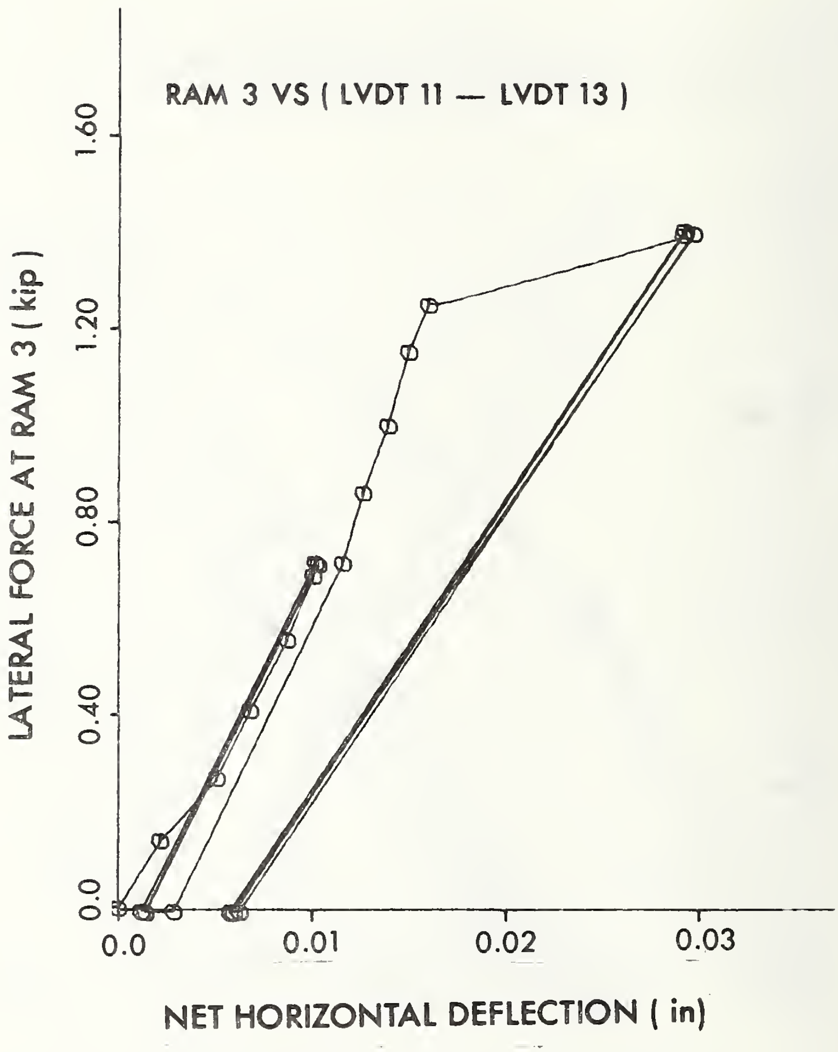


Figure C.7 Force at Ram 3 versus Deflection Along Plane 4 for Profile Shown in Figure 5.3a - Test 1

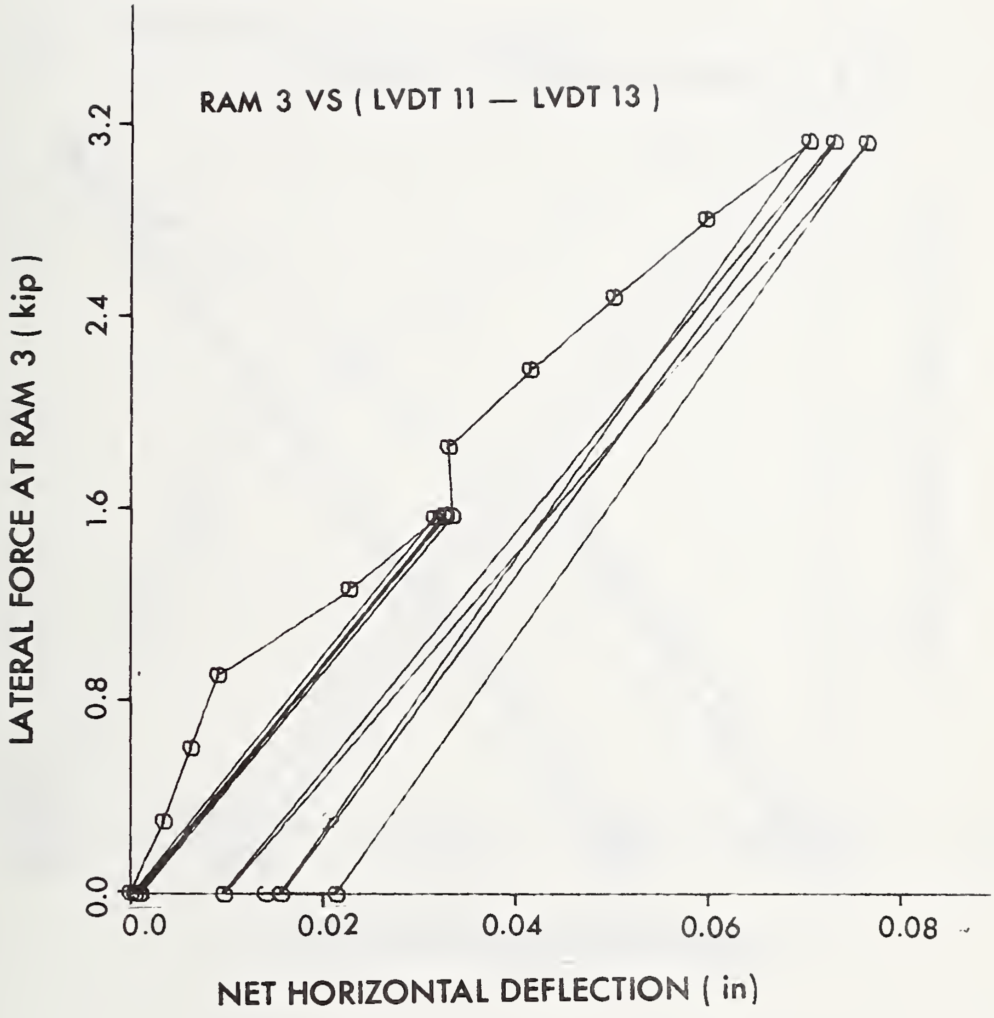


Figure C.8 Force at Ram 3 versus Deflection Along Plane 4 for Profile Shown in Figure 5.3b - Test 1

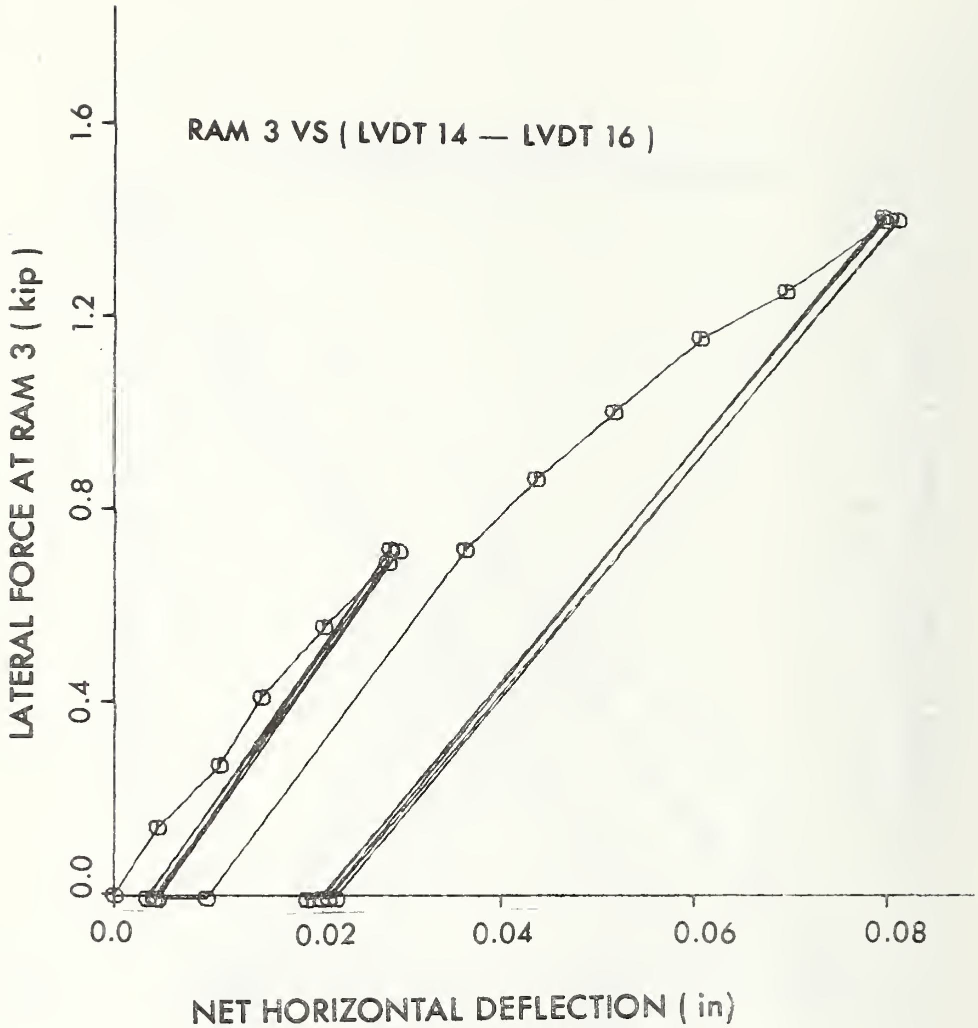


Figure C.9 Force at Ram 3 versus Deflection Along Plane 5 for Profile Shown in Figure 5.3a - Test 1

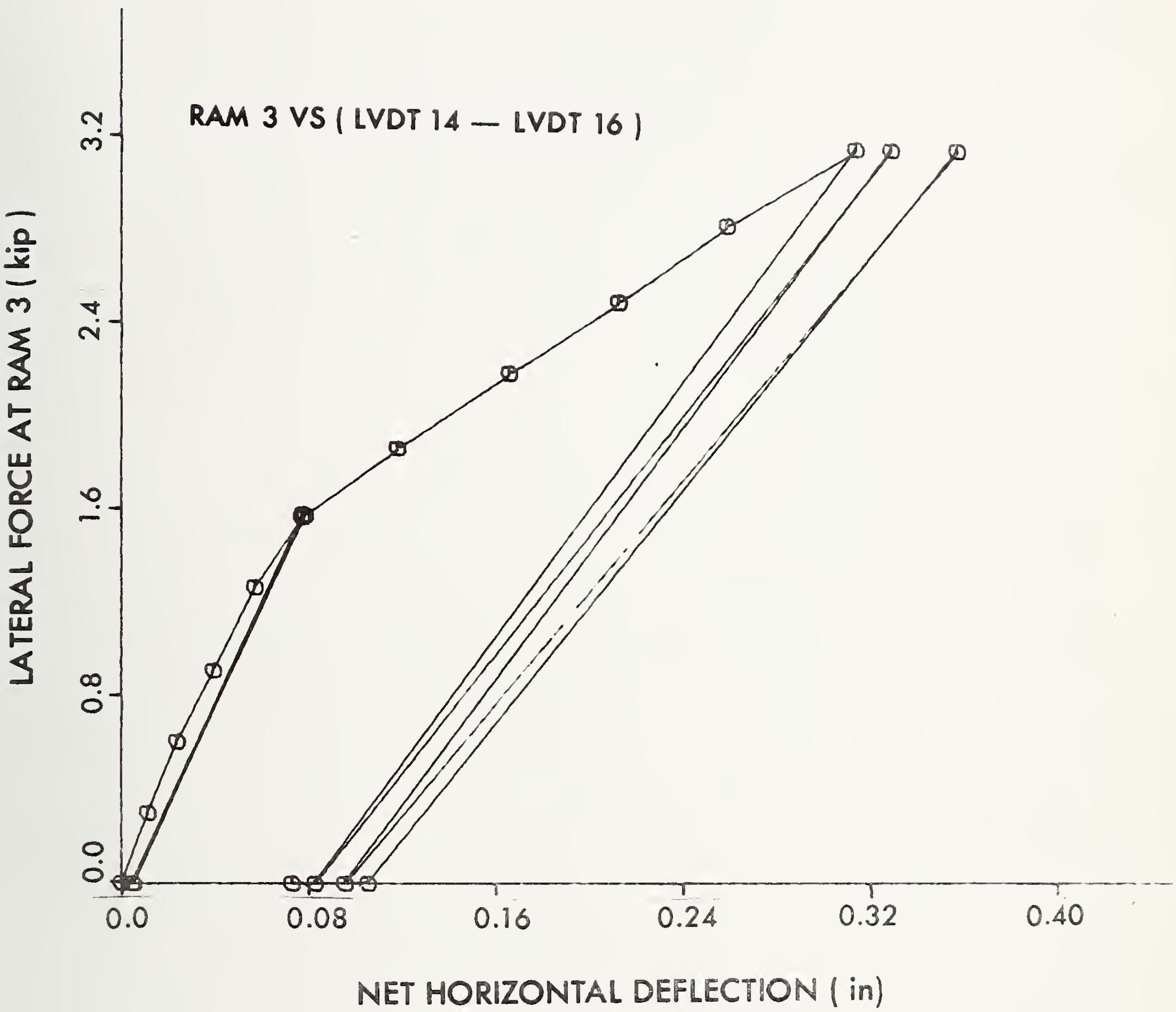


Figure C.10 Force at Ram 3 versus Deflection
Along Plane 5 for Profile Shown
in Figure 5.3b - Test 1