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THE USE OF STRUCTURAL FOAMS TO IMPROVE EARTHQUAKE RESISTANCE OF BUILDINGS

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by
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ABSTRACT

This report presents the results of a program to investigate the use of structural foams to improve earthquake resistance of buildings. This work was sponsored by the National Science Foundation under program solicitation 77-12 "Small Business Innovation Applied to National Needs".

The program was conducted by Scientific Service, Inc., Redwood City, California who utilized the Advanced Structural Laboratory at San Jose State University, San Jose, California for the experimental portion of the effort.

SUMMARY

This report presents the results of a research program to investigate the use of foams to improve the earthquake resistance of buildings. The program, which was conducted by Scientific Service, Inc. was sponsored by the National Science Foundation under the Small Business Innovation Applied to National Needs program.

The problem addressed by this study, the upgrading of structures to resist earthquakes, is truly a national one since there is a reasonable probability that as many as 28 states can experience moderate earthquake accelerations. Within these states there are literally hundreds of thousands of structures which in spite of improved building codes would be incapable of withstanding a moderate earthquake.

The objective of this program was to develop and test the feasibility of using polyurethane foam to increase the shear capacity of timber stud walls, timber joist floors, and ceilings and foundation to floor connections. The specific tasks were to develop foam placement techniques, document increases in strength due to foam, and determine the feasibility of using these techniques in new construction.

The results of this largely experimental program indicated that substantial increases in shear strength were achieved in walls, floors, and ceiling systems. For example, a typical sheathed roof or floor system by current code would have no seismic shear resistance. It was shown experimentally, however, that a floor system (2 x 8 joist, 1 x 8 sheathing) when foamed developed a 1650 lb/ft shear enhancement and 2450 lb/ft composite shear capacity. Also, from an energy standpoint the energy absorbed by a foamed panel was approximately 10 times that of an unfoamed panel. Tests of floor-to-foundation connections upgraded by foam also indicate substantial increases.

Based on the results of this study it is believed that the use of structural foam is a viable and inexpensive alternative to conventional rehabilitation techniques. It is recommended that this program be continued with the development of a users manual and a full scale structural demonstration.

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Section 1
INTRODUCTION AND BACKGROUND

Although building codes in areas of the United States subject to earthquakes have placed increasing emphasis on designing structures to withstand significant earthquake-generated forces, there are still literally hundreds of thousands of structures that could not withstand even moderate earthquakes. The Los Angeles Building Department, for example, estimated that in the City of Los Angeles alone, there are some 20,000 structures that could not have withstood even the relatively mild earthquake of February, 1971 which caused major structural damage in the Sylmar area.

It would clearly be in the public interest to reinforce such structures so that they could withstand earthquake-generated forces. Conventional rehabilitation techniques, however, would preclude rehabilitation of many of these structures, because rehabilitation costs are very high relative to the cost of new construction. For example, many of the unsafe buildings in California are one or two story, wood-frame buildings (some of which have heavy clay tile roofs) which were designed to withstand vertical loads but were not designed to withstand the substantial lateral loads that can be induced by earthquakes. To render these structures capable of withstanding such lateral loads, it would be necessary to convert ordinary timber stud walls to shear walls and to convert ordinary timber joist floors and roofs to shear diaphragms. Conventional methods of such conversion are often more expensive than is complete replacement of the offending wall or floor.

Thus, because of the substantial expense involved, it is quite doubtful whether such structures would ever be brought up to acceptable standards, even if legislation were passed requiring that structures be strengthened before occupancy would be allowed. Instead, they would more probably be torn down and replaced, that course being less expensive than the required rehabilitation by conventional methods. Yet, aside from their vulnerability to forces from a natural disaster, many of the structures are quite sound and serviceable, and many have historical significance. Clearly what is needed to assure continued use of these structures are rehabilitation methods far less expensive than conventional methods — methods that are basically so inexpensive that the alternative of replacement of the building would not be attractive.

The problem has national significance because such structures (generally non-engineered) are found throughout the United States — e.g., schools, single and multiple-family dwelling units, and small commercial structures; and because earthquakes themselves are truly a national problem. The recent Earthquake-Hazard Map (Fig. 1-1)* indicates that hard-rock accelerations greater than 0.1 g have a reasonable probability of occurrence in 28 states. Outside California, in relatively recent times, relatively high intensity quakes have occurred in the St. Lawrence Valley (1929), in Utah (1934), and in Montana (1935, 1959) and one of the strongest earthquakes in what is now the continental U.S. occurred in the Mississippi Valley in 1811 and 1812.

As testimony to the immediacy of the problem, it might be noted that in a recent six-month period, between April and September 1976, earthquakes were experienced in 22 states. They occurred with the greatest frequency in California, Alaska, and Hawaii, but they were also experienced in many states normally thought to be quiescent such as Connecticut, Virginia, and Indiana.

Previous work by Scientific Service, Inc. personnel had indicated that rigid polyurethane foam had the potential for significantly increasing the structural strengths of wall and floor systems. Graduate students at San Jose State University (SJSU), under the direction of the Principal Investigator, constructed a few typical floor and ceiling diaphragm sections

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* Algermissson, S.T., and D.M. Parkins, "Earthquake-Hazard Map of the United States", Earthquake Information Bulletin, Vol. 9, No. 1, U.S. Geological Survey, Jan.-Feb. 1977.

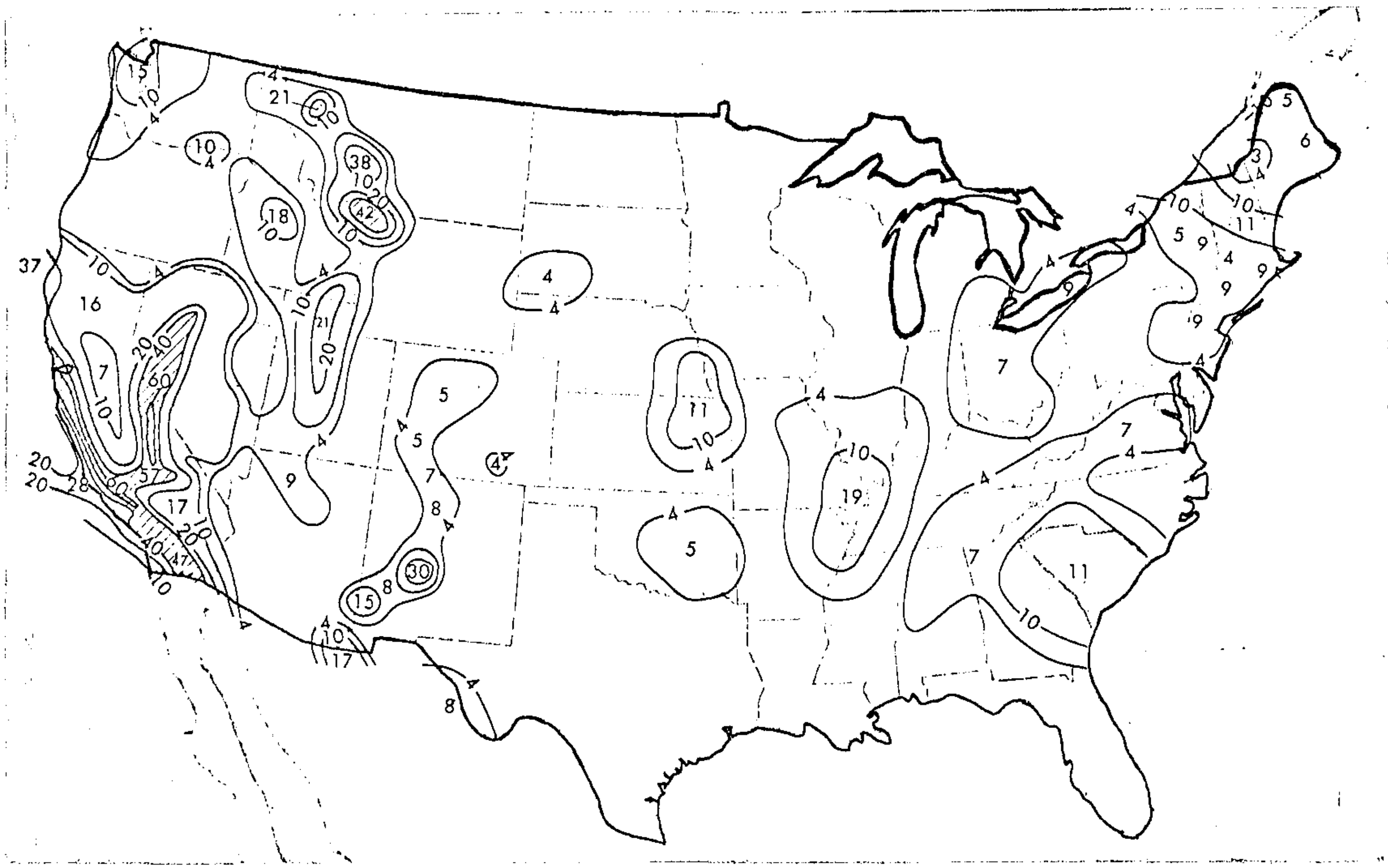


Fig. 1-1. Earthquake-Hazard Map of the United States. The numbers on the contours represent the horizontal acceleration in hard rock as a percentage of "g" at a constant probability level (90% probability the accelerations will not be exceeded in 50 years). Numbers within contours are maximum expected accelerations.

(using sheetrock, wood joists and sheathing). Foam was injected into these sections, and the results of tests of their shear capacity compared with those of unfoamed specimens. The results of these tests were sufficiently interesting—i.e., a doubling of the shear capacity of the floor systems and an increase in the shear capacity of the ceiling system of more than 600%—that the National Science Foundation subsequently funded a more extensive research program.

This program, which is the subject of this report, had the following objectives:

1. Determine the feasibility of developing simple practical methods for foam placement in walls, floors, and ceilings.
2. Document the increase in shear resistance due to foam and the bending capacity of the foam.
3. Determine the feasibility of using foamed elements in new construction.

This report is organized as follows:

Section 2 describes the foam installation in the test specimens;

Section 3 presents the primary test program and test results;

Section 4 presents the supplemental test program;

Section 5 discusses the conclusions from the program and the application potential of the foaming techniques developed during the program;

Appendix A contains the test data from the primary test program;

Appendix B contains the test data from the supplemental test program;

Appendix C describes the test equipment and instrumentation.

Section 2
FOAM EQUIPMENT AND INSTALLATION

One of the first tasks under this program was to investigate available foam placement equipment and to develop foam installation techniques.

FOAM EQUIPMENT

In the early experiments carried out several years ago at San Jose State University, the polyurethane foam was made by mixing the two components together and pouring the unfoamed mix into the wall cavities. Using this technique it was difficult to control the amount and density of the foam manufactured, even though both components were carefully weighed and mixed.

The next level of sophistication beyond the hand mix-and-pour techniques are foam placement kits. These kits, which are available in various sizes (1 lb to 100 lb), come with the two components in pressurized disposable containers, include all valves, hoses and a simple mixing and dispensing nozzle. Because of their high cost — $4 to $10 per lb of foam, depending on the size of the kit — their limited size and the difficulty of determining the amount of foam dispensed in a confined area, these kits would not be suitable for most structural foaming applications.

After an extensive survey of commercial foam dispensers, it was determined that the most desirable unit for this project would be a commercial unit sized for our particular application, but with the features and operating procedures of the much larger units. Thus, operating and installation procedures developed under this project with test specimens could be readily transferred to full-scale applications.

The unit which most closely met these requirements was an Auto Frothing Unit manufactured by Olin Plastics, Inc. The various components of this unit are pictured in Fig. 2-1. In the upper photograph, the black and white tanks contain the two components of the foam. The left-hand tank contains nitrogen gas for pressurization and the small tank in the foreground contains a solvent for cleaning the system. The lower photograph shows the timer which accurately regulates the amount of foam produced. For this program a rate of 6 lb/min (1 lb of foam/10 sec) was found to be adequate. Much slower or faster rates can also be generated with this particular system.

FOAM INSTALLATION

During this program three basic structural elements were investigated — floors, walls, and ceilings. The test specimens used were constructed to represent sections of a typical structure, that is, the materials, spacing, nailing schedules, etc, were all typical of common construction practices. The floor and ceiling test specimens were 4 x 8 ft; and both 4 x 4 ft and 4 x 8 ft wall specimens were constructed. The construction details are described in the Structural Test Section (Section 3) of this report.

The foam installation investigation was conducted in three phases with the first phase being an exploratory phase.

First Phase

The first item to be foamed was Ceiling Number 1, shown in Fig. 2-2. This test specimen was foamed in two lifts with a discharge pattern of passing the nozzle at different directions, sometimes longitudinally with the ceiling joists and sometimes crisscrossing between the joists in a seesaw pattern. The volume of foam required for one of the cells in the 2 x 6 in. ceiling joist system with joists 16 in. on center would be 4.15 lb or 2.07 cu ft, which would require 41.5 sec total placement time.

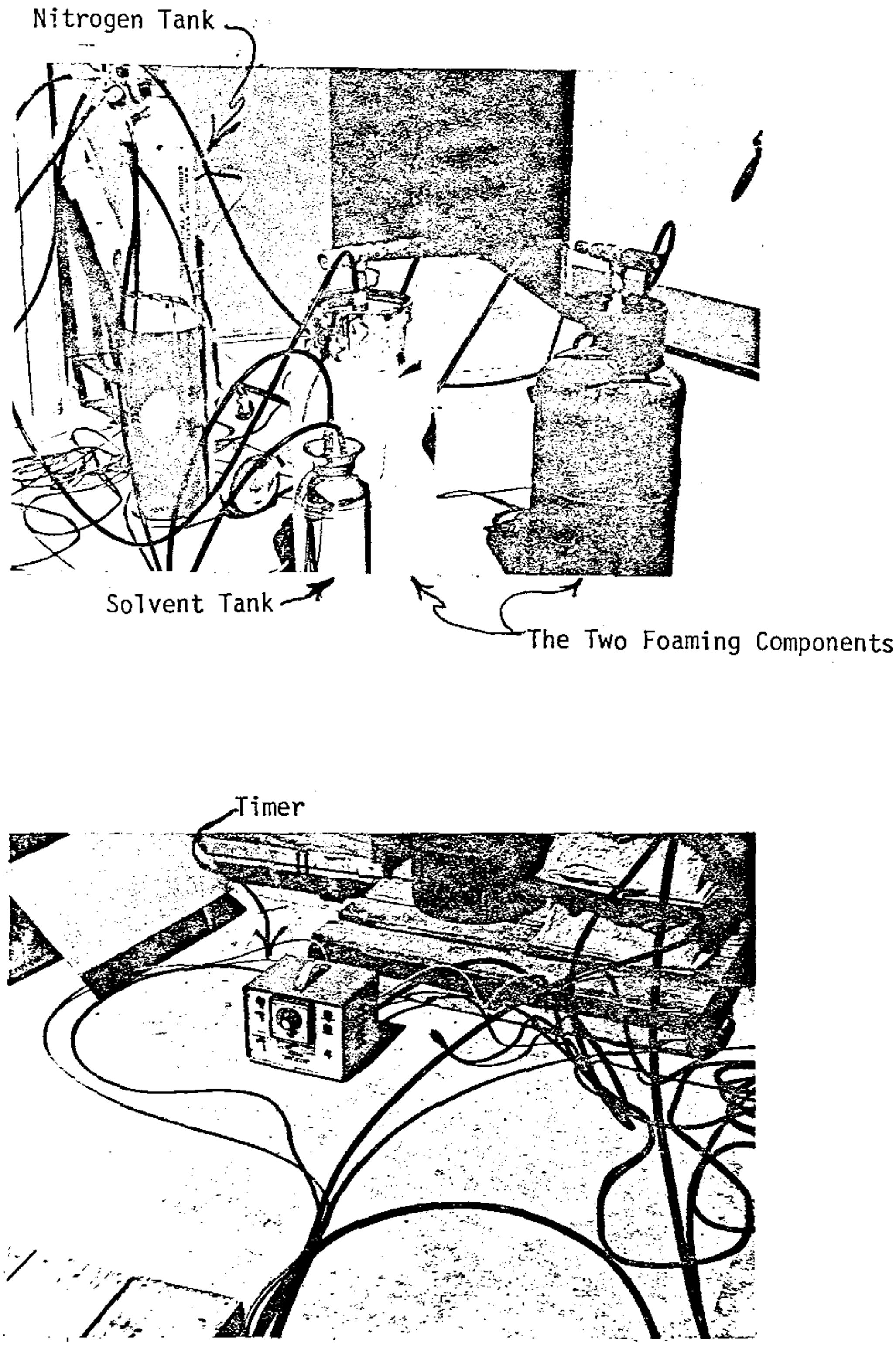


Fig. 2-1. Foaming Equipment Components.

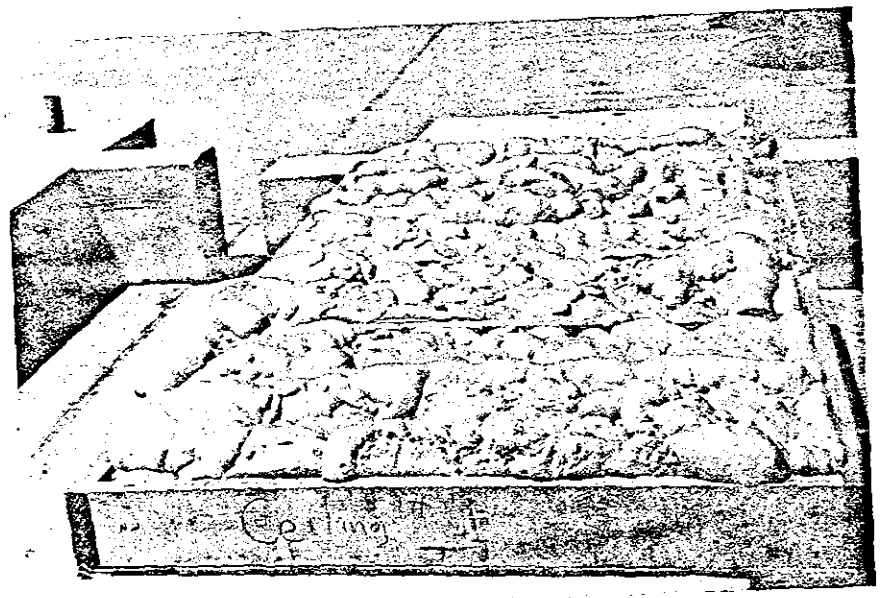


Fig. 2-2. Ceiling Number 1.

Therefore, two passes per cell were made, each taking 21 sec. As can be seen in Fig. 2-2, it is obvious that the void is full, but the job is not necessarily aesthetically pleasing.

The next structural element foamed in Phase 1 was a floor specimen. The floor specimens were basically 4 x 8 ft, representing the second floor of a small apartment building or similar type of construction with 2 x 6 in. joists at 16-in. centers running in the four-foot direction, 1 x 8 sheathing running in the eight-foot direction and sheetrock on the bottom representing the ceiling of the room below. In Floor No. 1 three holes were drilled in each of the cells. These holes were drilled in the center of the cell and 16 in. in from either side — that is, each hole was in the center of a 16 in. x 16 in. area. It was noted in the ceiling trial discussed above that, in spite of the full appearance, some voids remained along the edges. Because of this it was decided in this floor to use approximately 5% more foam than the calculated requirement. The procedure was as follows: 17 sec or 1.7 lbs of foam was injected in the center hole of each cell, that is, the center row of holes between each floor joist. This quantity was approximately 5% more than 1/3 the total volume. Then 16 sec of foam was injected into the edge holes of each cell. As the foam began to rise, however, it started pouring through the cracks in the flooring (Fig. 2-3) and a few seconds later the sheetrock underneath cracked, as shown in Fig. 2-4. The maximum deflection of the sheetrock was 3/4 in. at one end.

From this experience, it was obvious that a different technique was needed. On the next trial, Floor No. 2, the volume of foam was reduced to the calculated volume, and since the cracks occurred on the outside pour, the filling procedure was reversed. A 16-sec charge of foam was injected into each of the edge holes and after these had fully expanded, a 10-sec charge injected into the center holes. This 10-sec charge was, in fact, reduced to 8 sec in the last four cells, resulting in approximately 93% of theoretical volume. The results of this procedure were a bit more successful even though the center of the sheetrock did bulge slightly causing about 1/8-in. dents at the nail heads.

Fig. 2-3. Floor Number 1 — Top View.

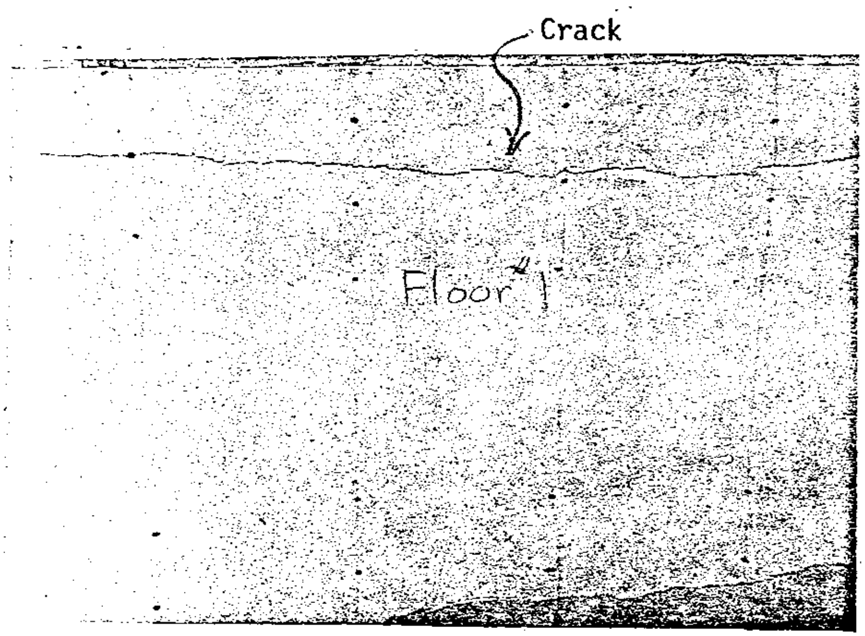


Fig. 2-4. Floor Number 1 — Bottom View.

In an attempt to obtain a floor pour to full theoretical volume, a third floor specimen (Floor No. 3) was foamed using a sequential injection procedure such that no two adjacent cells would be foamed at the same time. This resulted in a 3-ft crack in the sheetrock and excess foam pouring out through the cracks in the flooring and fill holes, as shown in Fig. 2-5. This indicates that, even though the correct amount of foam was being injected, there were still a few voids in the floor specimen.

Next on the agenda was the problem of foaming walls. The walls were constructed conventionally, with 2 x 4 studs at 16-in. centers, 1 x 8 exterior sheathing, 4 x 8 sheetrock interiors and fire blocking at mid-height, or 4 ft. On Wall No. 1 holes were drilled between each stud at 16, 32, 48, 64, 80, and 94 inches in height (see Fig. 2-6A). Fig. 2-6B shows the foam being injected into the 32-in. height hole. The method used was as follows: approximately a 5% surplus was injected into the lower half of the wall in ten second lifts; that is, at the 16-in. height, 10 sec of foam was injected into each hole. After it completed its foaming, an additional 10 sec was injected at the 32-in. height and finally 10 sec of foam was injected into the third, or 48-in. height just below the fire break. Fig. 2-7 shows a slight crack that formed in the right hand cell when the third lift was injected, demonstrating that the 5% surplus of foam was not needed. For the upper portion of the wall the procedure was changed and it was foamed in three eight-second lifts. The first lift, of course, was at the 64-in. height, then the 80-in. height, and then the 96-in. height. On this section of the wall it was estimated that approximately 10% less foam was injected than required to fill the void and that the third injection did not foam to the top of the wall. Upon inspection, it was calculated that two 4-sec pours and one 5-sec pour were needed to completely fill the voids.

Based on the results of Wall No. 1, Wall No. 2 was foamed as follows: three holes were drilled just below the fire break and three holes were drilled just below the top of the wall. Again, foam was injected in three lifts for each cell, that is 10 sec worth of foam was injected into each of the three holes at the fire stop level. As shown in Fig. 2-8 some spillage occurred out the back of the wall as the siding was not put on as tightly

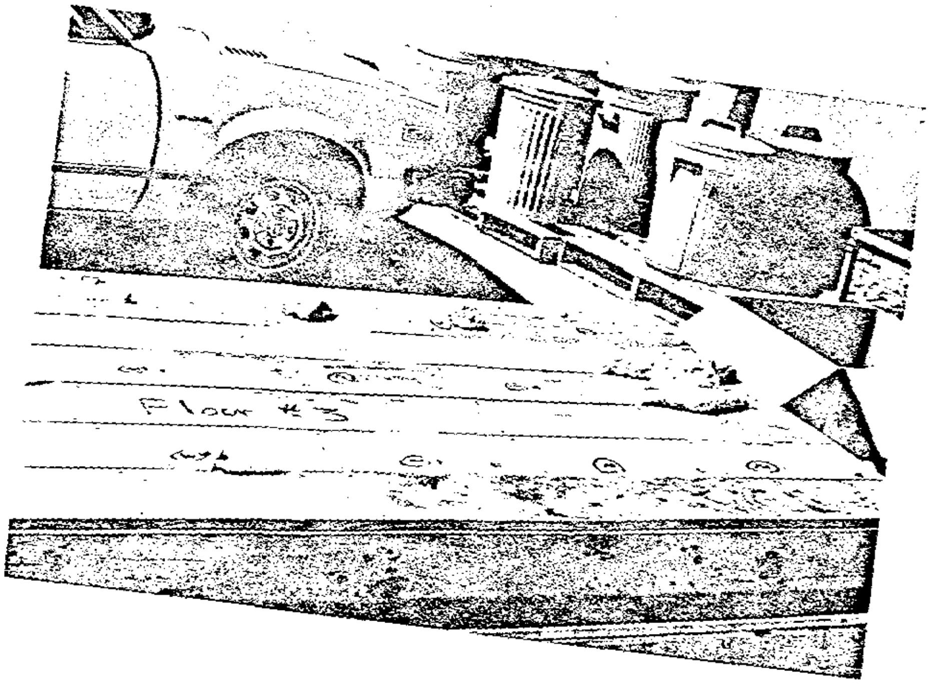
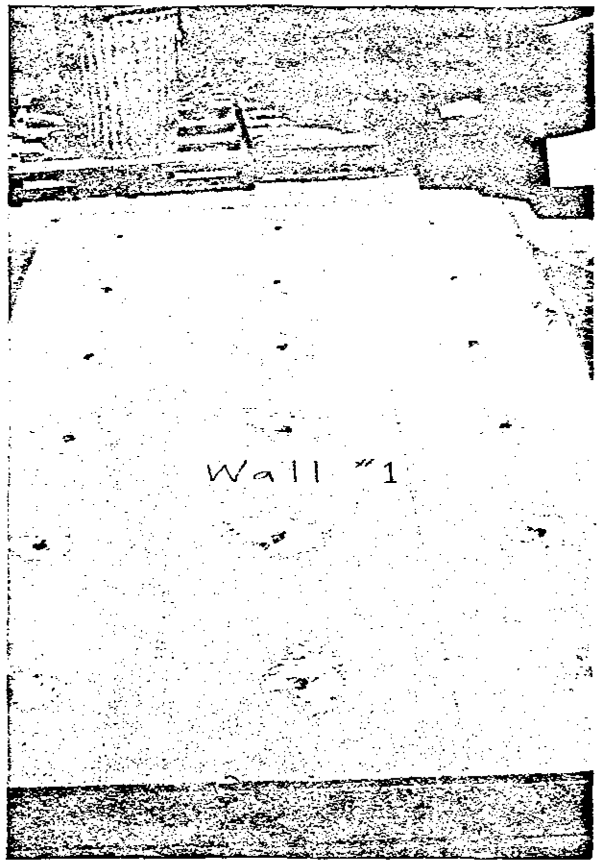


Fig. 2-5. Floor Number 3.

A



B

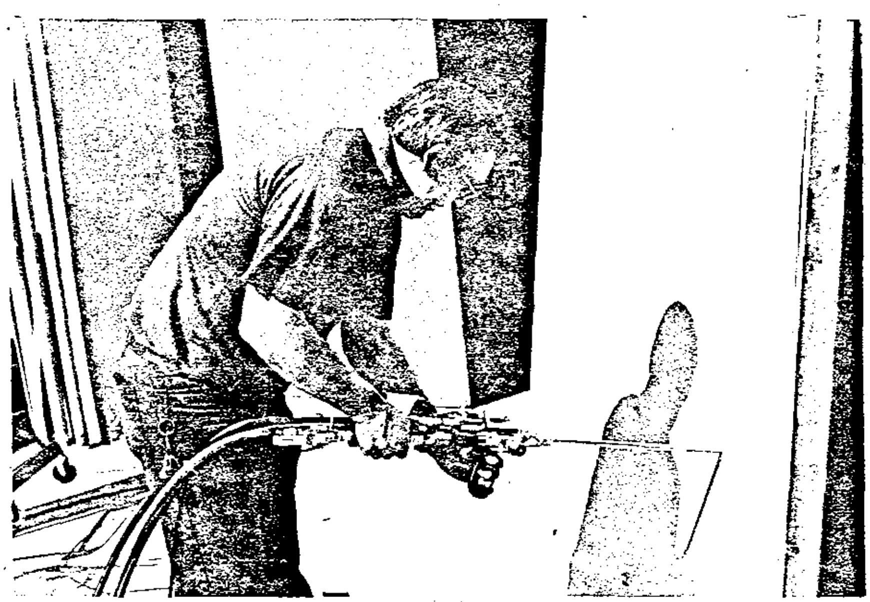


Fig. 2-6. Wall Number 1.

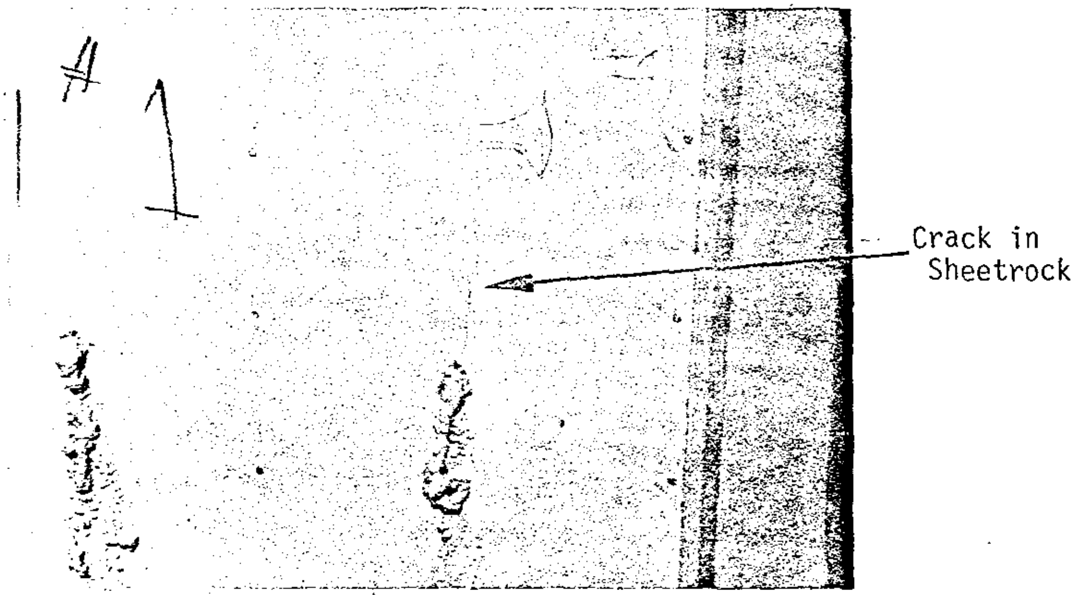


Fig. 2-7. Wall Number 1.

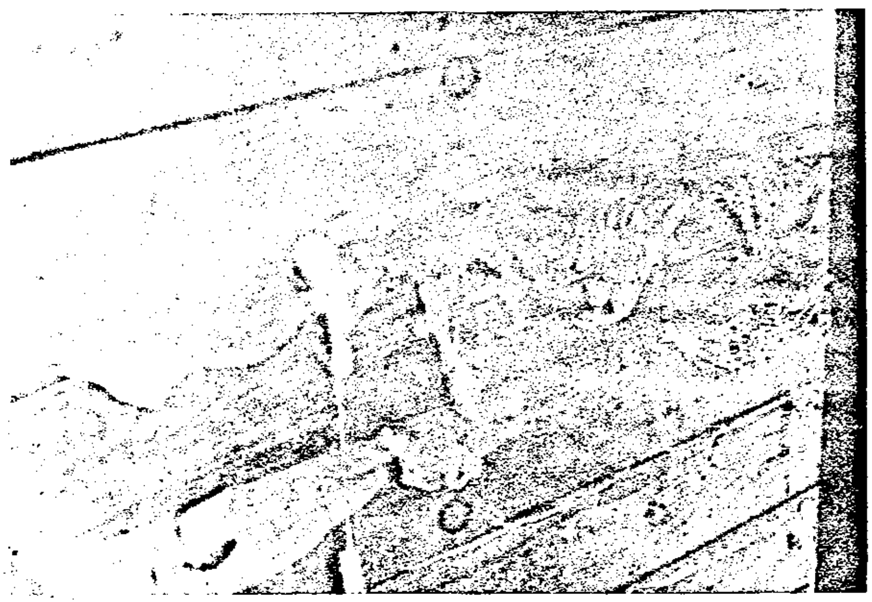


Fig. 2-8. Wall Number 2—Foam Spilling out the Back of the Wall Through Poorly Placed Siding.

as one would desire. Two more 10-sec injections were made up to the fire break, however, the amount of relief that was generated out of the back of the wall was not quite adequate to take care of the surplus foam injected (approximately 5%) and indeed, small cracks generated vertically in the two outside cells of the sheetrock at the fire break. Hence, the injection rate for the top half of the wall was reduced to 9½ sec per injection. The top portion of the wall was completed without any further problems.

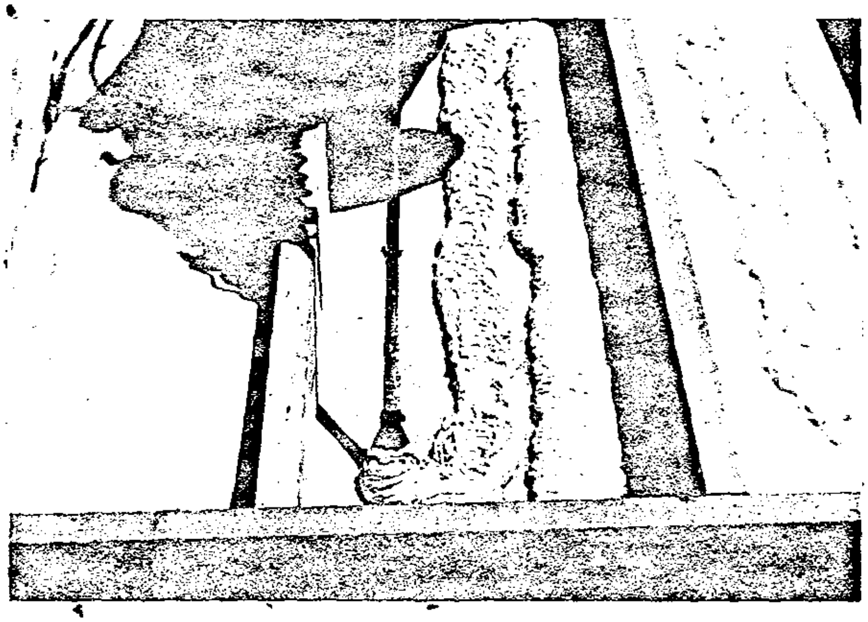
Second Phase

The purpose of this second phase was to improve the foam placement techniques based on the observations of the Phase 1 tests. For example, in the foaming of Ceiling No. 1, it was noted that it would be desirable to have a nozzle that spread the foam over a wider area. The use of an improved spreader nozzle is shown in Fig. 2-9A and the results of the first injection are shown in Fig. 2-9B. The distribution pattern is sketched in Fig. 2-10.

The first basic pass was a three-pass pattern of 22 sec which is just slightly more than one half the volume of the void. The second pass was made after the first pass had achieved near maximum rise. This was a circular pass to ensure the voids between the first foaming and the ceiling joists were filled. Finally a pass was made up the center if there was remaining foam. Fig. 2-11 shows the final pass of the circular pass between the loaf-of-bread-like first foaming and the final or second foaming.

From the first effort of foaming floors it became obvious that, although the injected foam was quite accurately calculated to just fill the voids, it extruded between the planking and back through the fill holes, and further, it cracked sheetrock from the interior pressure. Having tried several patterns of injection without success, it became obvious that it would be desirable to observe what was going on in the floors before a rational and successful foaming scheme could be developed. Hence, a segment of floor representing the void between two floor joists was constructed and covered on one side with plexiglas. The specimen was 8 ft long,

A



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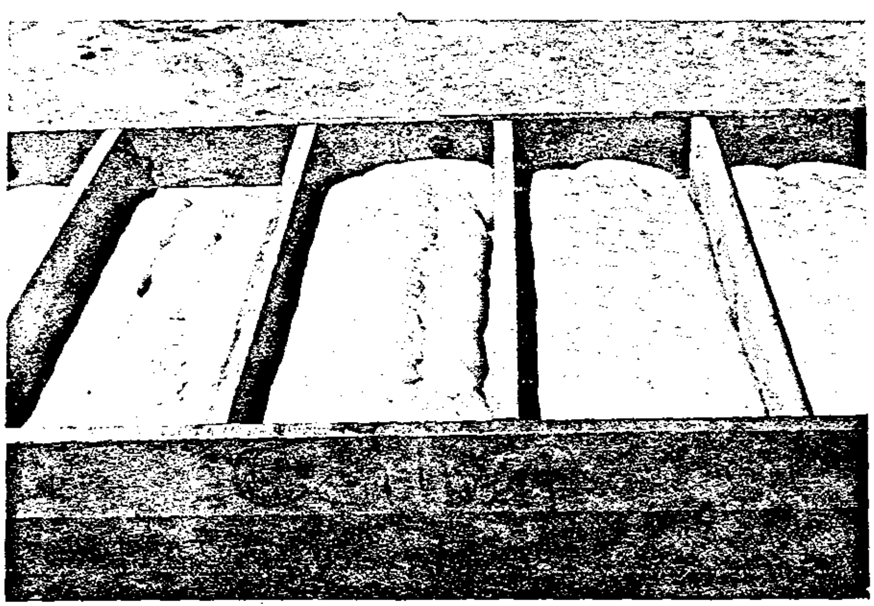


Fig. 2-9. Ceiling Number 2.

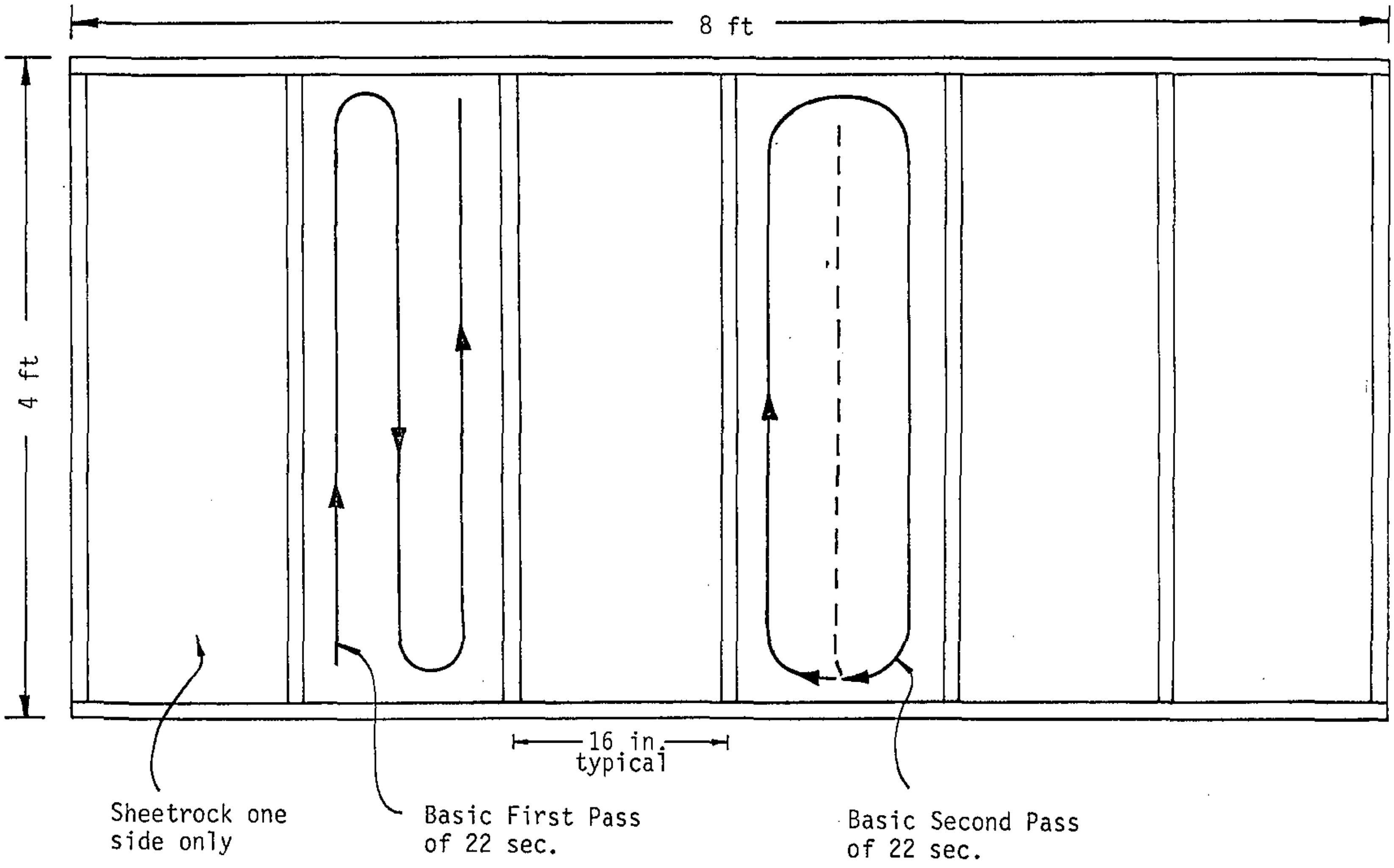


Fig. 2-10. Ceiling Number 2 — Foam Distribution Sketches.

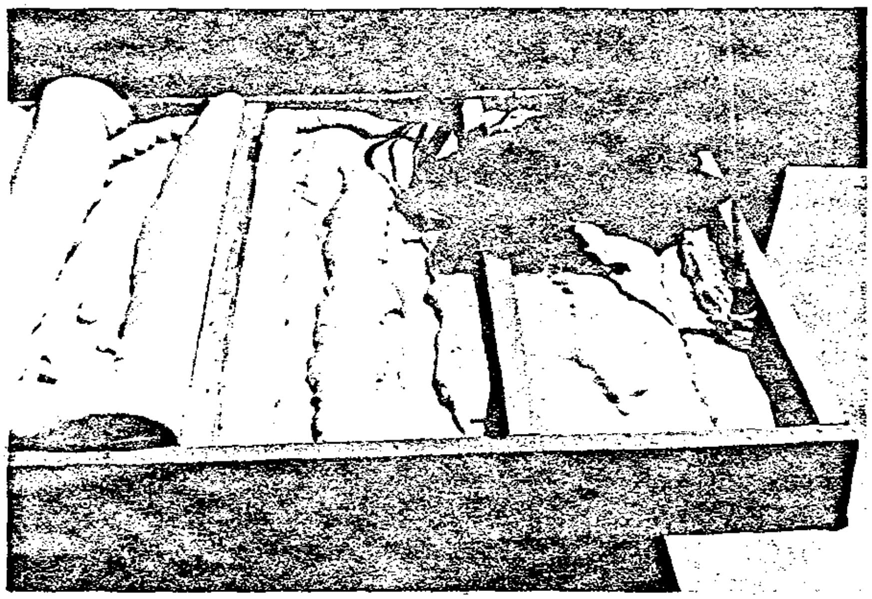


Fig. 2-11. Ceiling Number 2 — Second Foaming Pass Being Performed.

16 in. wide, and 6 in. deep, similar in size and nature to the floor sections injected previously.

The construction details and the injection schedule used are shown in Fig. 2-12. It had originally been intended to inject the specimen sequentially, however, by the third injection, Hole No. 4 was covered and was skipped. A number of interesting things were learned from this test. From the sketches in Fig. 2-12 and the photographs in Fig. 2-13, it can be seen that, although the correct amount of foam was injected, the tendency of each additional injection is to merely add to the previous injection. This almost precludes totally filling a floor system, particularly one made with sheetrock on one side which is very weak to internal pressure, as noted by cracks in the vicinity of injection Number 5, see Fig. 2-14.

As with floors, a few problems were observed in the first foaming trials with walls. Although the problem seemed less severe in the wall systems, it was decided to proceed with a similar plexiglas model and observe what actually happens in a wall. Fig. 2-15 shows a sketch of the wall. It is basically one cell of the 4 x 8 walls — 8 ft long, 16 in. wide, with 2 x 4 studs, 2 x 4 top and bottom members and a 2 x 4 fire block at the center. A single hole was bored into the wall just below the fire block and just below the top of the wall. The foam was injected in three injections of accurately calculated foam, 9½ sec per injection. The first two injections of both the lower and upper segments went well as shown in Fig. 2-16 A and B. Photograph A shows the bottom section after one injection and B shows the top section after two injections. A big difference observed between the wall system and the floor system is that the foam fills all the voids. On the third injection, however, of both the top and bottom sections a slight excess of foam was noted and the sheetrock cracked, as can be seen in Fig. 2-17 A and B.

To aid in understanding of the foam expansion process, a series of free pours were made. The first, a 10-sec (1-lb) pour can be seen in Fig. 2-18. This pour was totally unconfined and spread 19½ in. in diameter and was approximately 4½ in. deep at the center — a height to radius ratio

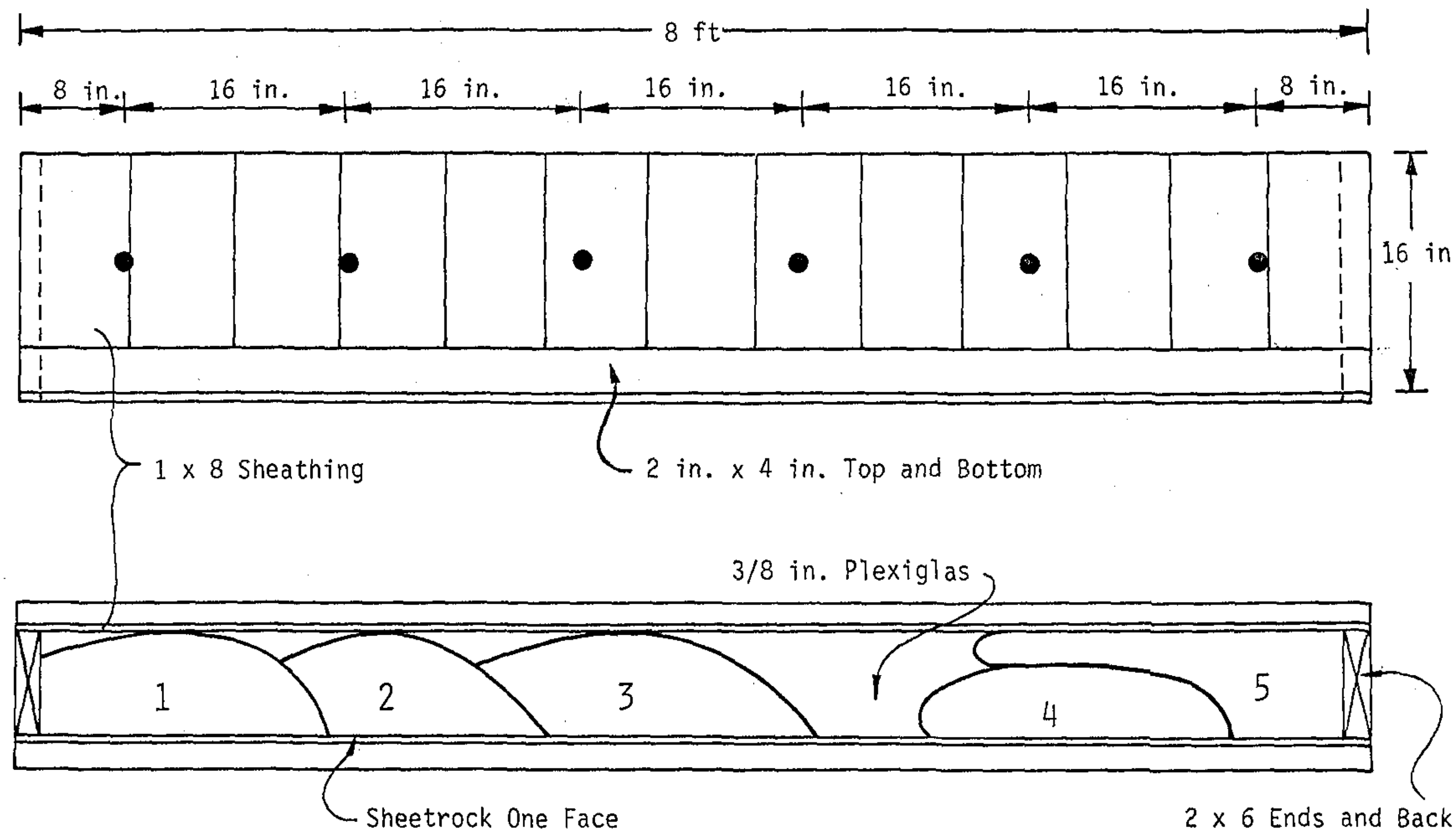


Fig. 2-12. Plexiglas Floor Number 1 — Construction Details and Pour Schedule.

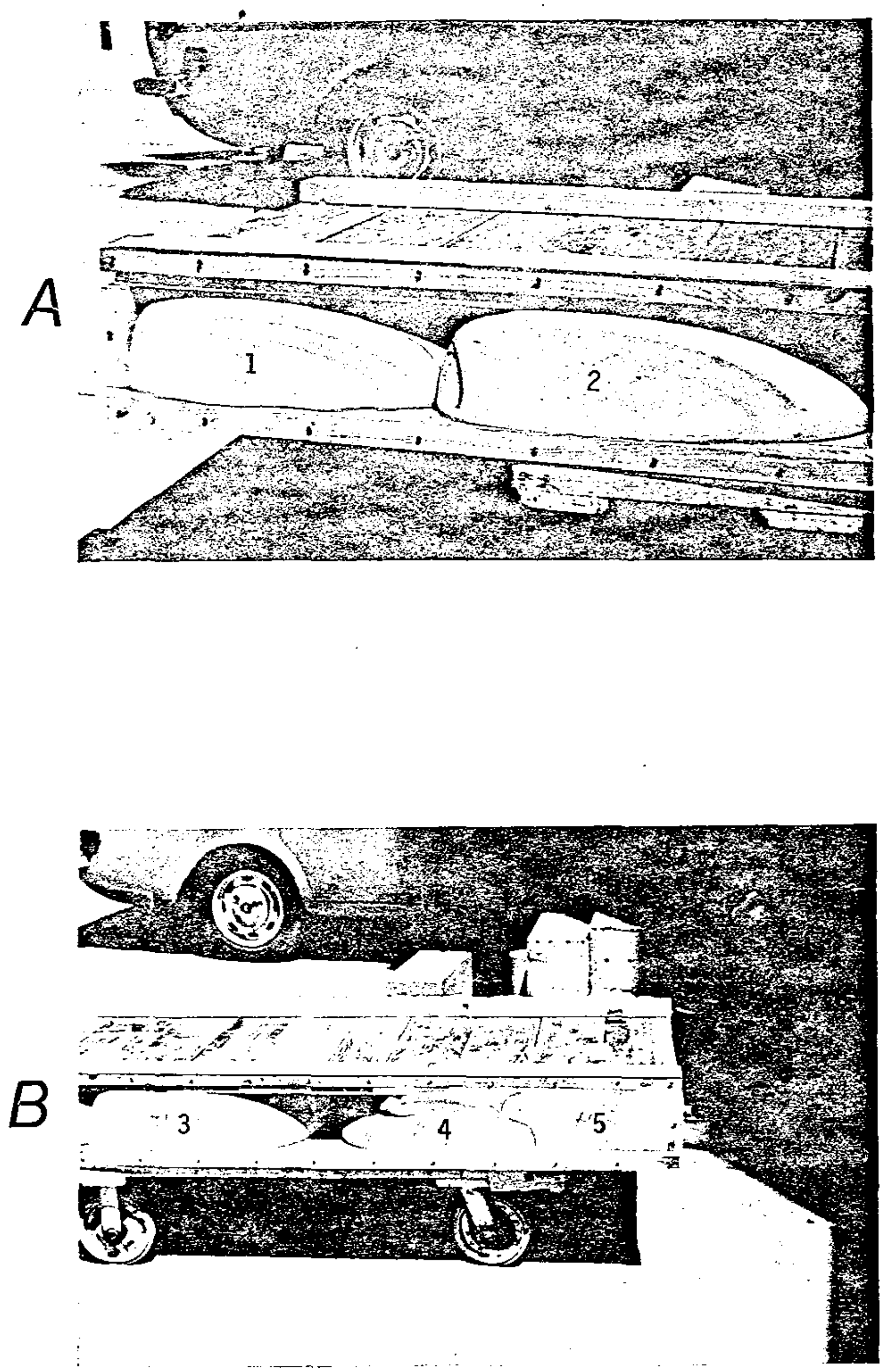


Fig. 2-13. Plexiglas Floor Number 1.

Fig. 2-14. Plexiglas Floor Number 1.

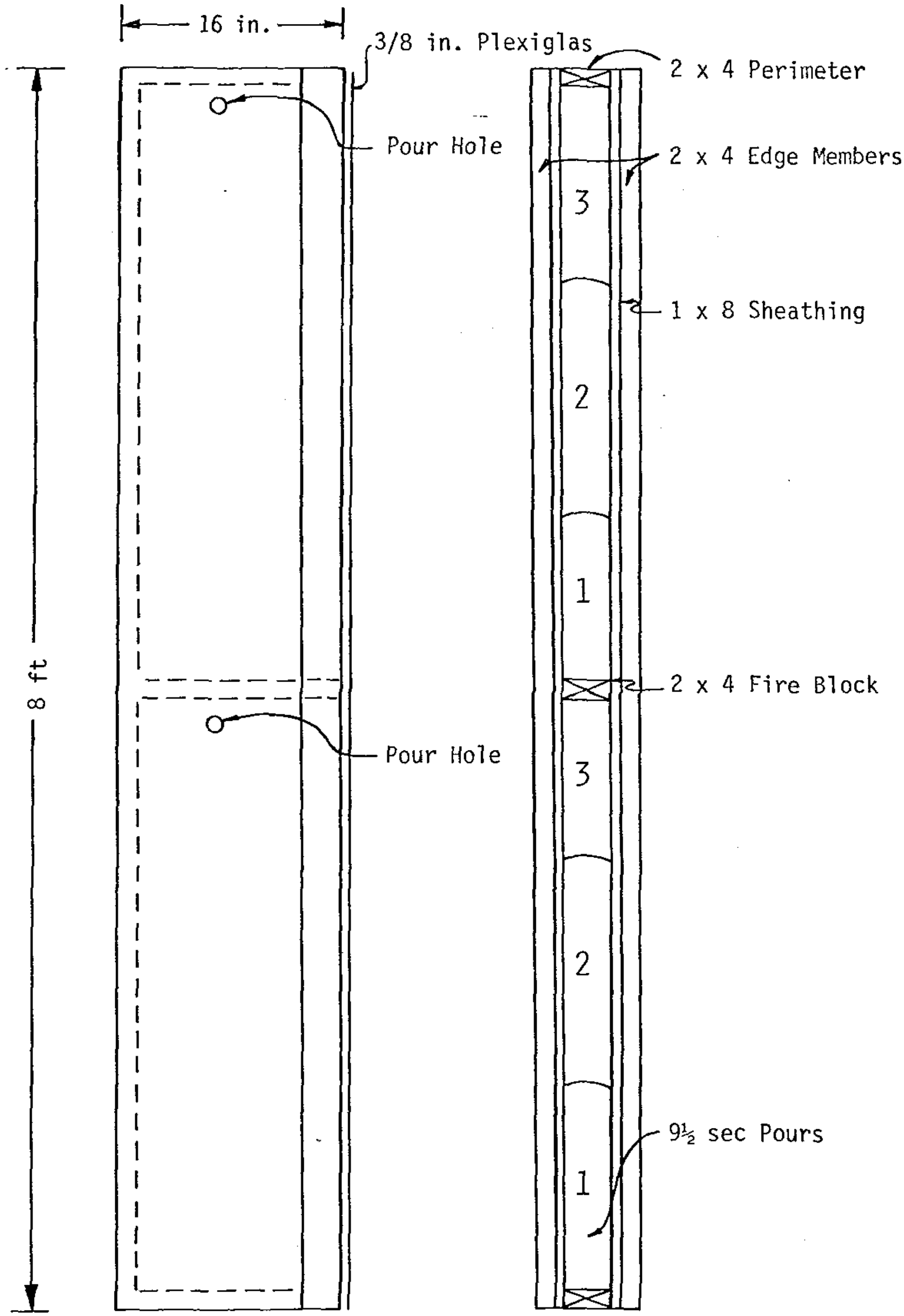


Fig. 2-15. Plexiglas Wall Number 1 — Construction Details and Pour Sequence.

A

B

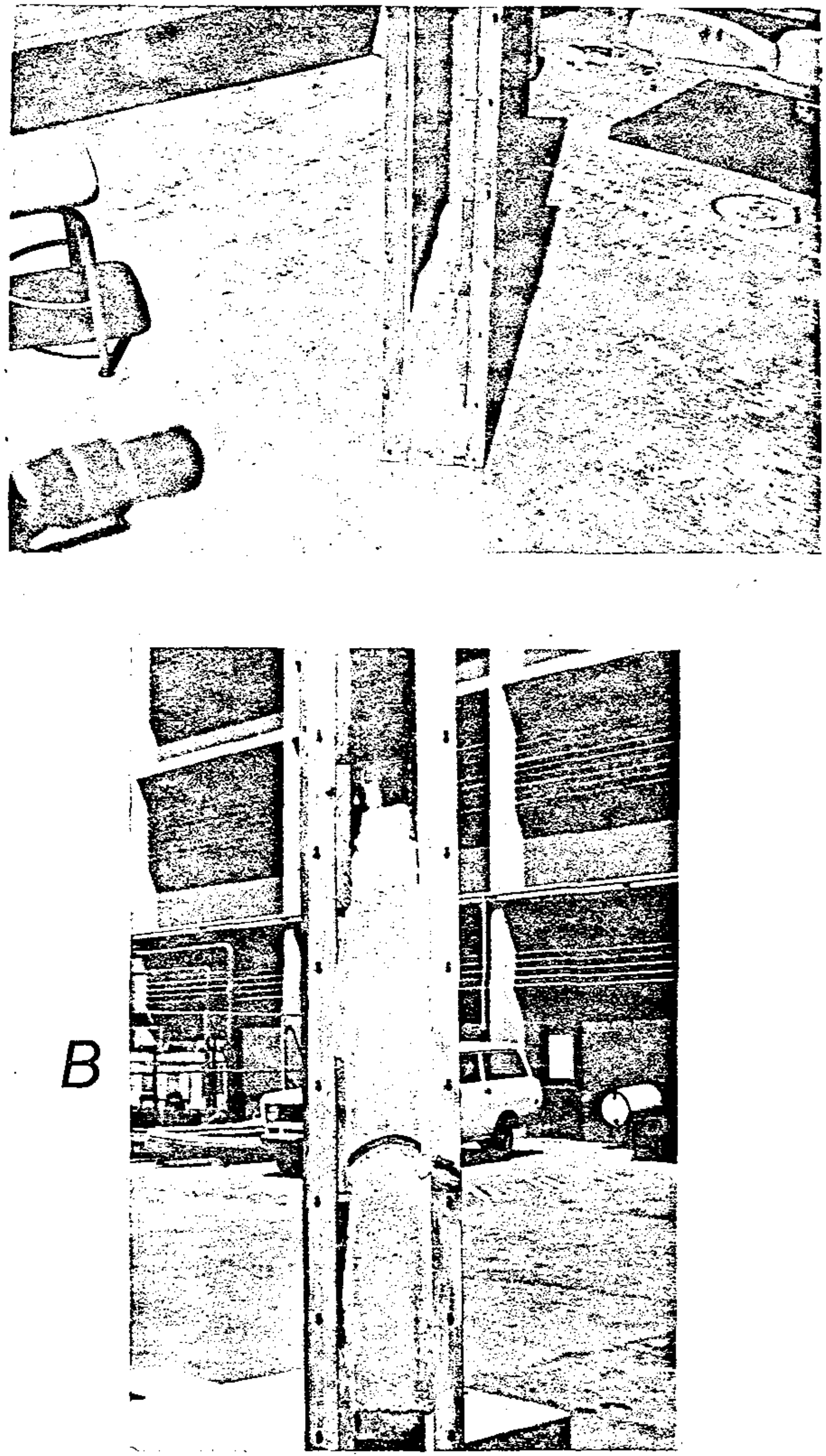
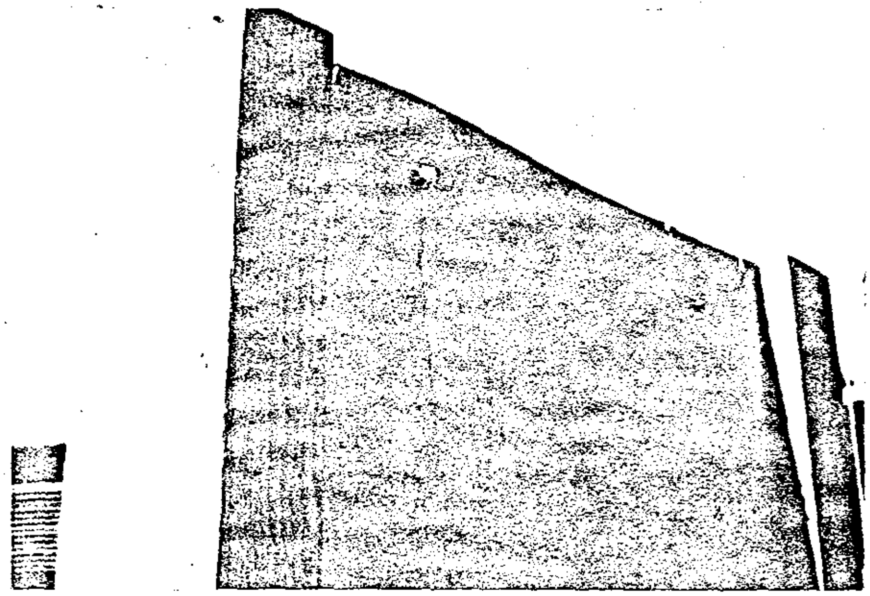


Fig. 2-16. Plexiglas Wall Number 1.

A



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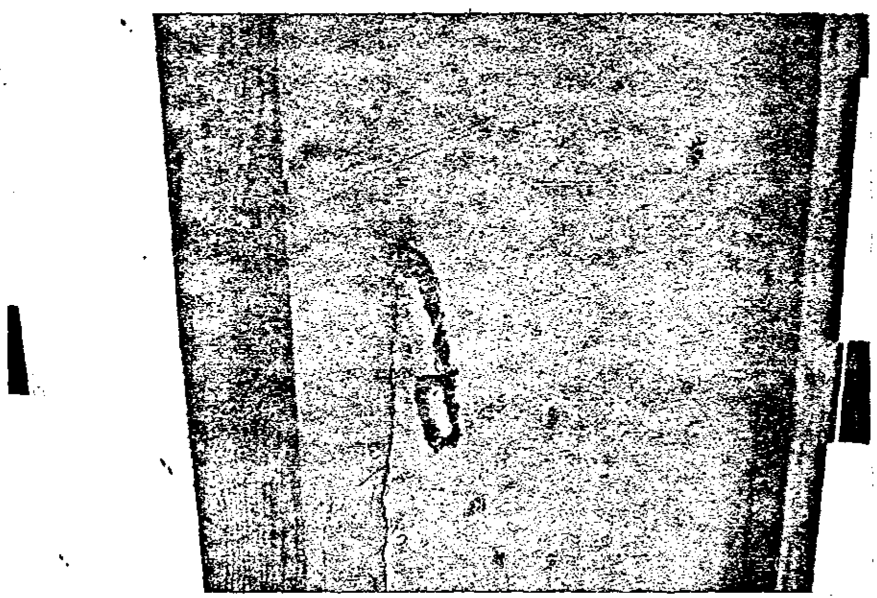


Fig. 2-17. Plexiglas Wall Number 1.

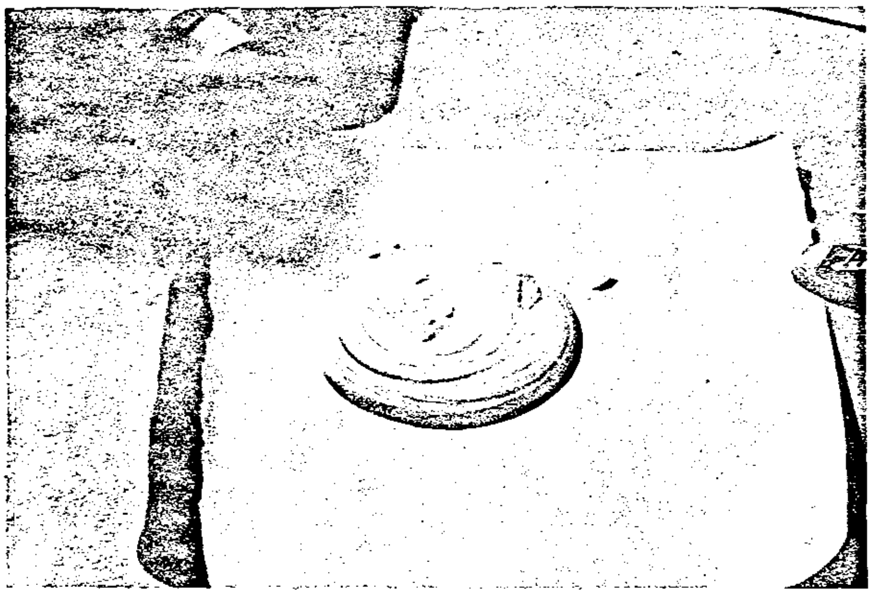
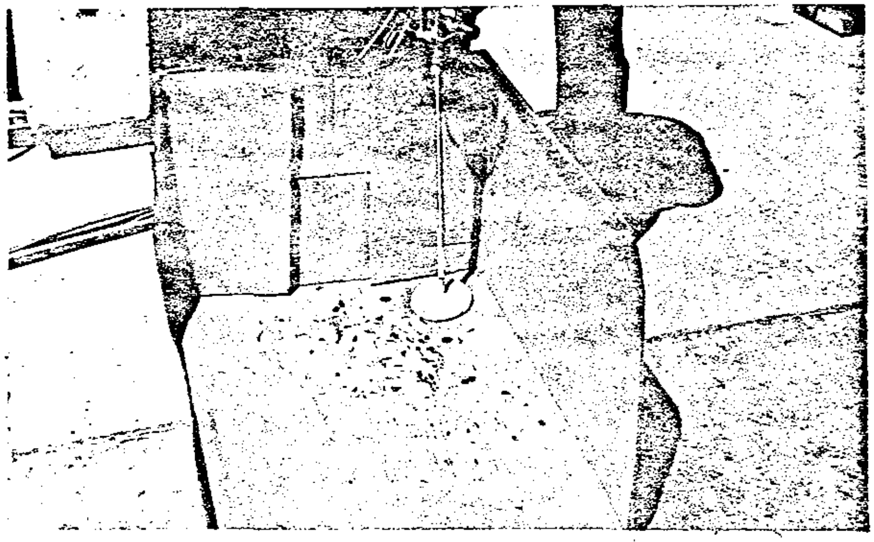


Fig. 2-18. Unrestrained 1-lb Foam Pour.

of 0.46. The second trial was a lightly restrained injection (4 in. from the inside corner of a cardboard box) which is pictured in Fig. 2-19 A, B and C. These are a sequence of photographs showing the initial injection (A) partially expanded (B), and fully expanded (C). This injection achieved the height of approximately 6 in. maximum and spread radially about 10 in. along the constrained sides and a maximum of 14½ in. radially to the outermost point. This gave a slope, a height-to-radius ratio of about .41 and approximately .57 along the restrained edges or the confining edges. Sketches of each of these pours are given in Fig. 2-20.

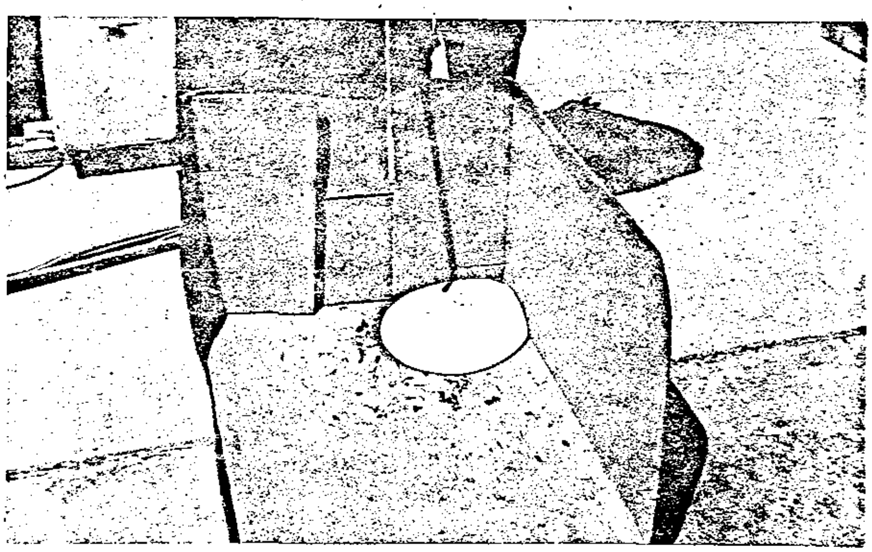
Third Phase

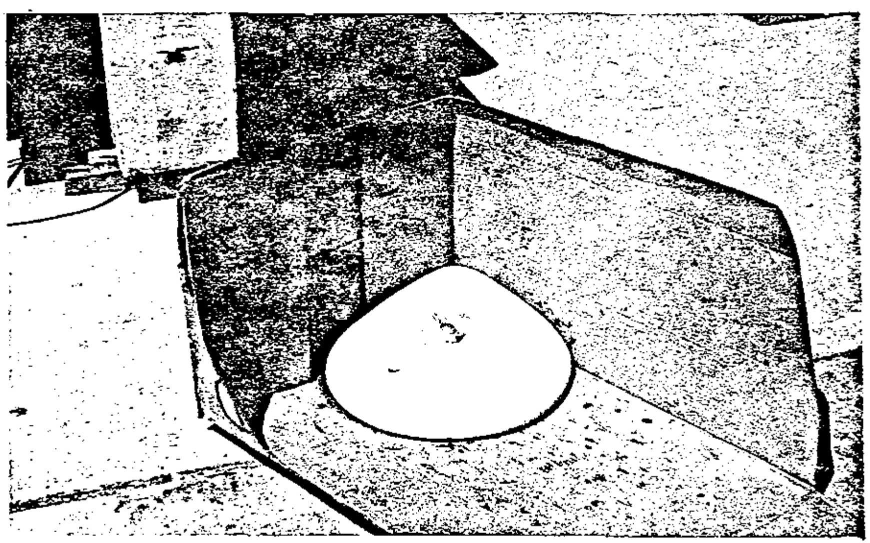
Based on the results of Phases 1 and 2 and the free pour tests, a third and final series of tests were conducted. The wall problem was considered first. Plexiglas Wall No. 2 was constructed, which was identical to plexiglas Wall No. 1 (shown in Fig. 2-15) except that there was no fire block installed. This meant that the void was nominally 16 in. wide by 8 ft high by 3½ in. deep. Three injection holes were made across the top of the wall and no injection hole was made at the mid-height. The volume of the wall was such that it needed six 9.7-sec injections. It was decided, based on earlier work, that the injections would be approximately 10% less and to alternate the location (hole) of the injection in the wall. That is, the first injection was made through the center hole; after it achieved its maximum rise, the second injection was made through the left hole; and after the rise the third injection was made through the right-hand hole. This procedure was maintained through the six pours up the wall. It is interesting to note that the alternating pattern had little effect on the filling, and essentially the wall filled uniformly across whether it was poured right, left, or center. Further, by the time the sixth injection was completed, the foam was approximately 10 in. short of the top of the wall, which is roughly the 10% volume shorted each injection. Hence, the earlier conclusion that in a wall injection all voids are essentially filled was still correct. Another interesting and important observation is that although a full 8-ft height was injected instead of the 4-ft, this created no additional distress in the sheetrock or the nailings of the plexiglas or



A
Initial Injection

B
Partially
Expanded

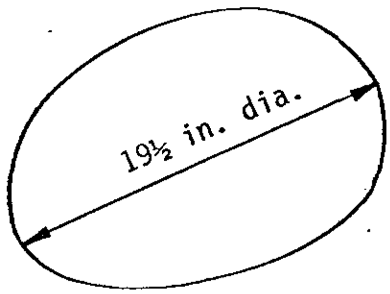




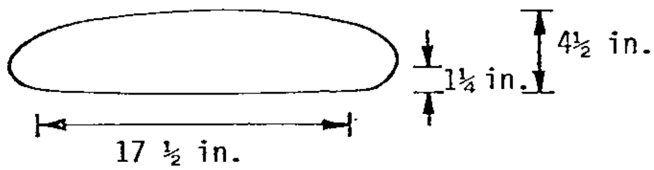
C
Fully Expanded

Fig. 2-19. Lightly Restrained 1 lb Foam Pour.

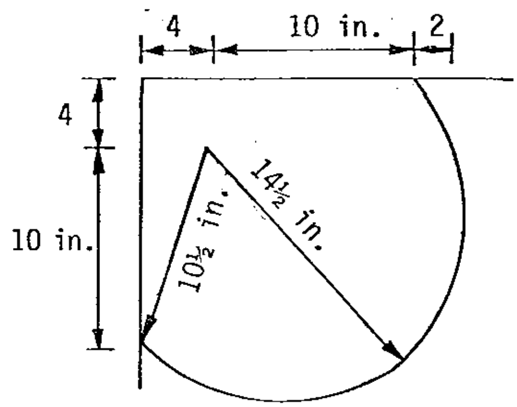
Unrestrained Blob — 10 sec Foaming, 1 lb



$$\frac{h}{r} = \frac{4.5}{9.75} = 0.46$$



Lightly Restrained Blob



$$\frac{h}{r} = \frac{6}{14.5} = 0.41 \text{ max.}$$

$$\frac{h}{r} = \frac{6}{10.5} = 0.57 \text{ min.}$$

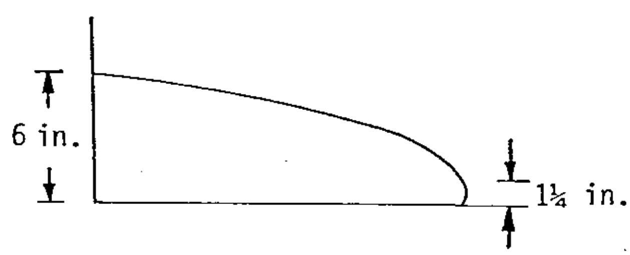


Fig. 2-20. Sketches of Unrestrained and Restrained 1 lb Foam Pours.

the other components of the wall. With the known amount of void left at the top, a 5-sec injection was made and completed the wall solid to the top without fracturing the fiberglass.

Since the variation of injecting (i.e., left, center, right) did not seem to make any difference, two 4 ft x 4 ft wall specimens were constructed for use as shear test specimens. These specimens, shown in Figs. 2-21 and 2-22, are basically 2 x 4 stud wall sections with 2 x 4 top and bottom representing a half-height wall. Two injection holes, one approximately 3 in. from the top and one approximately 6 in. from the top were used. Three 9-sec injections were made in each cell, which again is approximately 10% (in this case actually 7%) low. The first three lifts were injected from the lowest holes and it was assumed that, if all was going well, the foam would rise to approximately 5 in. from the top, if it was consistent with previous walls and the plexiglas Wall No. 2. Two walls were foamed this way, both walls with success. After the first three lifts in both walls had made their final rise, the motive for two holes then became obvious: if indeed the foam rose to the lower hole or slightly above, it would be easy to determine how much foam to add, and finish the wall without breaking it. Of the two walls, one had a slight bulge on one side after the third injection. No problems were encountered in the fourth, or topping, injection. Note: both walls had sheetrock on both sides, the worst possible of wall types, an interior partition with sheetrock on both sides.

Next foamed was a 4 ft x 4 ft wall shear test specimen with sheetrock on one side and timber on the second side. On the remaining walls — shear test specimens — the hole pattern was changed to three holes along the top approximately three inches down, and one hole about 6 in. down from the top (see Fig. 2-23). The foaming was again done in approximately 16-in. lifts from the lower hole. The idea behind the three holes at the top was not only to get a more accurate reading of the remaining voids, but also to allow for relief if too much foam was accidentally injected in the last lift. Again, two of these panels were made with the board back and they were injected in three 9-sec lifts. The first wall was foamed without a problem, the second wall began to show distress during the second injection,

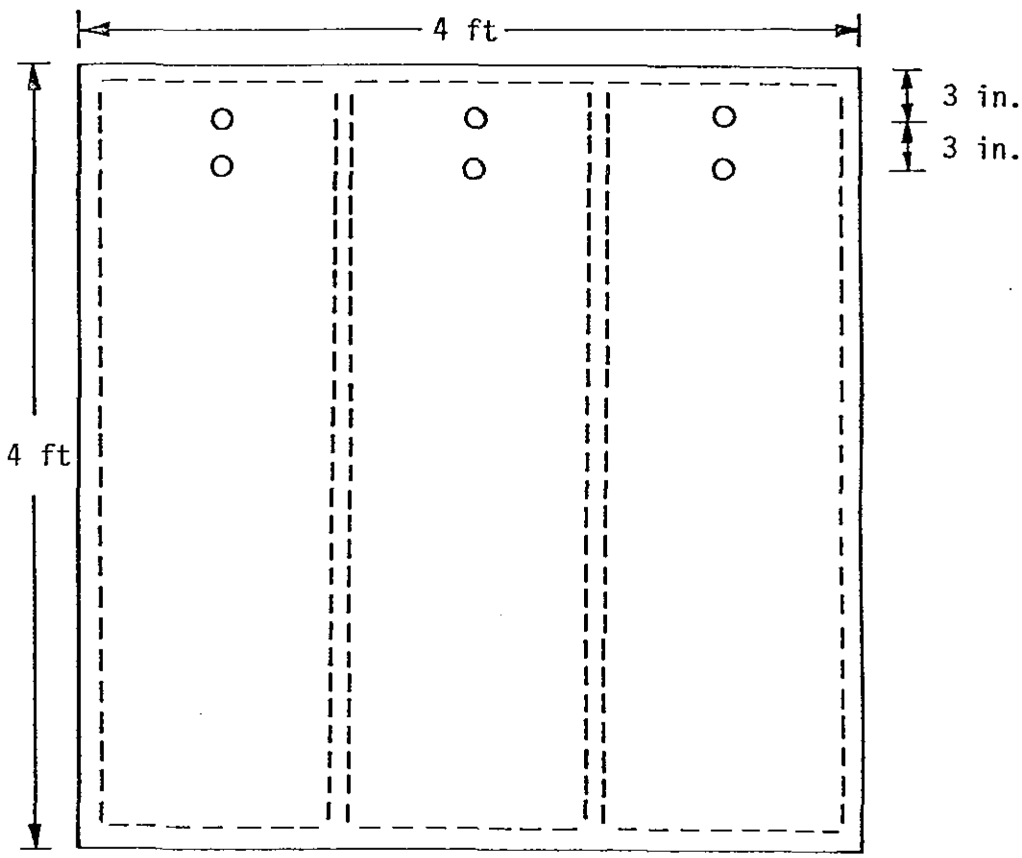


Fig. 2-21. Sketch of 4 ft x 4 ft Shear Test Specimen.

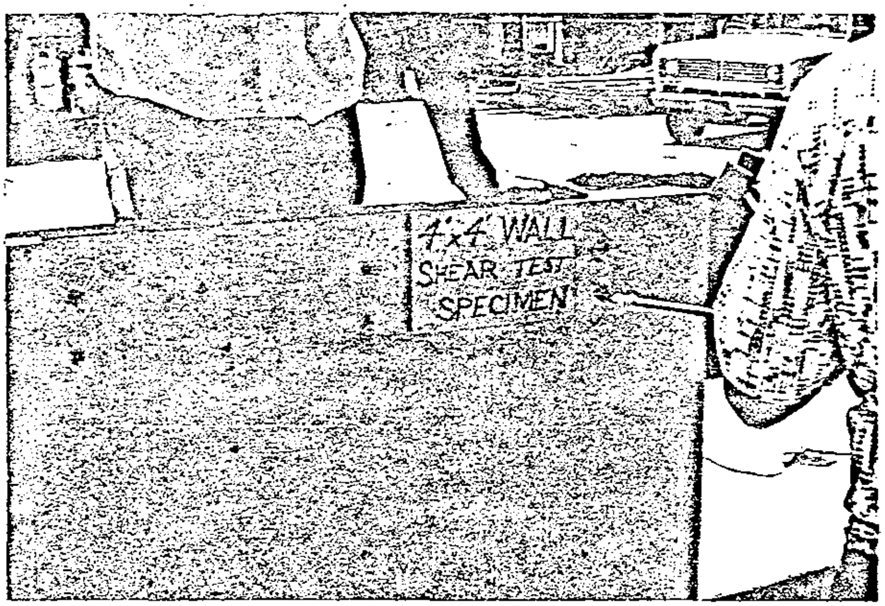


Fig. 2-22. Photograph of 4 ft x 4 ft Shear Test Specimen Being Foamed.

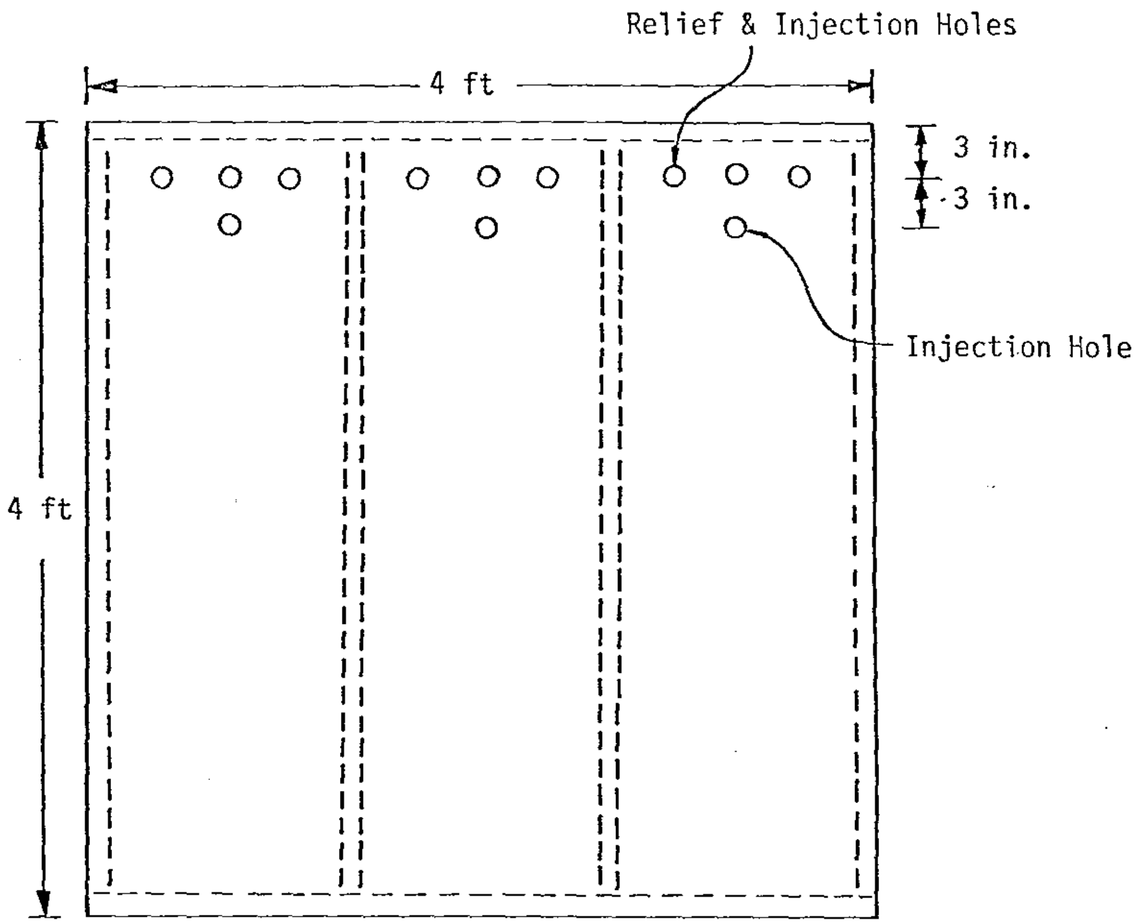


Fig. 2-23. Sketch of 4 ft x 4 ft Shear Test Specimen with Improved Hole Pattern.

that is, there were slight dimples approximately 1/8 in. deep at the nails. On the third lift the wall was completely foamed and a crack developed approximately 6 to 7 in. down from the top. Subsequent investigation indicated that this increase in volume of the injected foam was apparently caused by an approximate 5° rise in ambient temperature at the time this wall was foamed. A subsequent wall was successfully foamed using 8½-sec injections or about a 5% decrease. The ideal foaming temperature is somewhere between 75° and 80° F and corrections will have to be made for higher and lower ambient temperatures.

Floor problems were looked at next. Specimen Floor No. 6 was constructed as shown in Fig. 2-24. Having observed the plexiglas model tests, it was determined that a staggered hole pattern would be the best solution. The foaming was as follows: since there were 6 holes, 90% of 1/6 of the volume of the entire cell or, in this case, 13 sec of foam was injected in each hole. Injecting started at the left and progressed satisfactorily until the foaming at the far right-hand side started to ooze out and fracture the sheetrock. In light of the foregoing on Cell No. 2, the injection was reduced in the first hole on the left end to 8 sec, hence proceeding across four holes 13 sec each, leaving the sixth and last hole unfoamed to observe what happened. At the end of the rise time, there was only room for approximately 4 sec of injection in the far right hand void. Hence, the final void ratio is .74 instead of .90, which, of course, will reduce the net shear strength of this section. However, this particular foaming with a 74% void ratio seemed not to cause any distress in any portion of the floor system and the third cell was filled the same way.

Floor No. 7 was a duplicate of Floor No. 6 with the exception that an additional hole was added in the right-hand corner in the 12-in. spacing. An attempt to improve the void ratio to 90% was made by injecting 8 sec in the first hole, 13 sec in each of the next five holes and 4 sec in the seventh (new) hole. This gave a void ratio of .89 instead of .90 and presented no problems, so the entire floor was foamed in this manner.

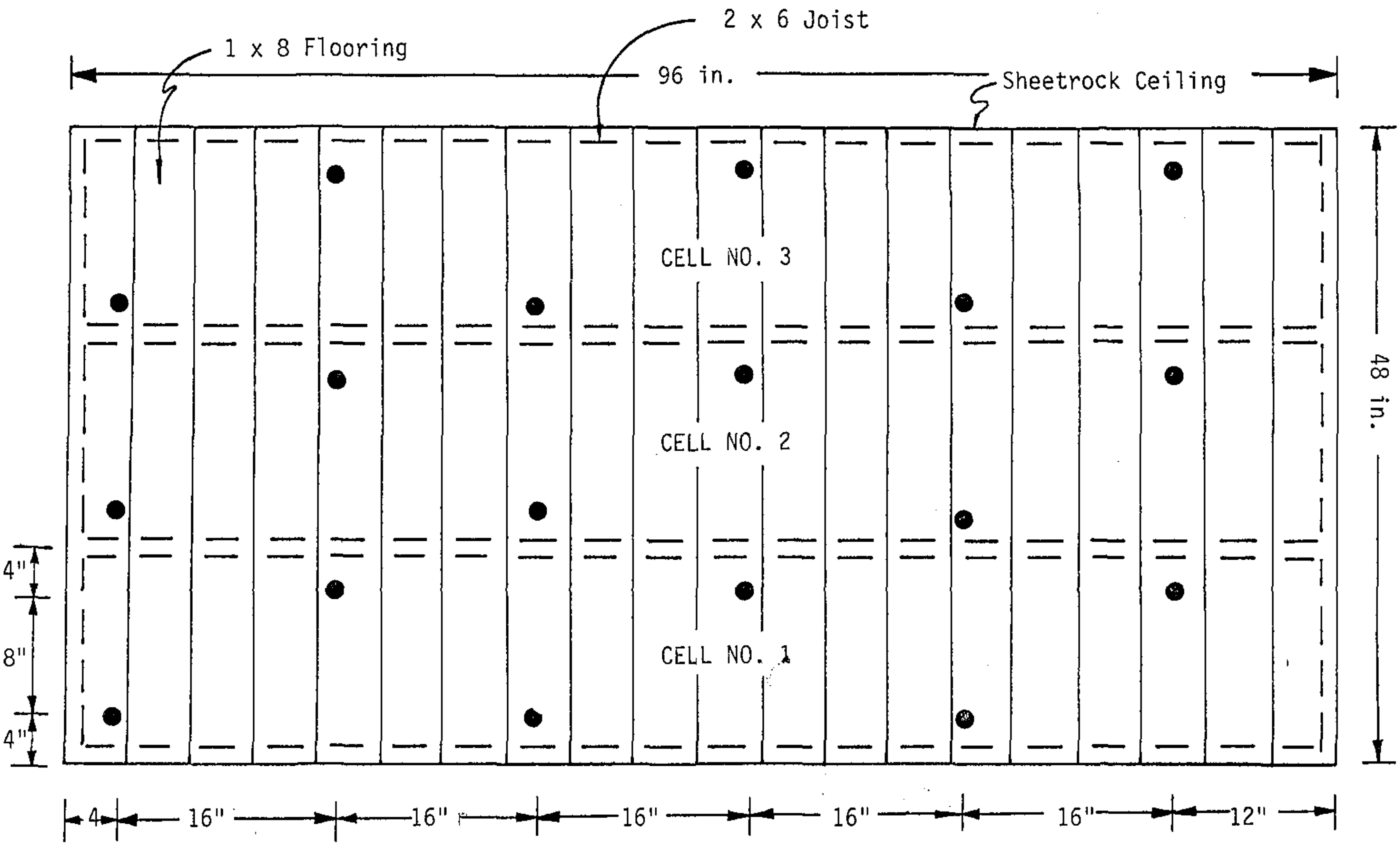


Fig. 2-24. Floor Number 6.

Because of the experience with Floor No. 6, it was decided to construct one more plexiglas floor, No. 2, shown in Fig. 2-25. In this floor, holes were drilled close to the corners and then spaced along the sides alternating so the final area of contact could be seen on the plexiglas side (since this controls the shear strength). It was observed that injections in the corners made very good contact at the boundaries, which is the area that needed to carry shear in or out of a floor diagram, and little distress occurred in the sheetrock. Each hole was injected with 90% of the required foam and the results are pictured in Fig. 2-26 A and B. The foaming was completely successful in that it had caused no harm to the sheetrock, the plexiglas, or the flooring. The contact surface area on the plexiglas by the foam was 65%, which was consistent with the volume ratio achieved on earlier floors, but now it was known that if 90% of the volume is injected in staggered holes fairly carefully located, a 65% bonding surface to the floor joists can be achieved with no breakage whatsoever on the sheetrock below. The work to this point shows that, for approximately 100% filling of floor voids, a nozzle to disperse the foam over a fairly wide region, perhaps 16 to 24 in. must be developed. This would allow uniform foaming with fewer problems with possible fracture or damage to the sheathing or sheetrock.

Using the techniques developed to date, the 8-in. floor shown in Fig. 2-27 was foamed. One third of the 90% of the volume per cell would require 17 sec of foam injection; therefore, 8½ sec of foam was injected into the corner holes and 17 sec of foam into the center holes. No problems were encountered and, if the previous work on foaming proves correct, approximately 65% of the area for foam bond and shear enhancement of the floor system should have been achieved.

Ceilings

Where the possibility of attic fire is of concern in perhaps an unsprinklered attic which is used as storage, it is a reasonable approach to put sheetrock on the top side of the ceiling joists in addition to the regular plaster or sheetrock that exists on the interior of the building.

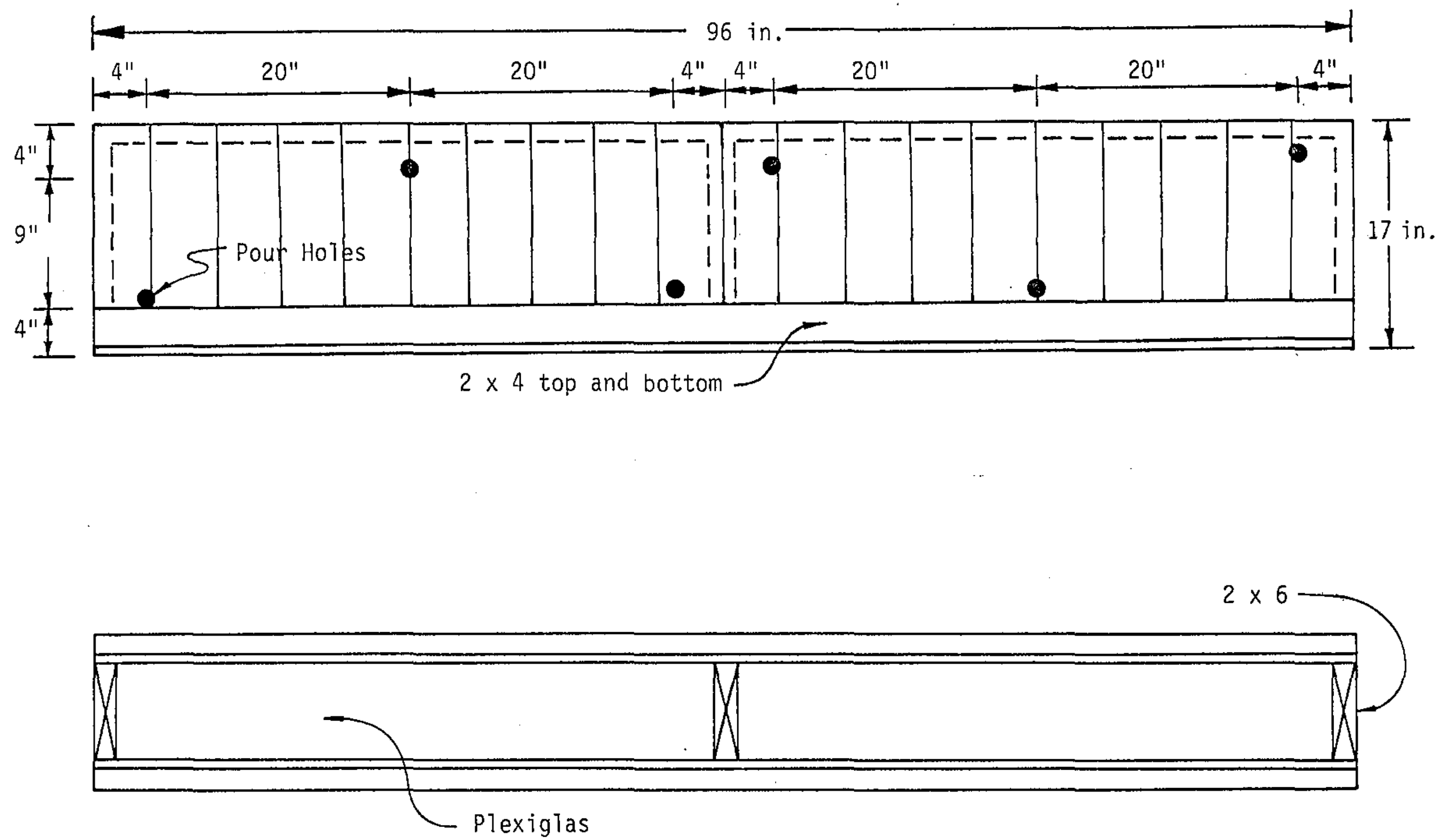
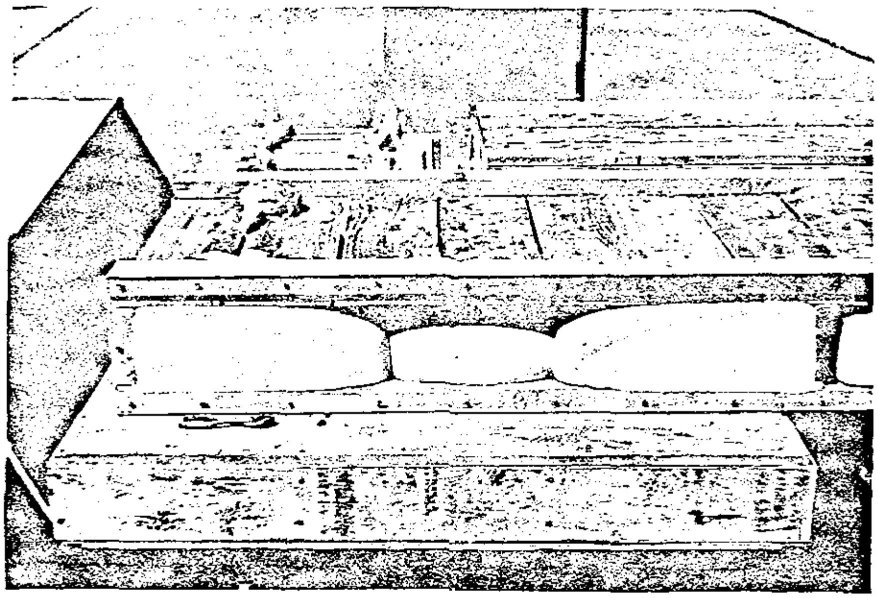
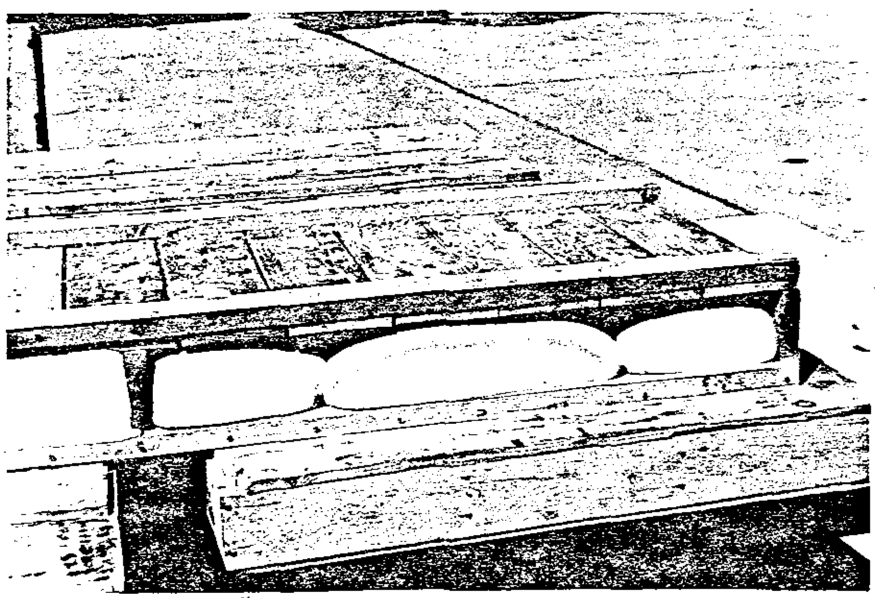


Fig. 2-25. Sketches of Plexiglas Floor Number 2.



A: Left Side



B: Right Side

Fig. 2-26. Plexiglas Floor Number 2.

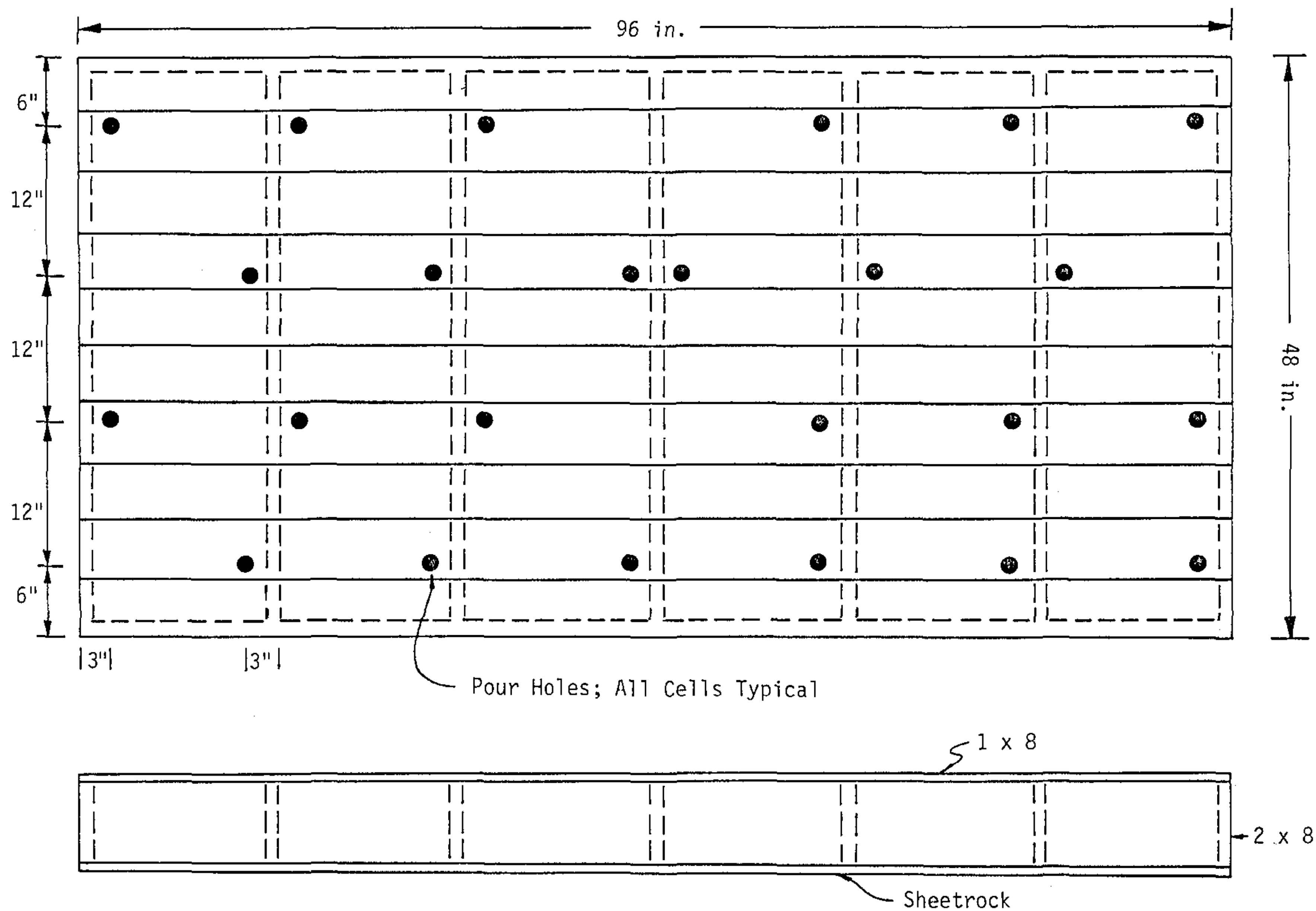


Fig. 2-27. Sketch of 8 in. Floor.

To illustrate this, Ceiling No. 3 was constructed of 2 x 6 ceiling joists at 16-in. centers spaced along the 8-ft direction, thus making the 4 x 8 panel with sheetrock applied to the bottom of the panel. Then 16-in. strips of sheetrock were nailed to the top of the ceiling joists and foamed sequentially, as shown in Fig. 2-28 and 2-29. The technique seemed completely successful, with no distress appearing in the bottom sheetrock (the side that would be in the dwelling) and no distortion in the 16-in. strips of sheetrock. A second ceiling was constructed (Ceiling No. 4); however, in this case the 2 x 6 ceiling joists were run the long, 8-ft direction, and the 2 ft x 4 ft pieces of sheetrock were nailed on top and foamed sequentially. (The thought here was that, as a person got away from the edge or into a less confined space, he would probably want to put in bigger pieces of sheetrock and foam at a faster pace.) From Ceiling No. 4 it appears that there would be no problem with using a full 4 ft x 8 ft piece of sheetrock and foaming the 4-ft direction using a longer stinger on the injection nozzle.

To gain additional data two sets of special test specimens were constructed and tested. Fig. 2-30 shows some special three-block shear specimens that were made in order to give a more accurate measurement of the shear strength and bonding capacity of foam to wood and the shear modulus. Another problem encountered in the earthquake area, or for that matter any lateral load area, is the connection of the floor system to the foundation. Some special short sections of 2 x 10 floor systems were bonded with foam, as shown in Fig. 2-31, to a concrete slab simulating a floor-to-foundation system. These were subjected to a shear test to demonstrate the bonding capability of the foam to the footing as well as to the floor system.

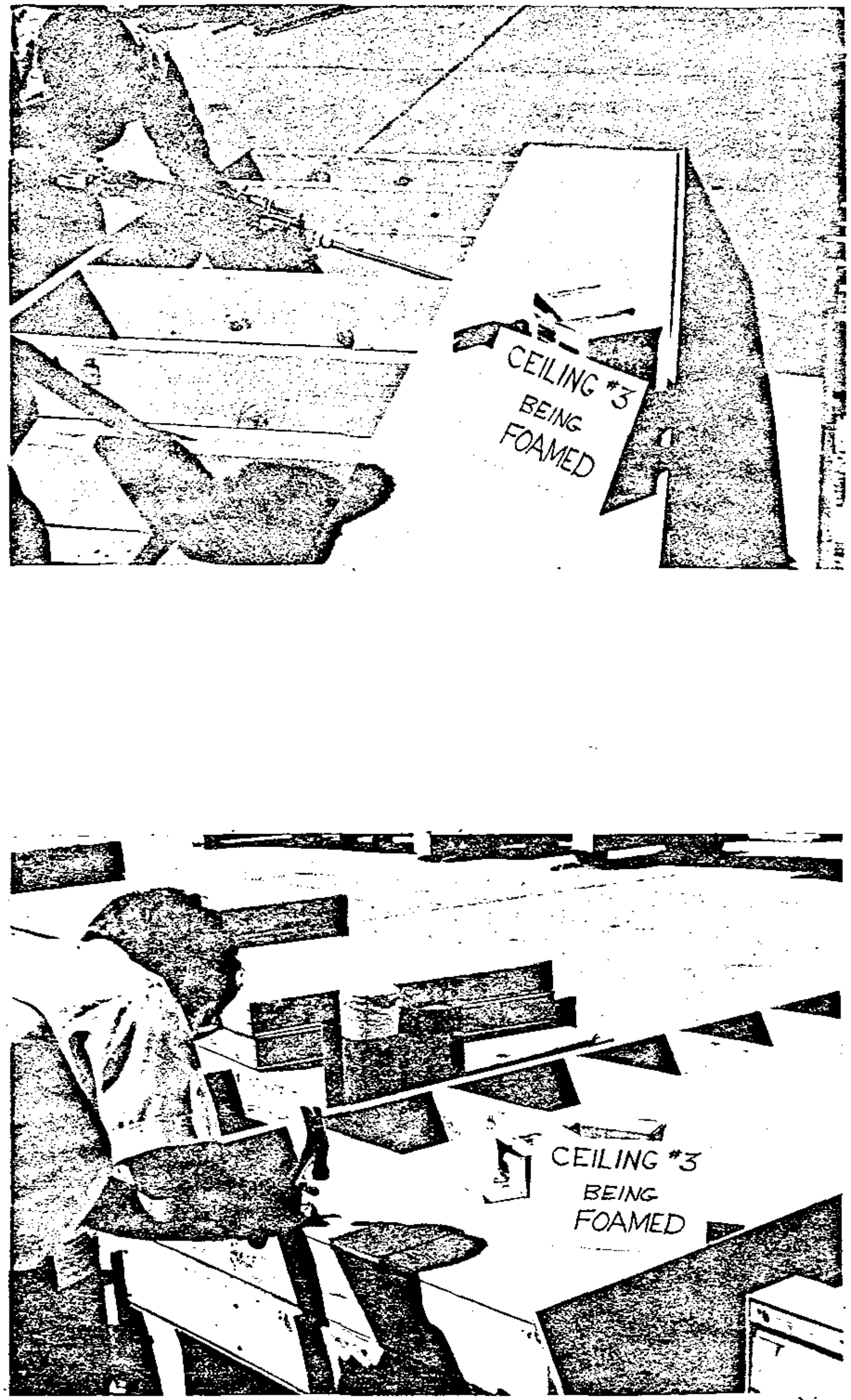


Fig. 2-28. Ceiling Number 3.

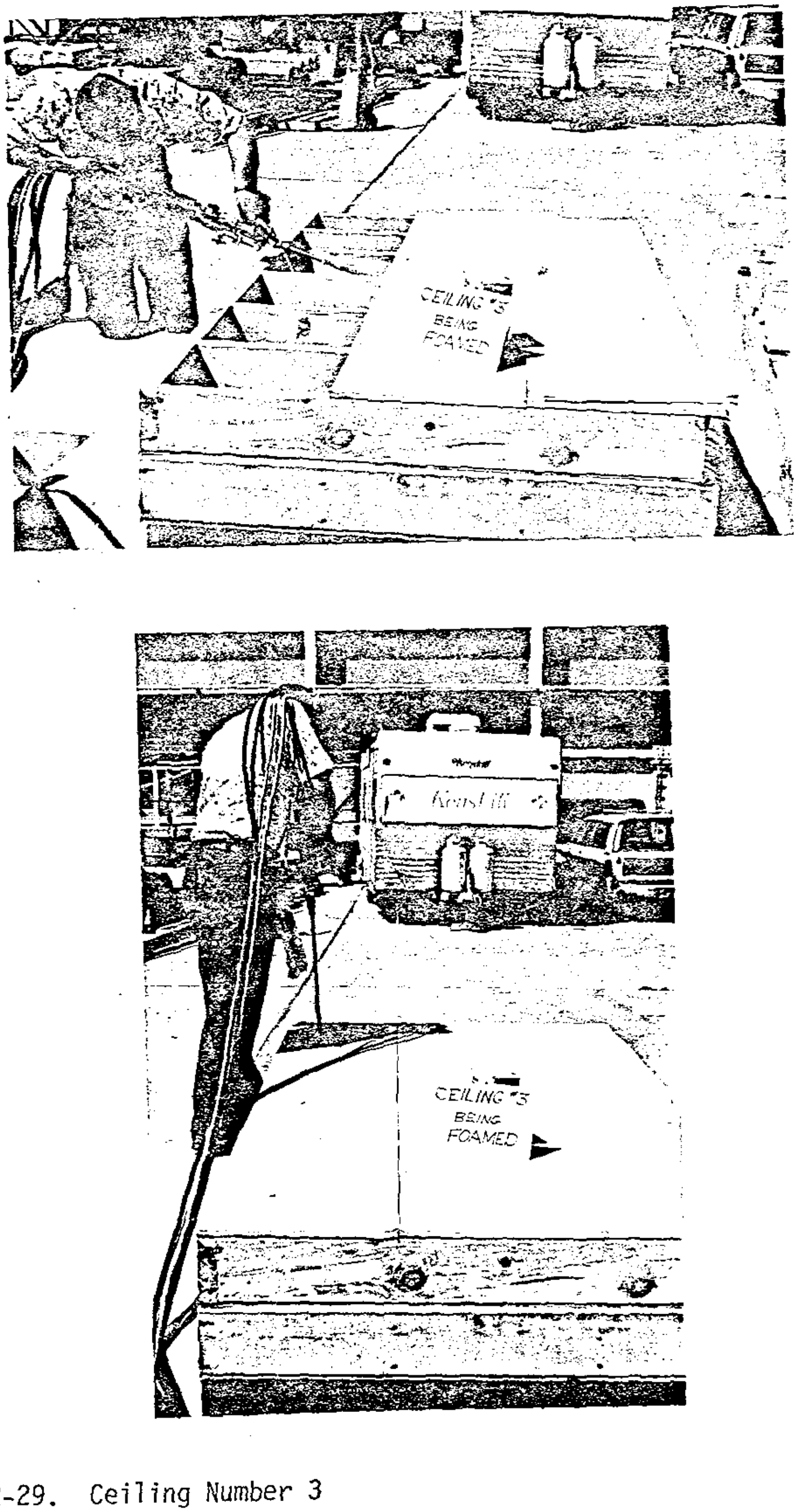


Fig. 2-29. Ceiling Number 3

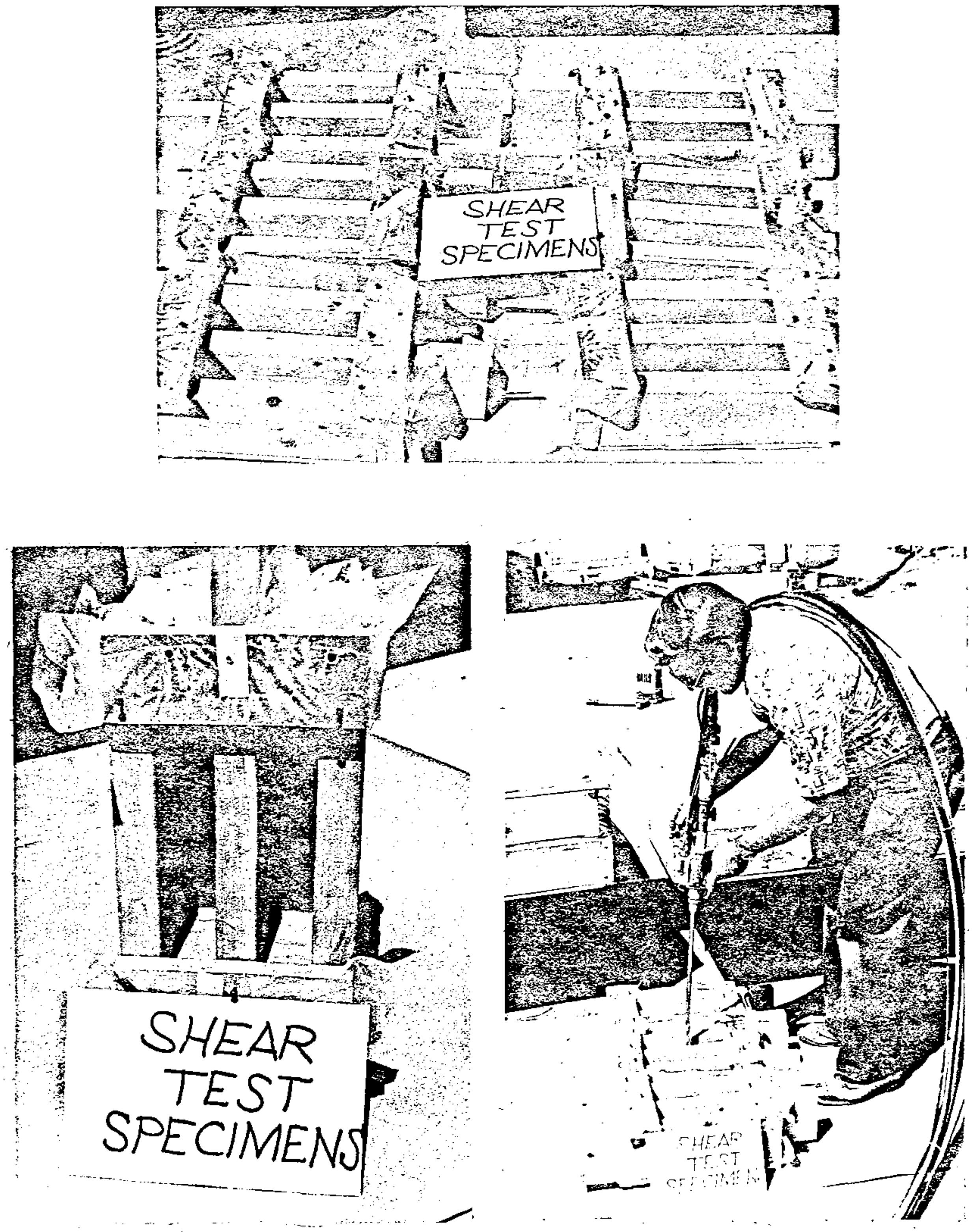
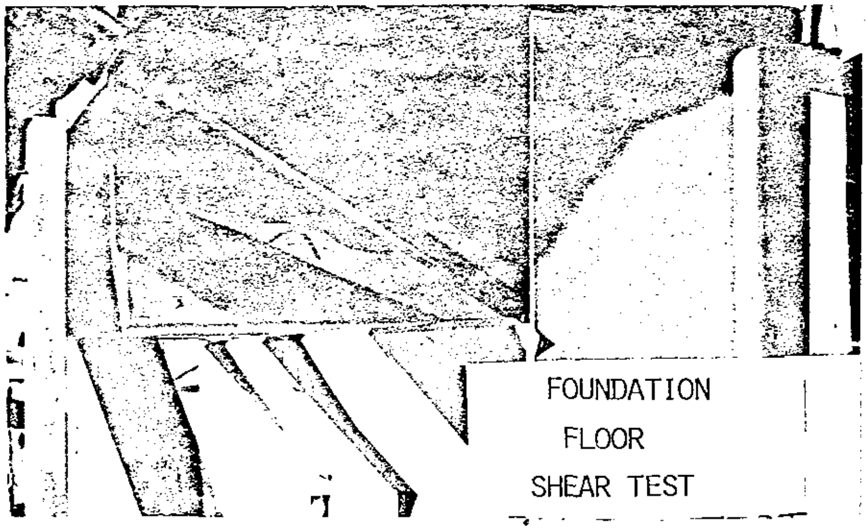
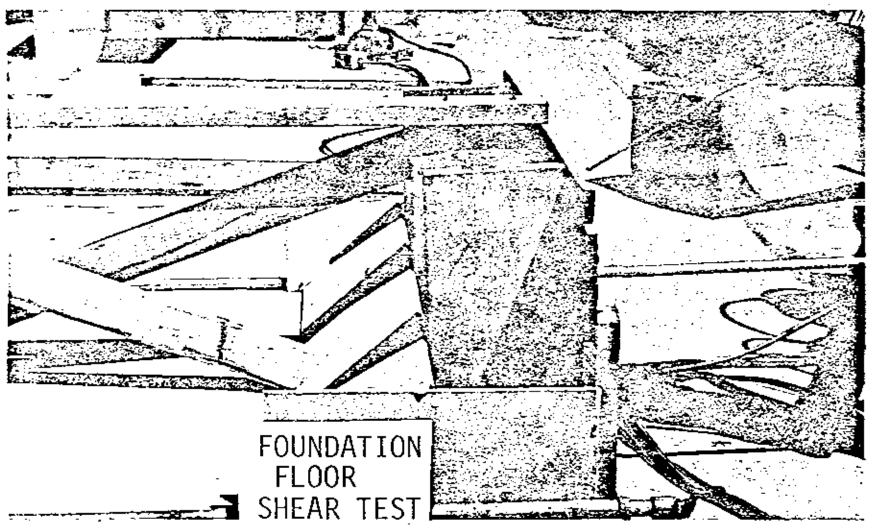


Fig. 2-30. Shear Test Specimens.





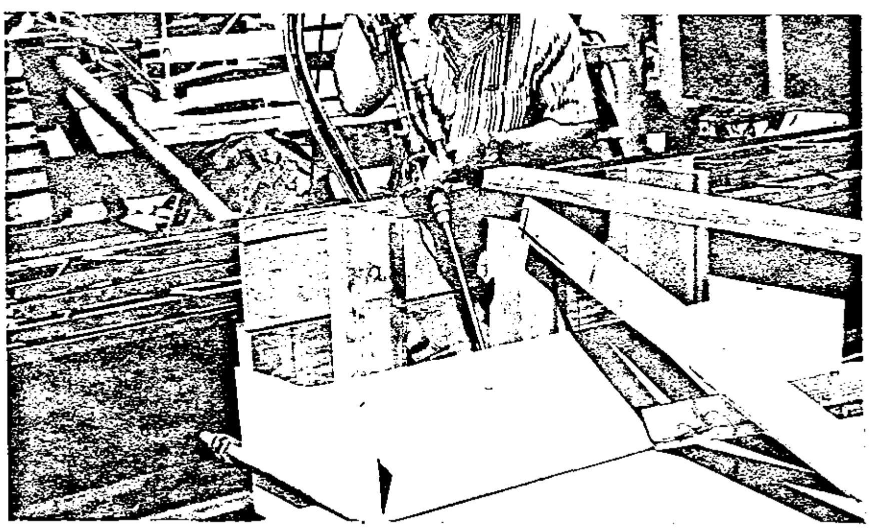


Fig. 2-31. Foundation Shear Test Specimens

Section 3
TEST PROGRAM

INTRODUCTION AND TEST DESCRIPTION

The test program included a series of evaluation tests of foamed and unfoamed structural building elements. Three types of building elements were investigated—ceilings, walls, and floors. A total of 23 large specimens were tested and these are summarized on the test matrix presented in Table 3-1. Also presented in this matrix are the following:

- o References to the figure number in this section which shows the construction details.
- o The size of the test specimen.
- o Reference to construction details such as nailing schedule.
- o The type of ultimate load test conducted on each specimen.
- o A brief description.
- o A remarks column.

Figs. 3-1 through 3-9 present the construction details for the various test specimens. The nailing schedules used in construction of the test specimens are illustrated in Fig. 3-10 A, B, and C.

TABLE 3-1: TEST MATRIX

TYPE	SPECIMEN NUMBER	FIG. NO.	SIZE (ft)	CONSTRUCTION FIGURE NO.	FOAMED	TEST TYPE*	DESCRIPTION	FOAM PLACEMENT
CEILING	0	3-1	4 x 8	3-10 A, B	NO	H S	BASE CASE: 2 x 6 joists, 4 ft direction; sheetrock one side.	
	1	3-1	4 x 8	"	YES	H S	2 x 6 joists, 4 ft direction; sheetrock bottom; top open.	Phase 1: Foam installed in exploratory manner.
	2	3-1	4 x 8	"	YES	H S	same as Specimen No. 1	Phase 2: Foam placed using spreader nozzle in two lifts.
	3	3-1	4 x 8	"	YES	H S	" " " " "	Phase 3: Foam placed between 16-in. sections of wallboard.
	4	3-2	4 x 8	"	YES	B	2 x 6 joists, 8 ft direction; sheetrock bottom; top open	Phase 3: Foam placed between 24-in. sections of wallboard.
WALLS	0	3-3	4 x 8	3-10 A,B,C	NO	H S	BASE CASE: sheetrock one side; 1 x 8 in. sheathing on 2nd side.	
	1	3-3	4 x 8	"	YES	H S	Sheetrock one side; 1 x 8 in. sheathing on 2nd side.	Phase 1: Lifts poured at increasing heights until full.
	2	3-3	4 x 8	"	YES	H S	same as Specimen No. 2.	Phase 1: Three lifts in three holes at same height per cell.
	0	3-4	4 x 4	3-10 A, B	NO	S	BASE CASE: Sheetrock both sides	
	1	3-4	4 x 4	"	YES	S	Sheetrock both sides	Phase 3: Three lifts of 9 seconds each per cell.
	2	3-4	4 x 4	"	YES	S	" " "	Same as 4 x 4 Wall No. 1.
	0	3-5	4 x 4	3-10 A,B,C	NO	S	BASE CASE: Sheetrock one side 1 x 8 in. sheathing on 2nd side.	
	3	3-5	4 x 4	"	YES	S	Sheetrock one side; 1 x 8 in. sheathing on 2nd side	Same as 4 x 4 Wall No. 1.
	4	3-5	4 x 4	"	YES	S	Same as 4 x 4 Wall No. 3.	Same as 4 x 4 Wall No. 1.
	5	3-6	4 x 4	"	YES	S	Sheetrock one side; felt and 1 x 8 in sheathing on 2nd side	Same as 4 x 4 Wall No. 1.

* H S = Horizontal Shear; S = Shear; B = Bending.

TABLE 3-1: TEST MATRIX (cont'd)

TYPE	SPECIMEN NUMBER	FIG. NO.	SIZE (ft)	CONSTRUCTION FIGURE NO.	FOAMED	TEST TYPE*	DESCRIPTION	FOAM PLACEMENT
FLOORS	0	3-7	4 x 8	3-10 A,B,C	NO	H S	BASE CASE: 2 x 6 joists, 4 ft direction; sheetrock bottom; 1 x 8 in. sheathing top.	
	1	3-7	4 x 8	"	YES	H S	2 x 6 joists, 4 ft direction; sheetrock bottom; 1 x 8 in. sheathing top.	Phase 1: Filled with foam.
	2	3-7	4 x 8	"	YES	H S	Same as Floor No. 1.	Phase 1: 93% foam filled.
	3	3-7	4 x 8	"	YES	H S	" " " " "	Phase 1: About 95% foam filled.
	4	3-7	4 x 8	"	YES	H S	2 x 8 joists, 4 ft direction; sheetrock bottom; 1 x 8 in. sheathing top.	Phase 3: 90% filled using staggered hole pattern.
	5	3-8	4 x 8	"	NO	H S	BASE CASE: 2 x 8 joists, 4 ft direction; sheetrock bottom; 1 x 8 in. sheathing top.	
	6	3-9	4 x 8	"	YES	B	2 x 8 joists, 8 ft direction; sheetrock bottom, 1 x 8 in. sheathing top.	Phase 3: 90% filled using staggered hole pattern.
	7	3-9	4 x 8	"	YES	B	Same as Floor No. 6.	Same as Floor No. 6.

* H S = Horizontal Shear; S = Shear; B = Bending.

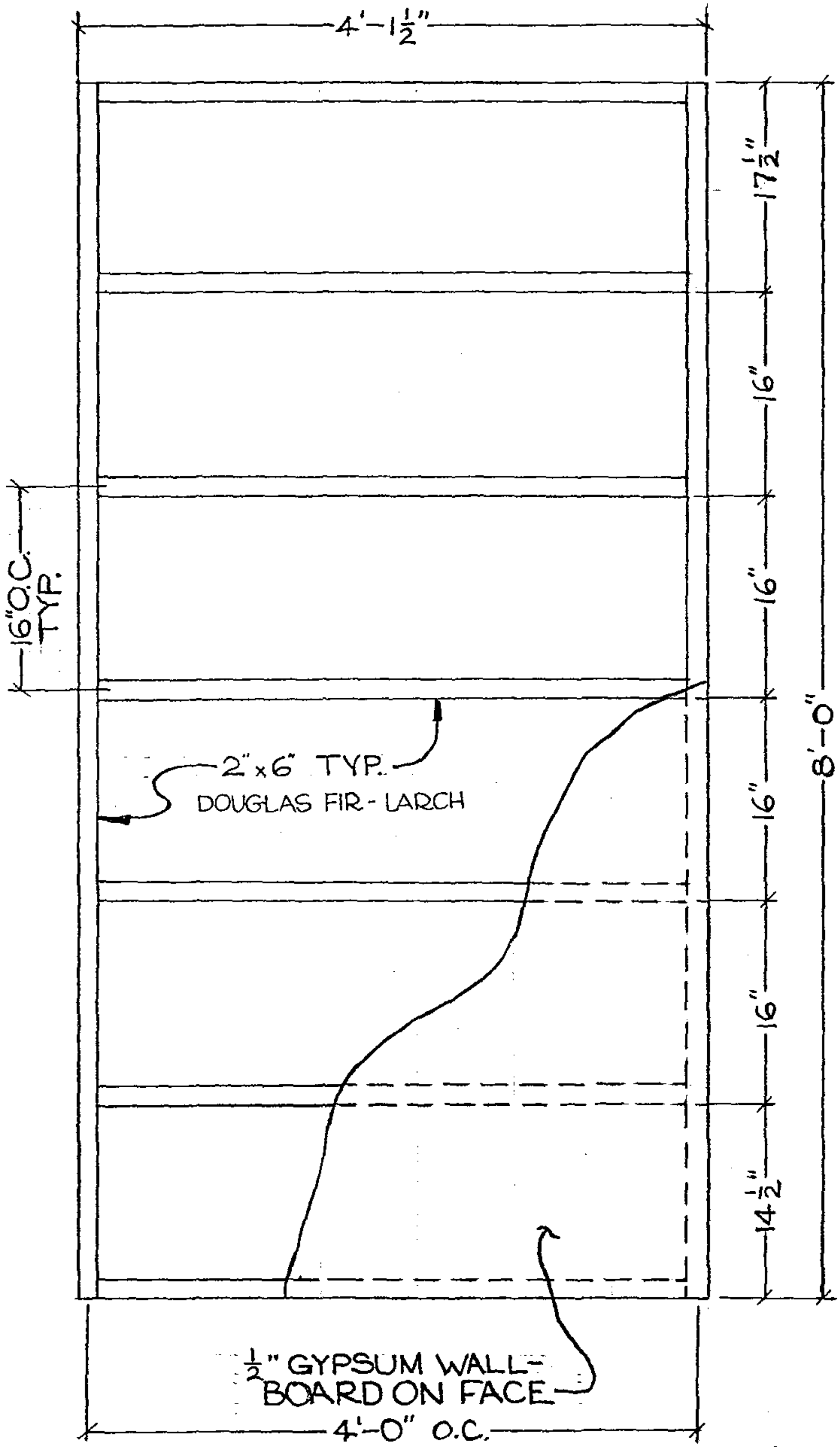


Fig. 3-1. Construction Details, Ceiling Base Case and Numbers 1, 2, & 3.

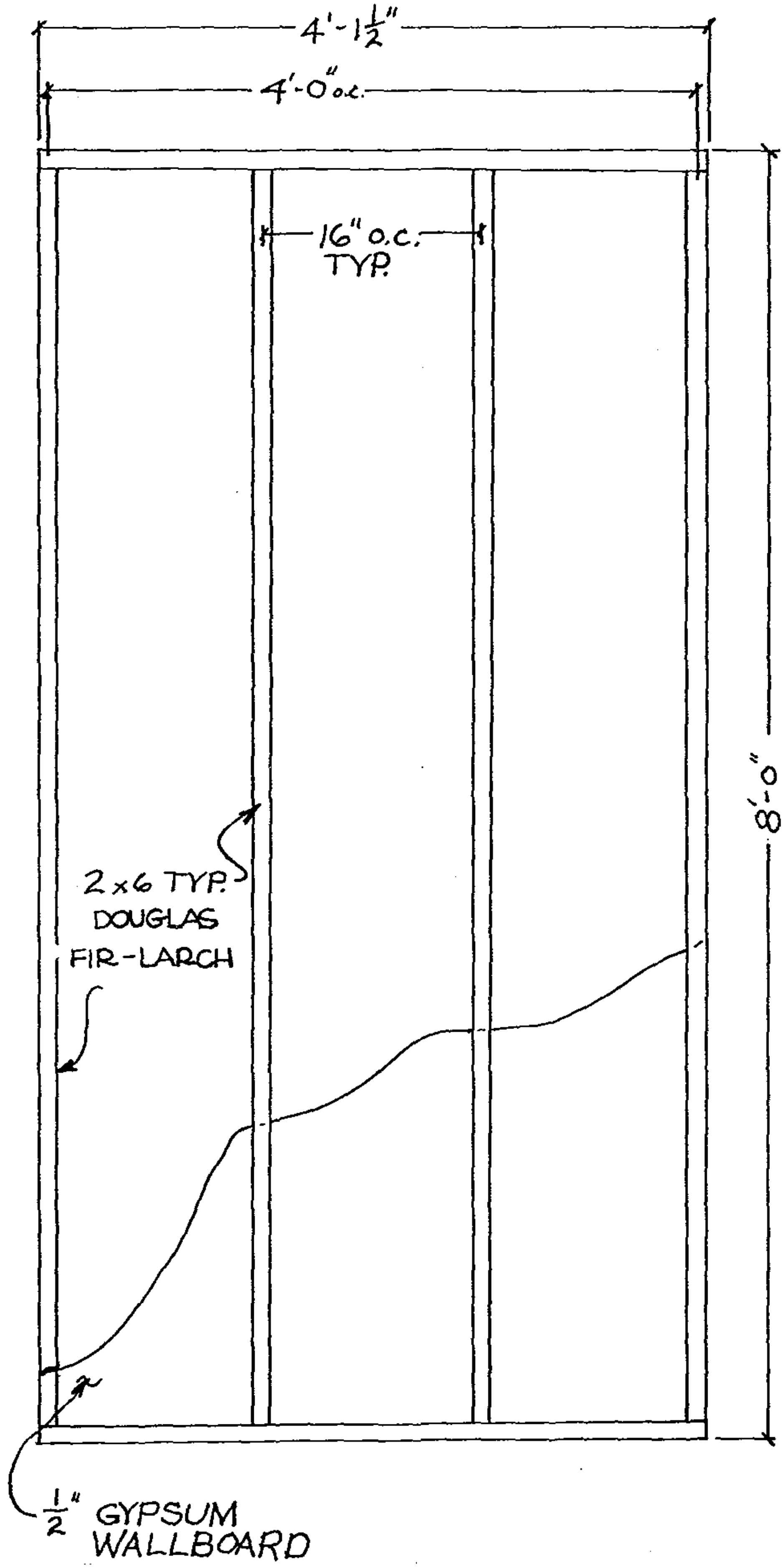


Fig. 3-2. Construction Details, Ceiling Number 4.

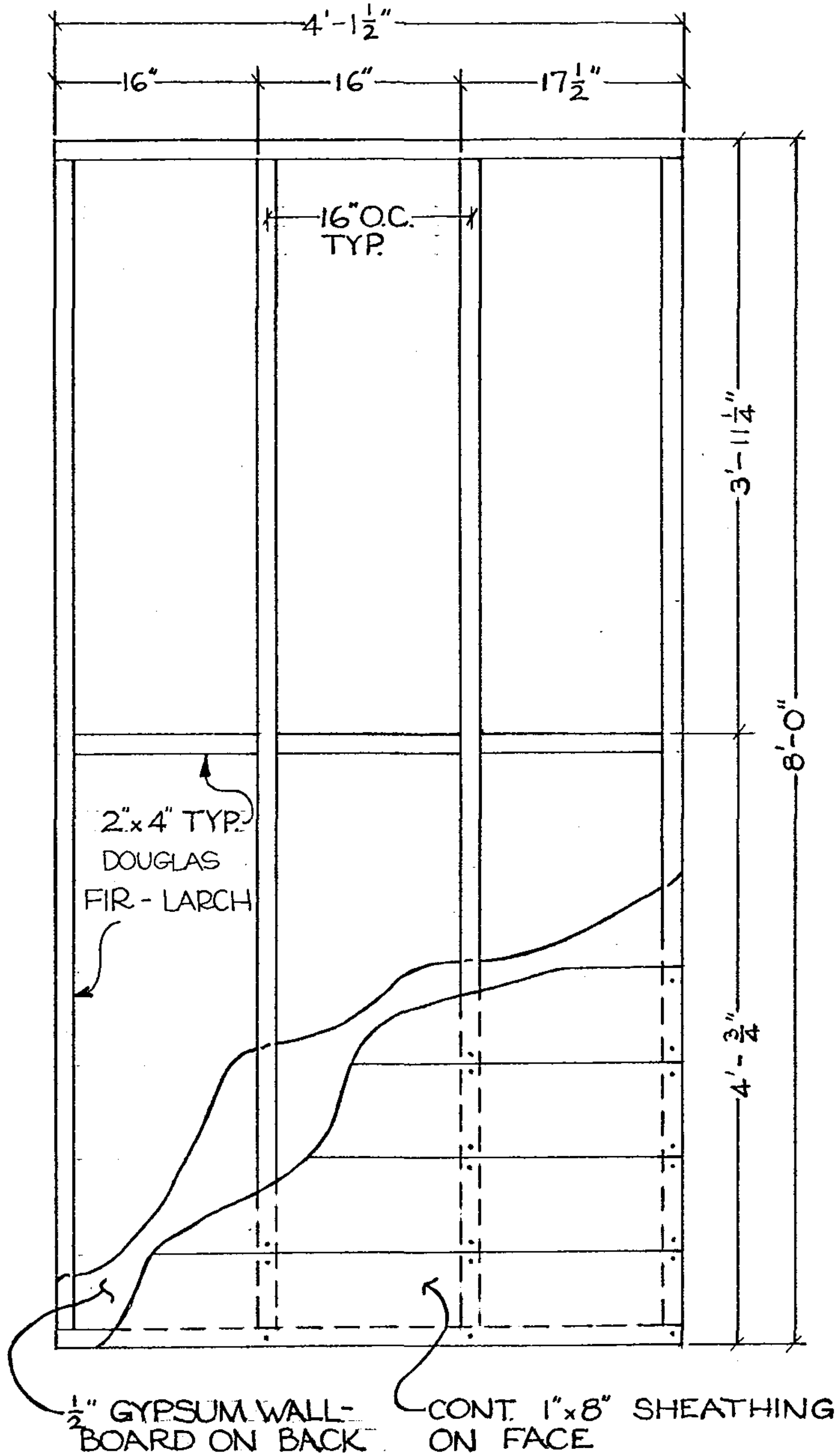


Fig. 3-3. Construction Details for 4 x 8 Wall Specimens, Base Case and Walls Number 1 & 2.

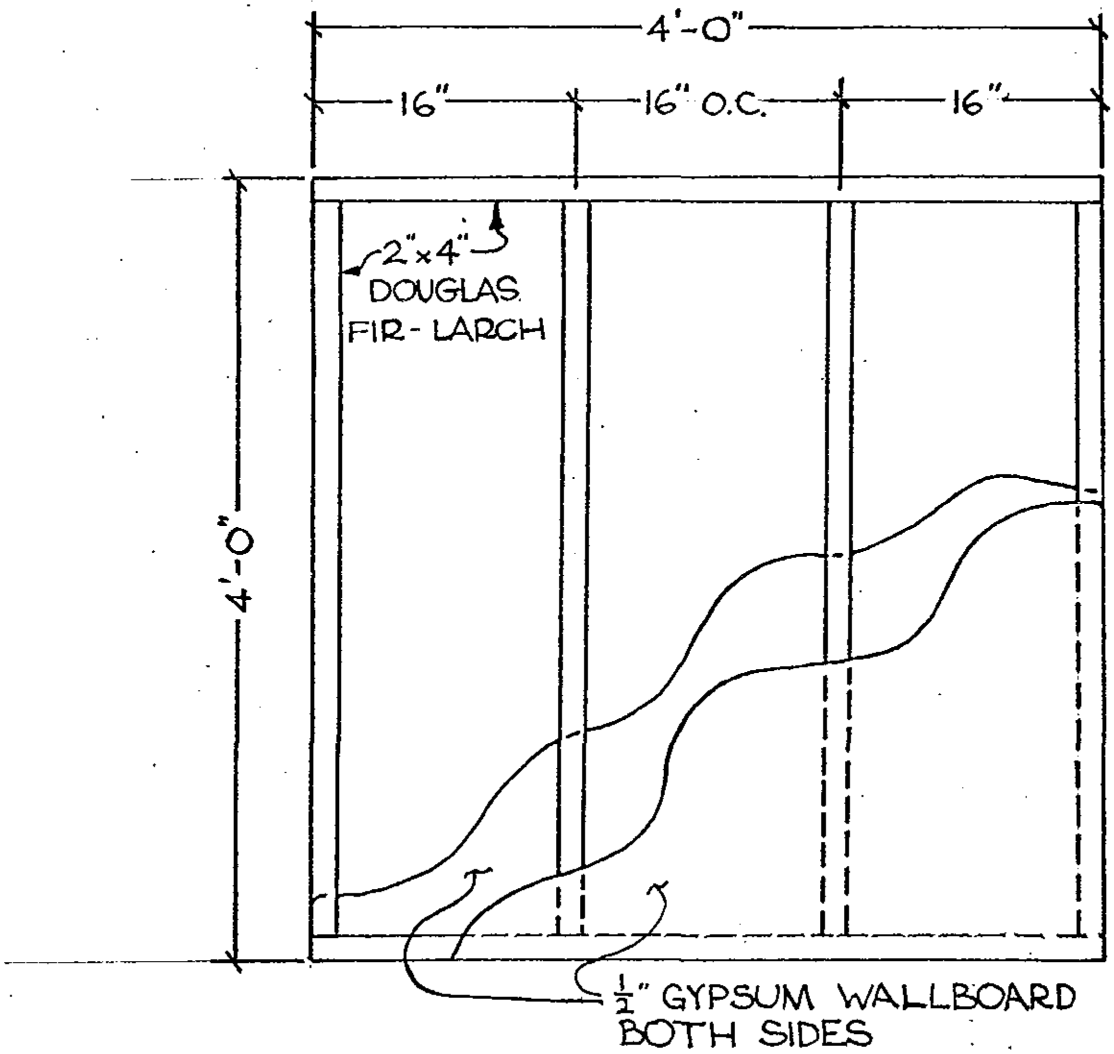


Fig. 3-4. Construction Details for 4 x 4 Wall Specimens, Base Case and Walls Number 1 & 2.

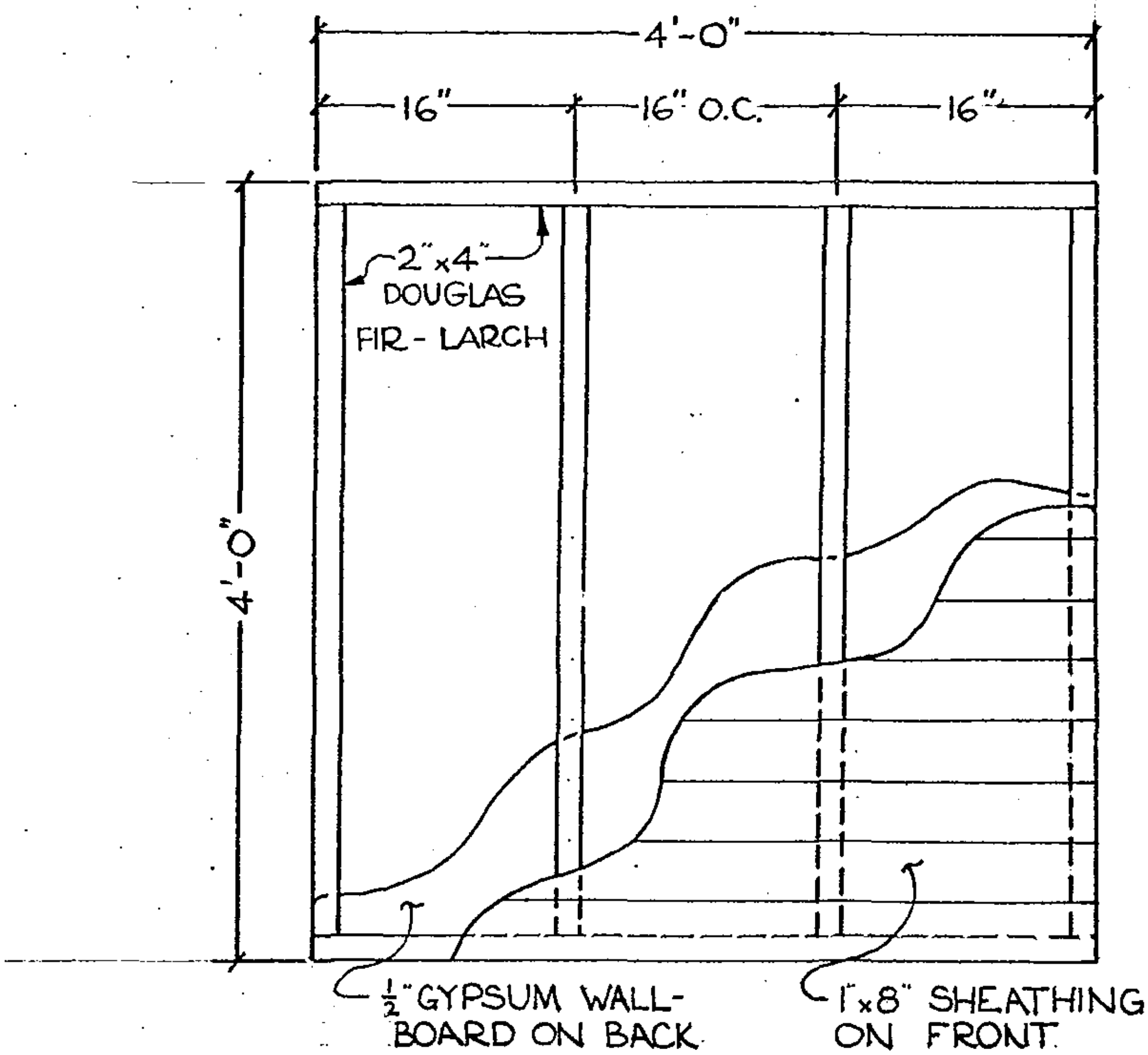


Fig. 3-5. Construction Details for Exterior 4 x 4 Wall Specimens, Base Case No. 2 and Walls Number 3 & 4.

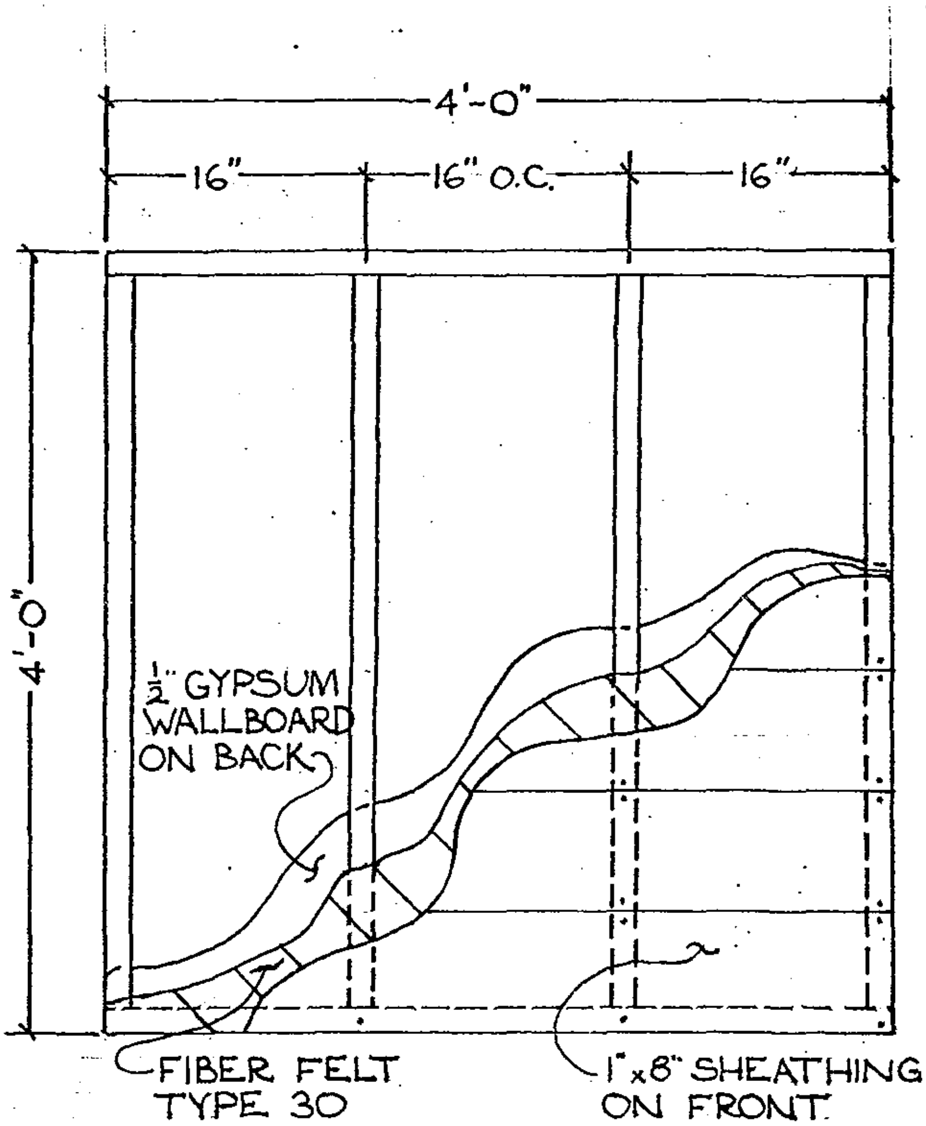


Fig. 3-6. Construction Details for 4 x 4 Wall Number 5.

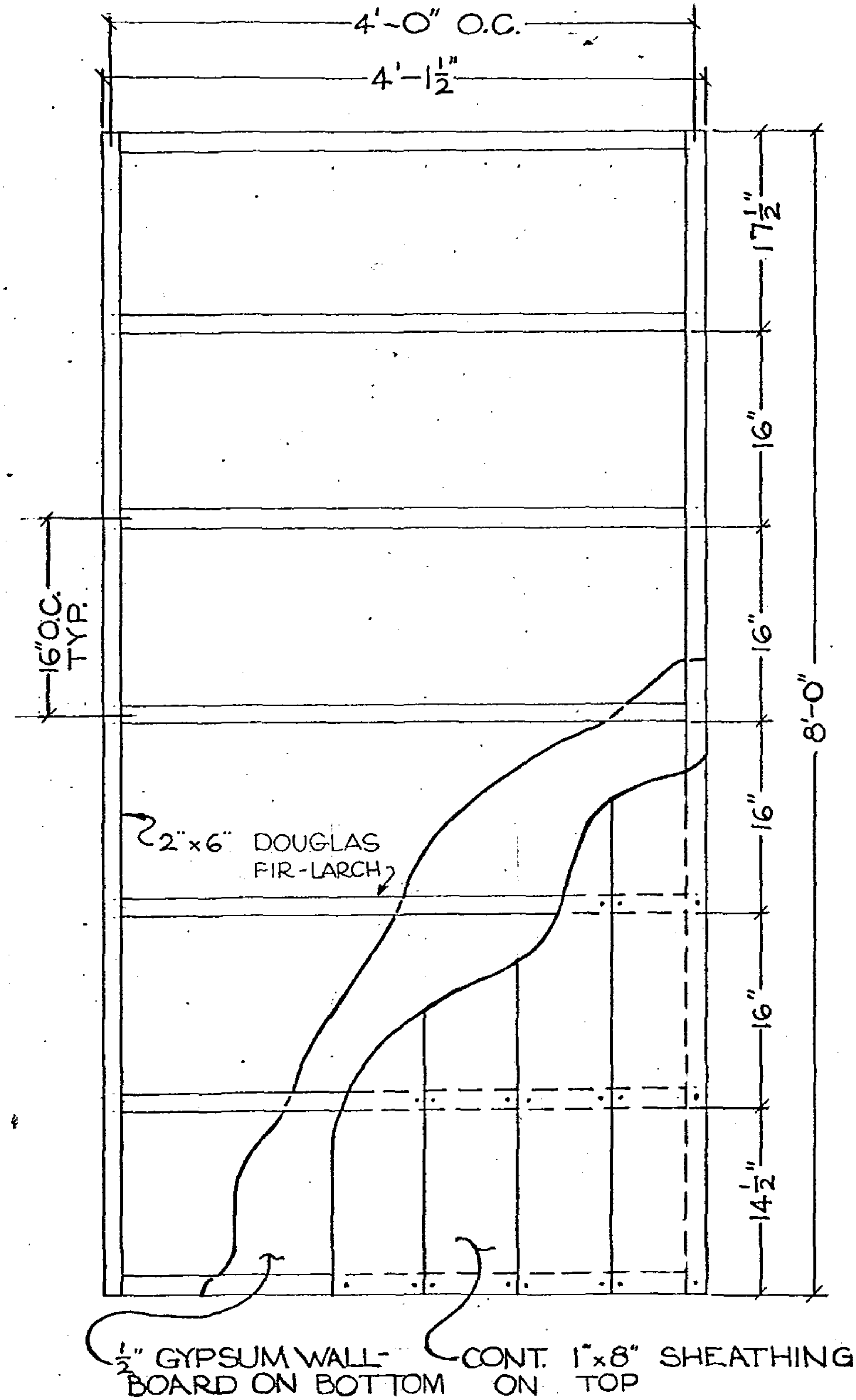


Fig. 3-7. Construction Details for Floor Specimens, Base Case and Floors Number 1 through 3.

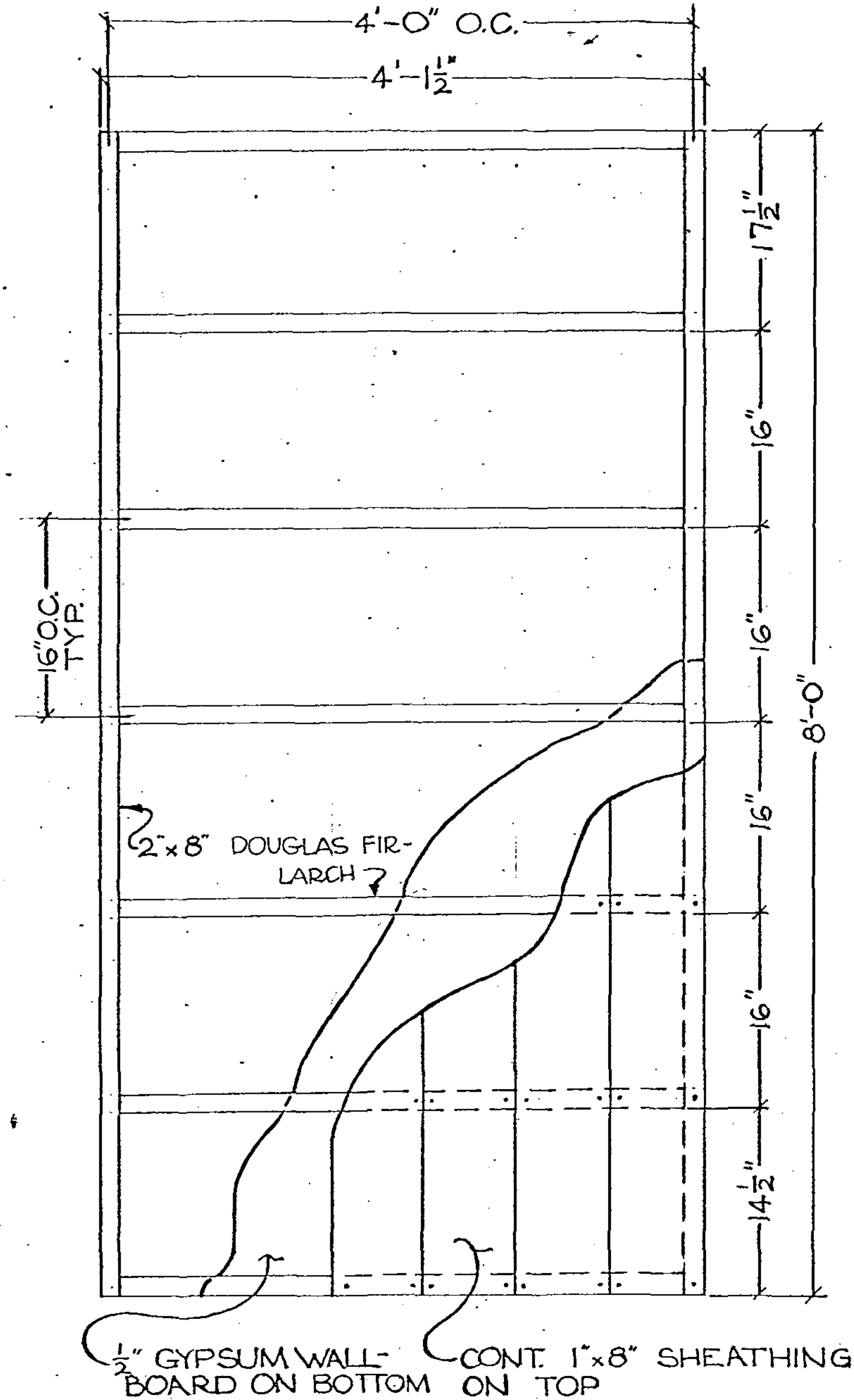


Fig. 3-8. Construction Details for Floor Number 5.

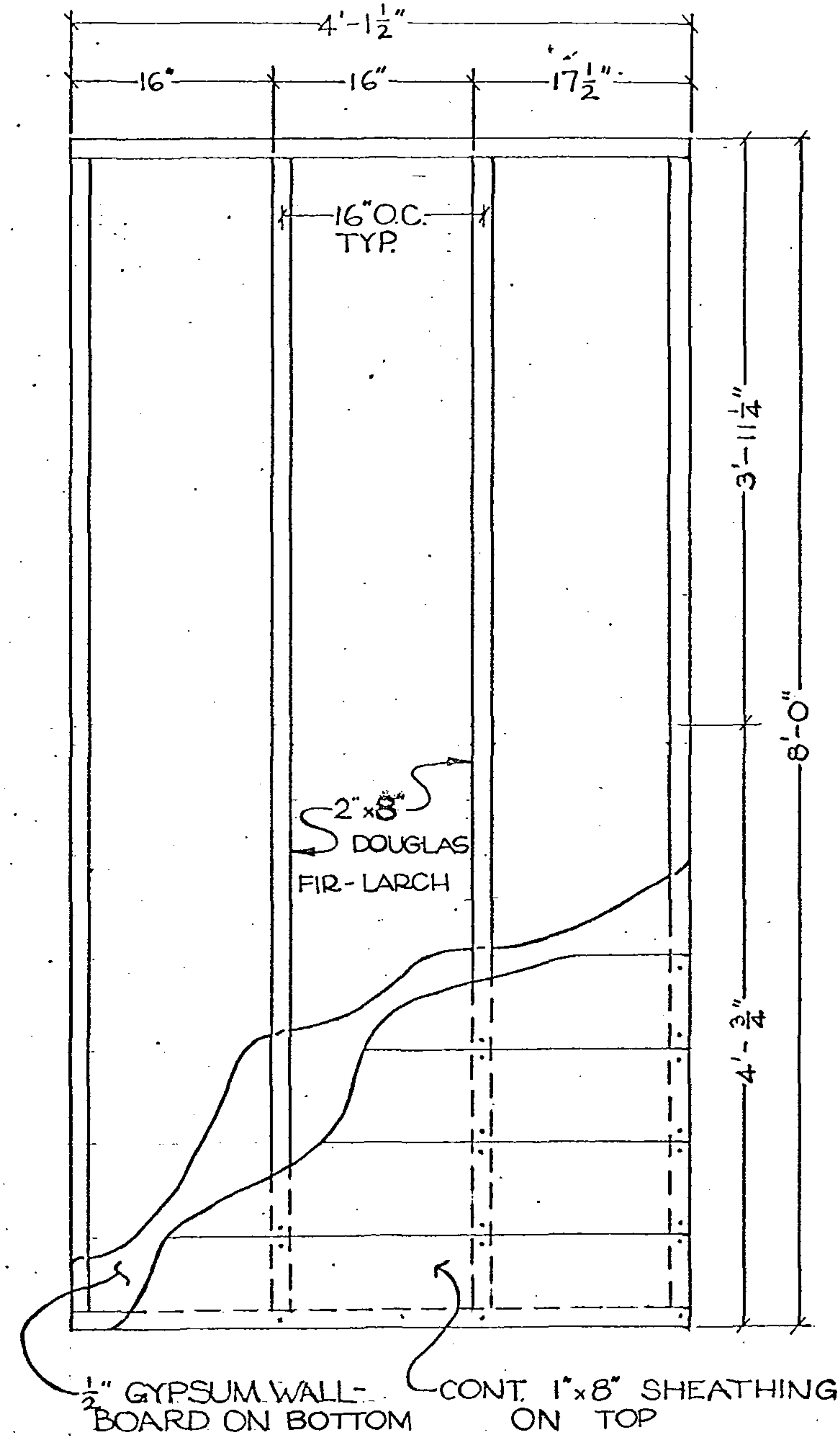


Fig. 3-9. Construction Details for Floor Specimens Number 6 and 7.

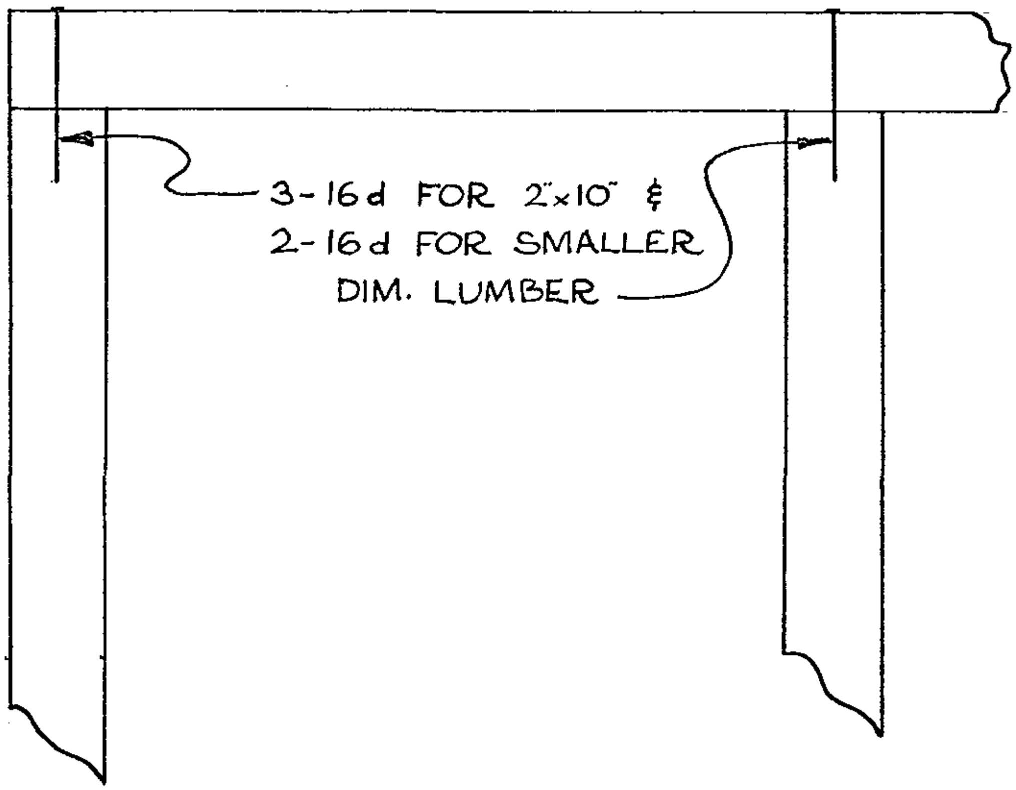


Fig. 3-10 A. Nailing Schedule for Framing Connections.

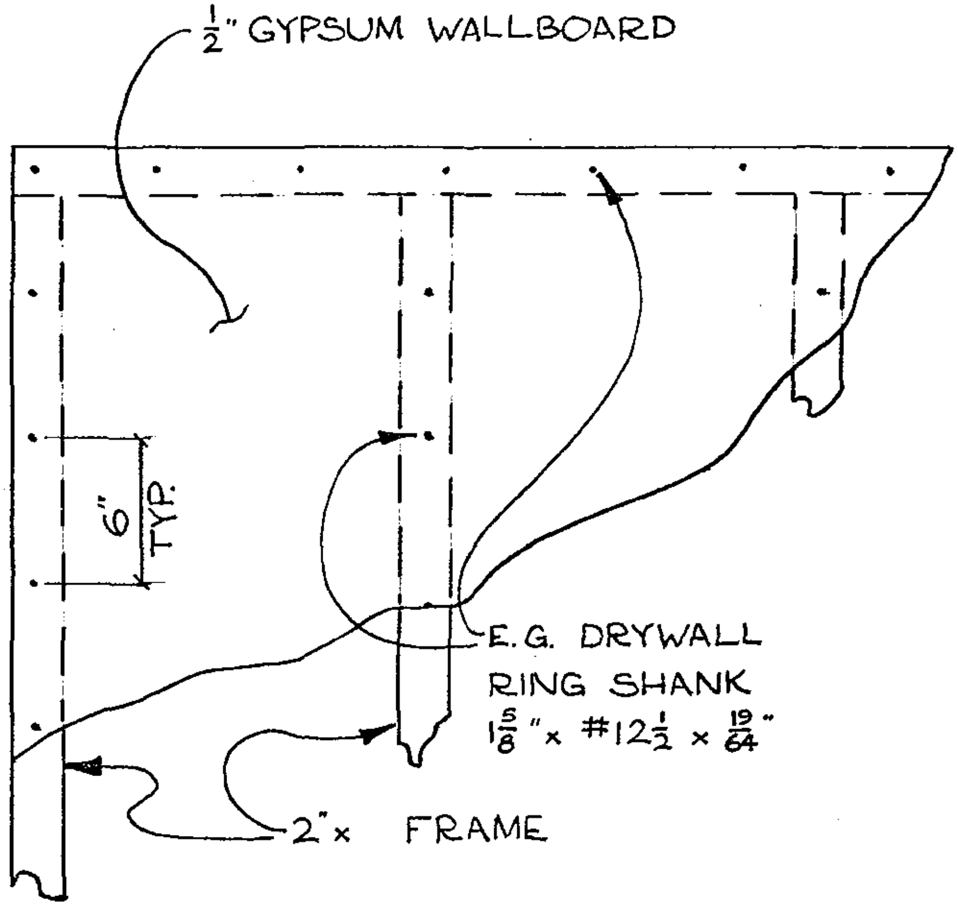


Fig. 3-10 B. Nailing Schedule for Gypsum Wallboard Connection to Framing.

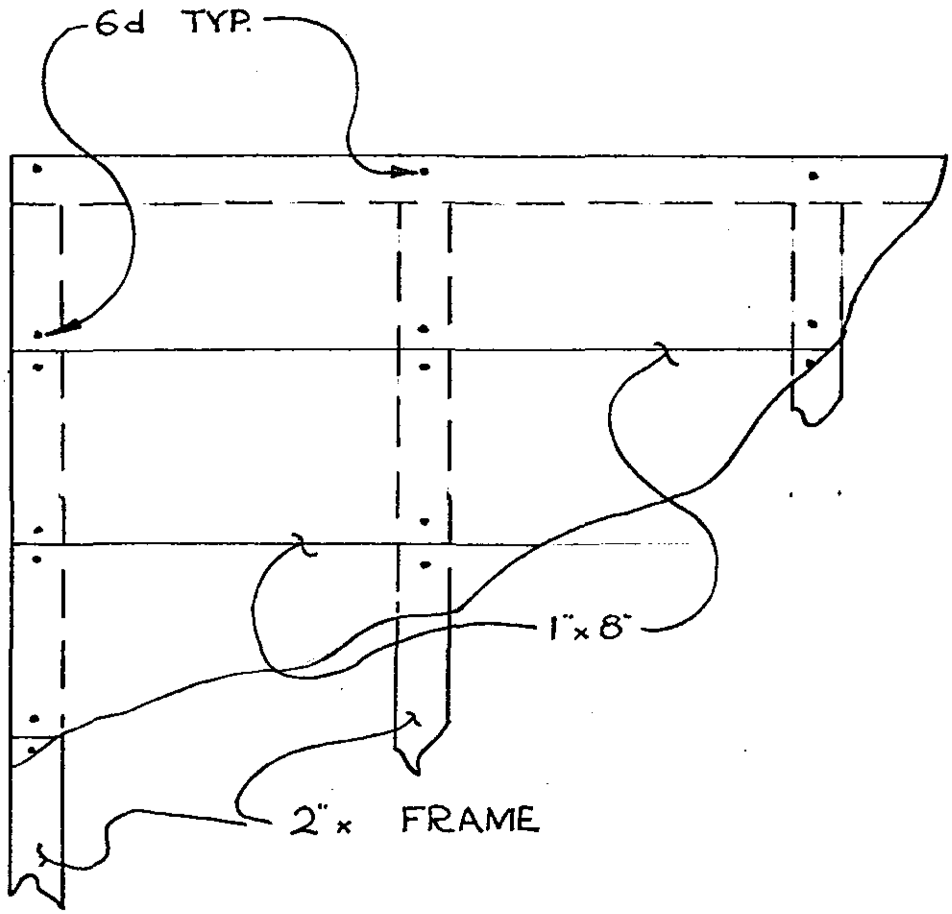


Fig. 3-10 C. Nailing Schedule for Sheathing Connection to Framing.

Three different test configurations were used in determining the strength of panels with and without foam. These were the horizontal shear test, shear test, and bending test. Each of these test configurations is briefly discussed below.

Horizontal Shear Test

Shear capacity, i.e., lateral load resistance, is one of the main deficiencies in older structures and one of the main requirements in the design of new structures in seismic regions. This particular test configuration, shown in Fig. 3-11, is more severe than seismic-induced shears in that the entire diaphragm is subjected to the maximum shear, not just at the boundary as in a real diaphragm. As shown in Fig. 3-11, the panels were laid flat with a roller support at each corner to allow movement in the direction of the applied load. There was no vertical restraint against upward movement of the test specimen.

Shear Test

The motive behind this test is twofold. First, it more closely resembles traditional shear tests from which actual shear parameters such as strength, rigidity, and ductility can be extracted; and second, it is planned that this test will evolve into a standard evaluative test for the multiplicity of wall, floor, roof, and ceiling combinations that will be encountered as this procedure becomes used commercially.

This test was conducted using a universal testing machine in the compression mode with 4 ft x 4 ft wall panels. The panels were loaded diagonally causing pure shear along the panel's perimeter as shown in Fig. 3-12.

Bending Test

The bending test, conducted on Ceiling No. 4 and Floors No. 6 and No.7, applied equal vertical loads at the one-third span locations, as shown in Fig. 3-13. From this test the vertical load stiffness enhancement from adding foam was obtained. For this test arrangement and all others the deflection and load were continuously monitored; the resulting load versus deflection graphs are shown in the test data in Appendix A.

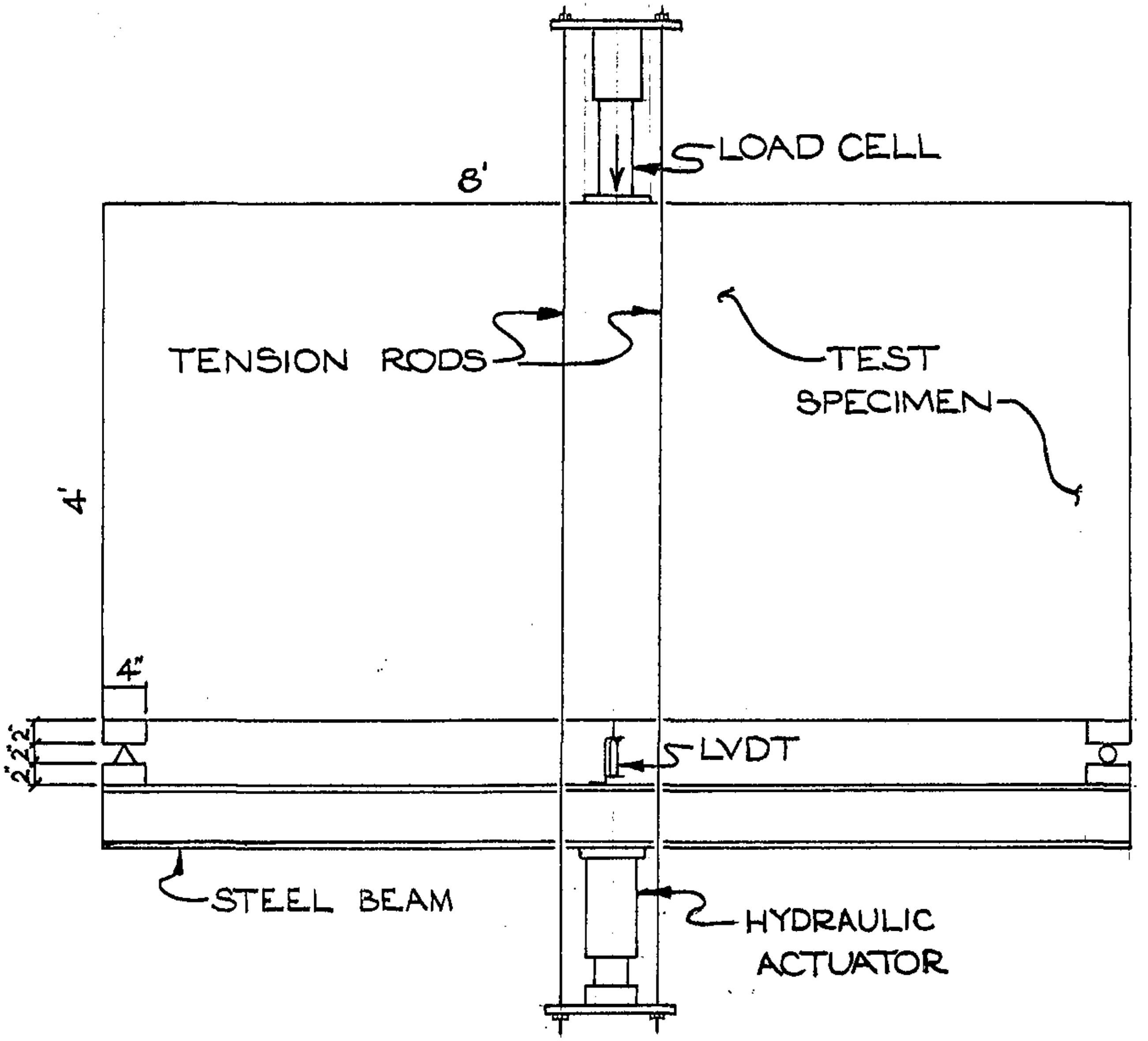


Fig. 3-11. Horizontal Shear Test Arrangement.

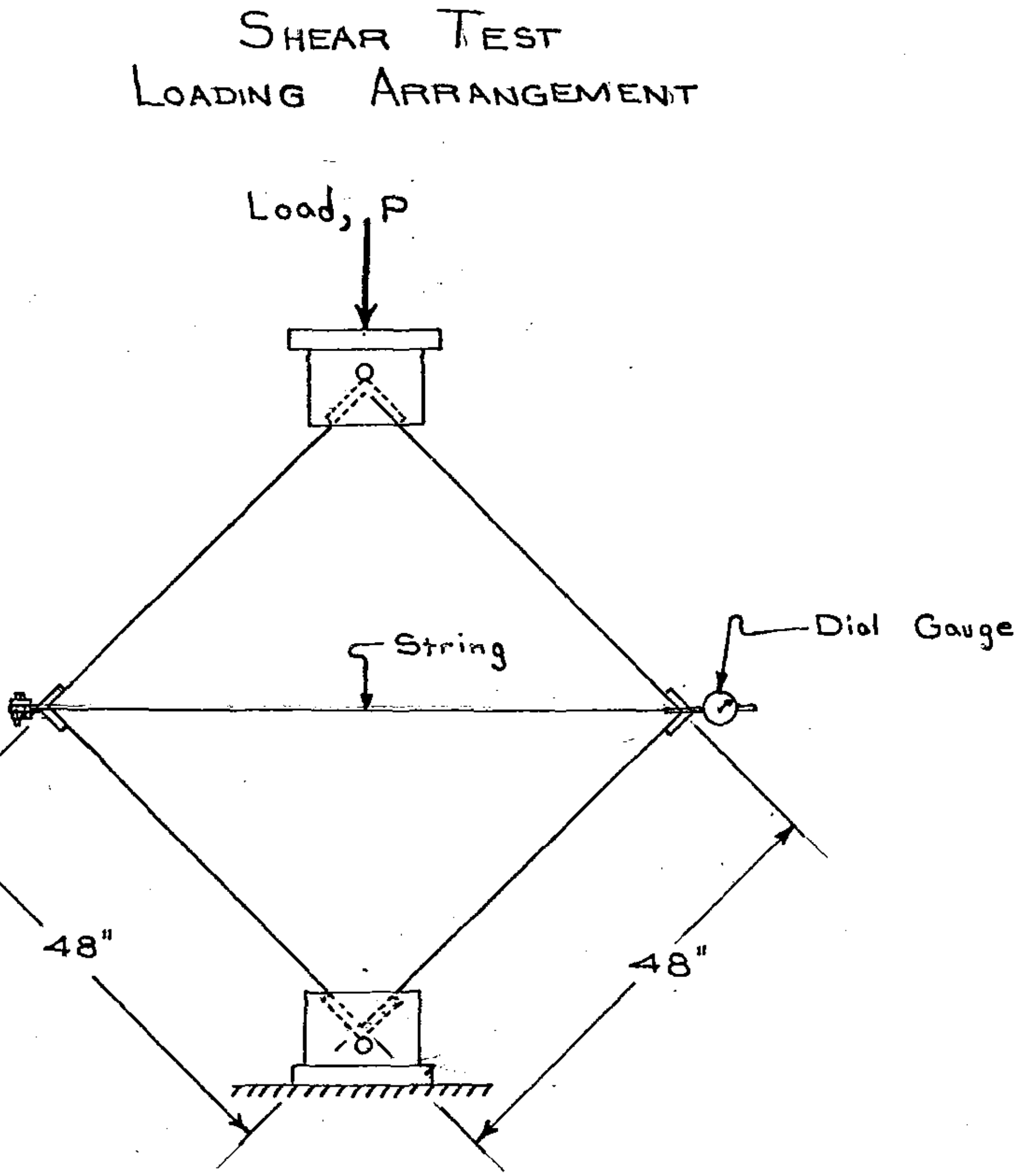


Fig. 3-12. Shear Test Arrangement.

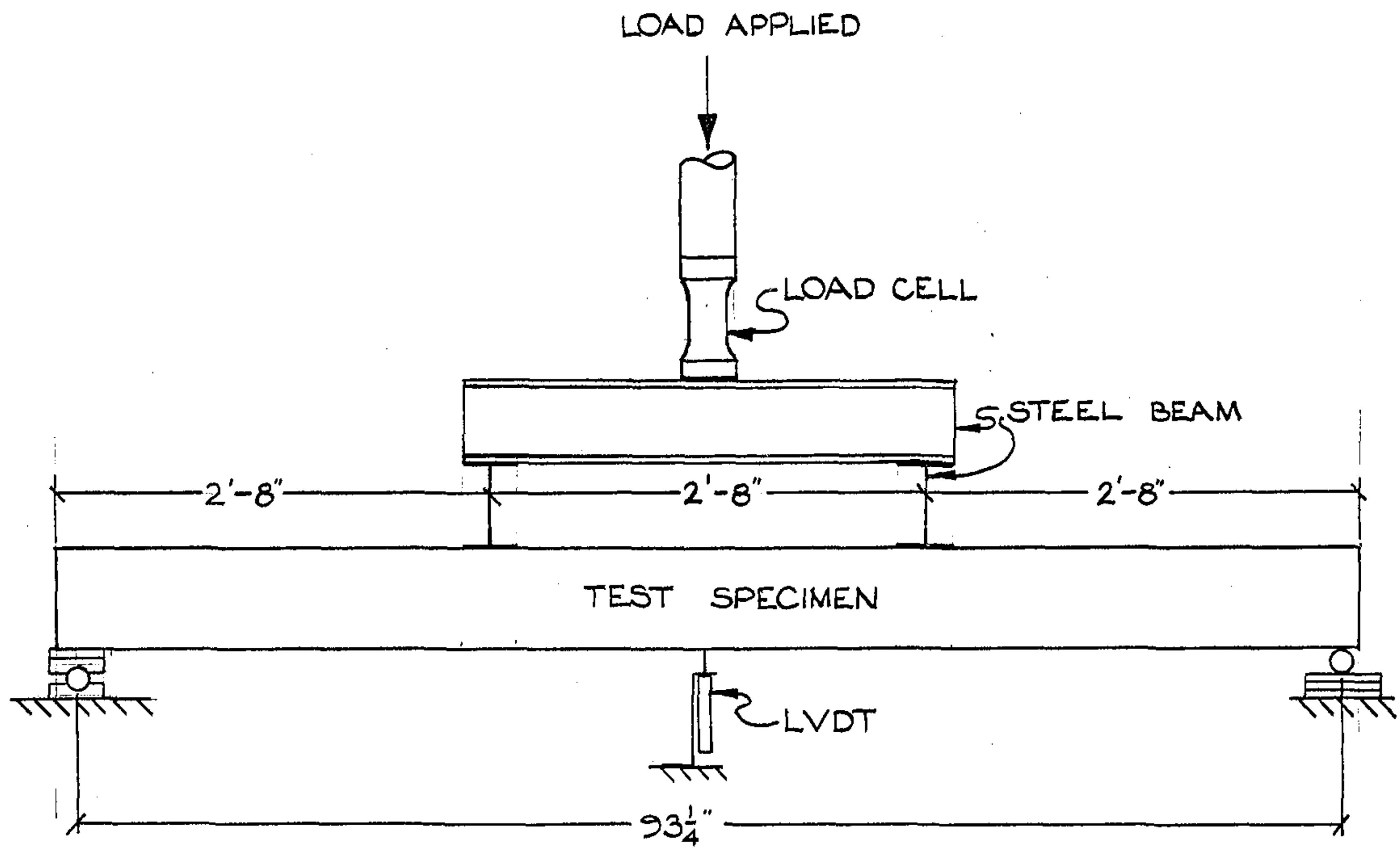


Fig. 3-13. Bending Test Configuration.

TEST RESULTS

Ceilings

The horizontal shear test results for the base case and ceilings Nos. 1, 2, and 3 are shown in Fig. 3-14. Ceiling No. 1 represented the first effort at foaming. The more refined Phase 3 foaming techniques used on the other ceilings resulted in increased strength. Neglecting the results for Ceiling No. 1, the average test values for No. 2 and No. 3 were plotted with the base case for comparison (Fig. 3-15). The area between the curves of Fig. 3-15 represents the enhancement of a foamed ceiling. This added shear strength is shown in Fig. 3-16 where the load and deflection axes have been normalized to ease application to any size ceiling.

Ceiling No. 4 was subjected to the bending test before and after foaming, and the results can be seen in Fig. 3-17. The ceiling stiffness increased from 8,000 lbs/in. to 11,700 lbs/in., that is, to 146% of the stiffness of the unfoamed ceiling. The ceiling weight also increased from 138 lbs to 212 lbs, which is 154% of the old weight. The increased weight from the additional layer of gypsum wallboard and urethane foam does not significantly increase the stresses in the ceiling frame because of the additional stiffness provided. However, the shear capacity of this type of ceiling has increased 450%.

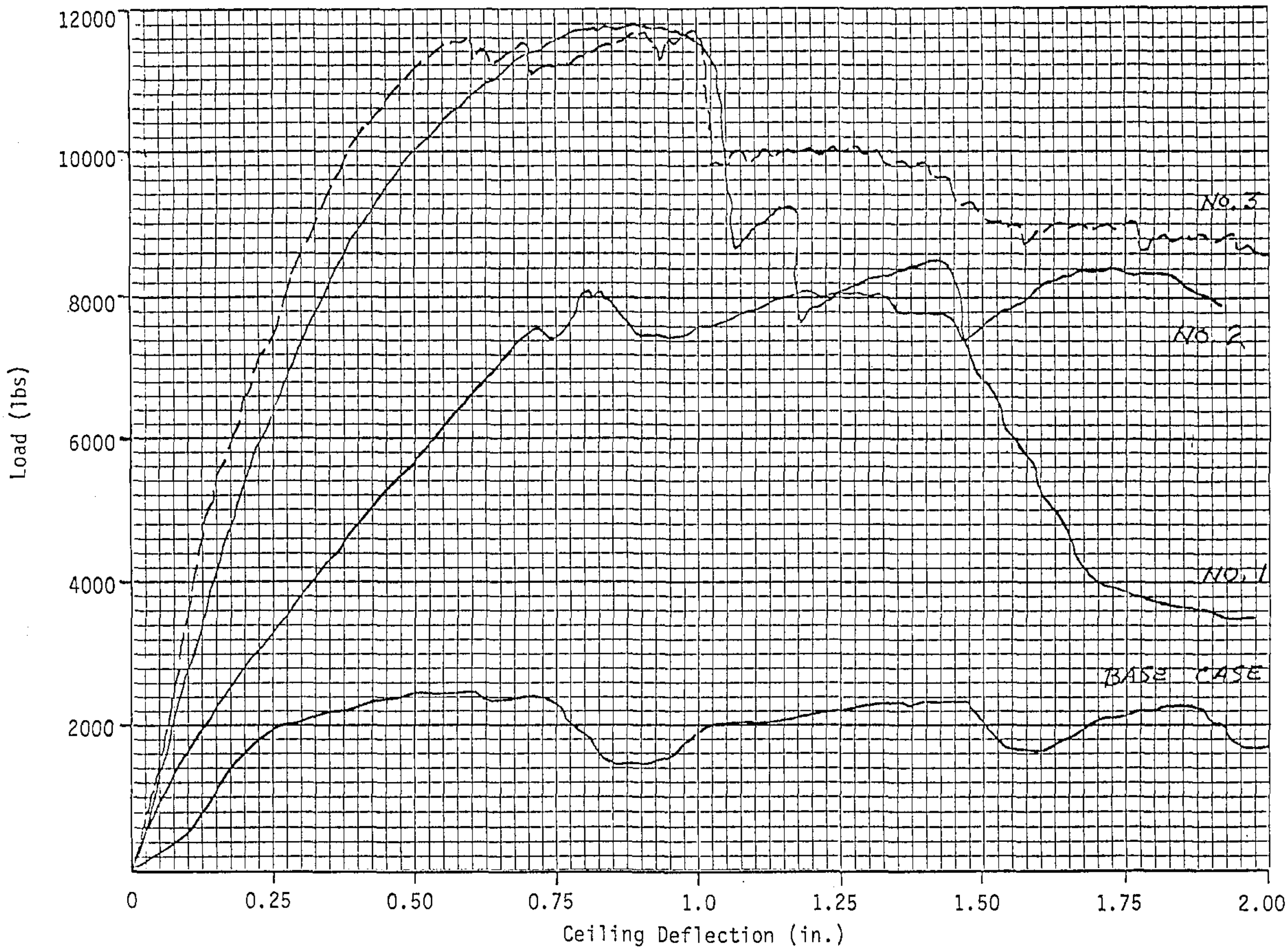


Fig. 3-14. Ceiling Horizontal Shear Test Results.

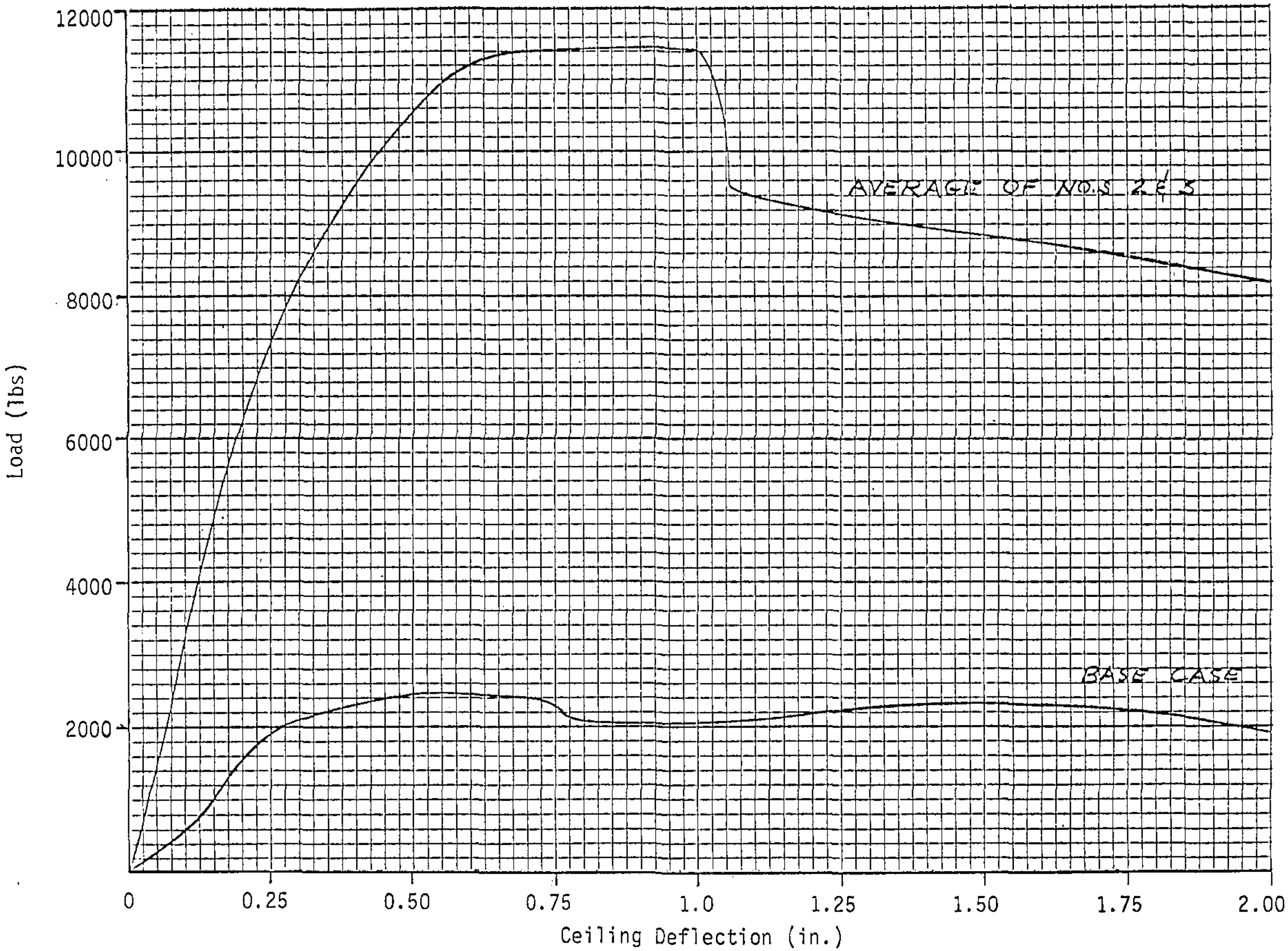


Fig. 3-15. Ceiling Base Case Strength Compared to Average Foamed Ceiling.

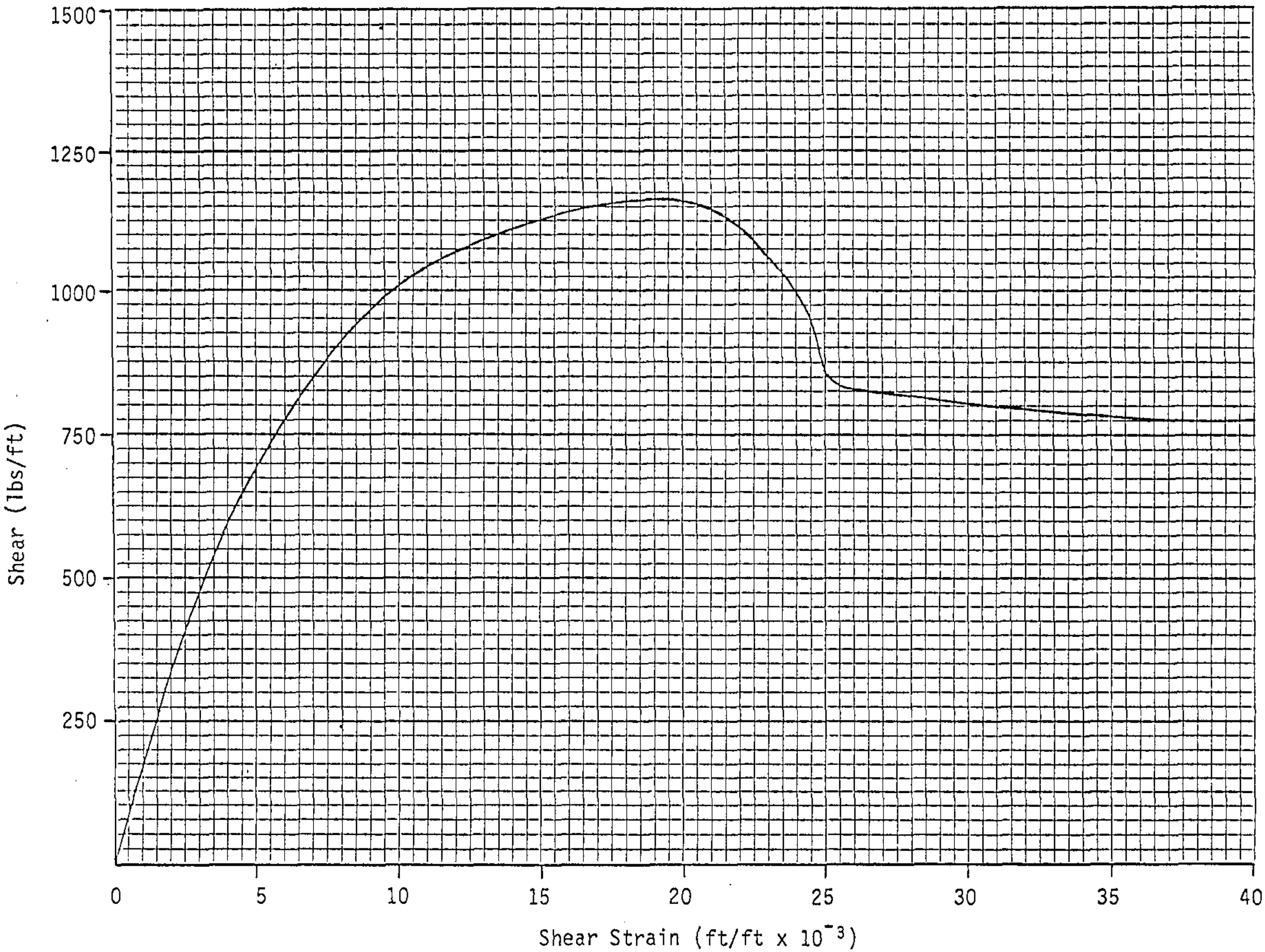


Fig. 3-16. Ceiling Shear Enhancement.

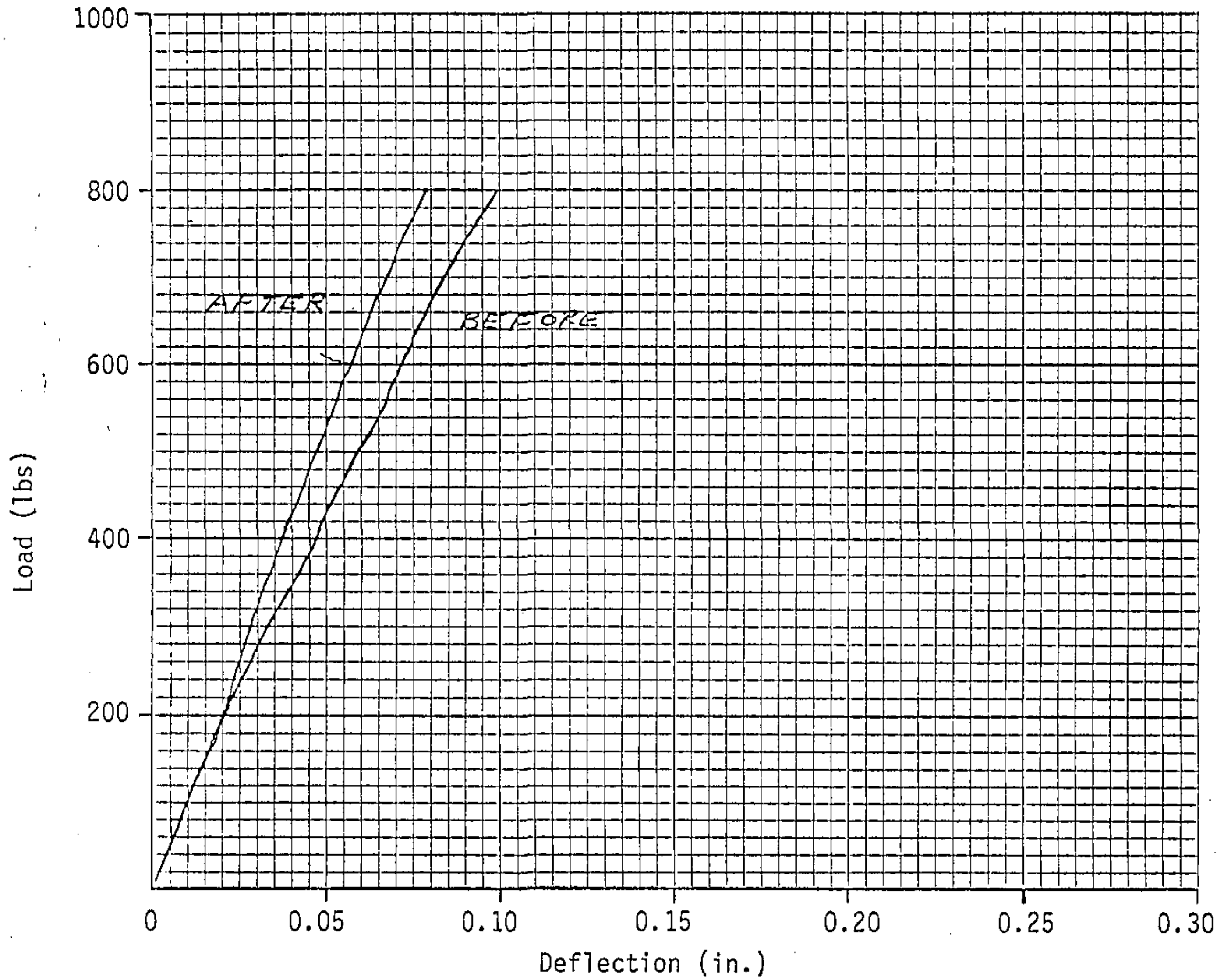


Fig. 3-17. Ceiling No. 4 Vertical Stiffness Before and After Injecting Foam.

Walls

All of the 4 ft x 4 ft walls were subjected to the pure shear test. The base case and Walls No. 1 and No. 2 are representative interior walls with gypsum wallboard nailed to both sides. Tables 3-2 and 3-3 show the shear modulus, G, and wall rigidity, R, for all three walls for various loads. The shear modulus and rigidity increased 168%, due to the application of foam for shearing forces in the elastic region. This means that foamed walls will deflect only 37% of the amount a non-foamed wall would deflect. Fig. 3-18 shows the shear force and deflection relationship. The area under this curve represents the total shear strain energy absorbed by a wall. The foamed walls absorbed 172% more energy than the non-foamed wall in the elastic region. Fig. 3-19 shows the enhancement to shearing strength from injecting foam into the 4 ft x 4 ft wall panels. This curve has been normalized to calculate shear deflections for any similar wall.

The pure shear test results for representative exterior walls with gypsum wallboard on one side and sheathing on the other are shown in Appendix A. Three specimens were tested, two with foam and one without (the base case). Tables 3-4 and 3-5 show the increase in rigidity due to the application of foam. The shear modulus, G, and rigidity, R, have increased by 186%. This means that the deflections of the foamed panels are only 35% of the base case panel. Fig. 3-20 shows the shear force versus deflection curve. The foamed panels will absorb 172% more shear strain energy than the unfoamed panel in the elastic region. Fig. 3-21 shows the added shear strength gained by injecting foam into 4 ft x 4 ft wall panels.

Wall No. 5 is a representative exterior wall with gypsum wallboard on one side and sheathing plus asphalt-impregnated felt paper on the other. The felt paper serves as a moisture barrier for the wall. The details of this wall are shown in Fig. 3-6. Wall No. 5 was subjected to the shear test after foaming, and the results compared with the base case for Walls No. 3 and No. 4 presented previously. Tables 3-6 and 3-7 show that the shear modulus, G, and wall rigidity, R, increased only 40%. Thus, the shear deflection of a foam-injected wall will only be 71% of the normal, non-foamed wall. Fig. 3-22 is a plot of the shearing force, V, versus deflection, δ, for both Wall No. 5 and its base case. Wall No. 5 absorbed 27% more energy than did the base case in the linear elastic region. Finally, Fig. 3-23 shows the increase of shearing force per foot of wall provided by foaming. Fig. 3-23 allows one to calculate the shearing deflection for any wall of similar construction.

The horizontal shear test results for the 4 ft x 8 ft wall are summarized in Fig. 3-24. Taking the average of Walls No. 1 and No. 2 and comparing to the base case, the increased shear strength can be seen in Fig. 3-25. Converting this enhancement into shear per linear foot, Fig. 3-26 shows a maximum shear strength of 1,150 lbs/ft. This represents a 300% increase in ultimate shear strength by foaming a typical wall.

TABLE 3-2: ENHANCEMENT OF WALLS NO. 1 and NO. 2

Load, P (lbs)	Shear Modulus, G Base Case	Shear Modulus, G Walls 1 & 2	Enhancement of Shear Modulus, G (psi)
1,000	1,542	3,461	1,919
2,000	1,525	3,937	2,412
3,000	1,464	4,279	2,815
3,500	1,416	4,266	2,850
Mean $\bar{x}$	1,487	3,986	2,499
Std. Dev.	57.9	384.0	434.8
Relative Enhancement of Wall Due to Application of Foam			168%

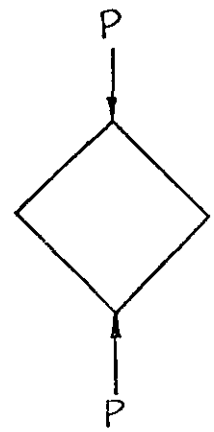
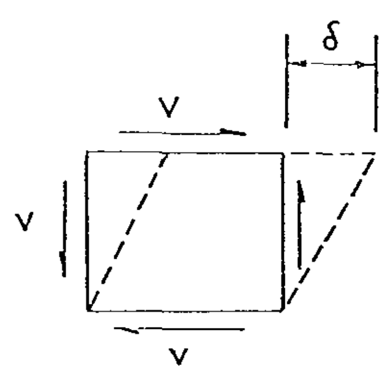


TABLE 3-3: RIGIDITY OF WALLS NO. 1 and NO. 2

Shear, V (lbs)	Rigidity (lbs/in.) Base Case	Rigidity (lbs/in.) Walls 1 & 2
707	5,398	12,191
1,414	5,336	13,730
2,121	5,123	14,939
2,475	4,960	------
2,828	-----	15,207
3,536	-----	14,670
4,243	-----	13,910
4,950	-----	13,129
Mean $\bar{x}$	5,204	13,968
Std. Dev.	201.0	1071.8

Rigidity, R

$$R = \frac{V}{\delta}$$



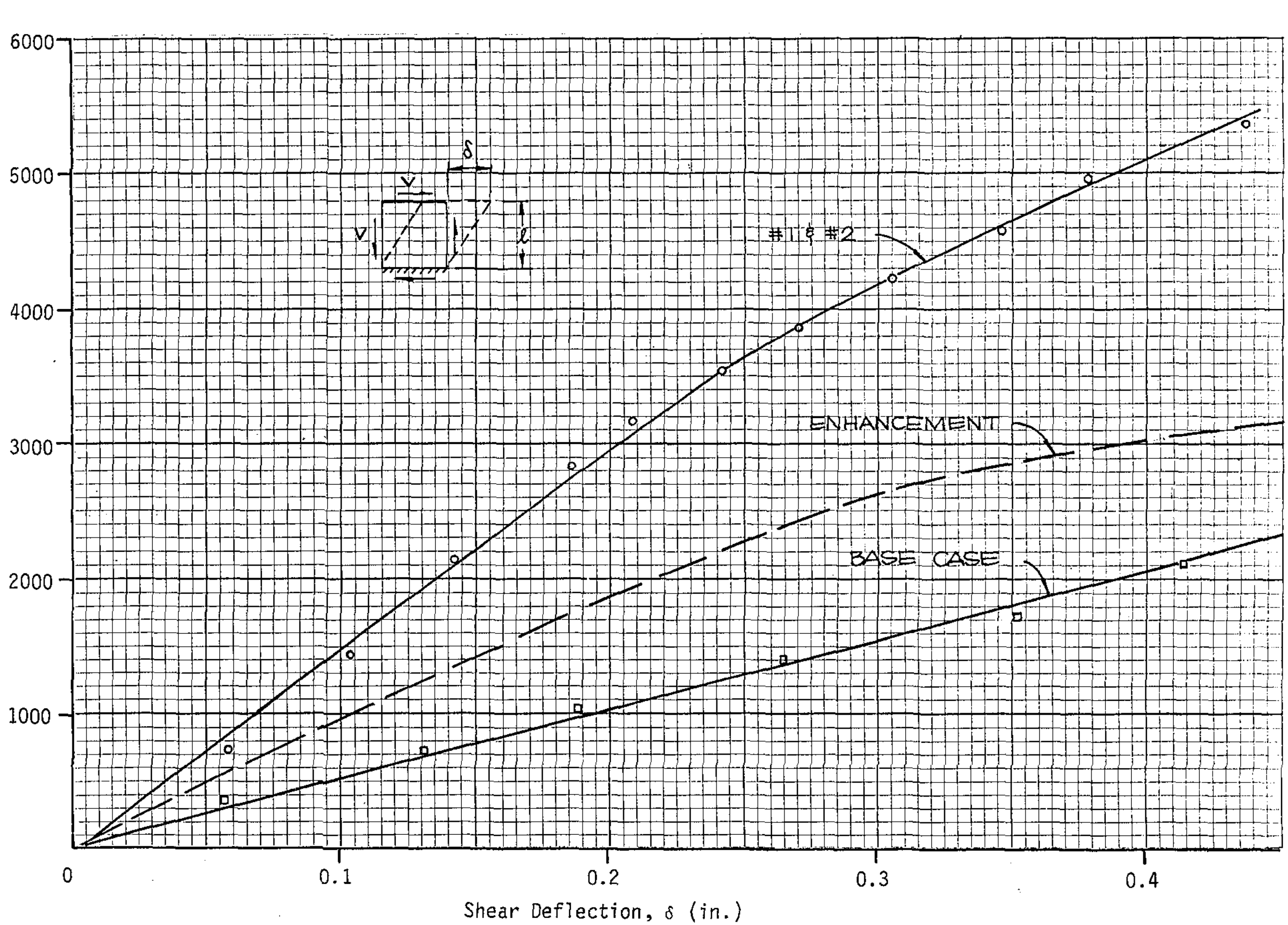


Fig. 3-18. Shear Force versus Deflection Graph for Walls Number 1 and 2.

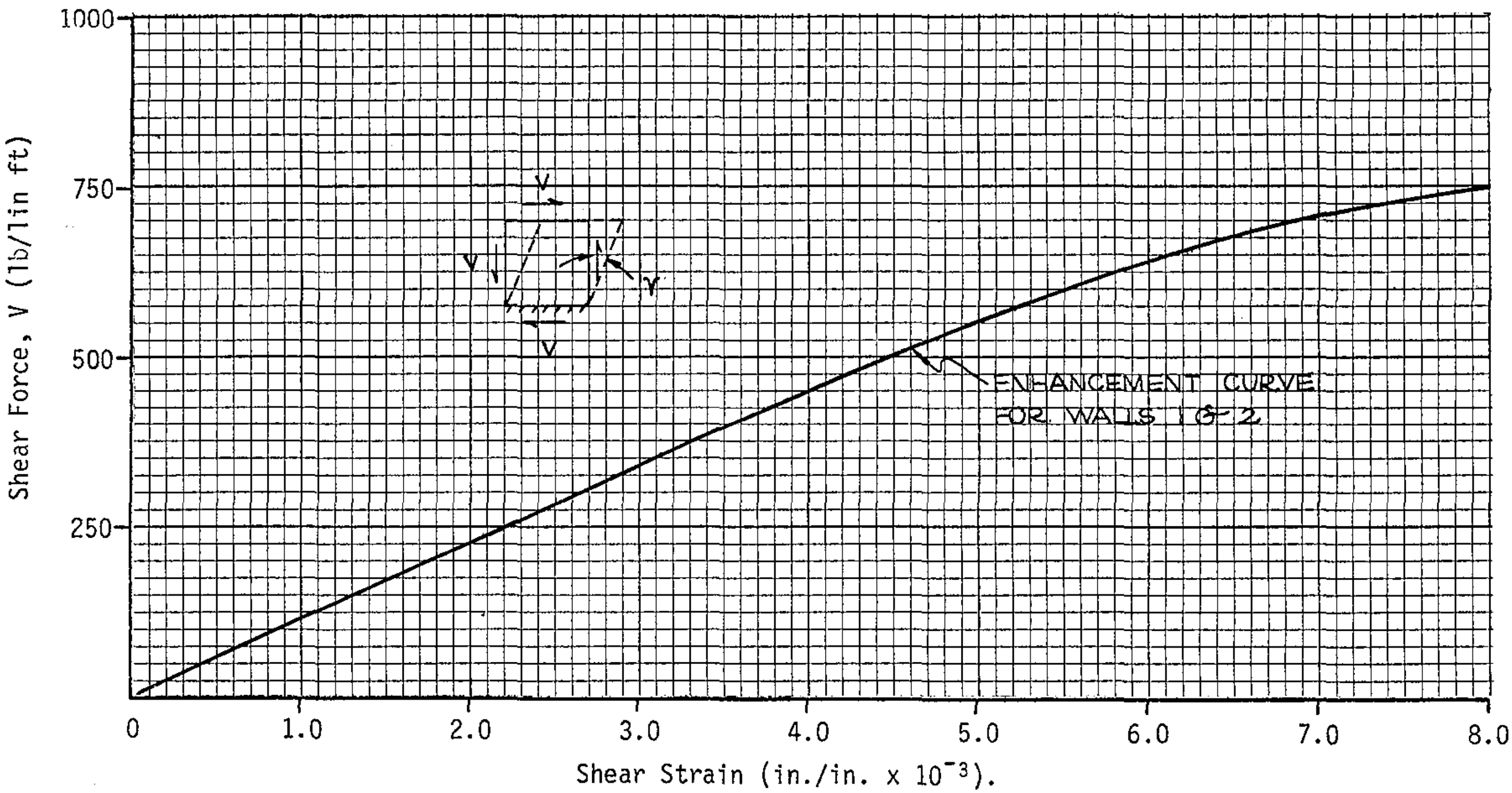


Fig. 3-19. Enhancement of Shear Strength.

TABLE 3-4: ENHANCEMENT OF WALLS NO. 3 and NO. 4

Load, P (lbs)	Shear Modulus, G Base Case	Walls 3 & 4	Enhancement of Shear Modulus, G (psi)
500	1,038	2,720	1,682
1,000	997	2,230	1,233
1,500	660	2,762	2,102
2,000	-----	2,724	-----
3,000	-----	2,593	-----
4,000	-----	2,422	-----
Mean $\bar{x}$	898.3	2,575	1,672
Std. Dev.	207.4	210.2	434.6
Relative Enhancement of Wall Due to Application of Foam			186%

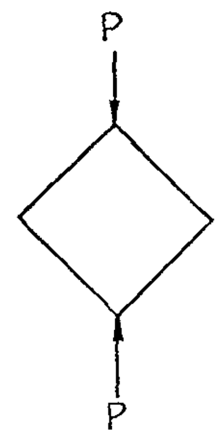
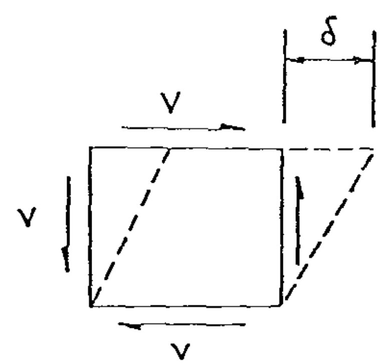


TABLE 3-5: RIGIDITY OF WALLS NO. 3 and NO. 4

Shear, V (lbs)	Rigidity (lbs/in.) Base Case	Walls 3 & 4
353	3,364	9,066
707	3,518	8,839
1,061	2,291	9,386
1,414	-----	9,304
2,121	-----	8,989
2,828	-----	8,468
Mean $\bar{x}$	3,148	9,009
Std. Dev.	744	333

Rigidity, R

$$R = \frac{V}{\delta}$$



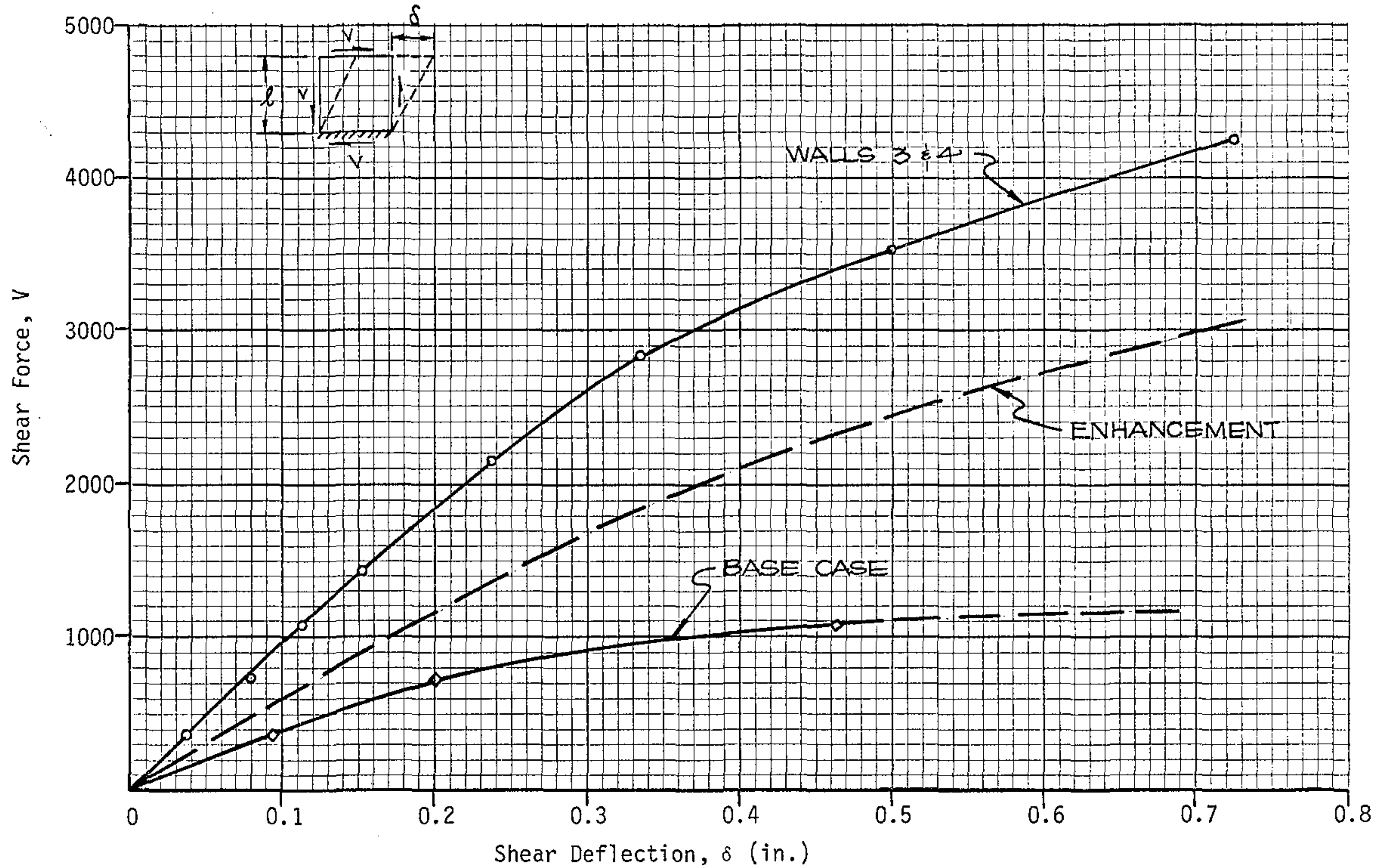


Fig. 3-20. Test Results for Base Case, and Walls Number 3 and 4.

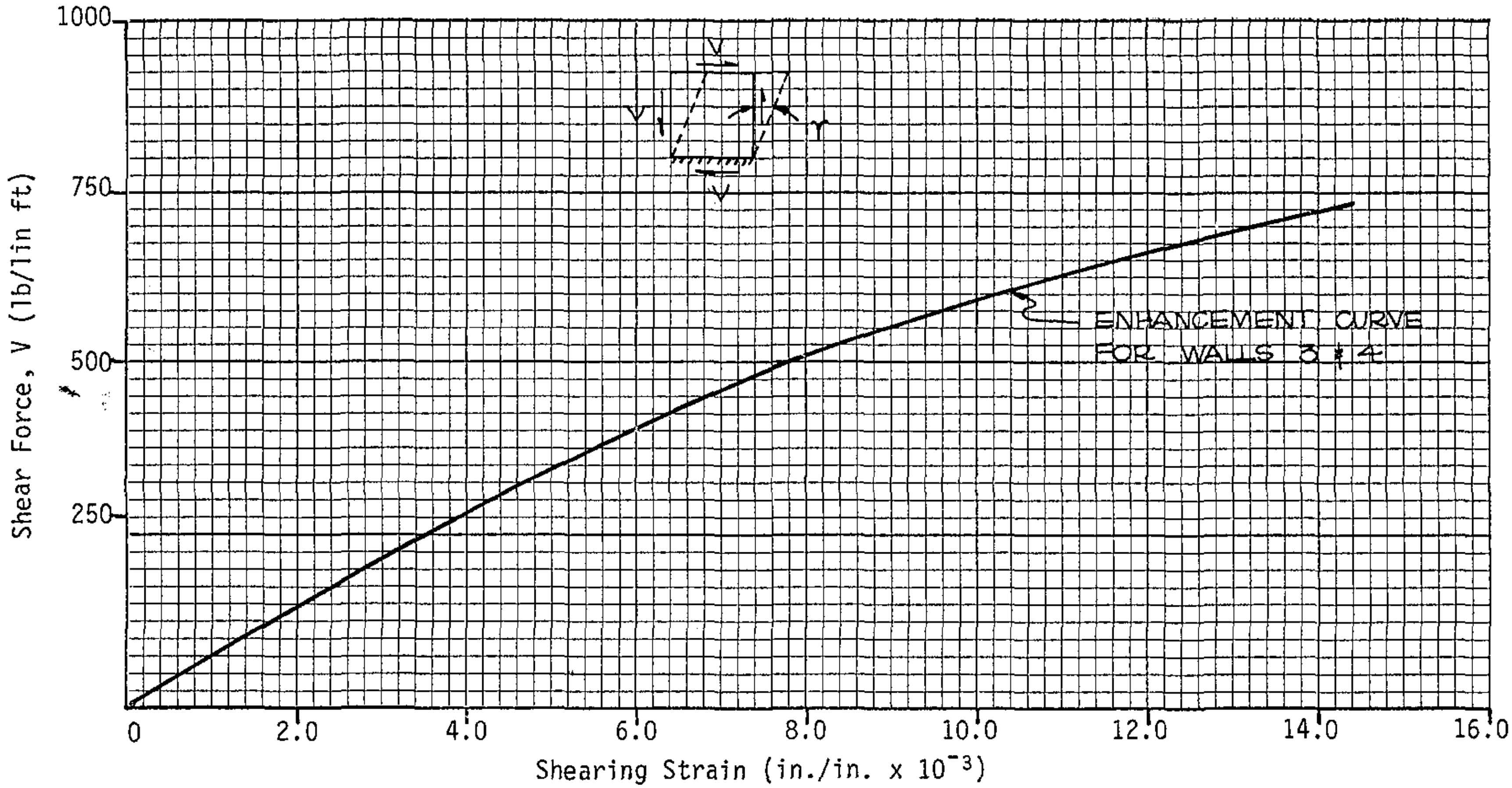


Fig. 3-21. Enhancement of Shear Strength for Walls No. 3 and No.4.

TABLE 3-6: ENHANCEMENT OF WALL NO. 5

Load, P (lbs)	Shear Modulus, G Base Case	Shear Modulus, G Wall No. 5	Enhancement of Shear Modulus, G (psi)
500	1,038	1,322	294
1,000	997	1,386	236
1,500	660	1,197	537
2,000	-----	1,053	-----
3,000	-----	1,036	-----
4,000	-----	1,049	-----
Mean $\bar{x}$	898.3	1,174	356
Std. Dev.	207.4	152.8	159.7
Relative Enhancement of Wall Due to Application of Foam			40%

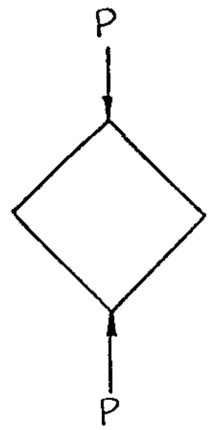
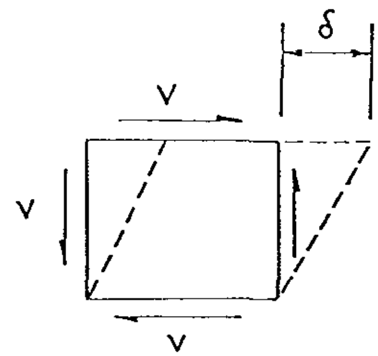


TABLE 3-7: RIGIDITY OF WALL NO. 5

Shear, V (lbs)	Rigidity (lbs/in.) Base Case	Rigidity (lbs/in.) Wall No. 5
353	3,634	4,652
707	3,518	4,843
1,061	2,291	4,192
1,414	-----	3,692
2,121	-----	4,329
2,828	-----	3,669
Mean $\bar{x}$	3,148	4,230
Std. Dev.	744	483.6

Rigidity, R

$$R = \frac{V}{\delta}$$



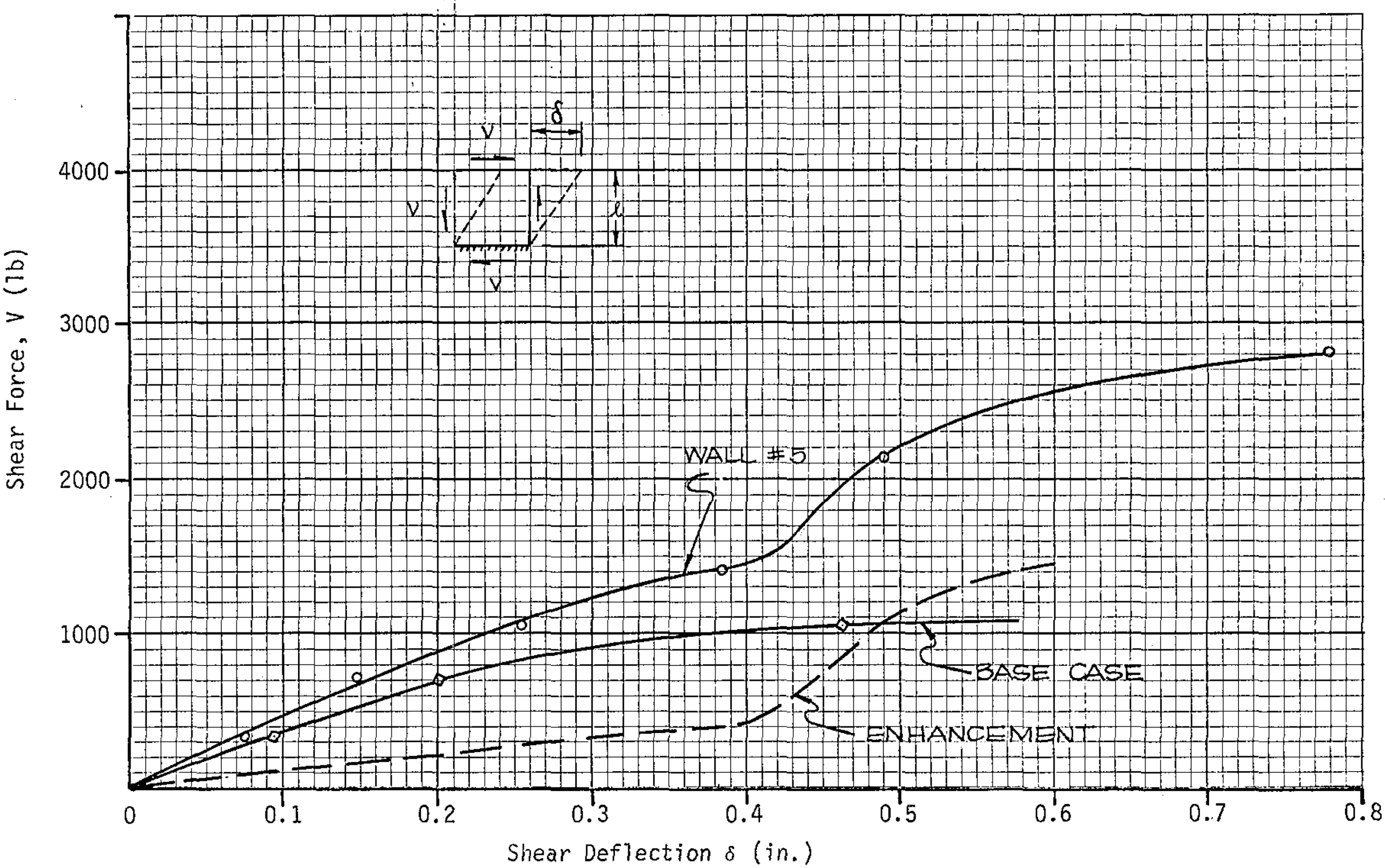


Fig. 3-22. Test Results for Base Case and Wall No. 5.

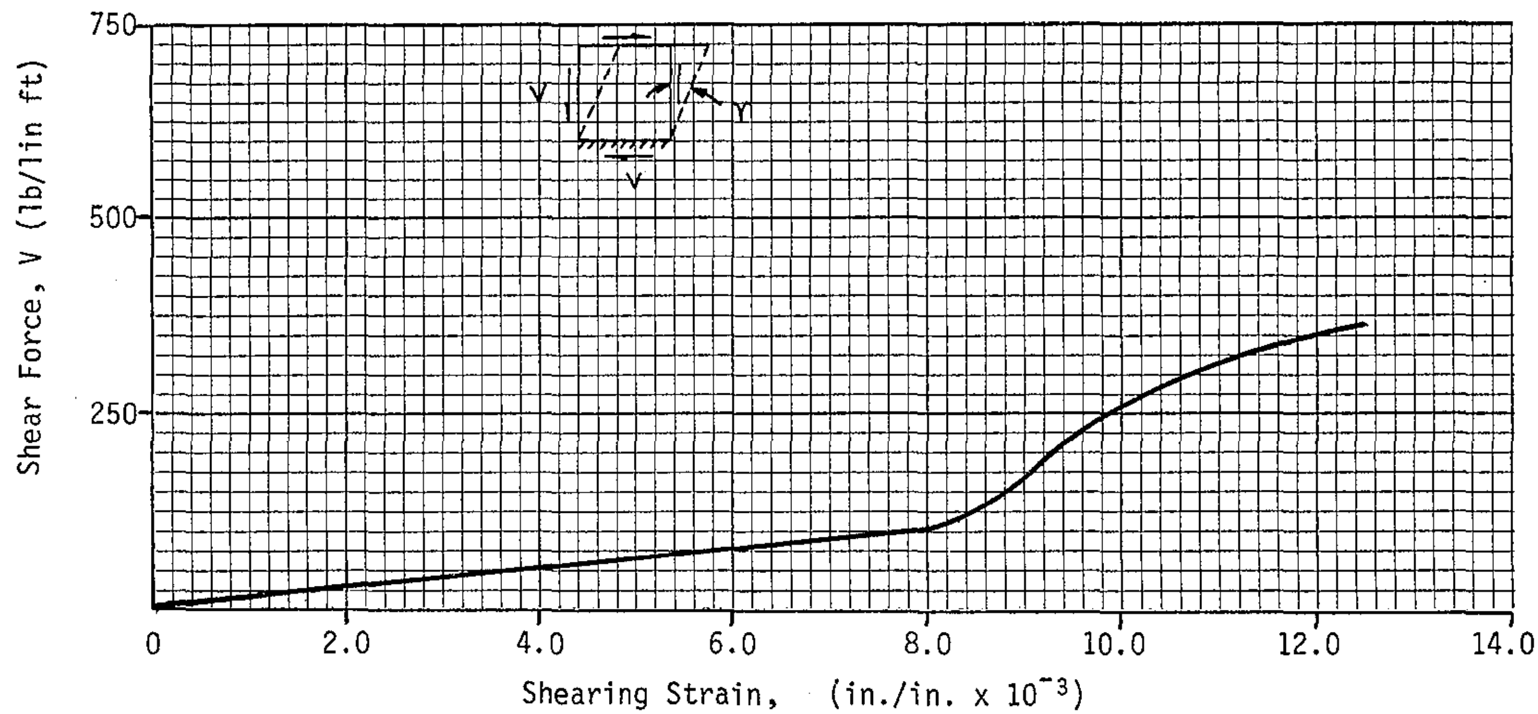


Fig. 3-23. Shear Enhancement of Wall No. 5.

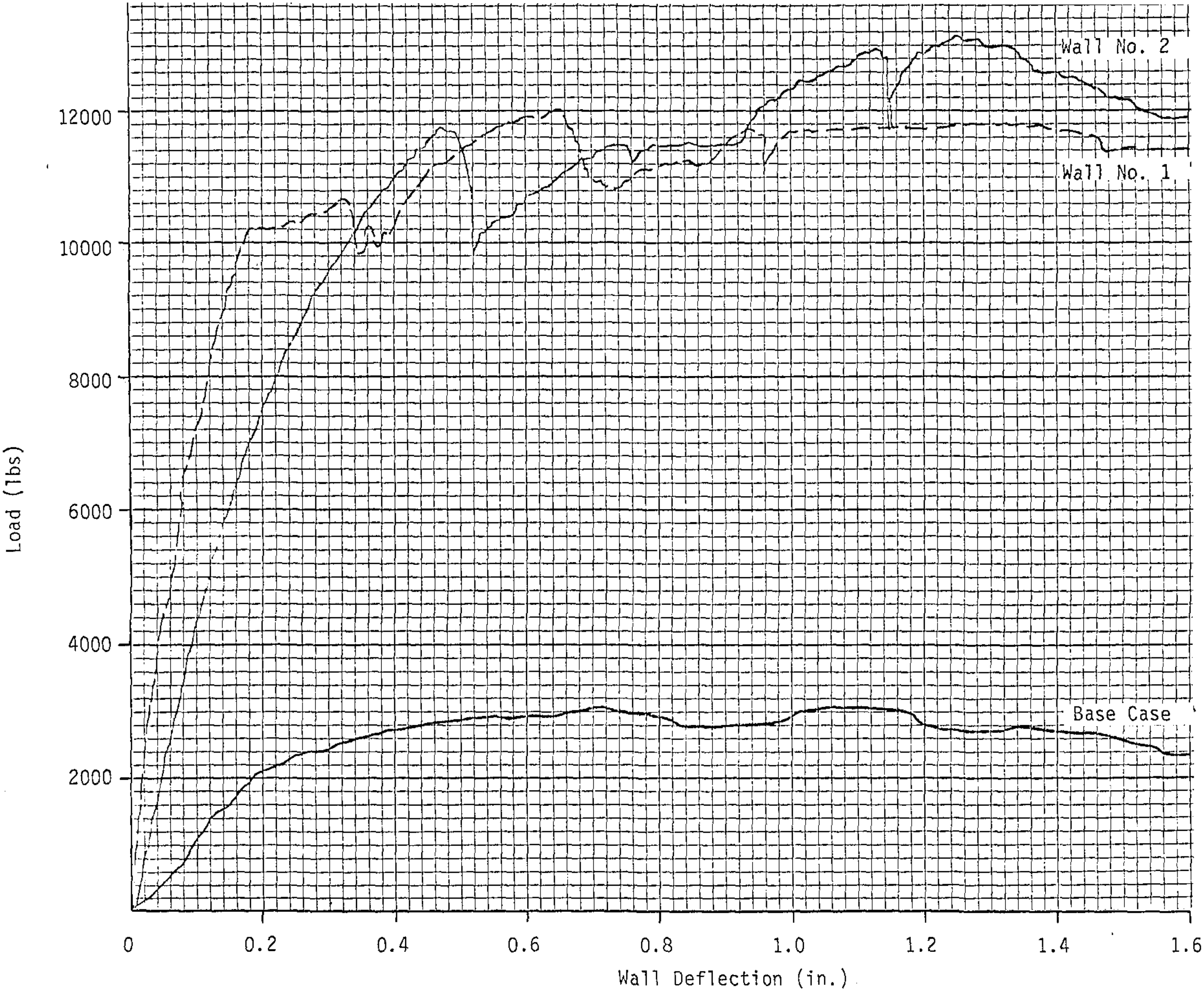


Fig. 3-24. Test Results for 4 x 8 Walls.

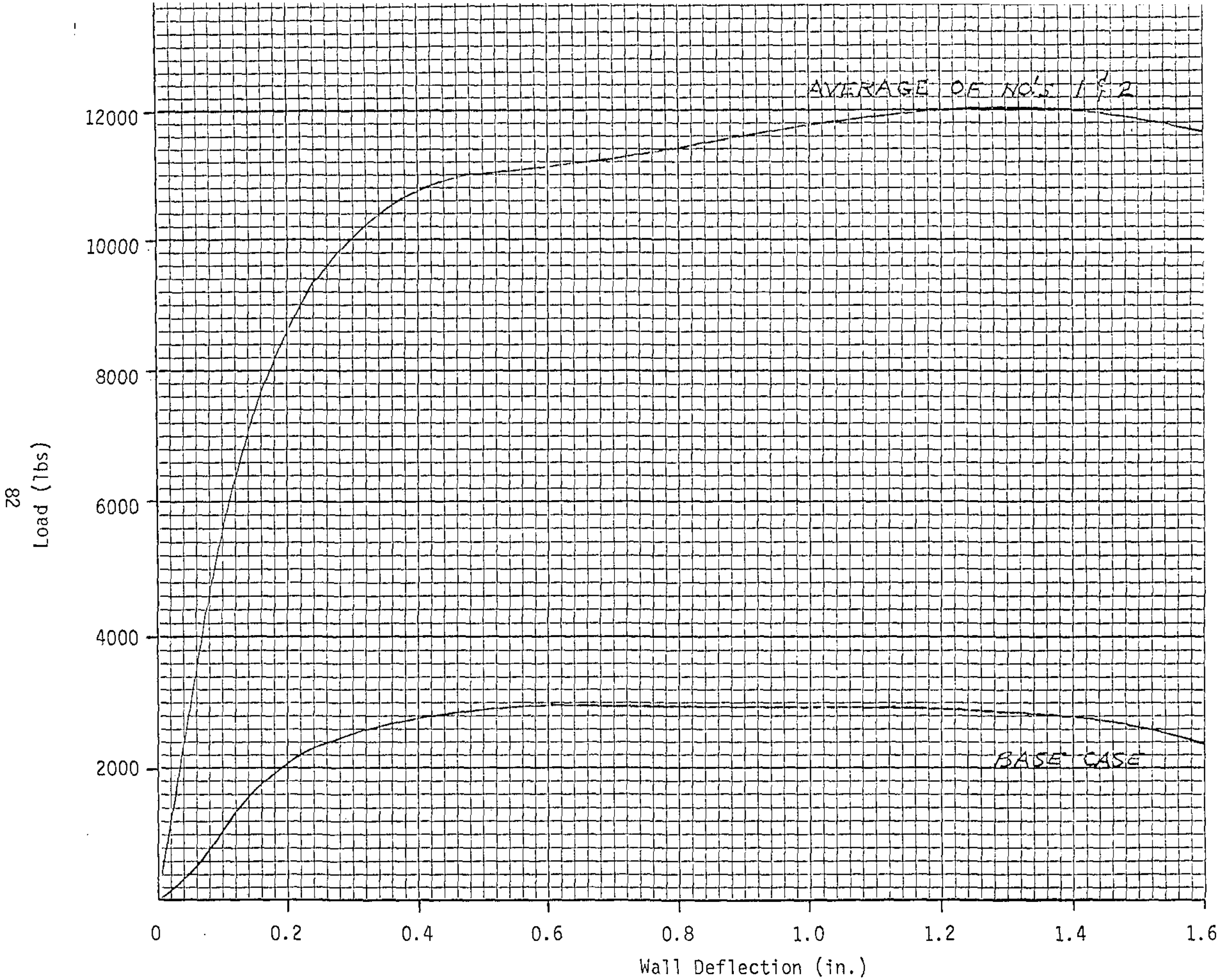


Fig. 3-25. Average Wall Test Results Compared to Base Case.

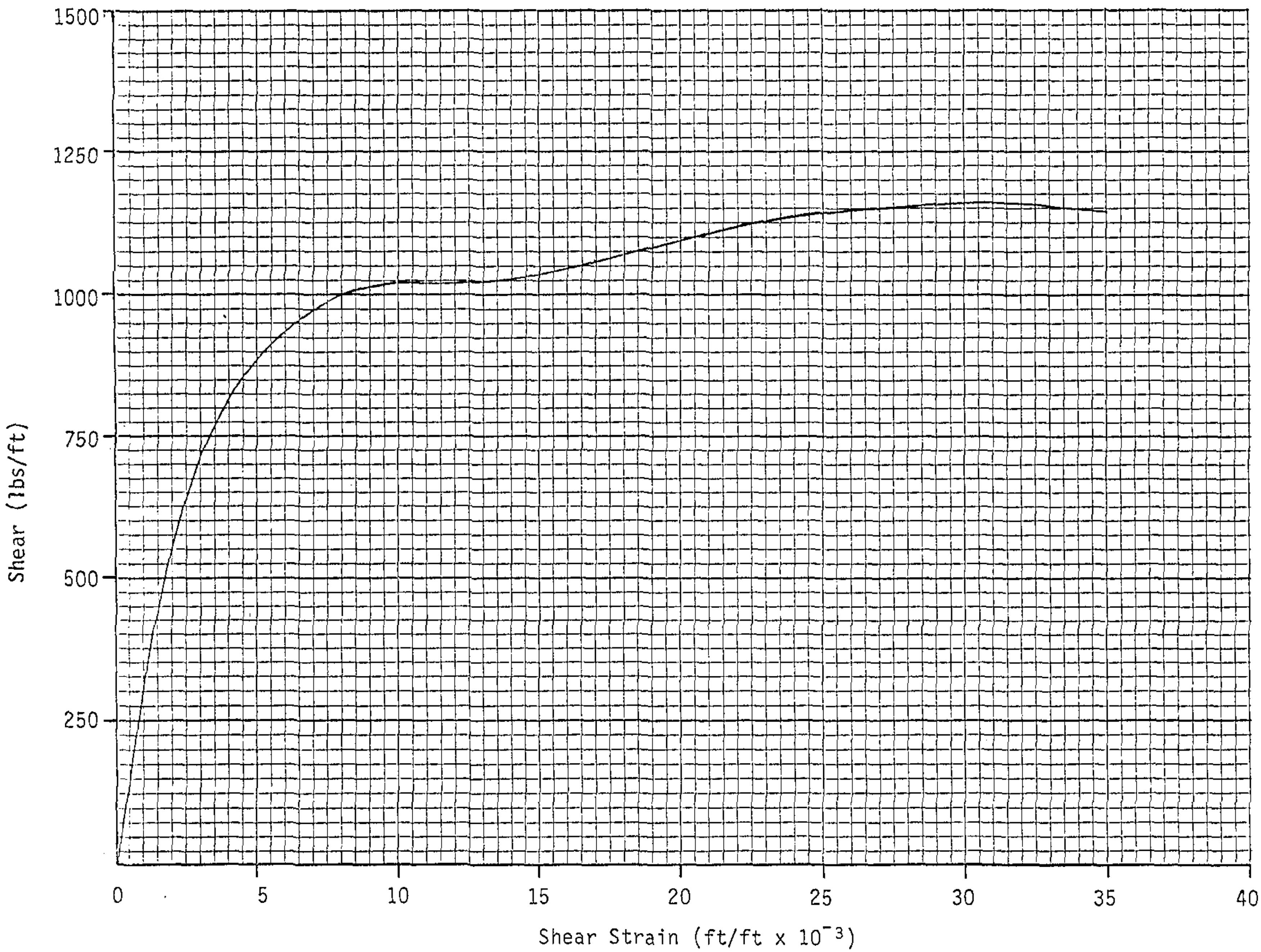


Fig. 3-26. 4' x 8' Wall Shear Strength Enhancement.

Floors

The base case floor and Floors No. 1, No. 2 and No. 3 were constructed as shown in Fig. 3-7. These floors were subjected to the horizontal shear test; the test results are summarized in Fig. 3-27. Note that Floor No. 1, which was overfilled in Phase 1 of foam installation, exhibited a greater strength than Floors No. 2 and No. 3, which were about 93% full. Fig. 3-28 compares the average test value for Floor No. 1, No.2 and No. 3 with the base case. The average ultimate strength for the foamed floors was 15,800 lbs at 6.85 inches of deflection. At this same deflection, the base case floor could resist only a load of 6,500 lbs. This represents an increased strength of 240% for foamed floors. Fig. 3-29 shows this enhancement of shearing strength on a normalized graph.

Floors No. 4 and No. 5 were also subjected to the horizontal shear test. These floors were constructed in a manner similar to the previous test floors, except that 2 ft x 8 ft (instead of 2 ft x 6 ft) frame members were used. Floor No. 5 was not foamed in order to provide a basis for comparison with a foamed floor. Fig. 3-30 shows the test results. Floor No. 4 exhibited an ultimate shear strength of about 21,000 lbs compared to 10,000 lbs for the non-foamed floor No. 5, that is, 210% of the shear strength of the unfoamed floor. Fig. 3-31 represents the shear enhancement of Floor No. 4 compared to Floor No. 5.

Floors No. 6 and No. 7 were subjected to the bending test before and after foam placement. The average test results are shown in Fig. 3-32. The bending stiffness increased from 8,200 lbs/in. to 11,100 lbs/in., that is, to 135% of the stiffness of an unfoamed floor. The average weight gained from the added sheetrock and foam was 27 lbs, or a 14% increase in weight.

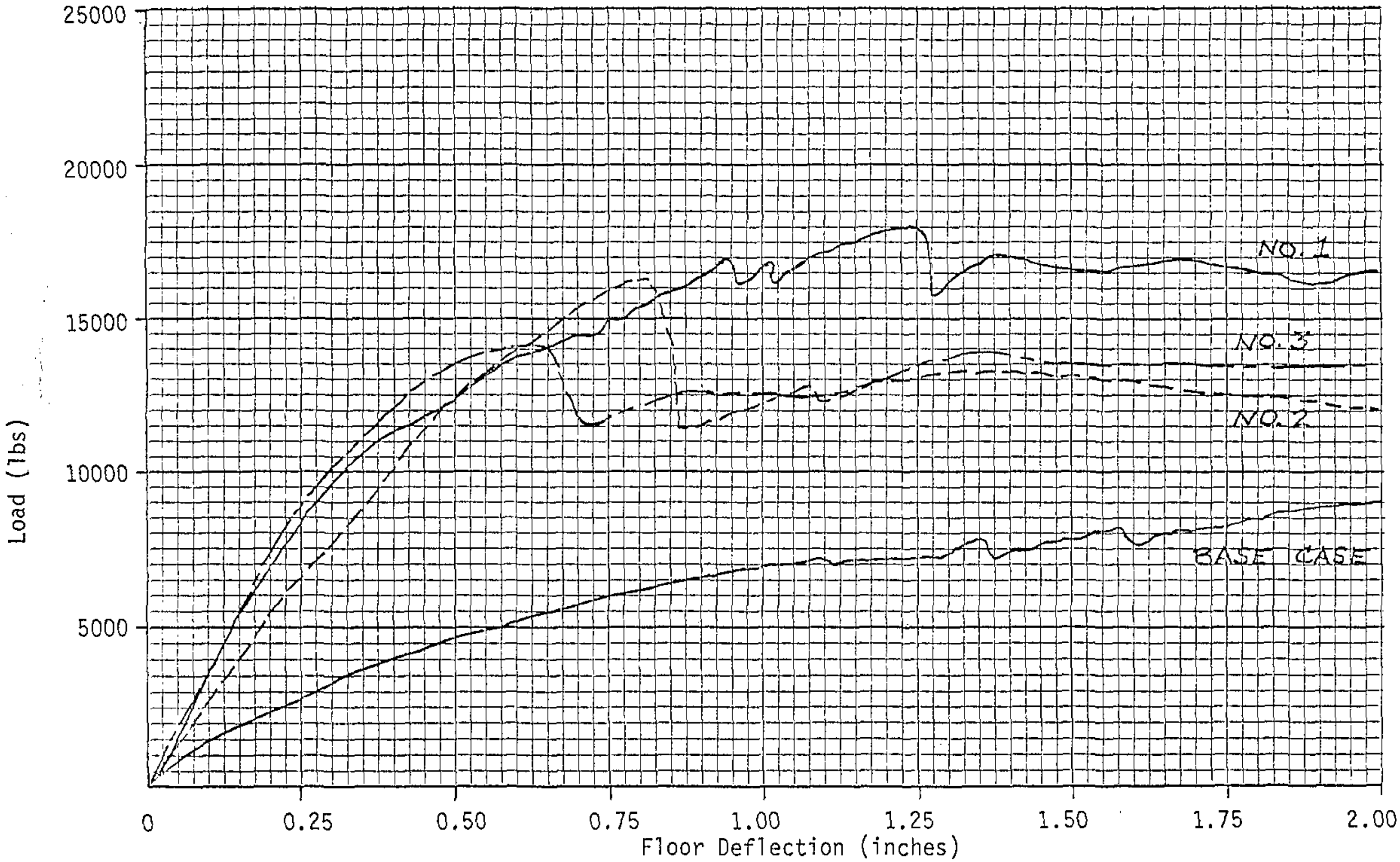


Fig. 3-27. Horizontal Shear Test Results for Floor Specimens (2 x 6 framing).

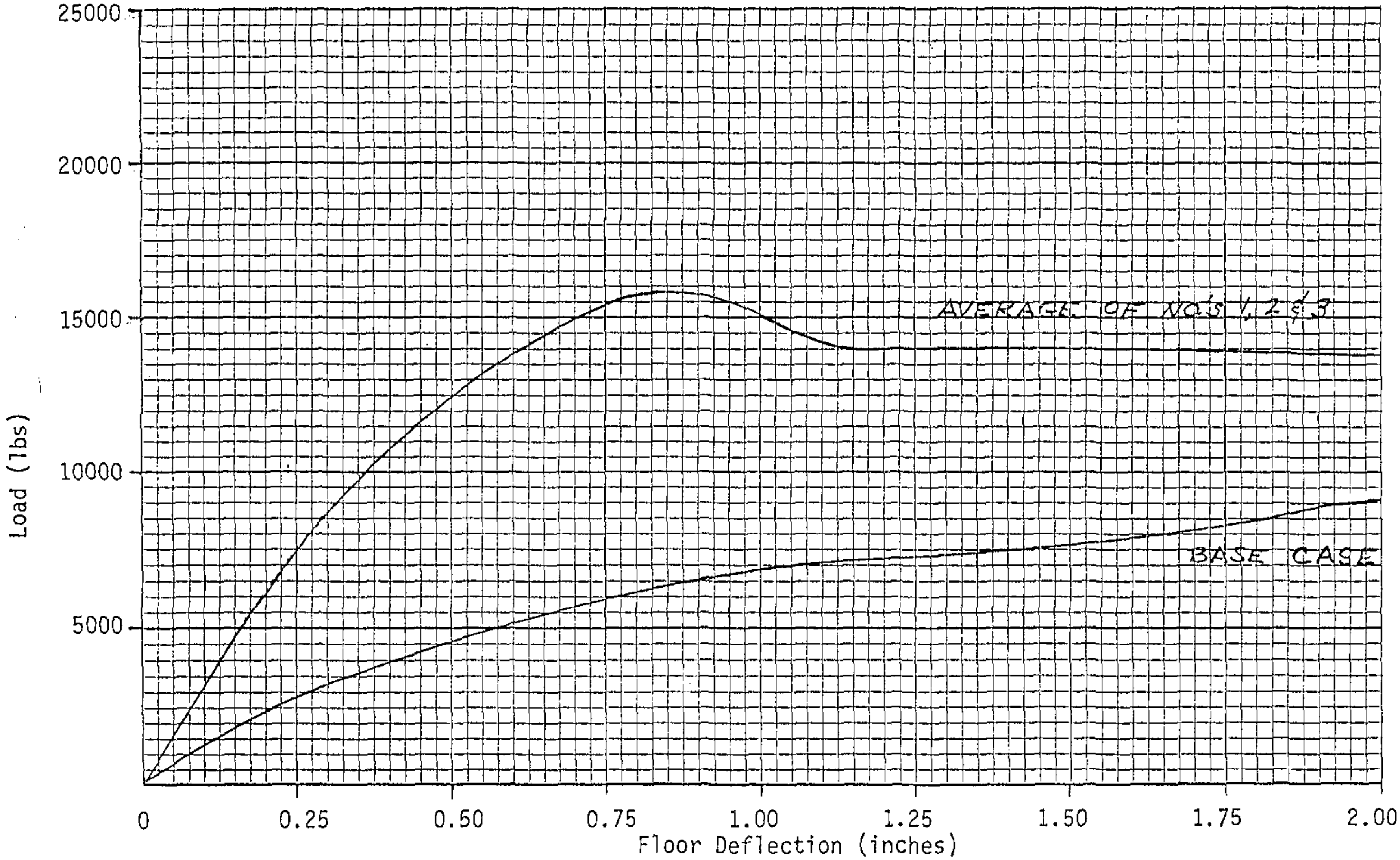


Fig. 3-28. Comparison of Base Case to Floors With Foam.

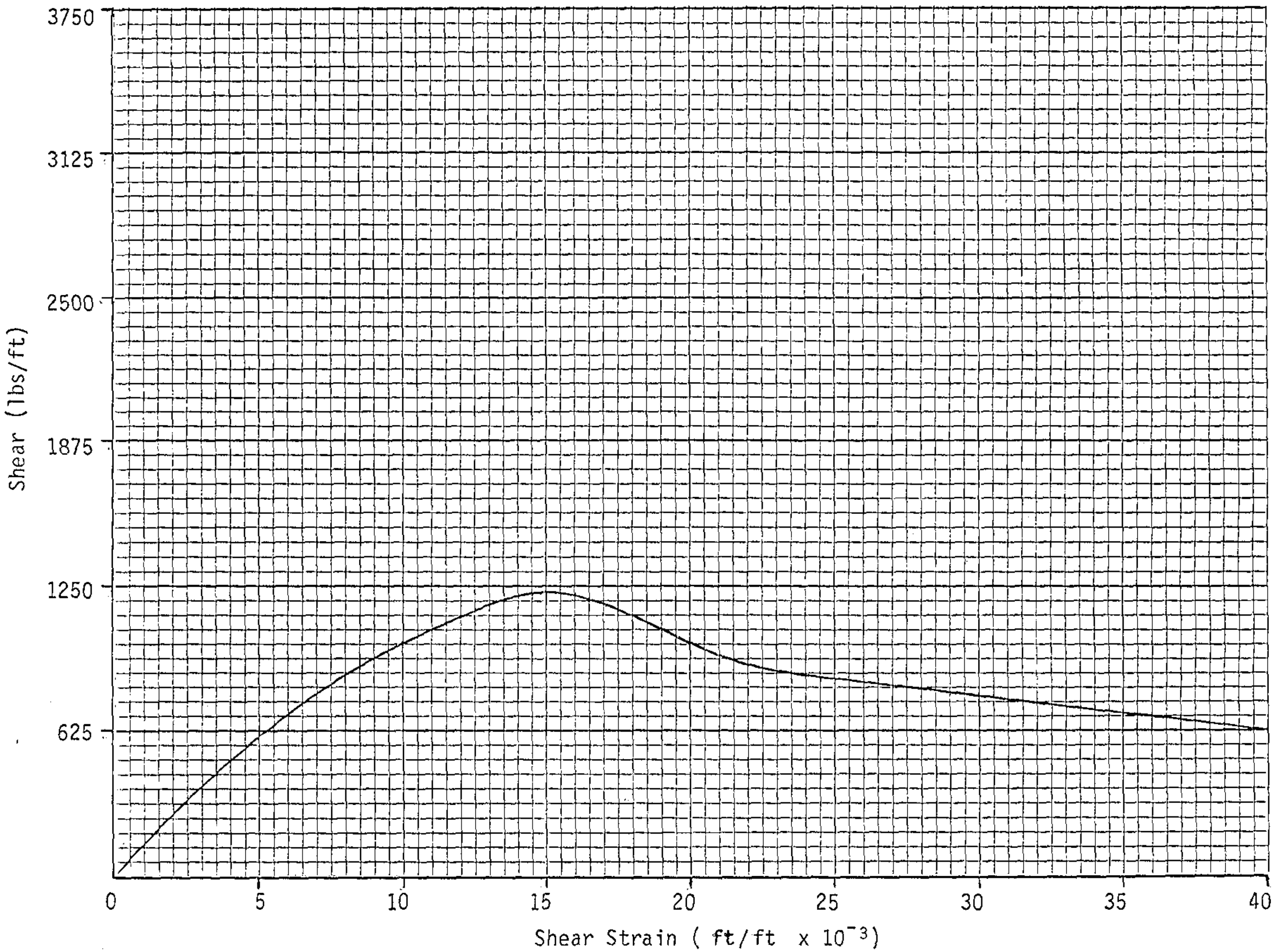


Fig. 3-29. Enhancement of Floors (2 x 6 framing).

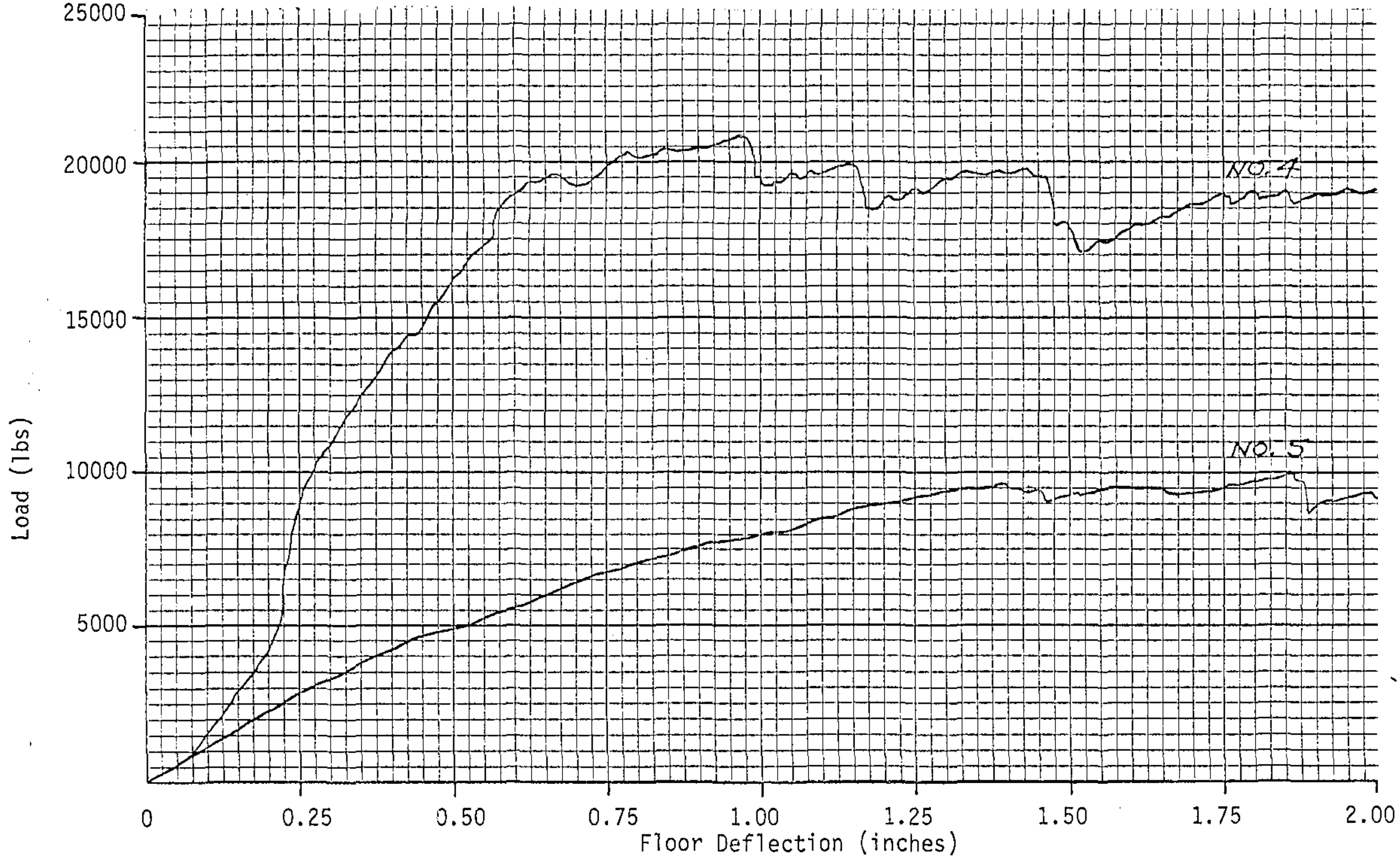


Fig. 3-30. Horizontal Shear Test Results for Floor Specimens (2 x 8 framing).

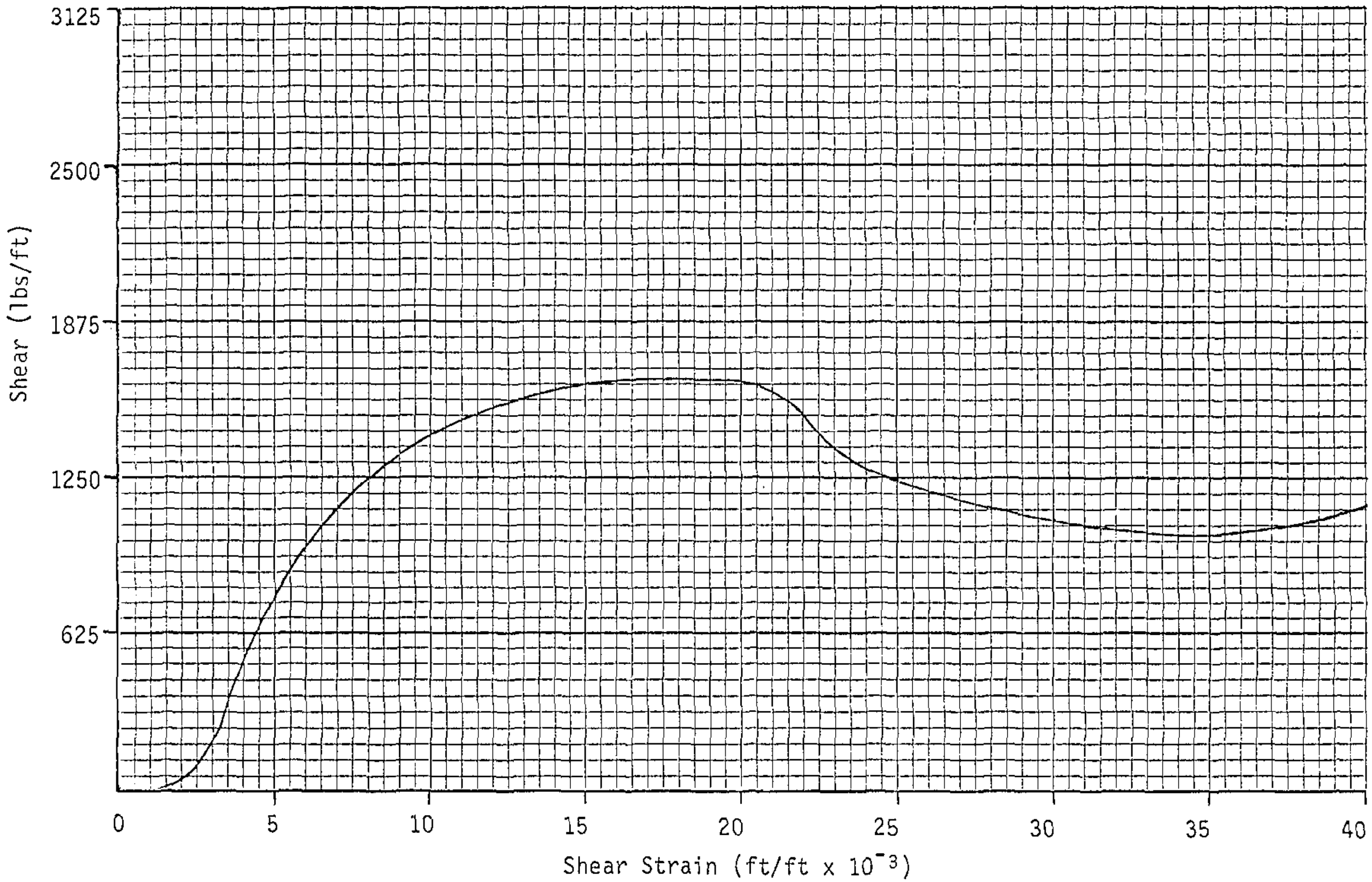


Fig. 3-31. 2 x 8 Floor Enhancement.

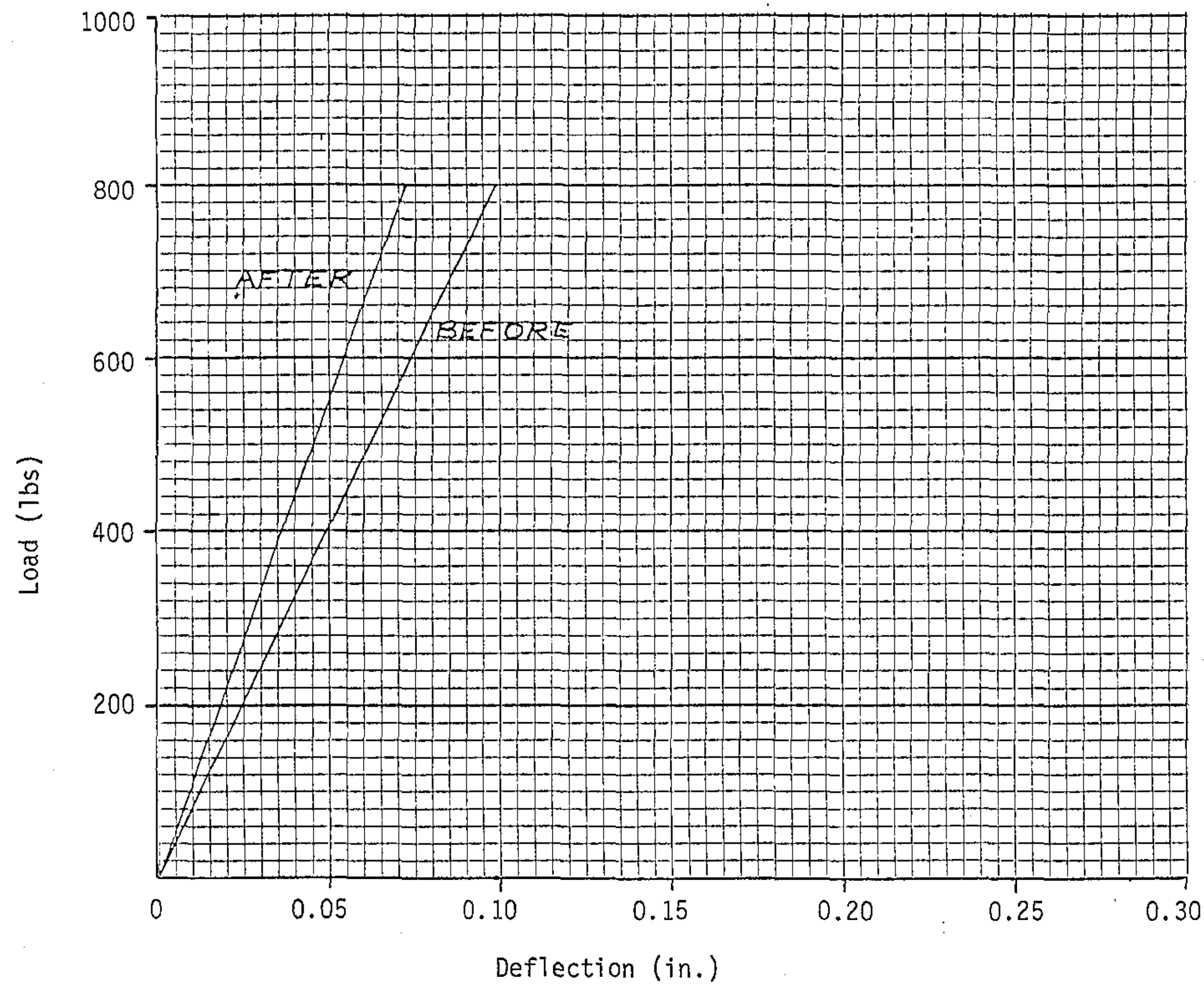


Fig. 3-32. Average Deflection Before and After Foam Placement for Floors No. 6 and 7.

Section 4
SUPPLEMENTAL TEST PROGRAM

INTRODUCTION

As part of the program, a series of supplemental tests were conducted to aid in the interpretation of the data from the primary test program and to gain information to help in projecting the use of foamed structural elements in full-scale building applications with similar products. This supplemental test program included material property and foundation shear tests, which are described in this section.

MATERIAL PROPERTY TESTS

Three types of material property tests were performed—shear, tension, and compression.

Shear Tests

Six specimens were constructed and tested for shear strength of foamed-in-place rigid urethane. Each specimen consisted of three 2 x 6 pieces of Douglas Fir/Larch (select structural), each 18 in. long. These pieces were placed edgewise and parallel to one another with a 2-in. gap between them and with the middle piece staggered 6 inches. The 2-in. gap was filled with foam over a 12-in. length. (See Fig. 2-30 for photographs of this process.) Twenty-four hours later, the foam was trimmed to be parallel to each 2 x 6 edge. A sketch of the sample configuration is shown in Fig. 4-1.

Each test specimen was placed in a Riehle Model FH-60 universal testing

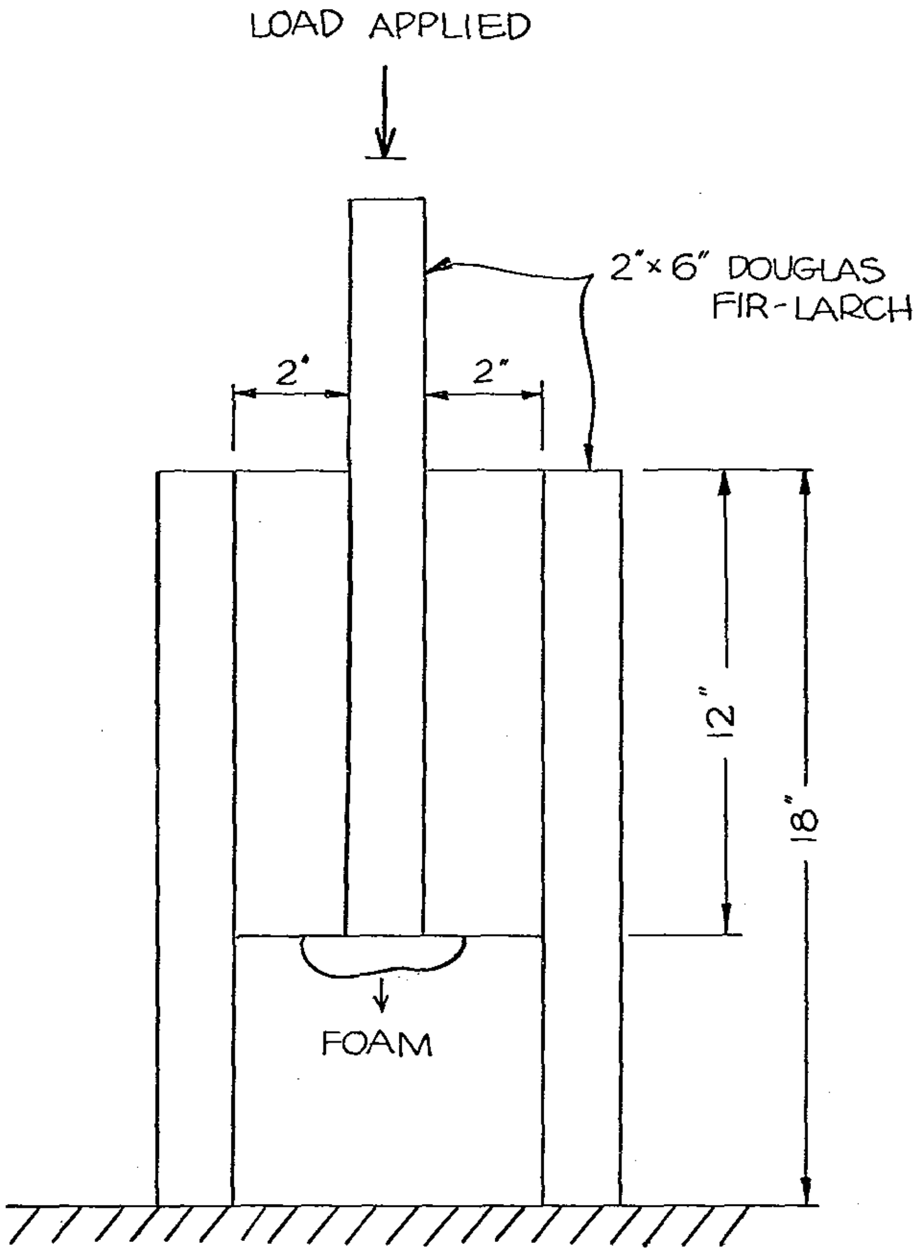


Fig. 4-1. Sketch of Shear Specimen.

machine. The machine was used in the compression mode with movement of the platen recorded with load. The test configuration in the testing machine is shown in Fig. 4-2.

The testing machine controls were set for a constant displacement rate of approximately 0.2 inches per minute. The test specimens were loaded to failure—where failure was determined to occur when the center 2 x 6 piece separated from the foam along its sides. Typical failures are pictured in Fig. 4-3. The load-versus-deflection graphs for each specimen are presented in Appendix B. Summary graphs are presented in Figs. 4-4 and 4-5.

Tension Tests

Eight tests were conducted to obtain a measure of the tensile strength of the foam used in the primary test program. Four of these specimens were cast so that the tensile load would be parallel to the rise of the foam, and four so that the load would be perpendicular to the rise.

The specimens were tested in a testing machine as shown in Fig. 4-6. Before and after photographs are shown in Fig. 4-7. A summary of the data is presented in Table 4-1.

Compressive Tests

Six tests were conducted to determine the compressive strength of the foam used in the primary test program. Test specimens, 6 in. in diameter and 12 in. long, were placed in the Riehle universal testing machine, as shown in Fig. 4-8. A typical data plot (from Test No. 1) is shown in Fig. 4-9. The remaining data plots are presented in Appendix B. Photographs of typical test results are presented in Fig. 4-10 and a summary of the data is given in Table 4-2.

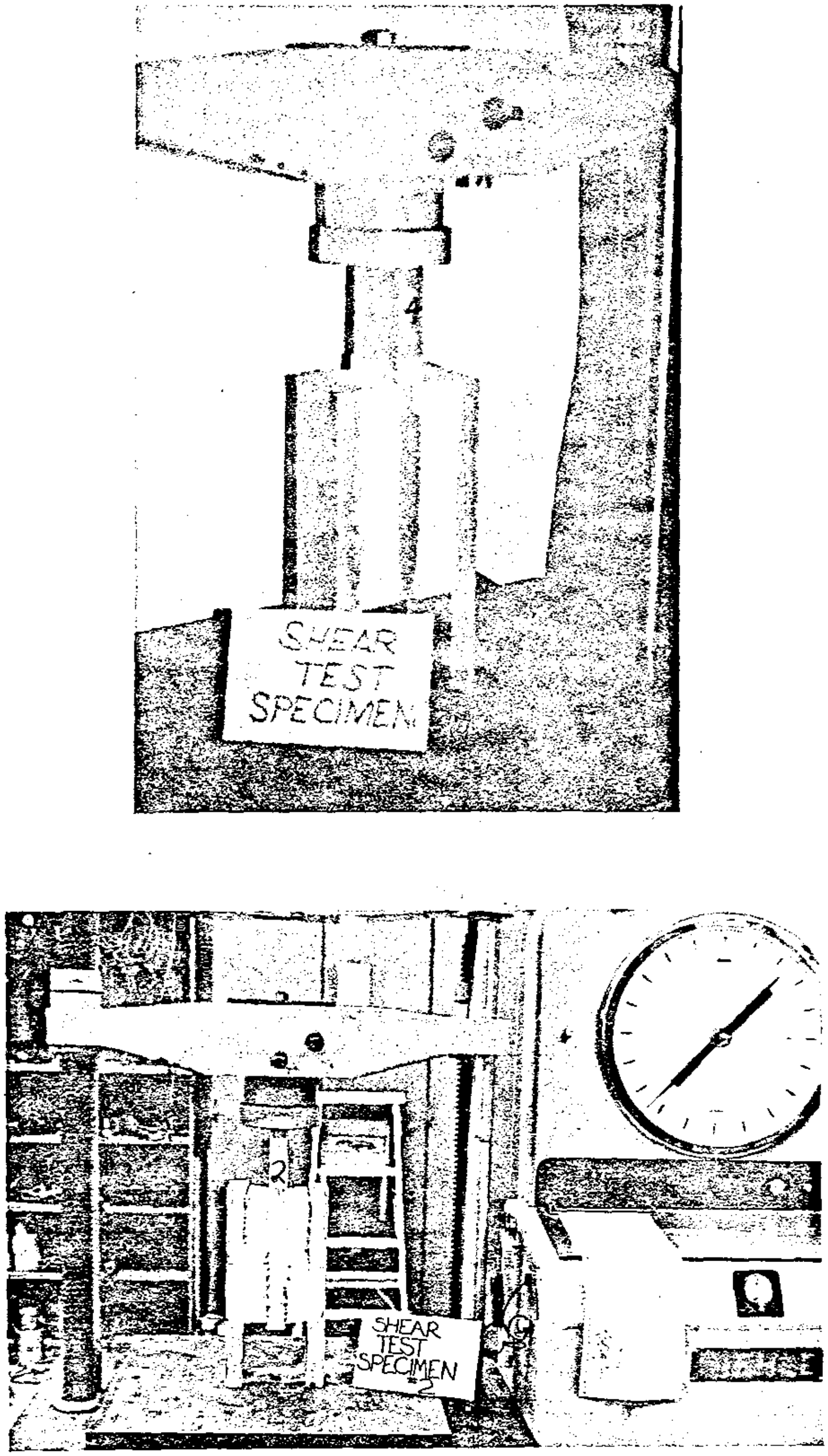


Fig. 4-2. Shear Test Specimens in Testing Machine.

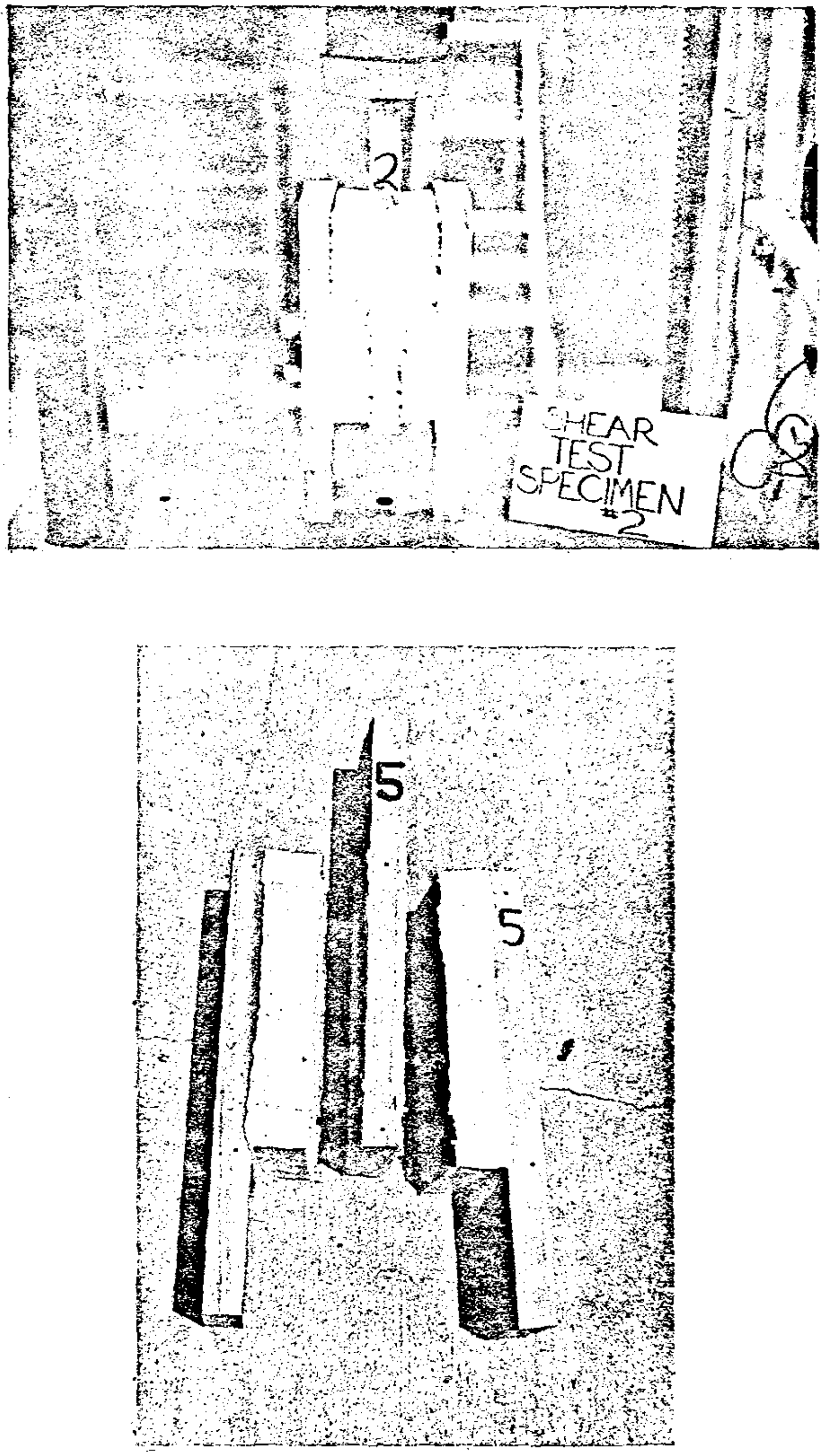


Fig. 4-3. Typical Failure of Shear Test Specimens.

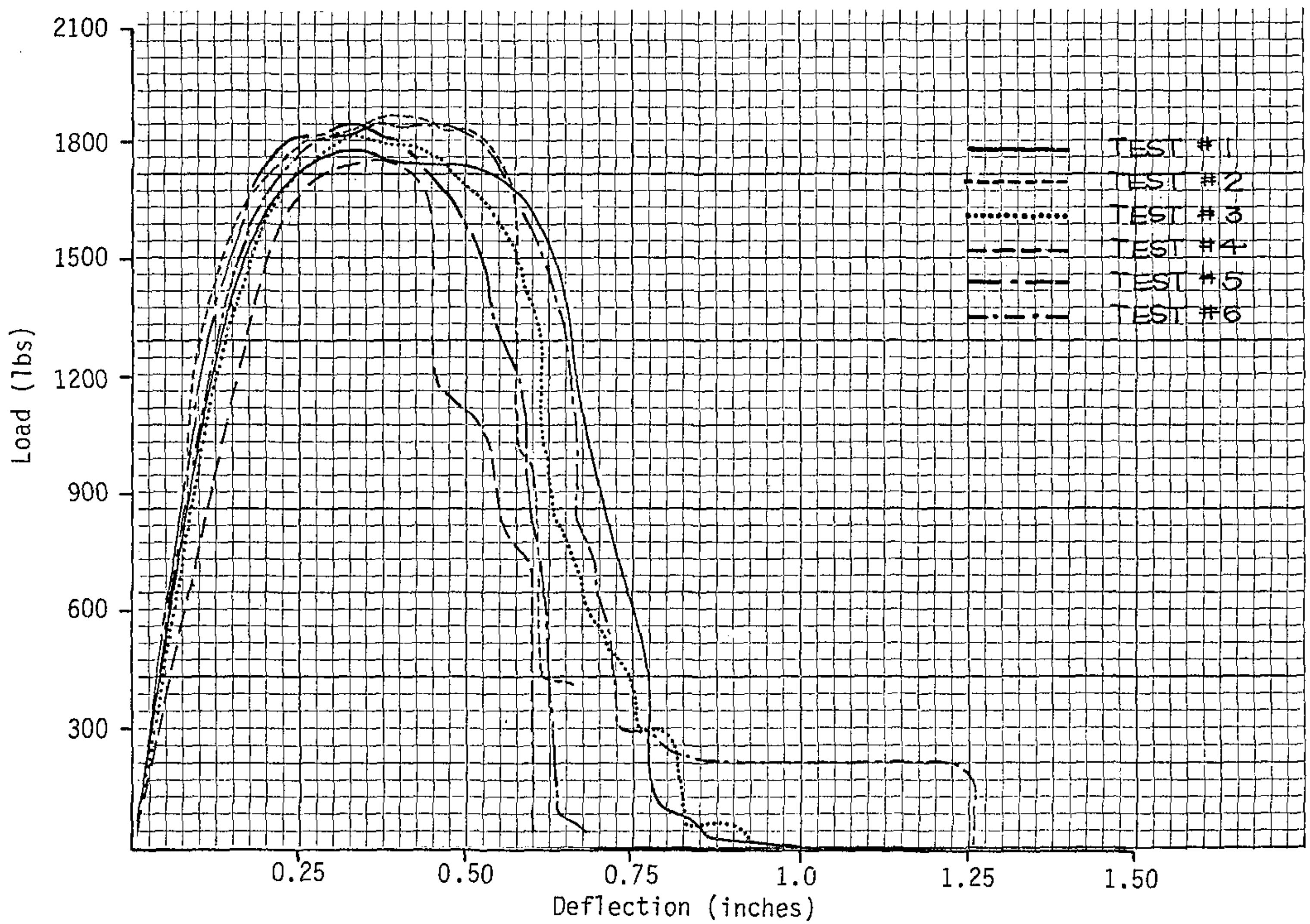


Fig. 4-4. Summary of Shear Test Data.

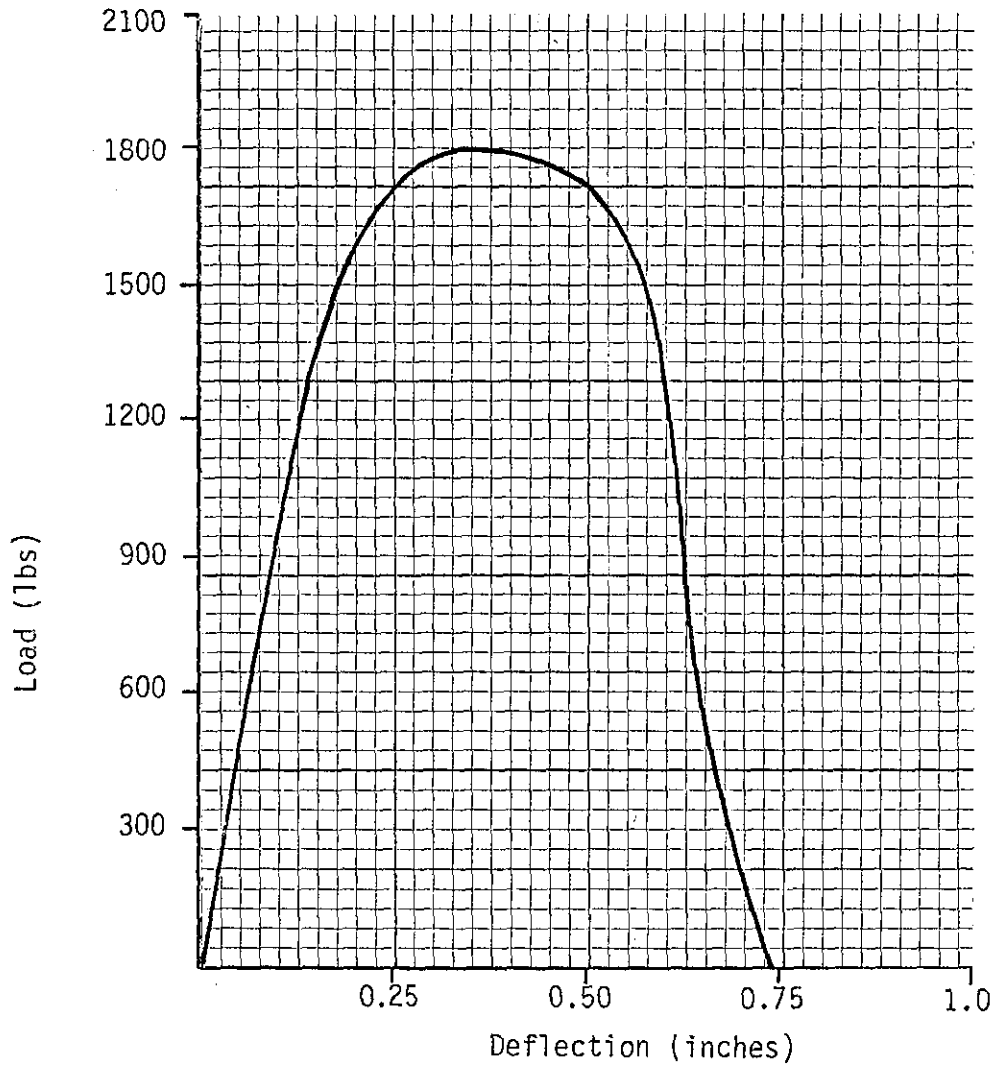


Fig. 4-5. Average Curve of Shear Test Data.

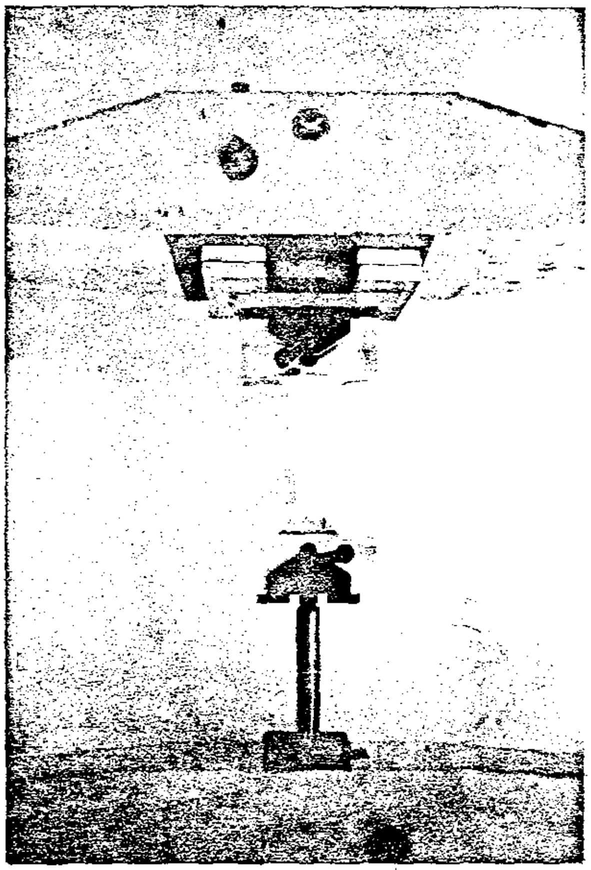


Fig. 4-6. Tensile Test Specimen in Testing Machine.

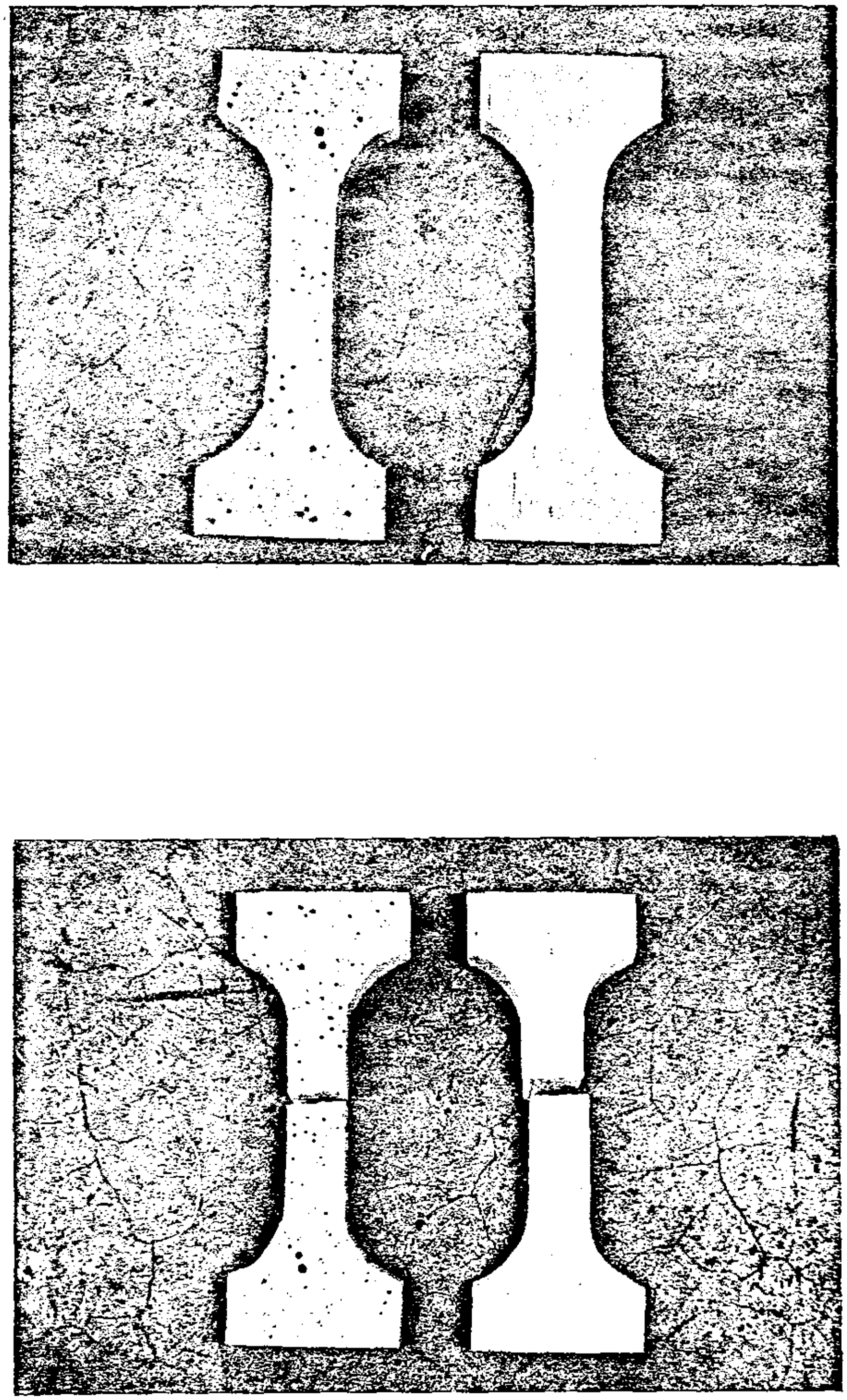


Fig. 4-7. Before and After Test Photographs of Tensile Test Specimens.

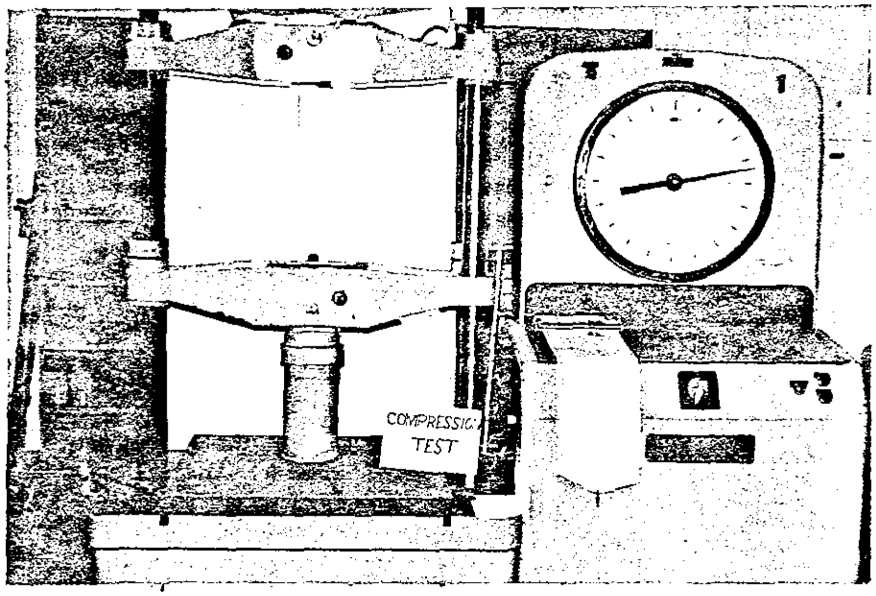
TABLE 4-1: SUMMARY OF TENSILE TEST DATA

PARALLEL TO RISE

Test No.	Failure Load (lbs)	Psi
1	48	31
2	44	28
3	46	29
4	44	28

PERPENDICULAR TO RISE

Test No.	Failure Load (lbs)	Psi
1	38	24
2	50	32
3	44	28
4	47	30



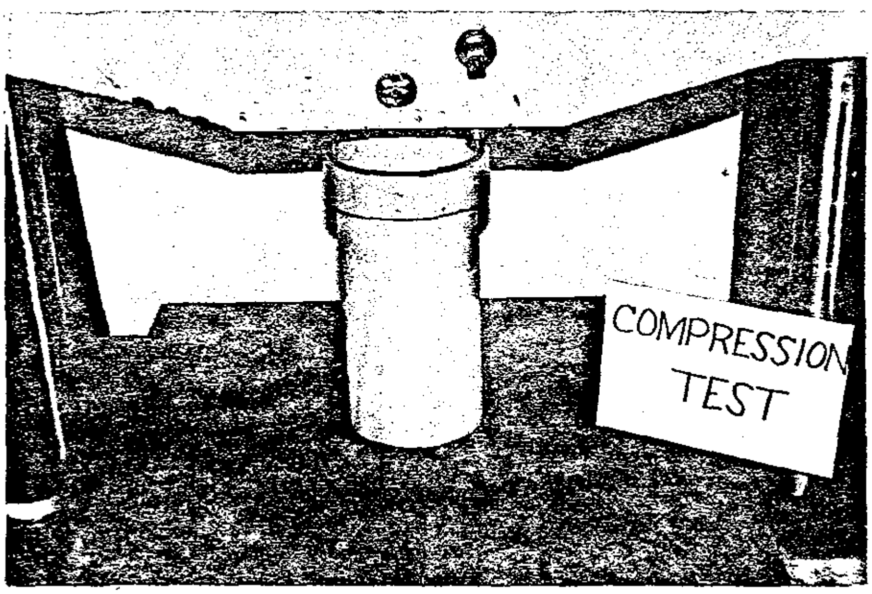


Fig. 4-8. Compression Test Specimen in Testing Machine.

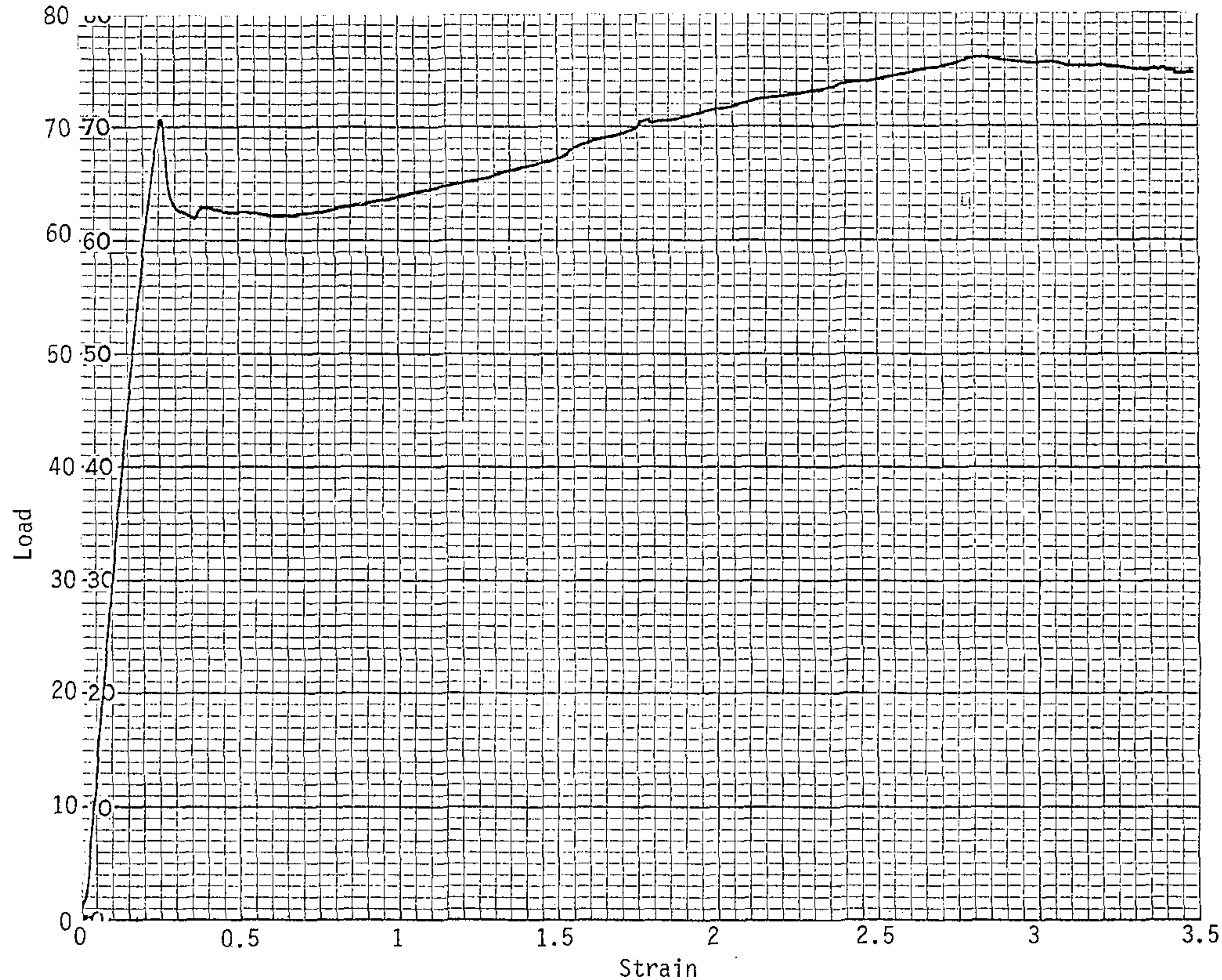


Fig. 4-9. Compression Data for Test Number 1.

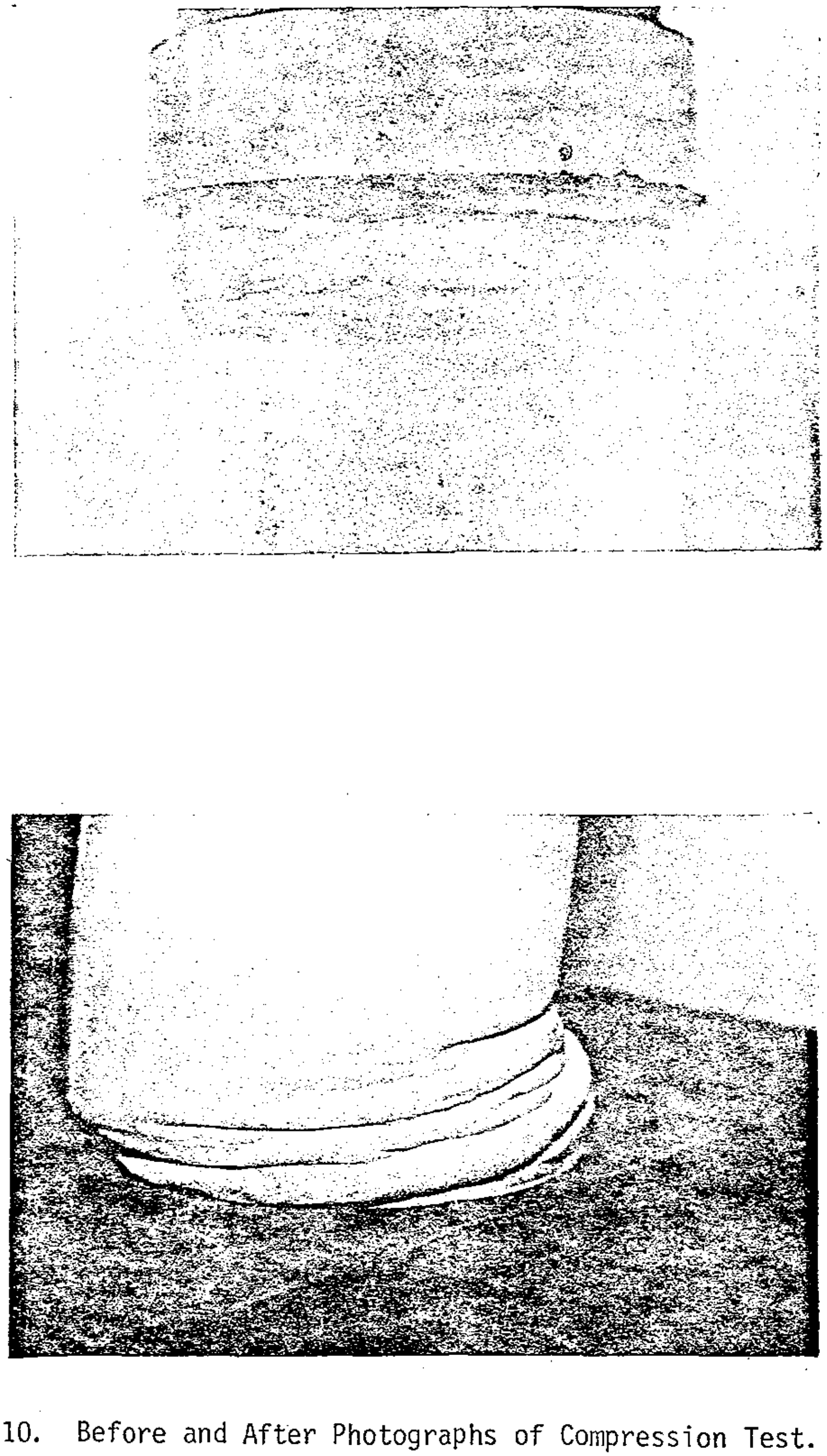


Fig. 4-10. Before and After Photographs of Compression Test.

TABLE 4-2: SUMMARY OF COMPRESSION TEST DATA

Test No.	Yield (lbs)	Deflection at Yield (inches)
1	850	0.175
2	554	0.245
3	739	0.190
4	627	0.295
5	710	0.200
6	613	0.350

FOUNDATION SHEAR TEST

One of the common failures of older structures in earthquakes is failure of the floor-to-foundation connections. To gain some preliminary data on the ability of foam to improve this connection, two portions of a typical wood floor system were set on a concrete foundation wall. Foam was poured into the cavity between the joists and down seven inches of the concrete wall. A section of gypsum wallboard held the foam in place until it cured (see Figs. 4-11 and 4-12). For construction details of these specimens refer to Fig. 2-31.

A hydraulic actuator applied an increasing horizontal load to the floor section (see Fig. 4-13 for a sketch of the test arrangement). Failure occurred when the foam separated from the concrete. A dial gauge at the opposite end measured the relative displacement of the floor to the concrete under loading (Fig. 4-14).

The load-versus-deflection data are summarized on the graphs in Fig. 4-15. Test Specimen No. 1 failed at 4,700 lbs and No. 2 failed at 4,300 lbs. In both cases, the failure occurred in the bond layer interface between the concrete and the foam, as shown in Fig. 4-16. The average ultimate shear strength provided by these connections was 1,900 lbs/ft^2.

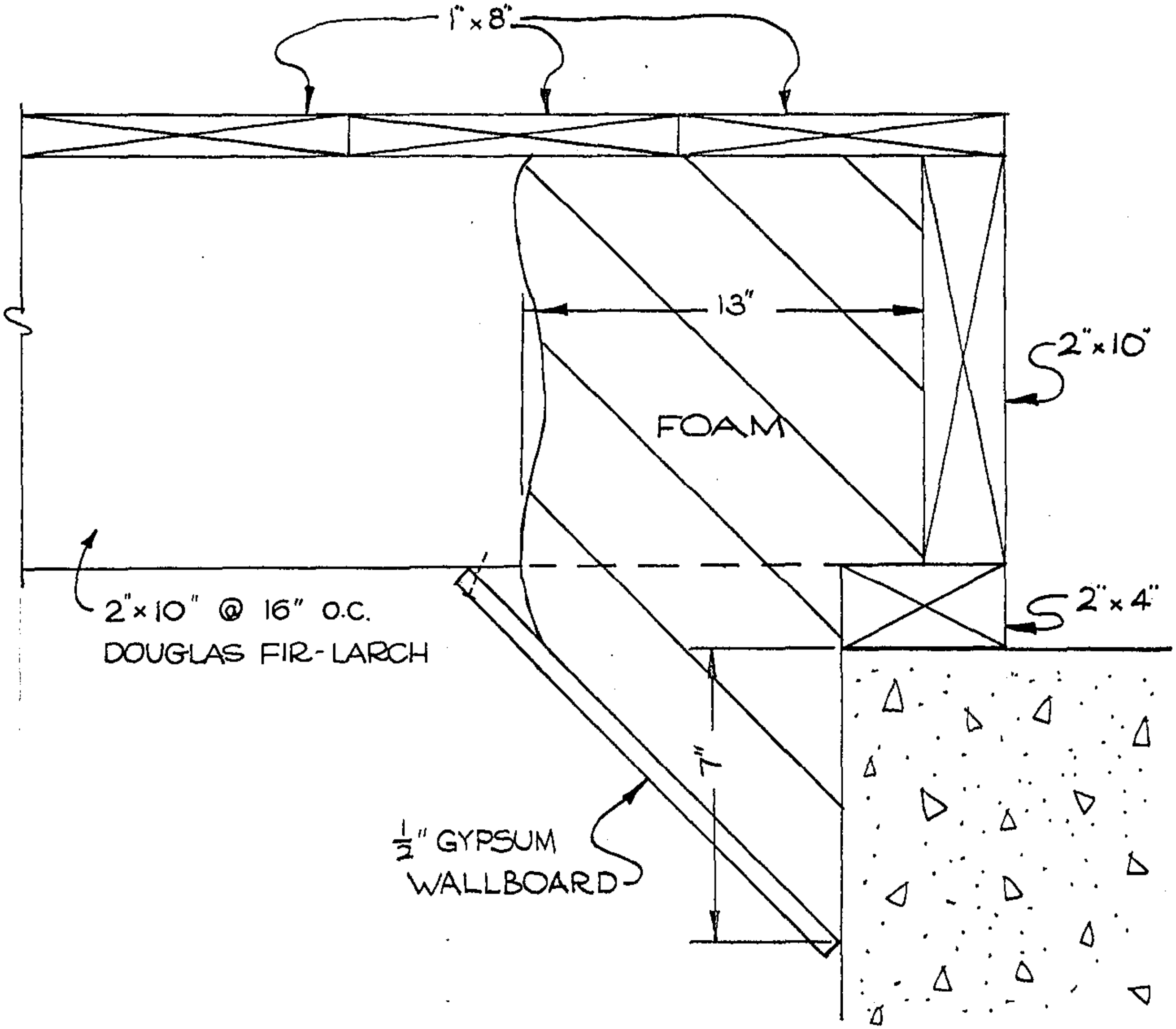


Fig. 4-11. Foundation Shear Test Specimen Construction.

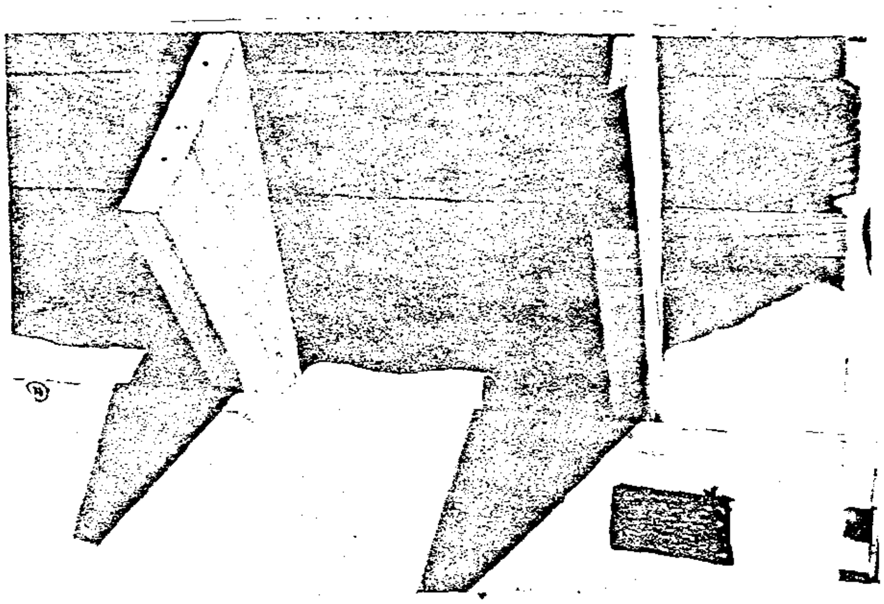


Fig. 4-12. Foam Poured Between Joists for Foundation Shear Test.

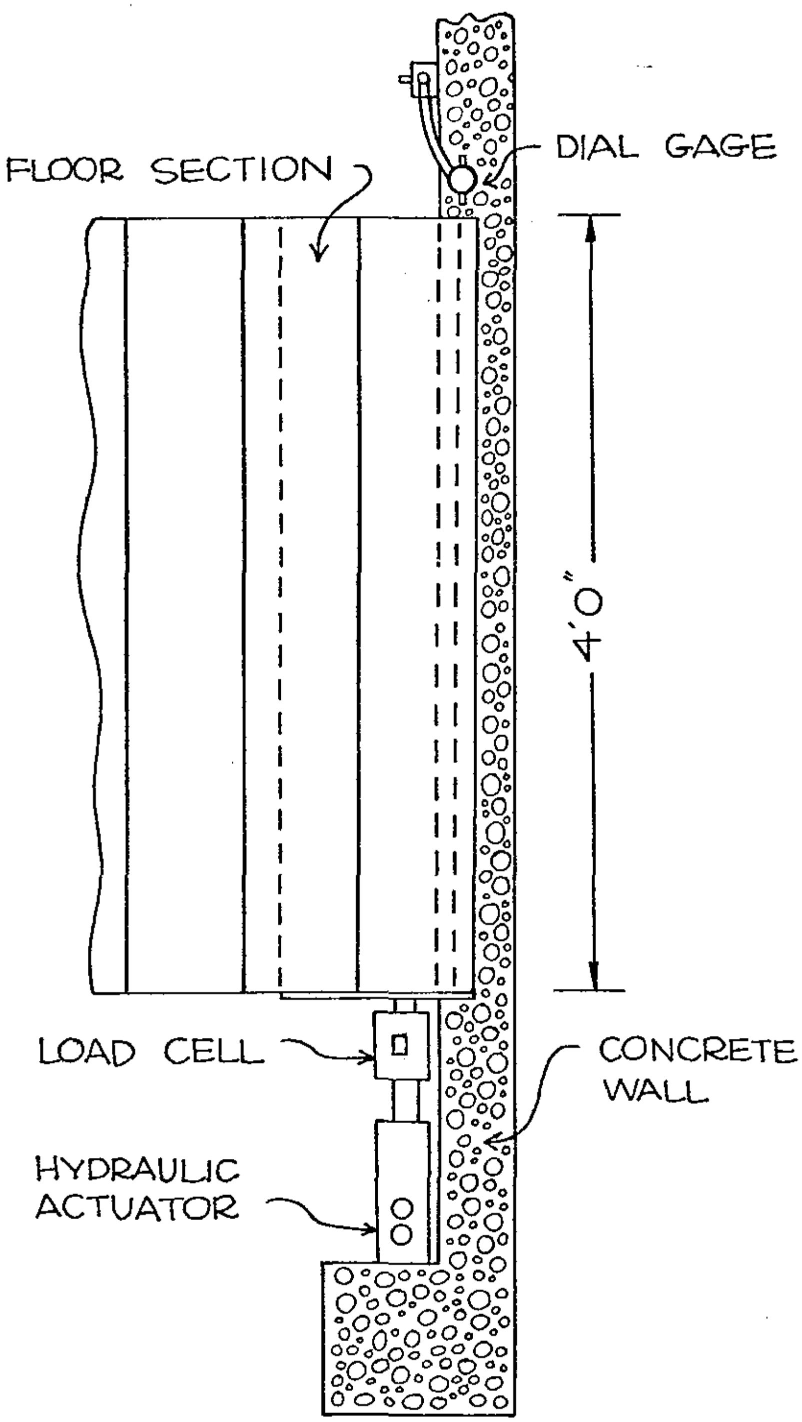


Fig. 4-13. Foundation Shear Test Arrangement.

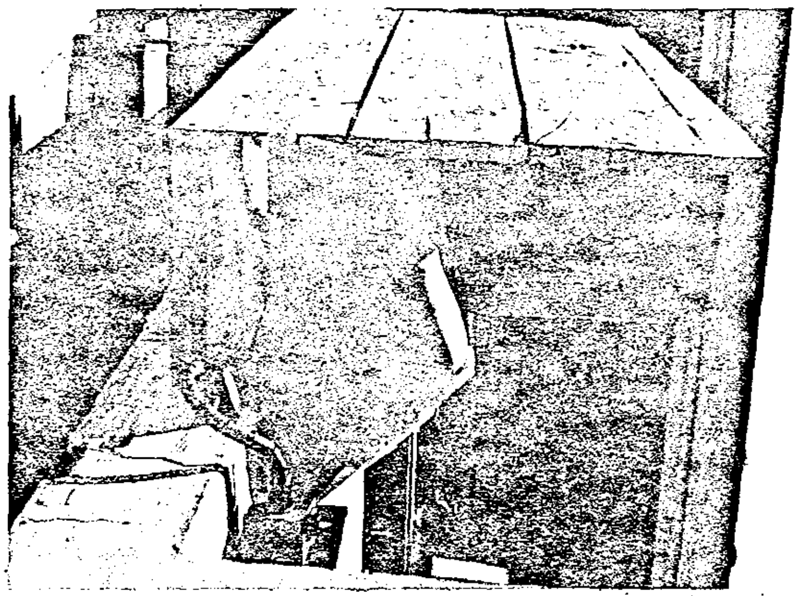


Fig. 4-14. Dial Gauge Placement for Shear Displacement Tests.

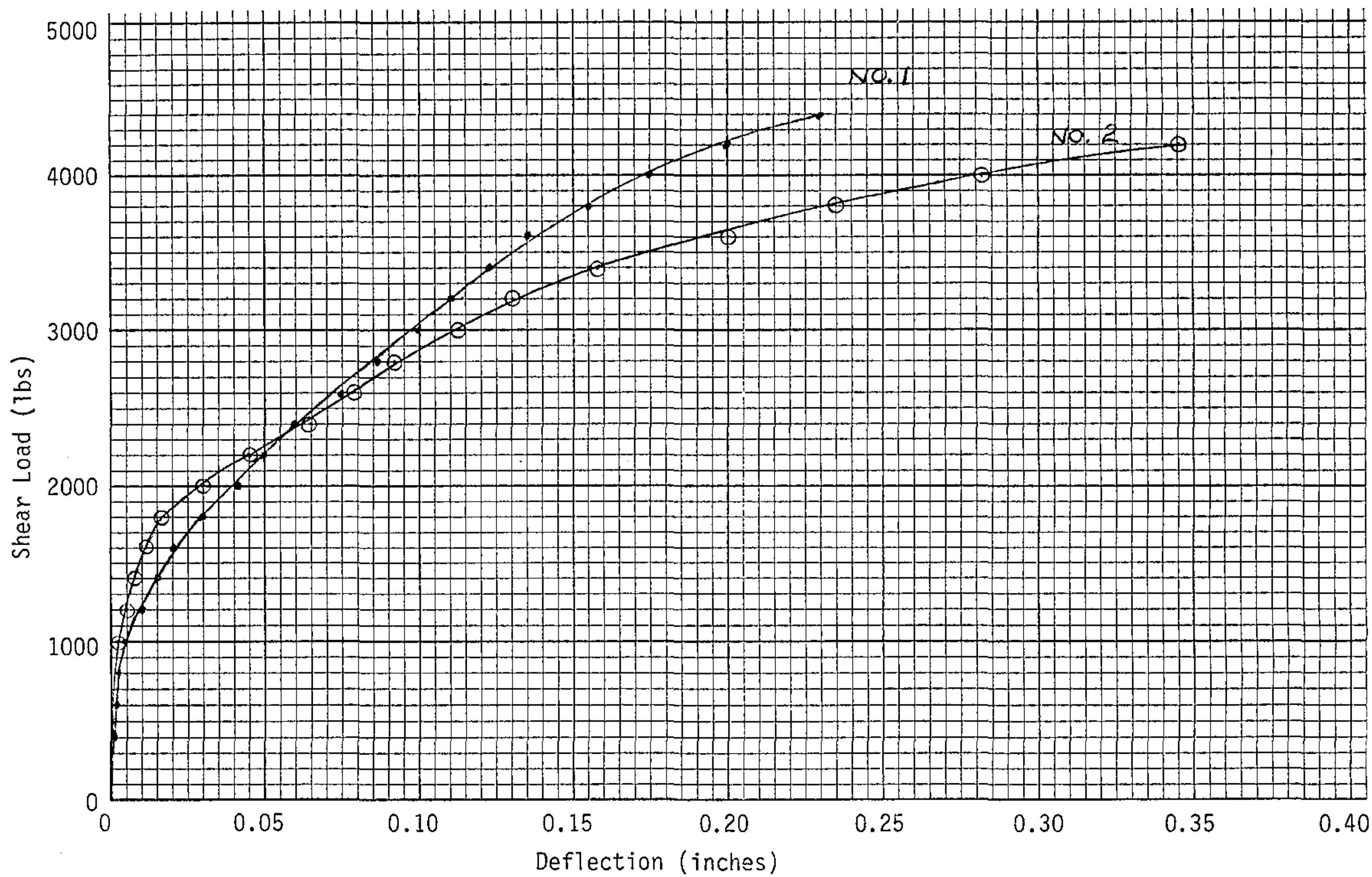


Fig. 4-15. Load Versus Deflection for Foundation Shear Test Specimens.

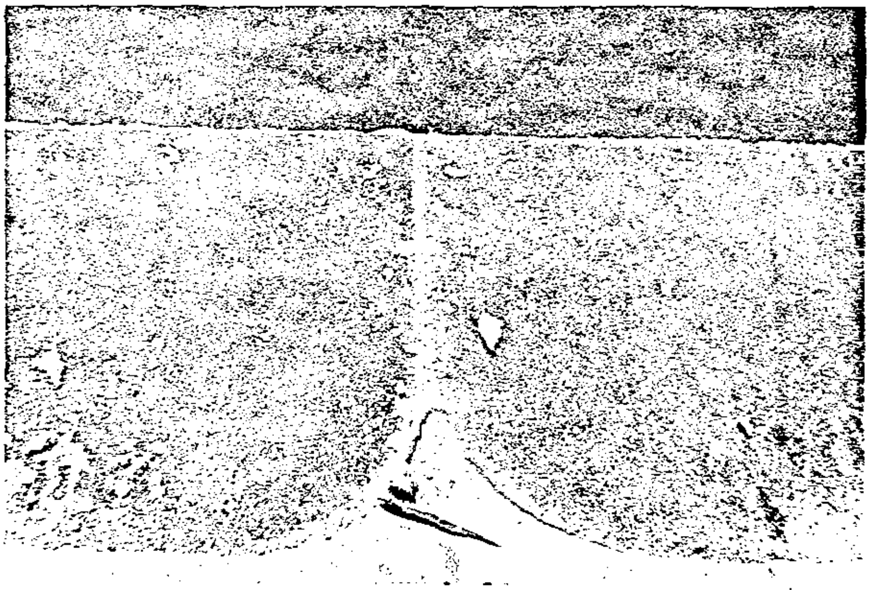


Fig. 4-16. Photograph of Shear Failure at Concrete/Foam Interface.

Section 5
CONCLUSIONS/APPLICATION POTENTIAL

From studying the test data, obviously the injection of foam does indeed enhance the structural characteristics of otherwise weak structural systems. The question that remains is how this technique can be applied to "real world" situations and in particular to improving the earthquake resistance of buildings. To answer this question it is convenient to look at several hypothetical cases where the technology developed in this study could be applied. Since these are hypothetical cases, many details will be neglected and the main focus will be on methods and materials.

ROOFS AND CEILINGS

For example, consider the 50 x 100 ft flat roof post and beam building shown in Fig. 5-1. This type of construction is common throughout the country and in California before the 1950's. This building could have timber, masonry, or concrete walls and is most likely designed with no consideration for seismic forces. If masonry walls are assumed, under current building codes* these walls and ceiling would induce a shear force of about 400 lbs/ft in a high seismic risk zone. The end shear walls would have to resist 20,000 lbs each and the equivalent seismic load would be a 400 lbs/ft uniform load acting on the roof as shown in Fig. 5-1.

To provide this shear capacity, it would be necessary to create a roof diaphragm to transfer the intertia forces to the end walls. If the bottom side of the roof is not finished as in Fig. 5-2, then the required structural diaphragm could easily be formed by nailing gypsum wallboard

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*1976 Uniform Building Code

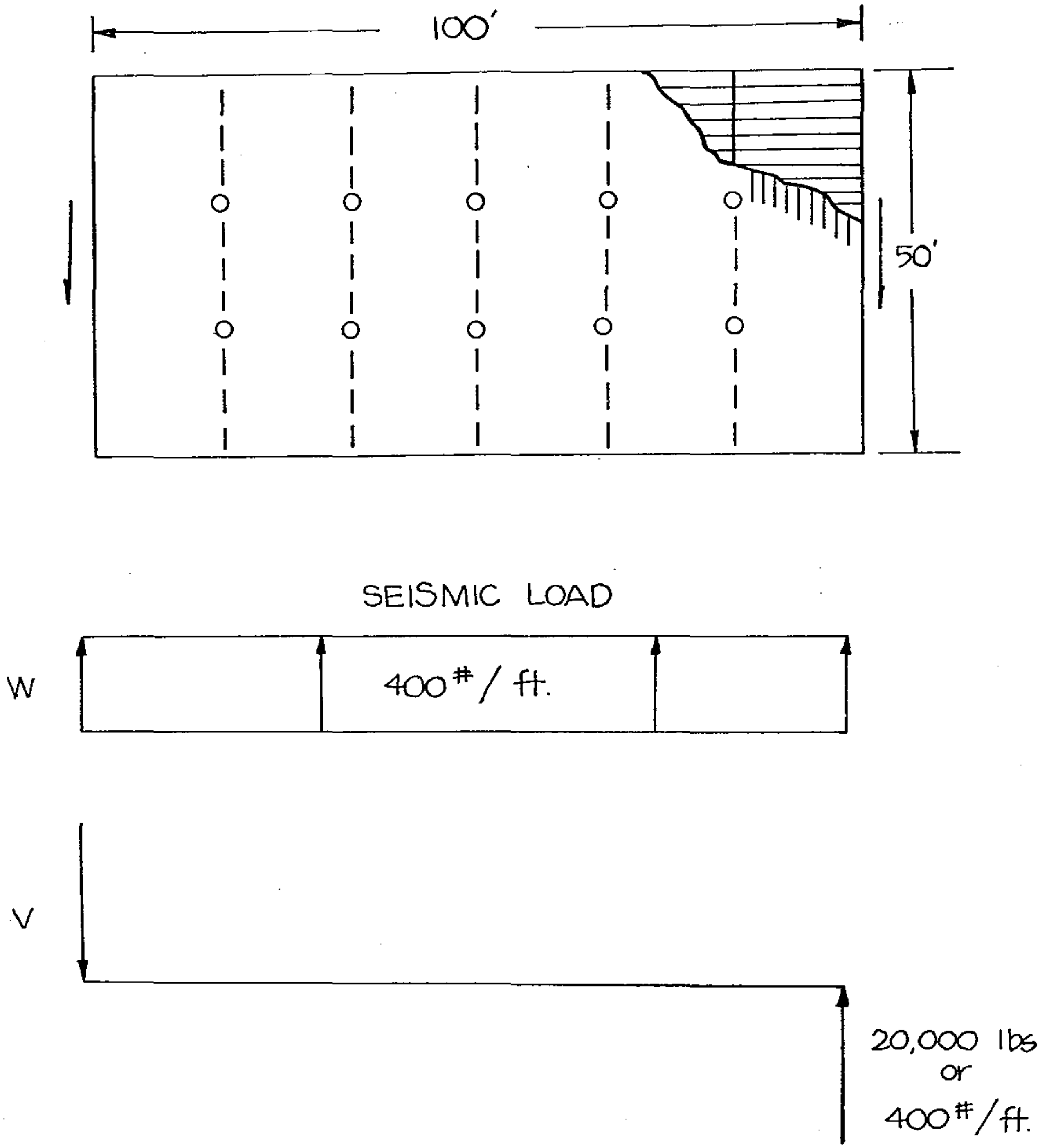


Fig. 5-1. Roof System (Flat Roof): 2 x 8 Joists at 16 in. on Centers, Live Load 20 psf; 1 x 8 Shiplap Sheathing, Dead Load 15 psf; Tar and Gravel Roof; Post and Beam Construction.

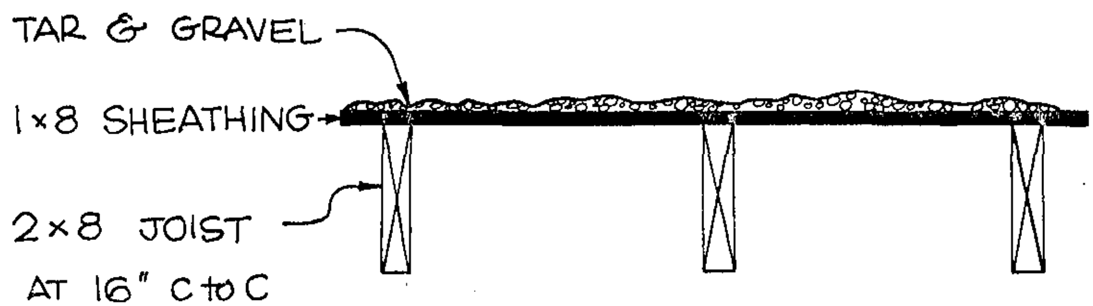


Fig. 5-2. Typical Roof Section.

(sheetrock) across the bottom of the joists and placing foam in the void (Fig. 5-3). For this type of installation, foam injections equal to 90% of volume between the 1 x 8 shiplap and sheetrock would be used, providing a structural diaphragm similar to the Floor No. 4 test specimen reported in Section 3. From Fig. 3-31, the ultimate enhancement is 1,650 lbs/ft. Using a conservative factor of safety of 3, the allowable shear for this system would be 550 lbs/ft due to the enhancement alone. The added weight of this installation would be about 3 psf or 10% of the design dead load. This additional dead load, however, is more than compensated for by the 35% increase in flexural stiffness (Fig. 3-32). An additional important benefit would be the improved thermal insulation properties of this roof system.

Another common roofing system in the southwest is the heavy clay tile shown in Fig. 5-4. The clay tile is attached to 1 x 8 shiplap sheathing supported by trusses which have practically no seismic capacity designed into it. The approach in this case would be to carry roof induced shears through a roof diaphragm to the end shear walls and other seismic loads through a ceiling diaphragm to the end shear walls. For masonry walls and this heavy roof, a total of 500 lbs/ft shear from the roof and ceiling diaphragms would be required.

To generate a roof diaphragm the same technique in the previous example could be used. Sheetrock would be nailed to the bottom of the rafters and foam (90% by volume) injected into the cavity (Fig. 5-5). This installation would be similar to Floors No. 1, 2, and 3 of this report. Fig. 3-29 shows an ultimate shear enhancement of 1,200 lbs/ft, or an allowable shear of 400 lbs/ft for a safety factor of 3. To obtain a ceiling shear diaphragm foam could be placed in the ceiling void between joists. Fig. 3-16 indicates foamed ceilings would enhance the allowable shear capacity 380 lbs/ft if filled. Since only 100 lbs/ft is needed, only 50% of the amount of foam would provide a ceiling shear capacity of 190 lbs/ft for a total of 590 lbs/ft for this system. Examining Fig. 5-1, note the shear force on the diaphragm decreases away from the end walls. Therefore it would be necessary to only place the foam for a few feet away from the

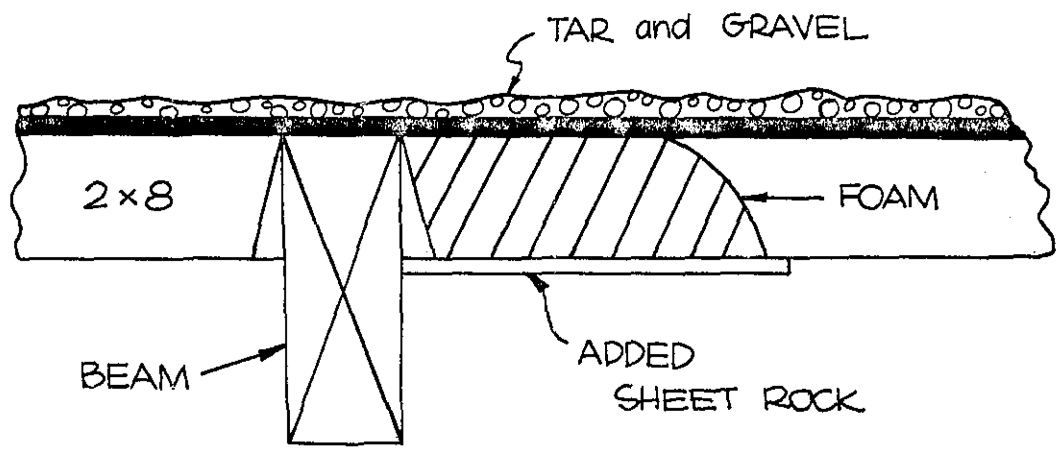


Fig. 5-3. Foaming of Roof System.

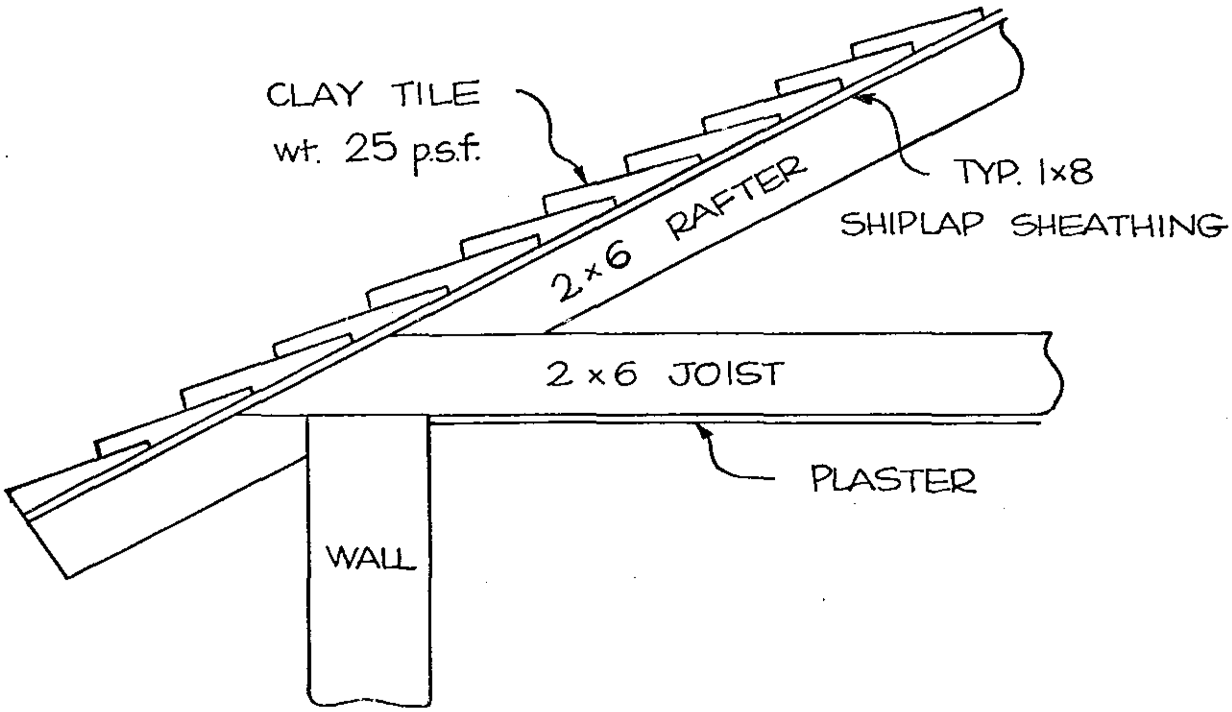


Fig. 5-4. Heavy Clay Tile Roof.

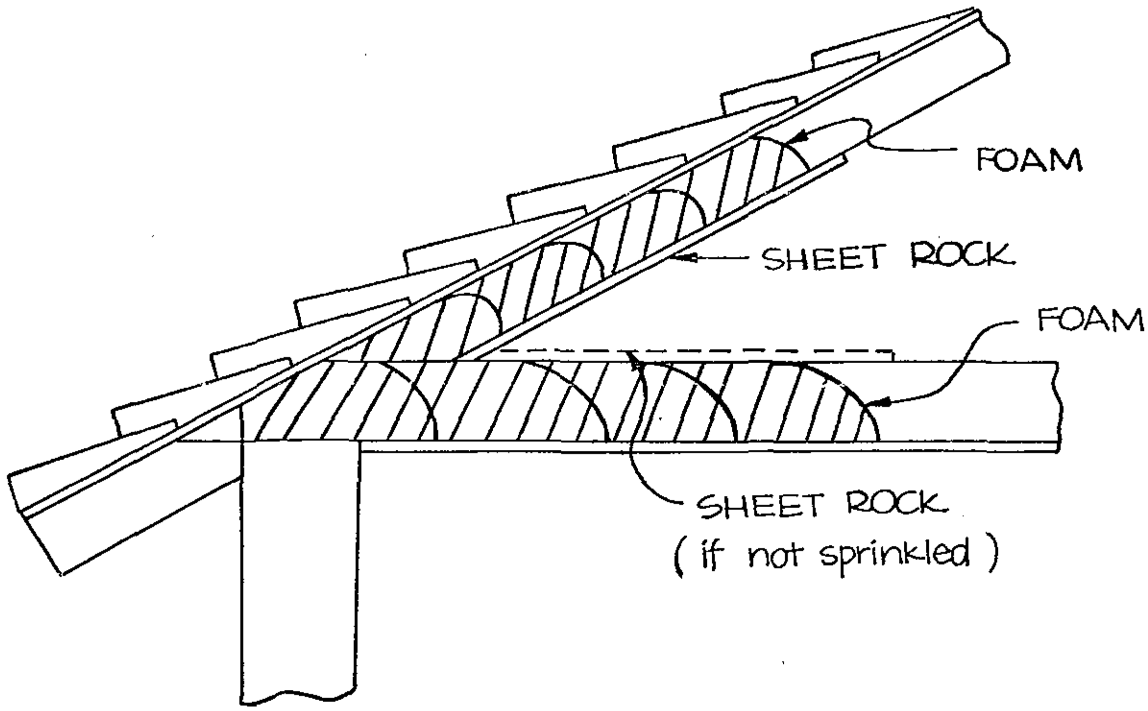


Fig. 5-5. Foaming of Clay Tile Roof System.

shear walls for the most efficient use of this technique. Once again, the added dead load is not detrimental to the structure due to the increased bending stiffness provided.

FLOOR SYSTEMS

Consider a two story post and beam building similar in construction to the one in Fig. 5-1. For masonry walls, assume the seismic shear at the second floor at 600 lbs/ft and the floor joists to be 2 x 12 lumber spaced at 16 inches on center. The test results for floors with 2 x 6 framing and 2 x 8 framing can be extrapolated for this example. For 2 x 6 frame floors the ultimate enhancement is 1,200 lbs/ft and for 2 x 8 frame floors is 1,625 lbs/ft. The ratio of the depth of a 2 x 6 to a 2 x 8 is 0.76 and the ratio of the corresponding ultimate enhancement is 0.75 -- nearly the same. Extrapolating these values, it would be expected that a 2 x 12 frame floor with 90% foam volume would have an ultimate shear enhancement of about 2,400 lbs/ft. This provides an allowable design shear value of 800 lbs/ft which is well above the 600 lbs/ft desired.

Another situation requiring shear enhancement could occur at the first floor over a crawl space or basement. The technique for solving this problem would be identical to the installation for the flat roof shown in Figs. 5-2 and 5-3 and discussed previously.

WALLS

If the example building in Fig. 5-1 had stucco and wood walls instead of masonry, the required seismic shear capacity would drop due to the lower inertia forces to about 10,000 lbs per end shear wall of 200 lbs/ft. For this type of structure, the wall could be 16 feet high and constructed using 2 x 6 studs spaced at 16 inches on center with sheathing on the exterior face. The shear enhancement for a 2 x 6 frame wall can be extrapolated from the 2 x 4 frame wall tests (Walls Nos. 1 and 2) in the same manner as in the floor example. The depth ratio of a 2 x 4 to a 2 x 6 is 64% indicating a shear enhancement of 1.56 times 1,150 lbs/ft (from Fig. 3-26) or 1,800 lbs/ft. Again using a safety factor of 3, the allowable shear value is 600 lbs/ft which is much greater than 200 lbs/ft desired. Thus if there were windows or doors along one portion of the wall, this foam technique could be applied to only 20 feet of wall providing a shear wall of 12,000 lbs capacity and for the heavy tile gabled roof of Fig. 5-5, a shear wall of only 25 ft would be more than adequate, see Fig. 5-6.

CONNECTIONS

Enhancing just the basic structural elements of a building is not sufficient in making it earthquake safe. Attention must also be given to the problem of transferring these seismic shear forces through the roof, wall, and floor connections to the foundation. A technique was developed and tested during this study which would dramatically increase the shear strength of connections to concrete foundations. As shown in Fig. 5-7, a section of sheetrock could be placed from the floor joists to a foundation wall and foam injected into the cavity. (Of course materials other than sheetrock could be used as shown in the alternative model in Fig. 5-7). Foundation shear tests were conducted in the supplemental test program and the results are presented in Fig. 4-15. An average ultimate shear value of 1,900 lbs/ft^2 was obtained using this method. Applying a safety factor of 3, the allowable shear capacity would be 630 lbs/ft. If the structure required a seismic shear capacity of 600 lbs/ft then the sheetrock (or

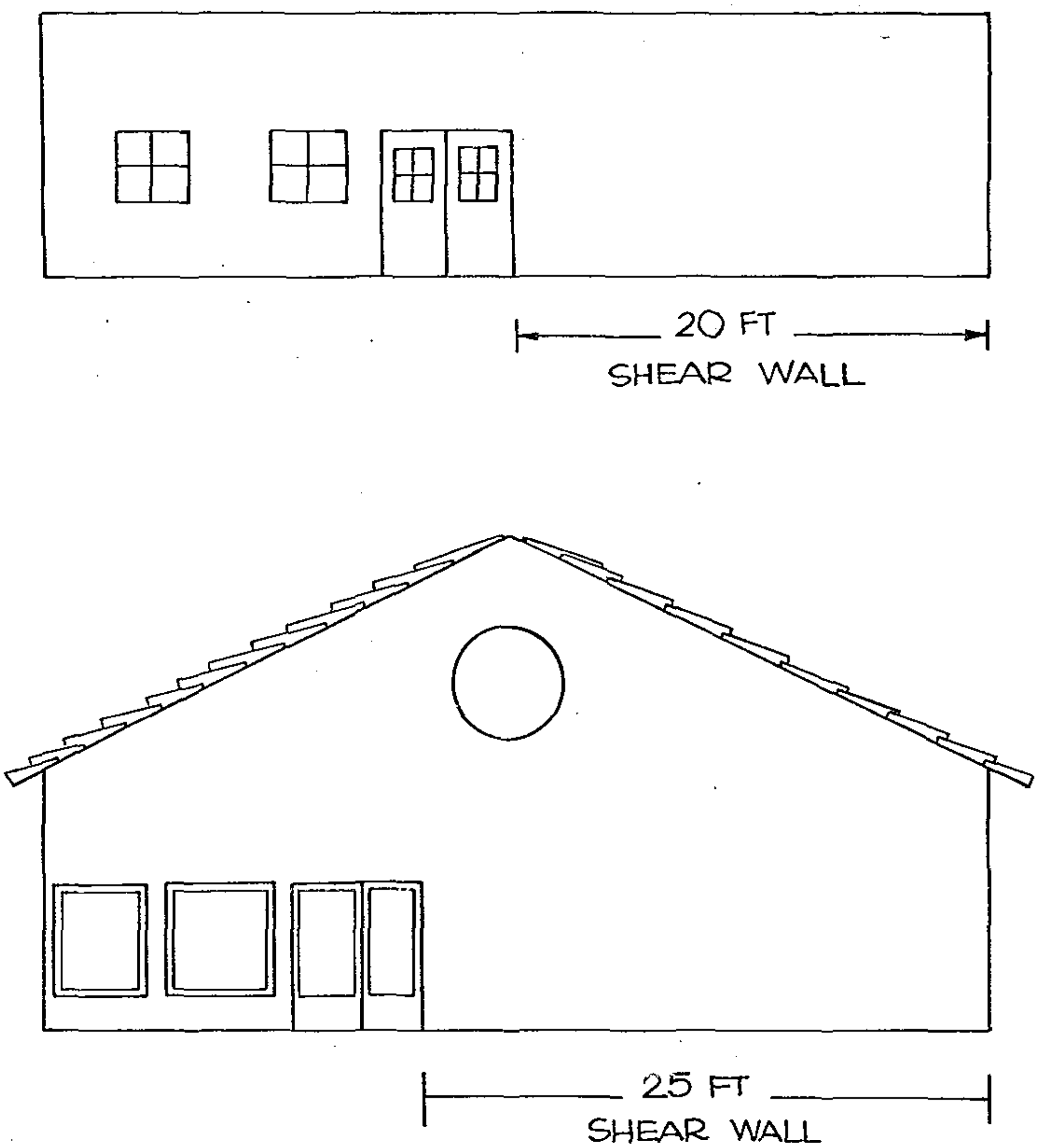


Fig. 5-6. Shear Wall Requirements.

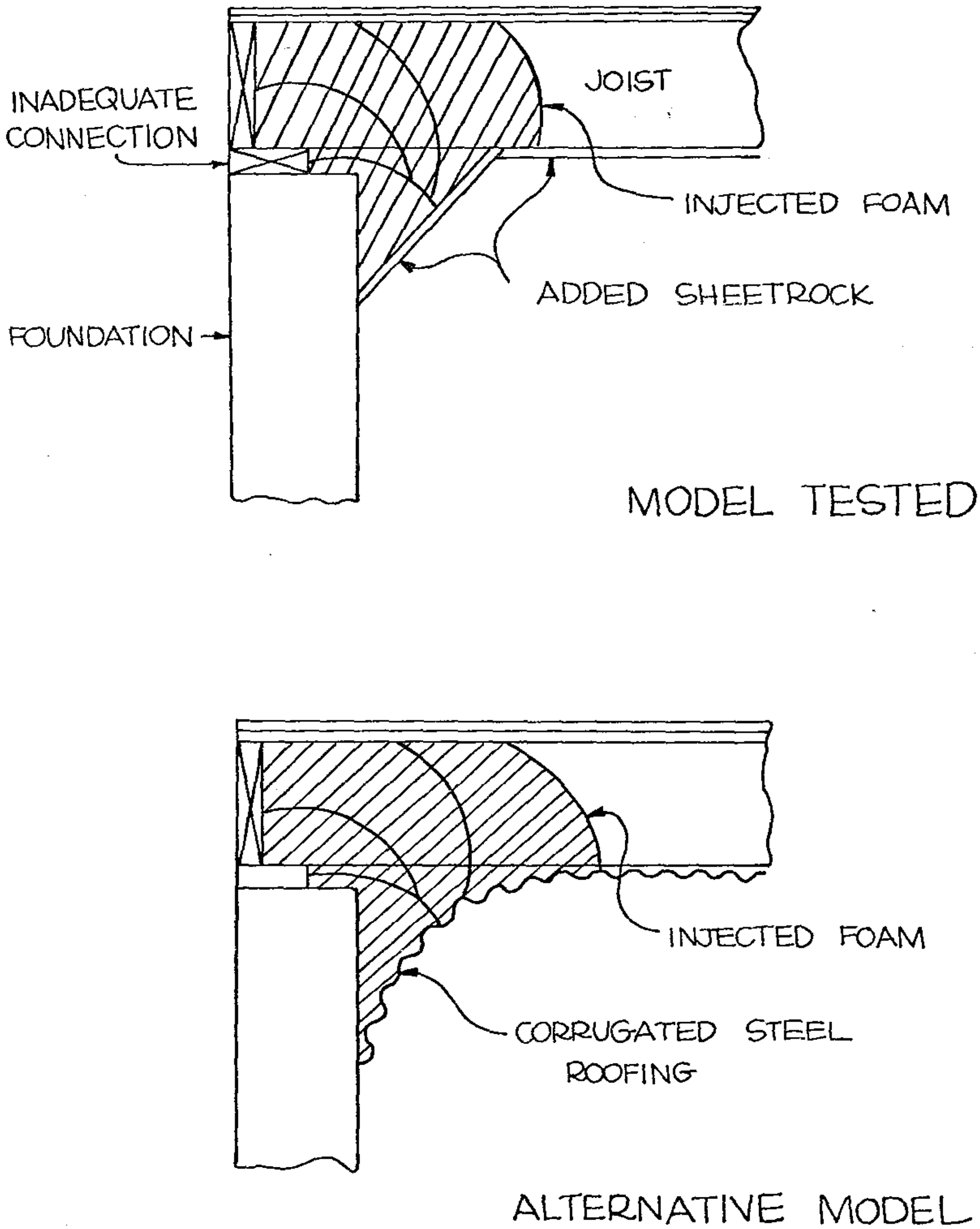


Fig. 5-7. Floor-to-Foundation Connections.

corrugated roofing) would be placed 12" below the top of the foundation providing a connection strength of 630 lbs/ft.

Another area requiring enhancement is a ceiling or second floor connection to a masonry wall. A shear test of foam to masonry was not conducted in this program, but the results would be similar to that for foam to concrete. By injecting the foam between joists as shown in Fig. 5-8, and using an allowable design shear value of 630 lbs/ft^2, this connection would provide 600 lbs/ft for a 2 x 12 size joist of 390 lbs/ft for a 2 x 8 joist. This would provide the structural strength and continuity required for the enhanced roofs, floors, and walls developed previously.

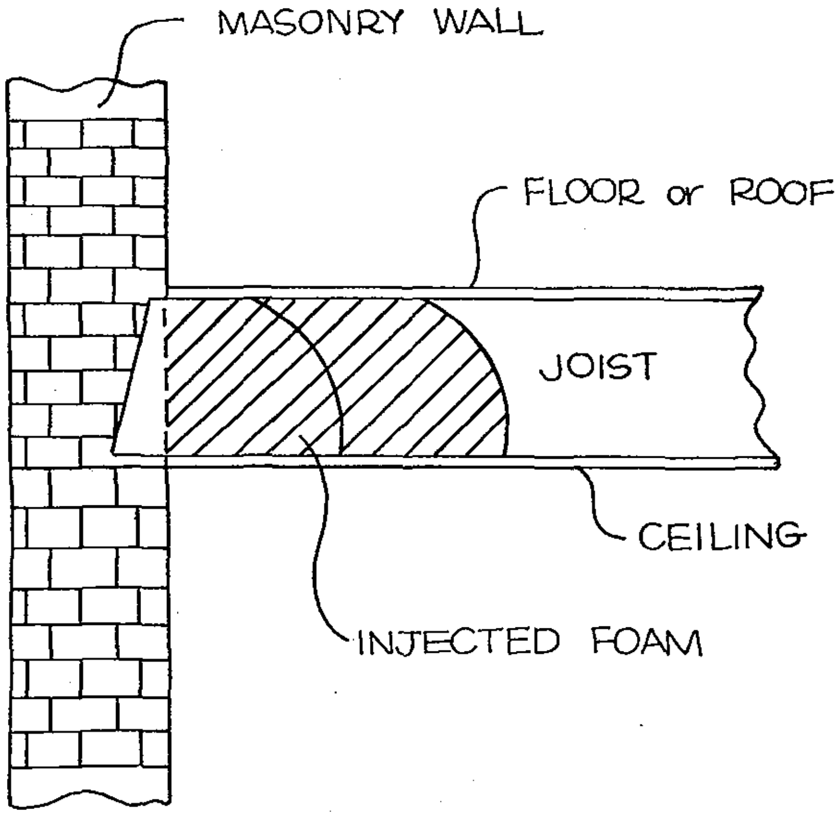


Fig. 5-8. Joist-to-Masonry Connection.

NEW CONSTRUCTION

In this report little has been said about new construction as such, but most of the techniques described here could be applied to new construction as well. For example, when building a residence or apartment, sheetrock is often applied horizontally, making it an easy matter to foam walls in lifts up to the four foot height prior to applying the second piece of sheetrock and then foaming the remaining half through holes. During construction there would be no problems with the volume required or unknown obstructions. Further, the patching of holes after the foam is injected would be far easier during this period since the standard taping procedure could be used to cover the holes. Shear diaphragms could also be easily developed in the attached or the second story. For example, in an attic it would be as easy to place foam as it is to blow in loose insulation and the additional cost would be only the difference in the cost of materials since the labor is similar.

From the laboratory work it also appears that the thickness requirements of flooring can be reduced when there is foam supplying additional support. For example, if 3/4 inch plywood is currently required to meet the deflection and load criteria for a floor, it could be replaced by using 1/2 or 5/8 inch thick sheetrock covered with 3/8 inch particle board. Foam would be placed between the joists supporting the sheetrock and particle board laminate thus preventing any puncture from concentrated loads and providing the shear diaphragm strength required.

COSTS

At this point in the program it is not possible to estimate the costs for rehabilitation of structures. It is possible, however, to indicate material costs and make some comparisons between currently used insulation and foam. Currently the Class 1 fire rated foam (that has a flame spread rating of 25 ASTM Standard E84) costs about 82¢/lb in large quantities. Thus an attic with 3 inches of foam insulation which would have an insulation value of R-21 would cost about 41¢/ft^2 for materials as compared to typical cost of blown-in insulation for an R-19 of about 30¢/ft^2. The blown-in insulation, however, offers no structural strength whereas 3 inches of foam would deliver as much as 1,000 lb/ft ultimate shear capacity in addition to providing insulation in excess of R-19.

CONCLUSION

The primary conclusion from this study is that the insulation of foam does significantly increase the structural strength of buildings. From an energy standpoint, the test results showed an increased elastic range and a very ductile behavior before failure and the energy absorbed by the foamed panels was roughly 10 times that of the base case (unfoamed) panels. The test results are more dramatic if the composite behavior is considered. For example, for Floor No. 4 the ultimate enhancement was 11,000 lbs, but the total ultimate load was 21,000 lbs or 190% more than the enhancement alone.

Further work is required, however, before this process will be fully accepted by the users -- i.e., contractors, local building departments, state officials, lenders, etc. This additional work would include the development of a users manual which will present application techniques, design procedures and calculations, and discuss other details such as torsion and compression connections.

Another area requiring more investigation is the improvement of development of nozzles for increasing the efficiency of foam placement. With improved nozzles, the injection of foam into confined spaces could approach 100% by volume providing more surface contact and significantly increased strength.

Some effort has been devoted to assessing the possibility of obtaining venture capital when the process is fully developed. However, since this is a construction process, it not only has to be acceptable to a contractor, it also has to be acceptable to the building department of the local community, state officials, lenders, etc. Those who were approached felt it was premature to invest their time and capital in such a project at this stage, but were very interested in the long range prospects. It is believed that once the process leaves the laboratory and is used in a prototype full-scale field application which has approval of the local building officials, then people associated with the construction industry will be willing to invest in this process.

APPENDIX A

TEST DATA (PRIMARY TEST PROGRAM)

Appendix A

TEST DATA (PRIMARY TEST PROGRAM)

INTRODUCTION

The test data for each structural type is presented in the following order:

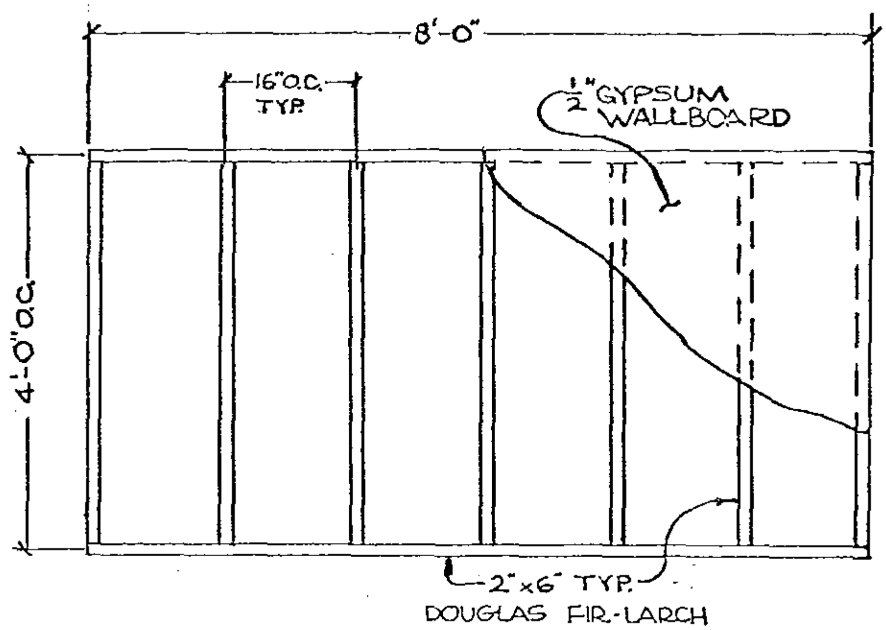
- o Ceilings
- o Walls
- o Floors

In each section, the structural test specimens are described starting with the base case (non-foamed) specimens. The construction for each specimen is described followed by the test procedure, resulting data and cause of failure. The test results have been summarized and are discussed in the text of this report. The equipment used in performing these tests is described in Appendix C.

CEILING TEST DATA

CEILING - BASE CASE

Description



The above frame was constructed with Douglas Fir-Larch (Select Structural) using the nailing schedule shown in the text.

Test Procedure

The base case was placed in the horizontal shear test frame (Fig. A-1) and loaded slowly to failure. The load and deflection were monitored continuously on an x-y plotter. Fig. A-2 shows the load versus deflection graph obtained.

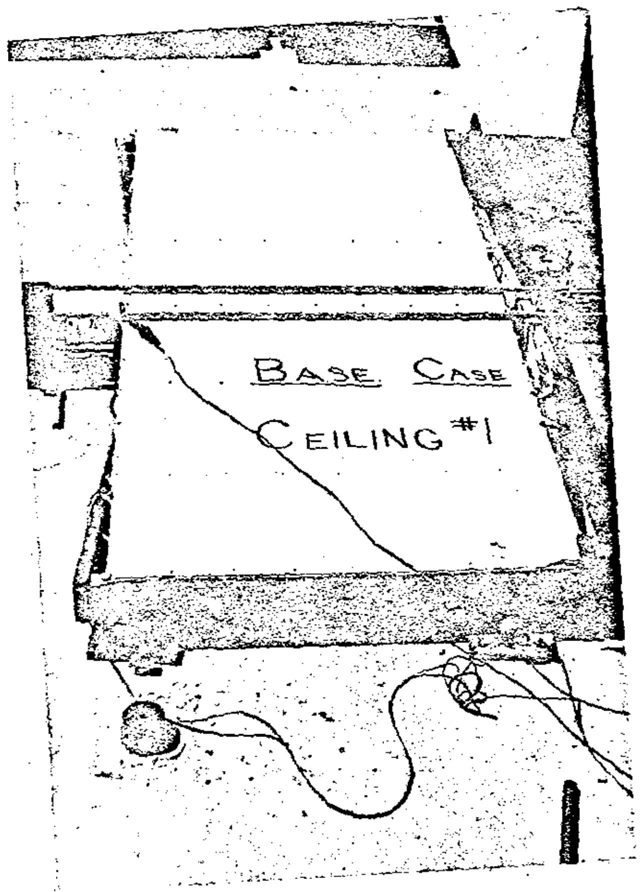


Fig. A-1. Base Case Ceiling in Horizontal Shear Test.

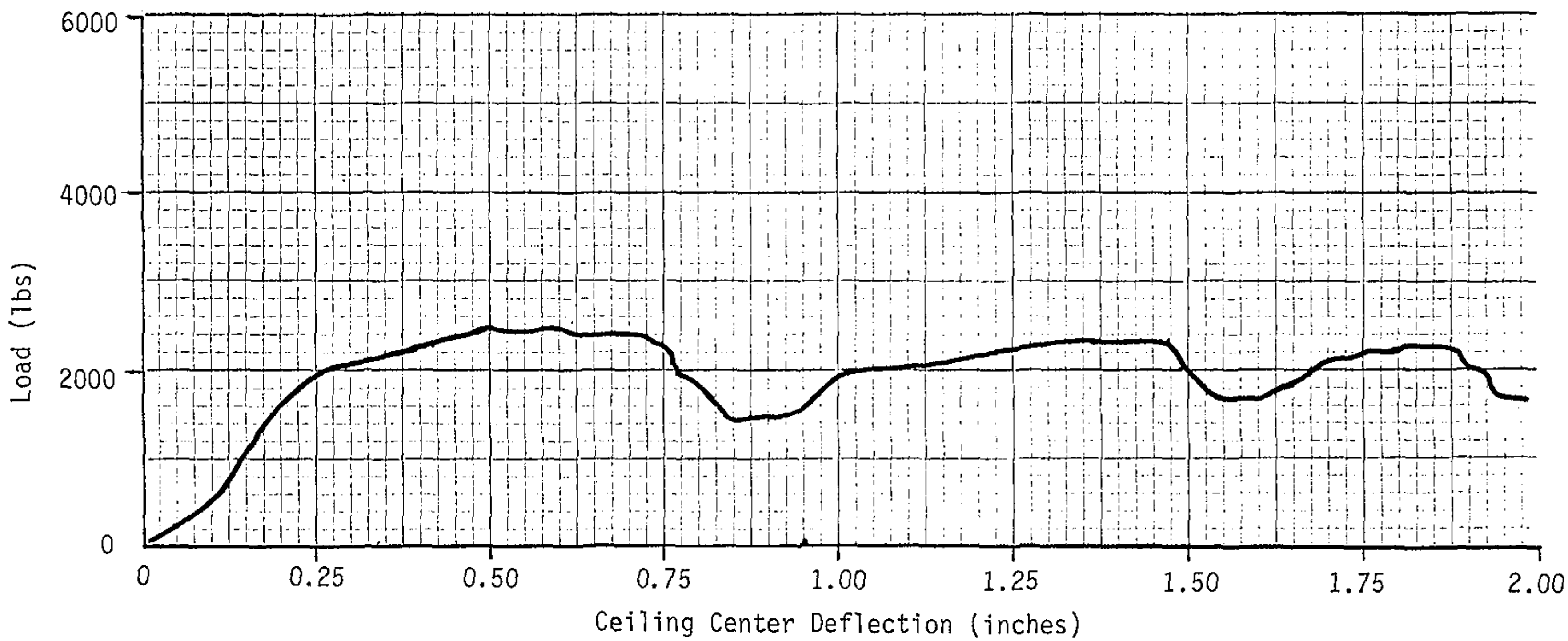


Fig. A-2. Base Case Ceiling, Load versus Deflection Graph.

Test Data

As shown on the graph, the maximum load resisted was 2,230 lbs. The elastic range extends to only about 1,000 lbs when the nails along the perimeter of the gypsum wallboard start tearing out. The elastic stiffness for the ceiling in this test configuration is about 6,500 lbs/in.

Failure

Initially the nails in the center portion tore through the sheetrock. As the load increased, the tearing extended towards the supports (Fig. A-3). Tearing also occurred on the top and bottom corners of the left side. At no time did cracks appear in the gypsum wallboard (sheetrock). Bending failure started in the center span of the longitudinal beams at about 0.75 inches of deflection (2,200 lbs).

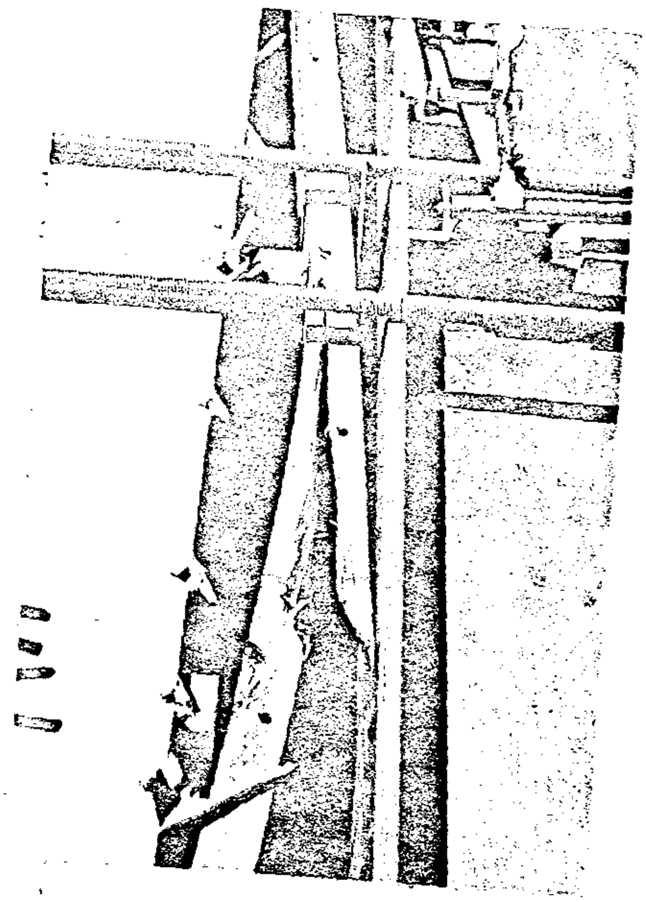
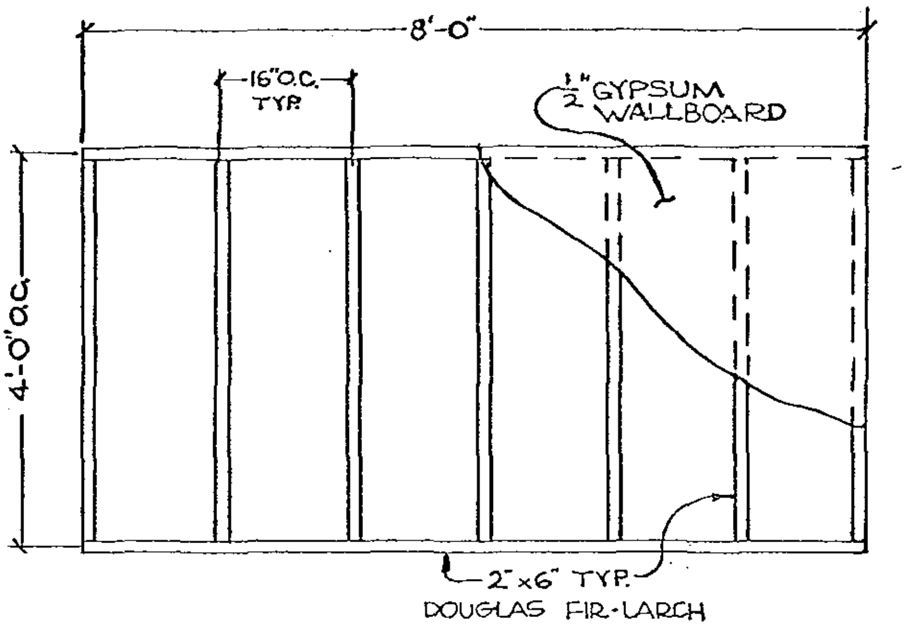


Fig. A-3. Base Case Ceiling Failure.

CEILING NO. 1

Description



Ceiling No. 1 was constructed similar to the base case. The urethane foam was placed in Phase 1 using a straight nozzle back and forth between the ceiling joists in several lifts.

Test Procedure

Ceiling No. 1 was placed in the horizontal shear test (Fig. A-4) and loaded slowly to failure. The deflection at the center of the ceiling was monitored with the load producing the load-deflection graph in Fig. A-5.

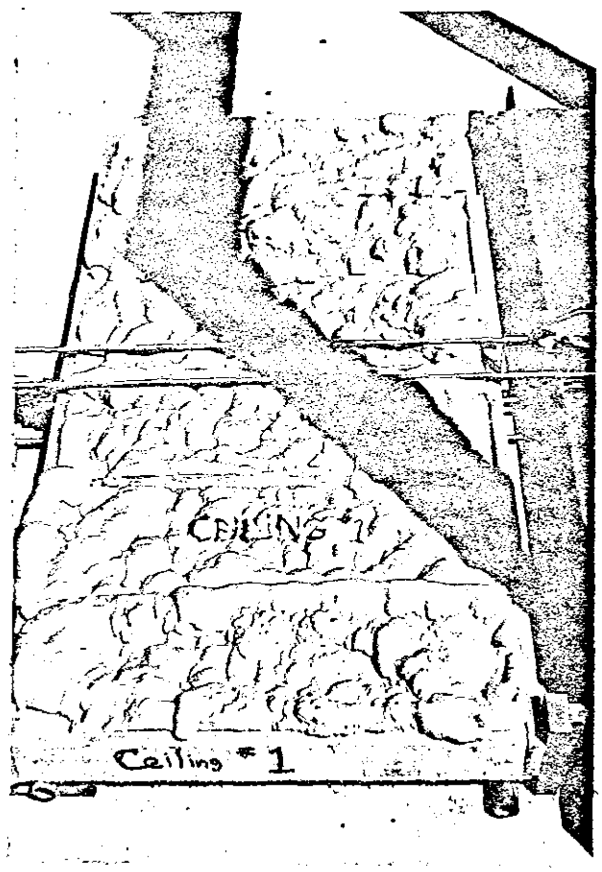


Fig. A-4. Ceiling No. 1 in Horizontal Shear Test.

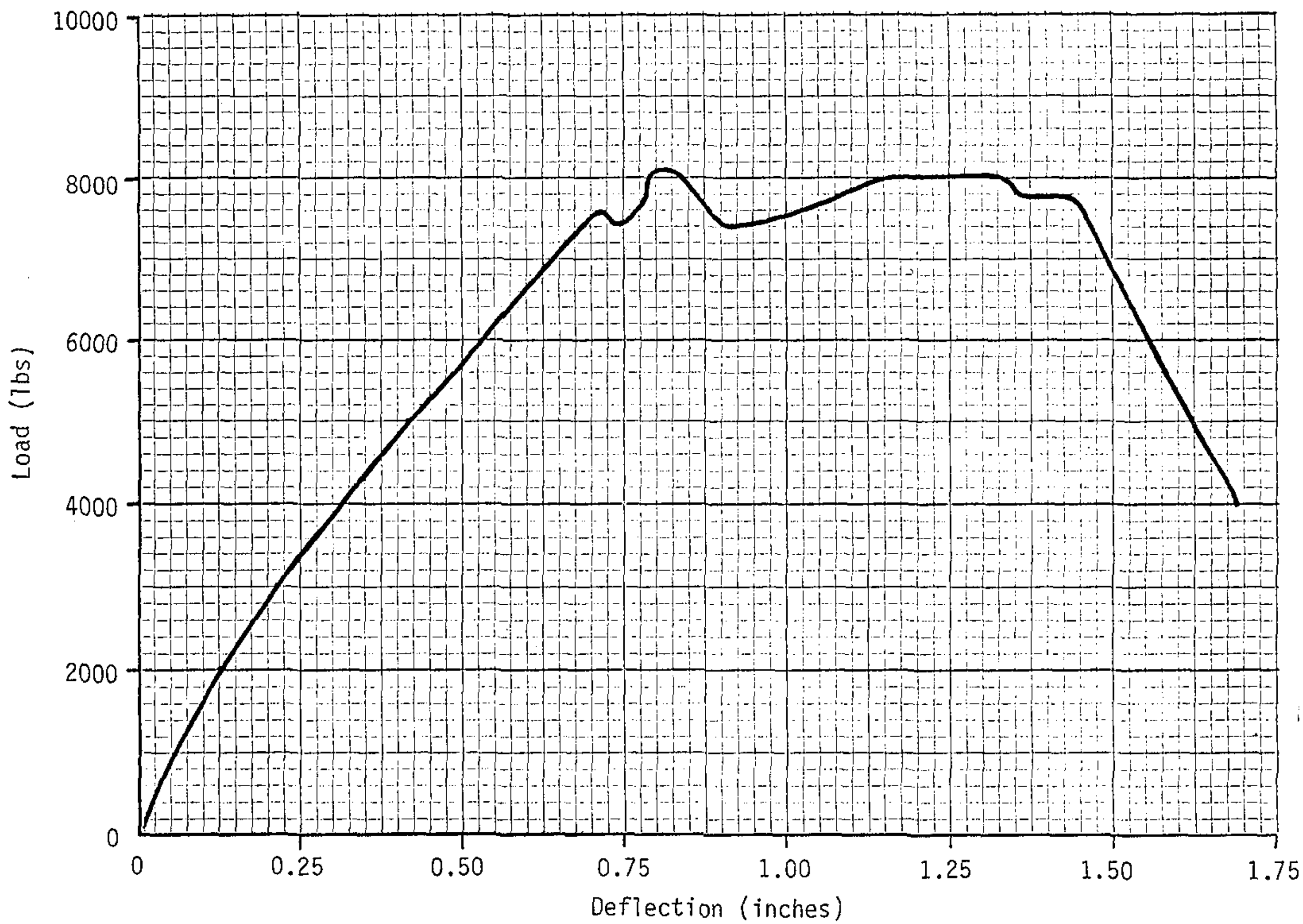


Fig. A-5. Ceiling Number 1, Load versus Deflection Graph.

Test Data

The ceiling behaved elastically to about 7,700 lbs exhibiting a stiffness of 11,200 lbs/in. The maximum load on the ceiling was 8,100 lbs. This load did not significantly diminish until the ceiling had deflected more than 1.4 inches at its center.

Failure

The ceiling failed when the foam separated from the center joists and along the bond interface to the sheetrock. Separation also occurred along the base perimeter member simultaneously and sounded like a loud crack. Fig. A-6 shows the diagonal tensile failure at the end cells. Sections cut through the center portion show the foam separation from the sheetrock (Figs. A-7 and A-8) and from the perimeter cord (Fig. A-9).

Fig. A-6. Ceiling No. 1 Tensile Cracks in End Cell.

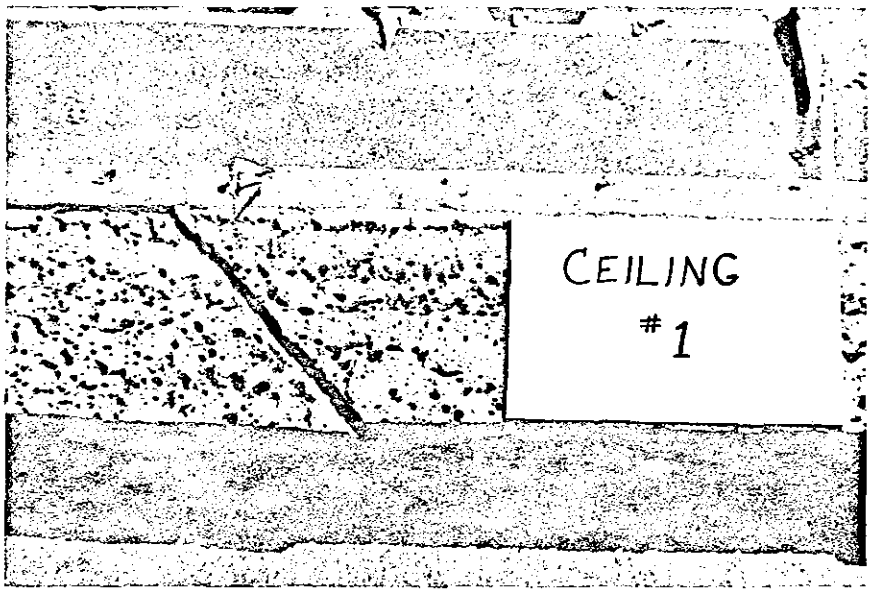


Fig. A-7. Ceiling No. 1 Foam Separation from Gypsum Wallboard.

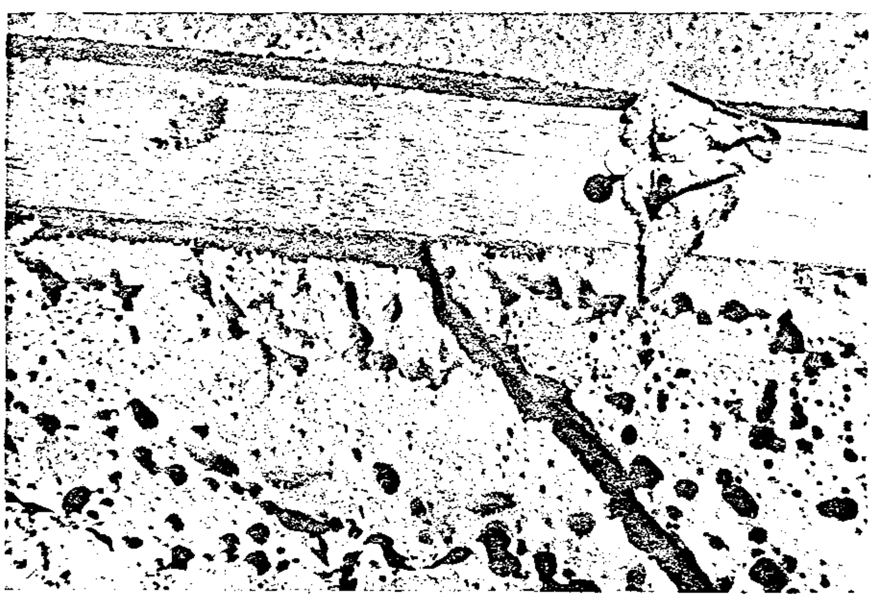
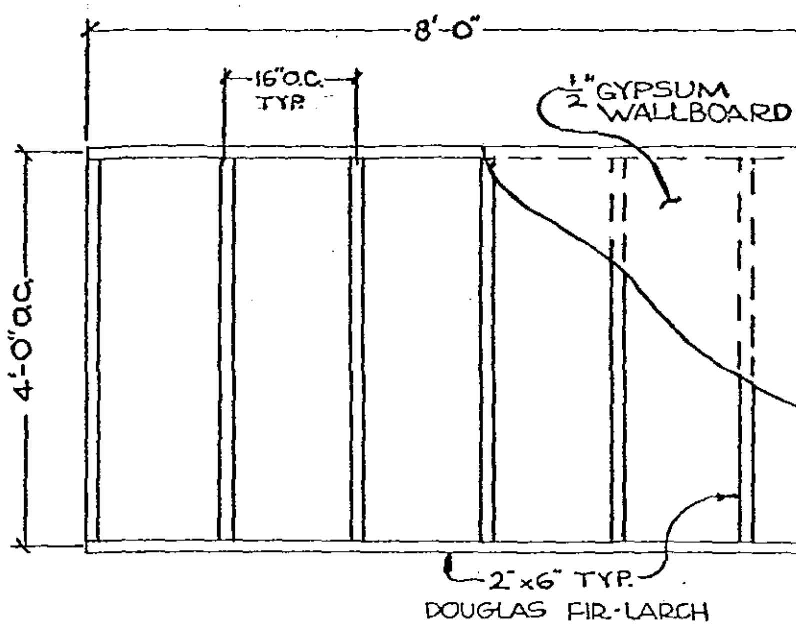


Fig. A-8. Closeup of Ceiling No. 1 Failure.

Fig. A-9. Separation of Foam Along Outer Cord Member of Ceiling No. 1.

CEILING NO. 2

Description



This ceiling was constructed in a similar manner to the base case. The foam was placed in phase 1 using a spreader nozzle and poured in two lifts per cell.

Test Procedure

The ceiling was subjected to the horizontal shear test (Fig. A-10) increasing the load until failure occurred.

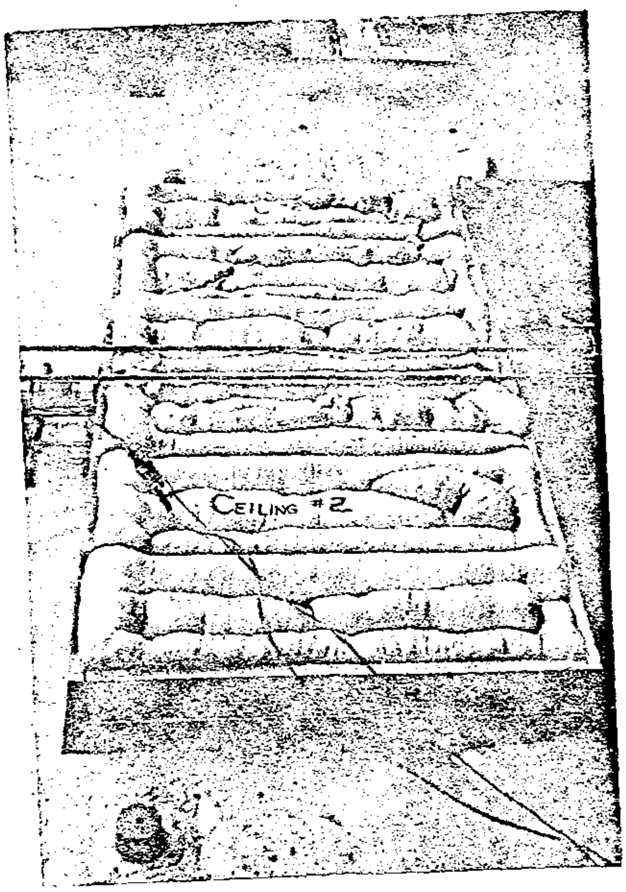


Fig. A-10. Ceiling Number 2 in Horizontal Shear Test Configuration.

Test Data

The load deflection curve is shown in Fig. A-11. The deflection was linear with respect to load to about 7,000 lbs. There was no definitive yield point as in Ceiling No. 1. Instead, the specimen slowly yielded until the load reached 11,700 lbs maximum.

Failure

Failure was preceded by a crackling sound followed by several loud cracks. Fig. A-12 shows the test panel after failure. The test panel failed in shear started by a crack between the center joist and the foam on both sides (Fig. A-13). The crack propagated to the perimeter member, and towards the corner where a diagonal crack appeared (Figs. A-14 and A-15). A section cut through a center cell shows the foam had separated from the gypsum wallboard (Fig. A-16).

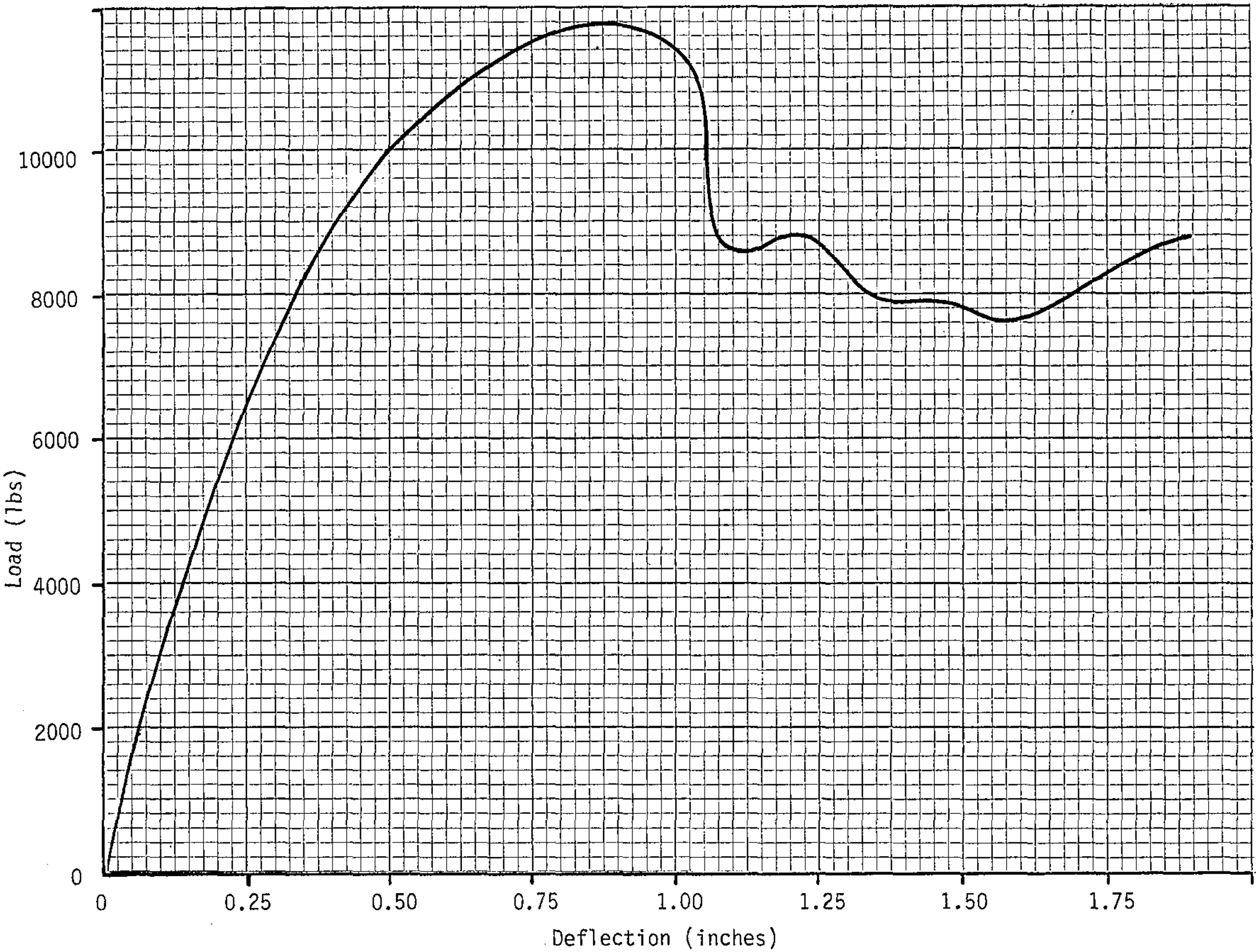


Fig. A-11. Ceiling Number 2 Load versus Deflection Graph.

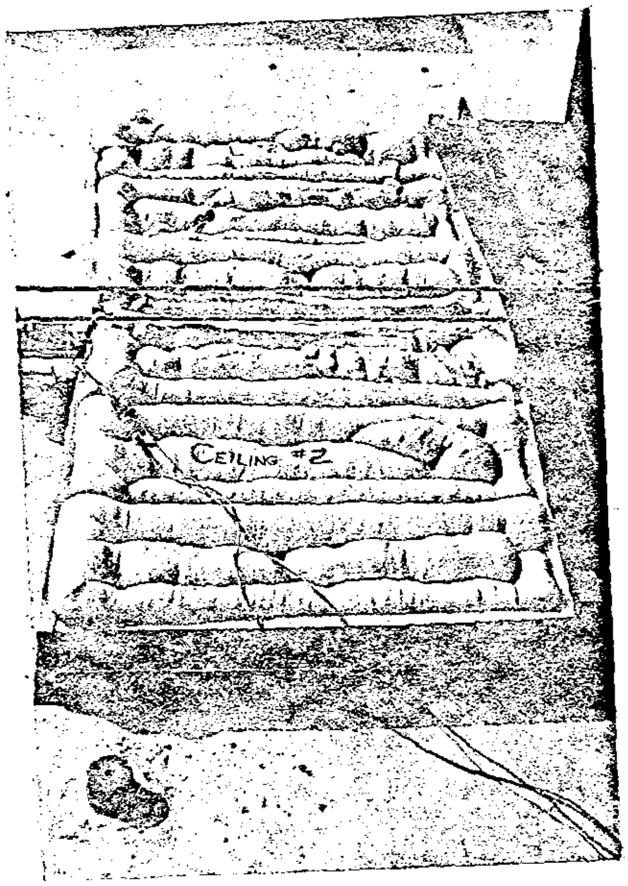


Fig. A-12. Ceiling Number 2 After Failure.

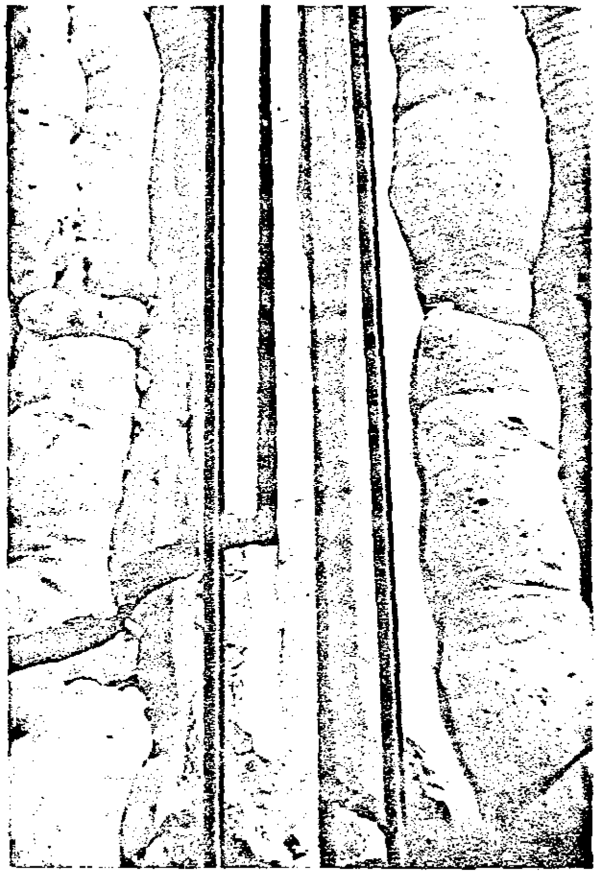


Fig. A-13. Failure Along Center Joist of Ceiling Number 2.

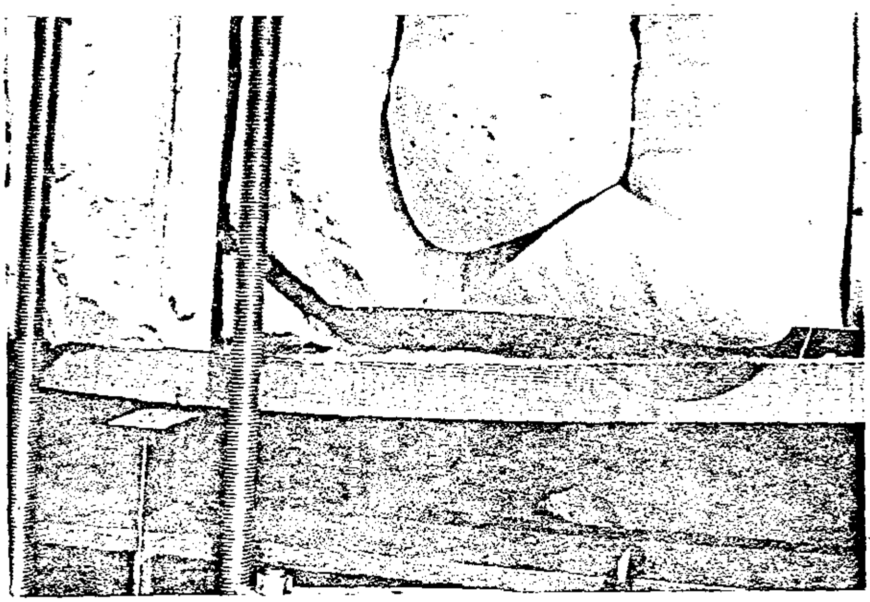


Fig. A-14. Crack Propagation to Perimeter Member in Ceiling Number 2.

Fig. A-15. Diagonal Crack Across End Cell of Ceiling Number 2.

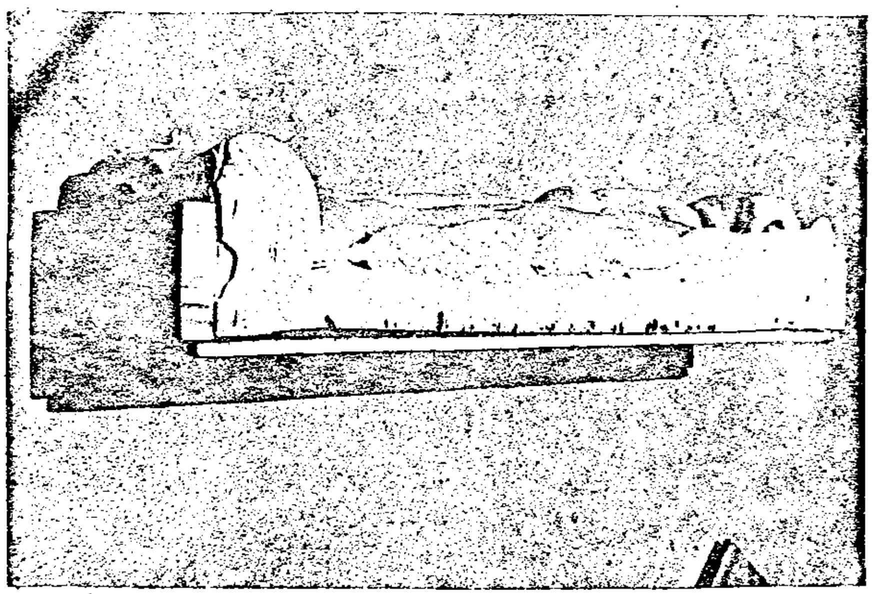
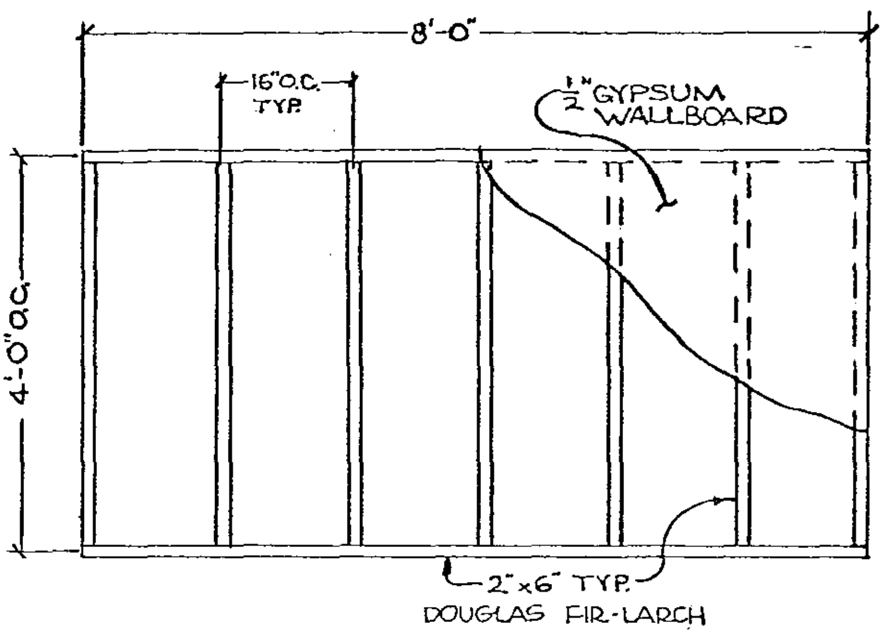


Fig. A-16. Cut Section Showing Separation of Foam from Wallboard in Ceiling Number 2.

CEILING NO. 3

Description



Ceiling No. 3 was constructed in the same manner as the base case ceiling. Foam was placed using the method developed in phase 3 of foam installation. This consisted of nailing a 16-inch wide by 8-foot long piece of gypsum wallboard to the top of joists on one side. Foam was then injected into the cavity created as shown in Fig. A-17. After the six cavities were filled, another piece of wallboard was nailed adjacent to the first. For the third and last section, holes were drilled through the wallboard at the center of each cell and filled with foam to about 90% of the total volume.

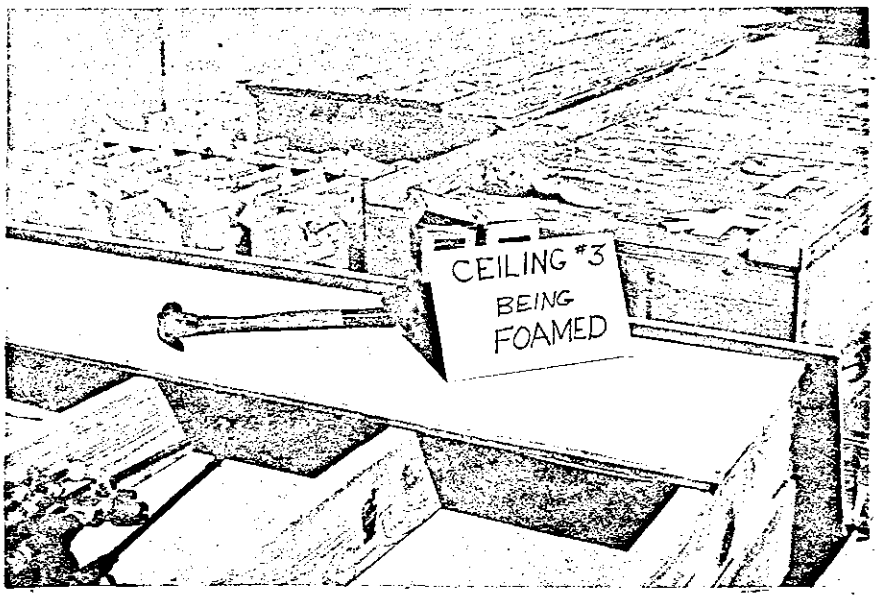


Fig. A-17. Placement of Foam for Ceiling Number 3.

Test Procedure

This ceiling was subjected to the horizontal shear test (Fig. A-18). The ceiling was tested by increasing the load until significant failure occurred.

Test Data

Ceiling No. 3 exhibited plastic behavior at 11,600 lbs for a distance of one-half inch until failure occurred (Fig. A-19). Ceiling No. 3 was also linearly elastic to about 7,000 lbs as were Ceilings Nos. 1 and 2.

Failure

The gypsum wallboard on top was the first element to fail. Cracks appeared across the center portion of each section and the nails along the perimeter tore through the edge of the sheetrock. Significant structural failure occurred when the foam separated from the center joist in a very similar manner to Ceiling No. 2 (Fig. A-20).

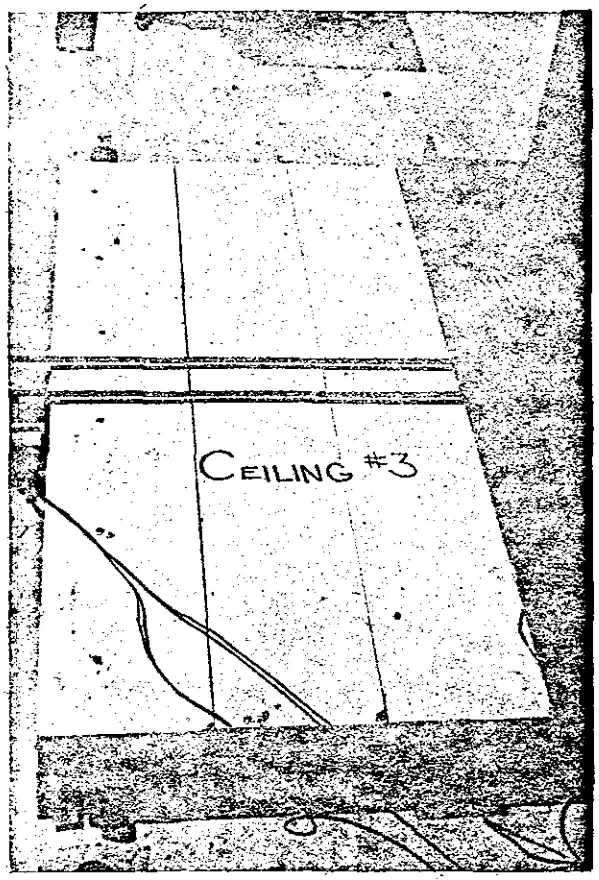


Fig. A-18. Ceiling Number 3 in the Horizontal Shear Test.

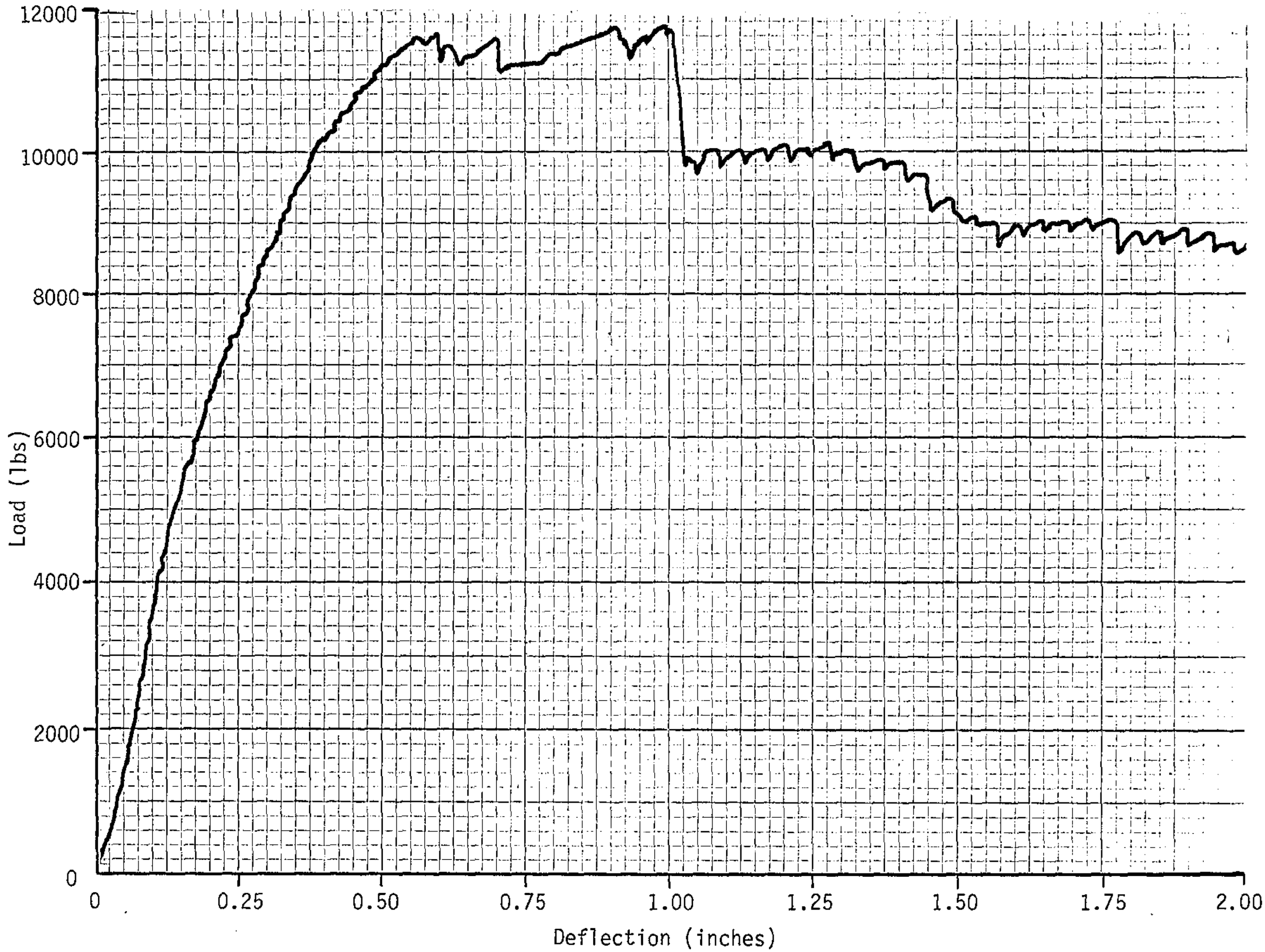


Fig. A-19. Load versus Deflection Graph for Ceiling Number 3.

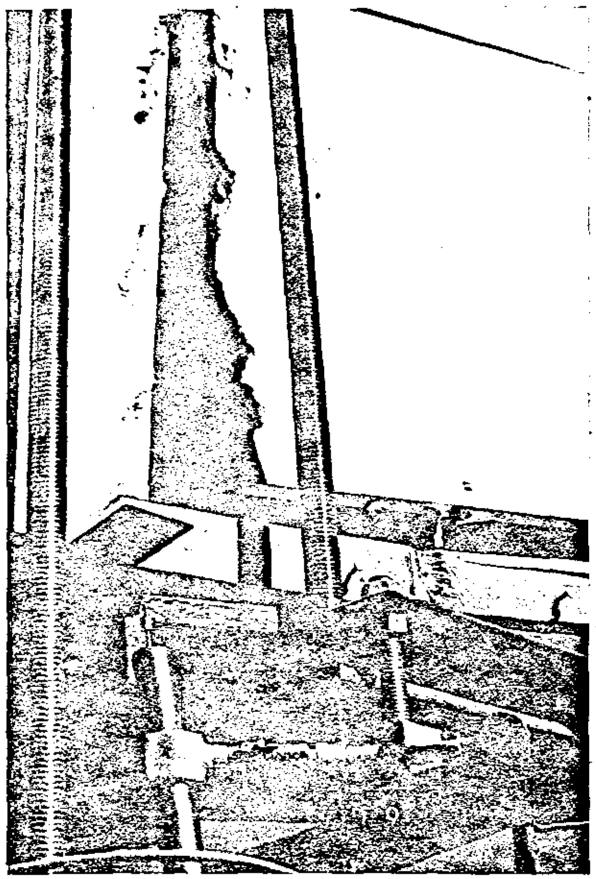
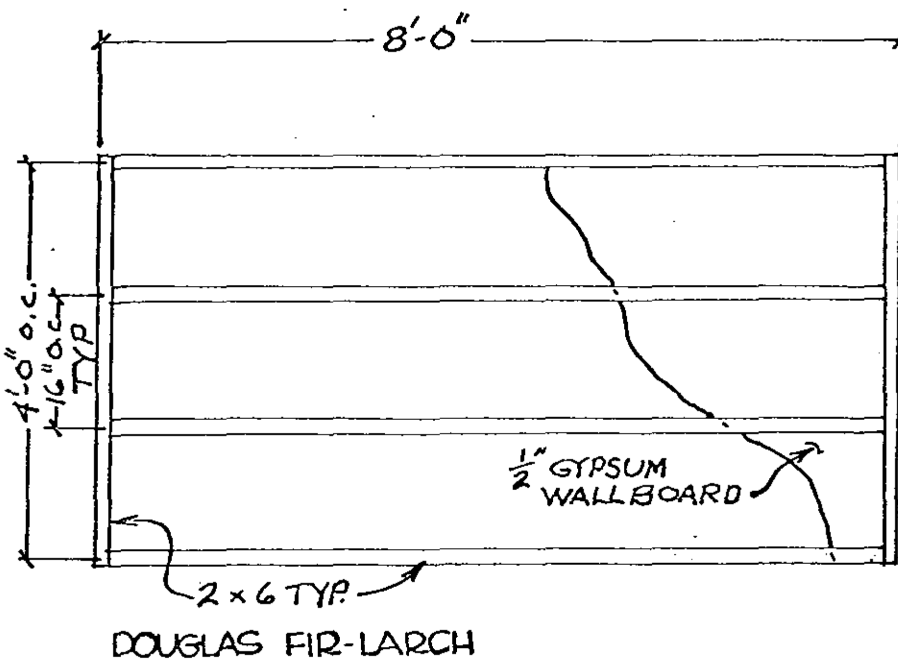


Fig. A-20. Crack Across Wallboard and Separation of Foam from Center Joist of Ceiling Number 3.

CEILING NO. 4

Description



The construction of Ceiling No. 4 was similar to the others except the joists were placed longitudinally instead of in the transverse direction (Fig. A-21). This ceiling was foamed using the same method as for Ceiling No. 3, except 2 ft x 4 ft sections of wallboard were used.

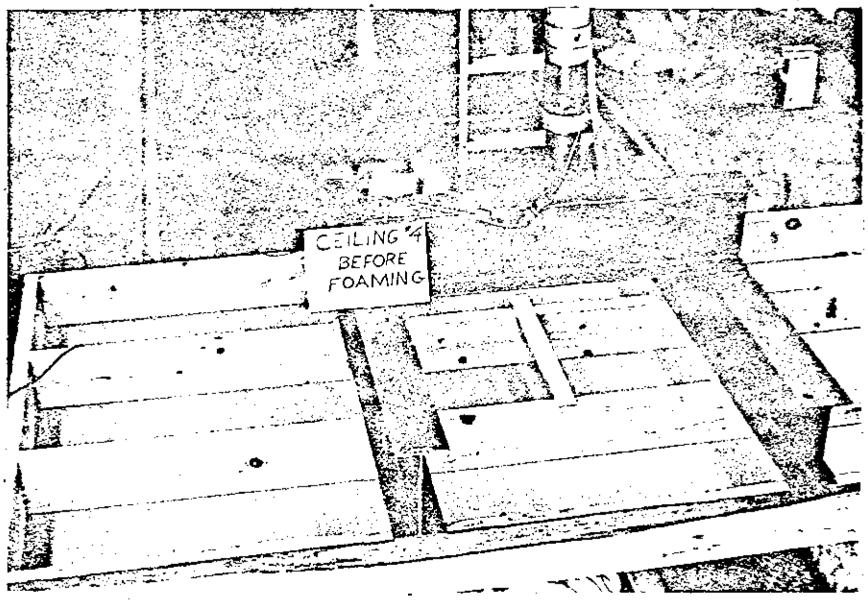


Fig. A-21. Ceiling Number 4 in Bending Test Before Foaming.

Test Procedure

After construction and before foaming, Ceiling No. 4 was weighed and placed in the bending test configuration. The vertical load was applied at the one-third points causing pure bending in the center third of the ceiling. A total load of 800 lbs (representing the service live load equivalent to about 25 lbs/ft^2) was applied and released twice. On the third test a plot of load versus deflection was recorded.

After foaming, the test panel was again weighed and placed in the bending test (Fig. A-22). The service load of 800 lbs was applied a total of three times being recorded on the third test. Ceiling No. 4 was tested to failure using a 20-second ramp displacement input to the hydraulic actuator. The load and center span deflection were recorded on an x-y plotter.

Test Data

The ceiling weight increased from 138 to 212 lbs or 2.3 lbs per sq ft of surface area after sheetrock and foam were added. The load-deflection curves for the service live load before and after foam are shown in Fig. A-23. The ceiling stiffness increased from 8400 lbs/in. to 10,600 lbs/in. or 126%.

The bending test to failure results are shown in Fig. A-24. The ultimate load was 10,600 lbs which caused a bending moment of 14,100 ft-lbs in the center portion.

Failure

A bending failure occurred in the area of a knot between the third point loads. Fig. A-25 shows the failure. The sheetrock pulled through where failure occurred and the foam had separated from the joists in the same area.

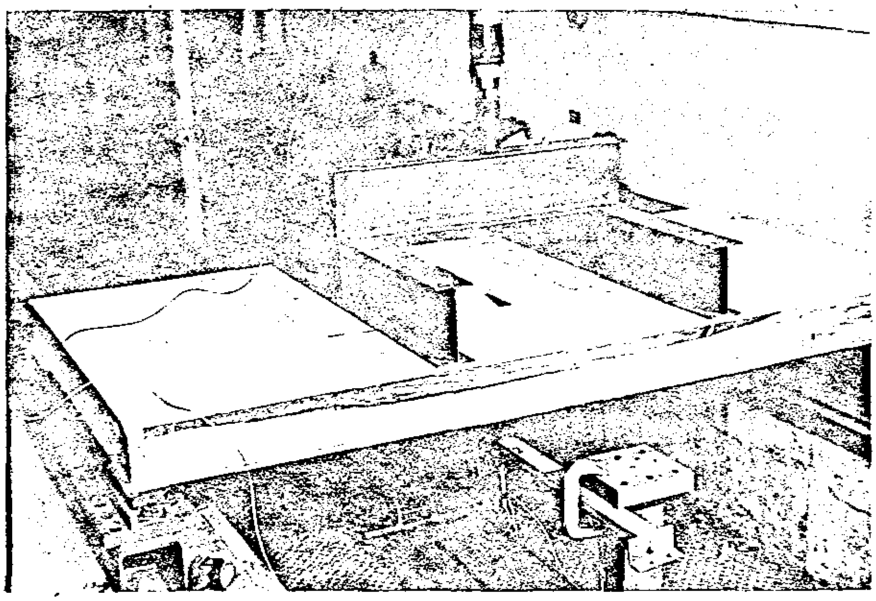


Fig. A-22. Ceiling Number 4 in Bending Test After Foaming.

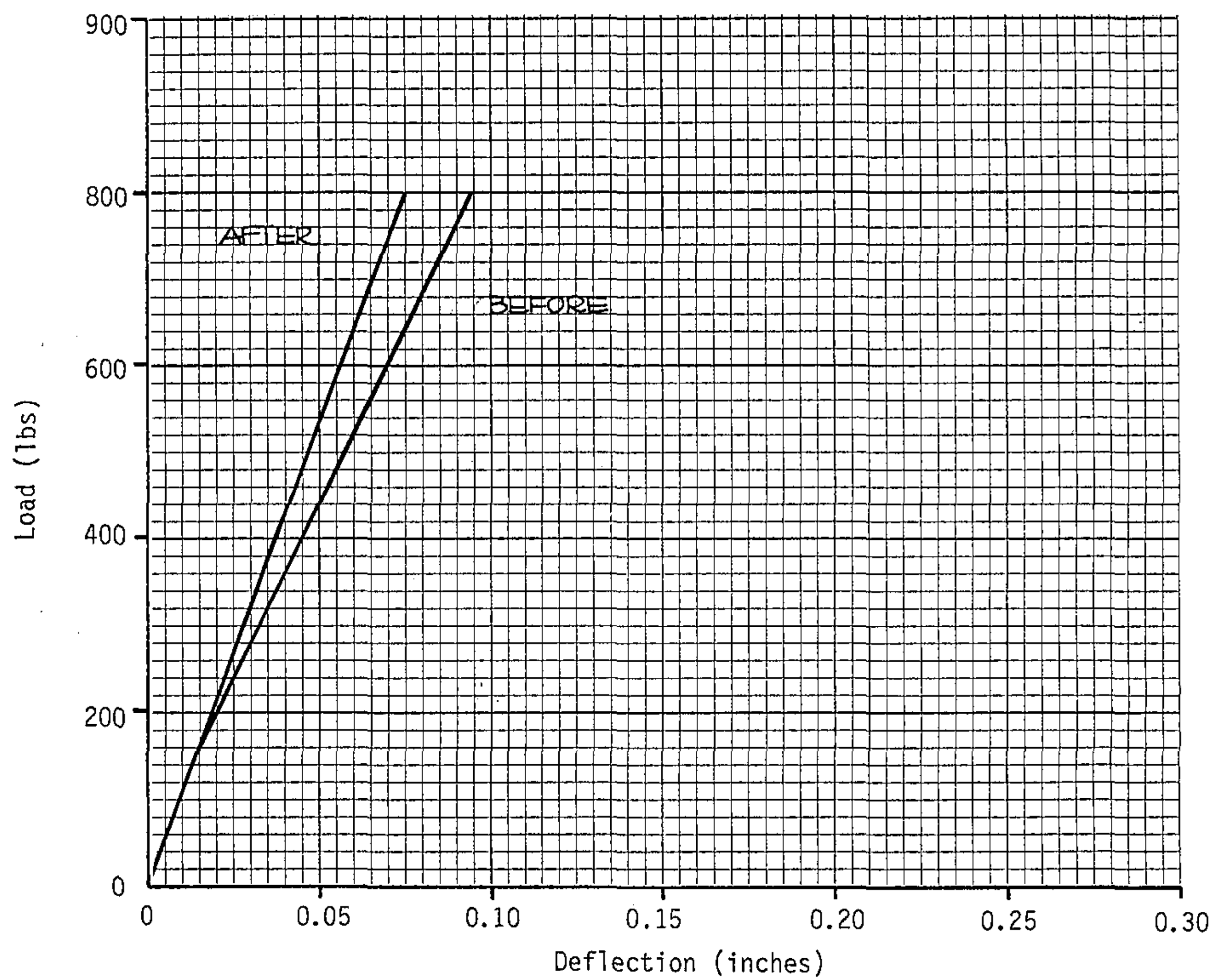


Fig. A-23. Ceiling Number 4 Bending Test to Service Load Before and After Foam Placement.

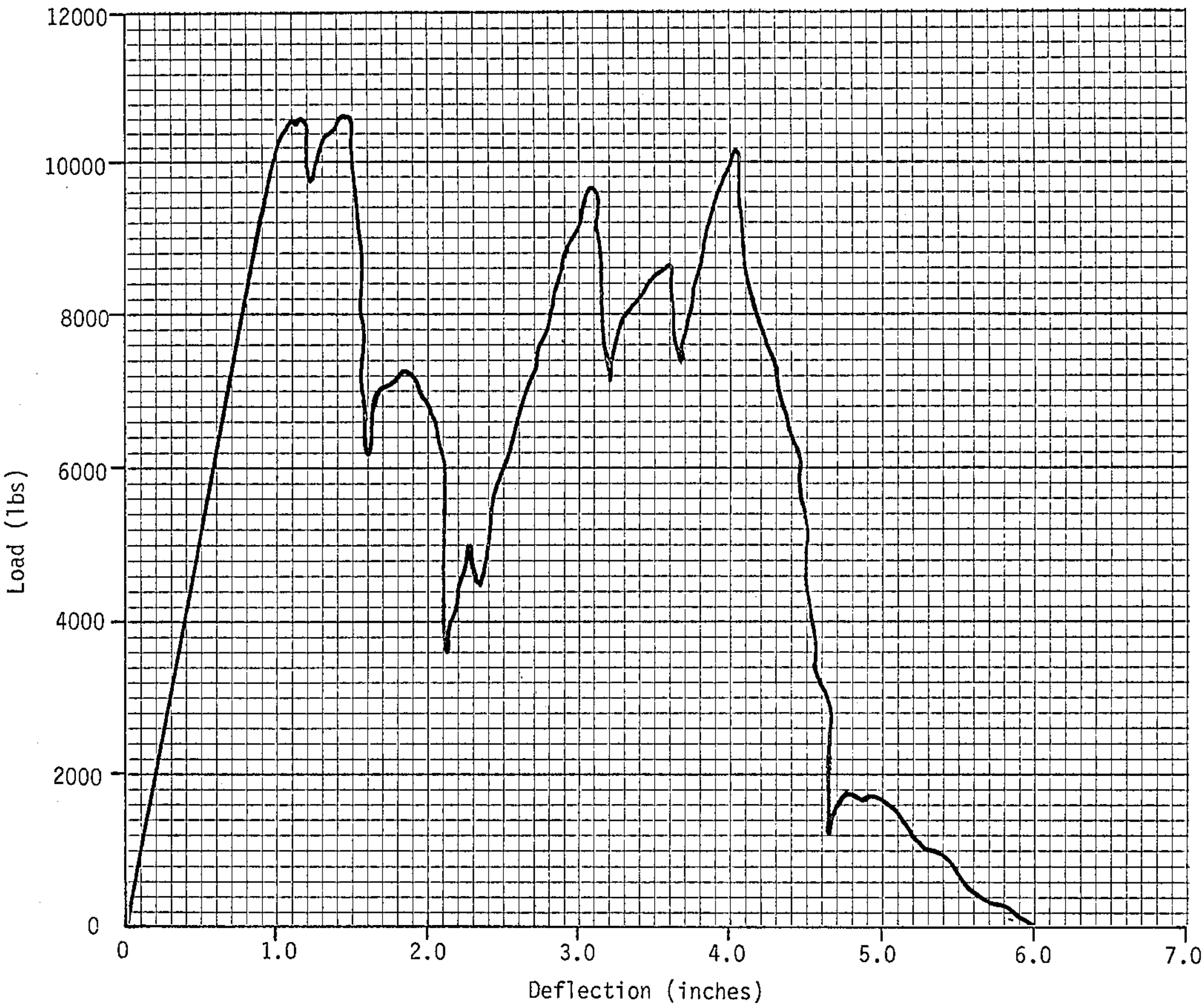


Fig. A-24. Ceiling Number 4, Load versus Deflection Graph to Failure.

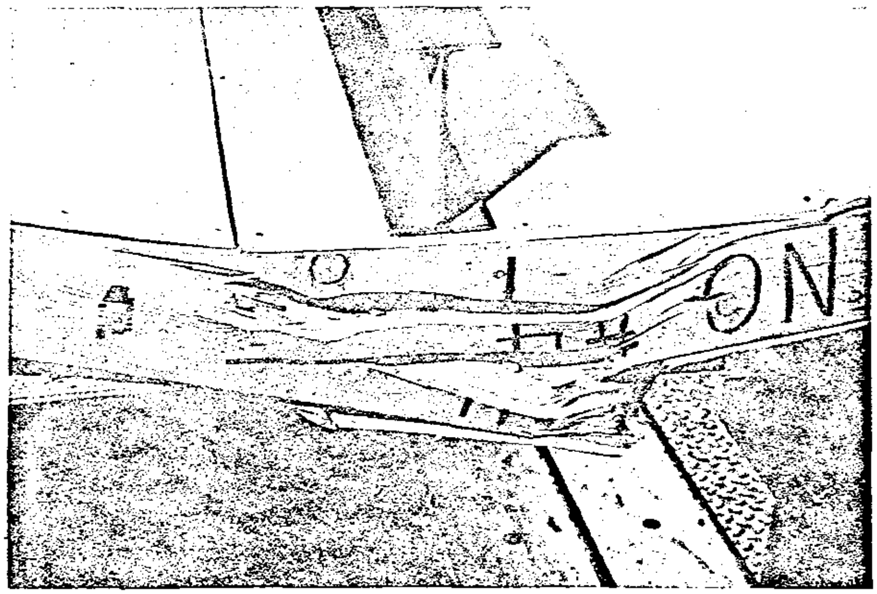
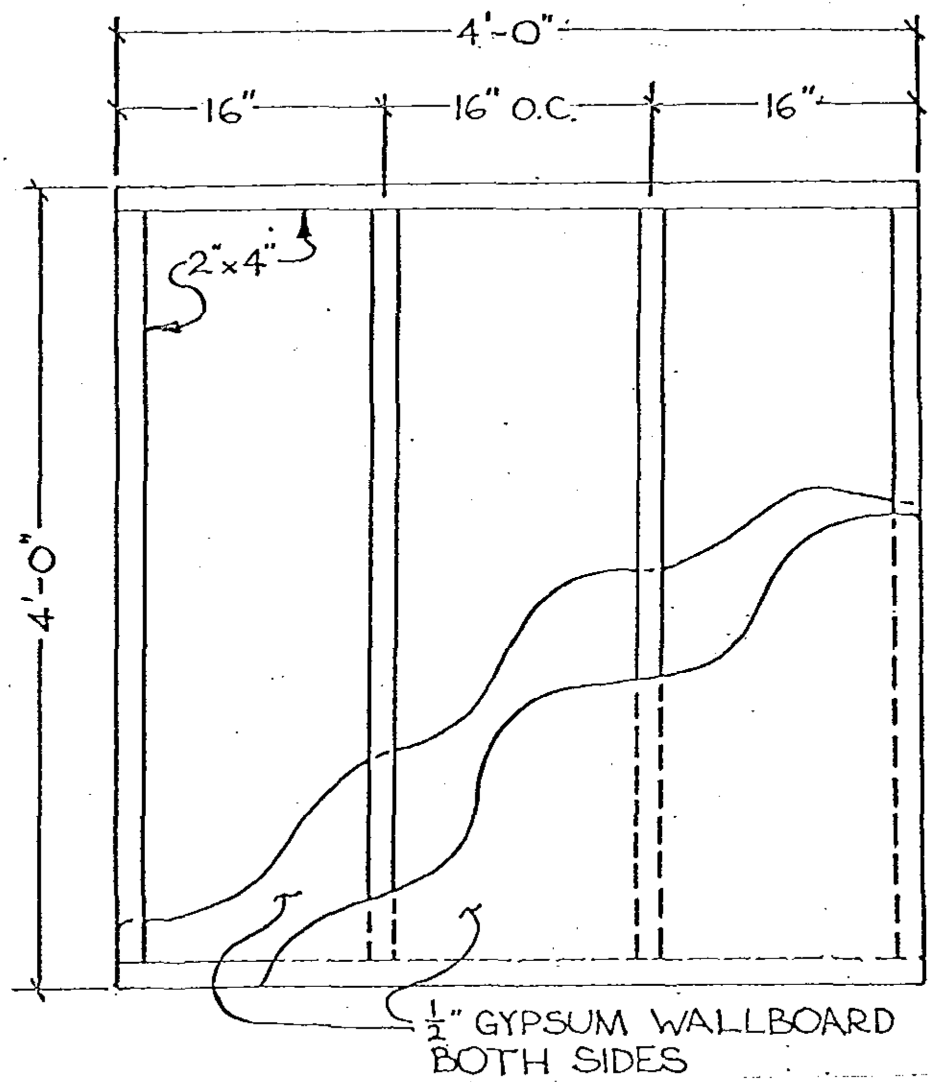


Fig. A-25. Bending Failure of Joist in Ceiling Number 4.

WALL TEST DATA

INTERIOR 4' x 4' WALL - BASE CASE

Description



The above wall was constructed with Douglas Fir-Larch (Select Structural) using the nailing schedule shown in the text.

Test Procedure

The base case wall was placed in the testing machine with one of its diagonals in the vertical position as shown in Fig. A-26. The dial gauge used in measuring the horizontal diagonal deflection can be seen in Fig. A-26. The wall was loaded slowly to failure and load versus vertical diagonal deflection was monitored by the testing machine plotter. The resulting plot is shown in Fig. A-27. The horizontal diagonal deflection was also recorded at various load increments and has been plotted as shown in Fig. A-28.

Test Data

As shown on the graph (Fig. A-27), the ultimate load was 3,925 lbs. The elastic region extends to about 3,300 lbs at which point the nails along the horizontal diagonal corners began to tear. The elastic rigidity for this wall is 5,200 lbs/in.

Failure

The nails along the perimeter of the wall tore out of the gypsum wallboard (sheetrock) as shown in Figs. A-29 and A-30. The wall continued failing along the perimeter until all of the nails had torn out, and the interior nails began to fail leading to the final collapse of the wall.

Fig. A-26. The Interior Wall Base Case (Without Foam) Testing Arrangement.

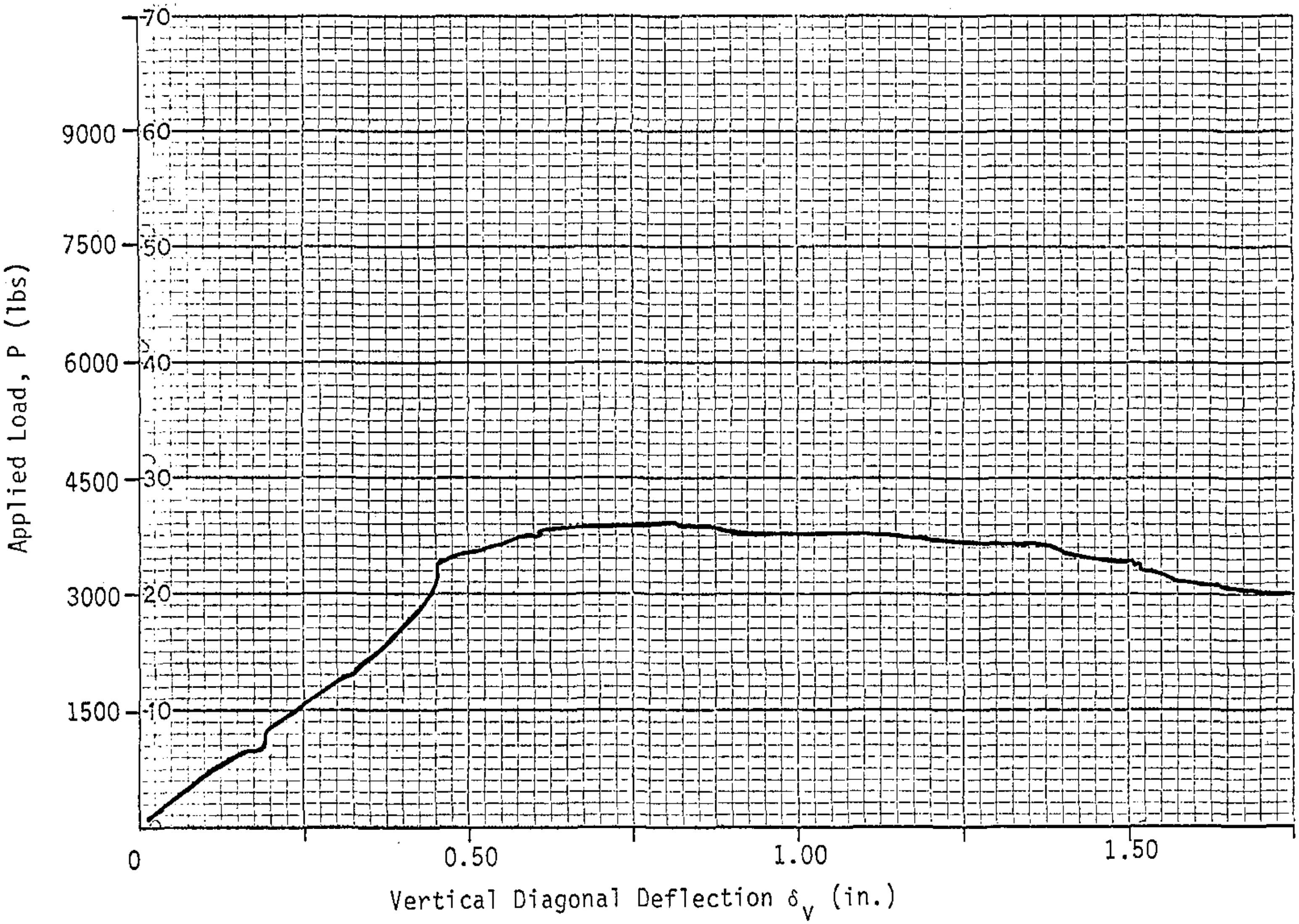


Fig. A-27. Load Versus Vertical Diagonal Deflection for Base Case Wall.

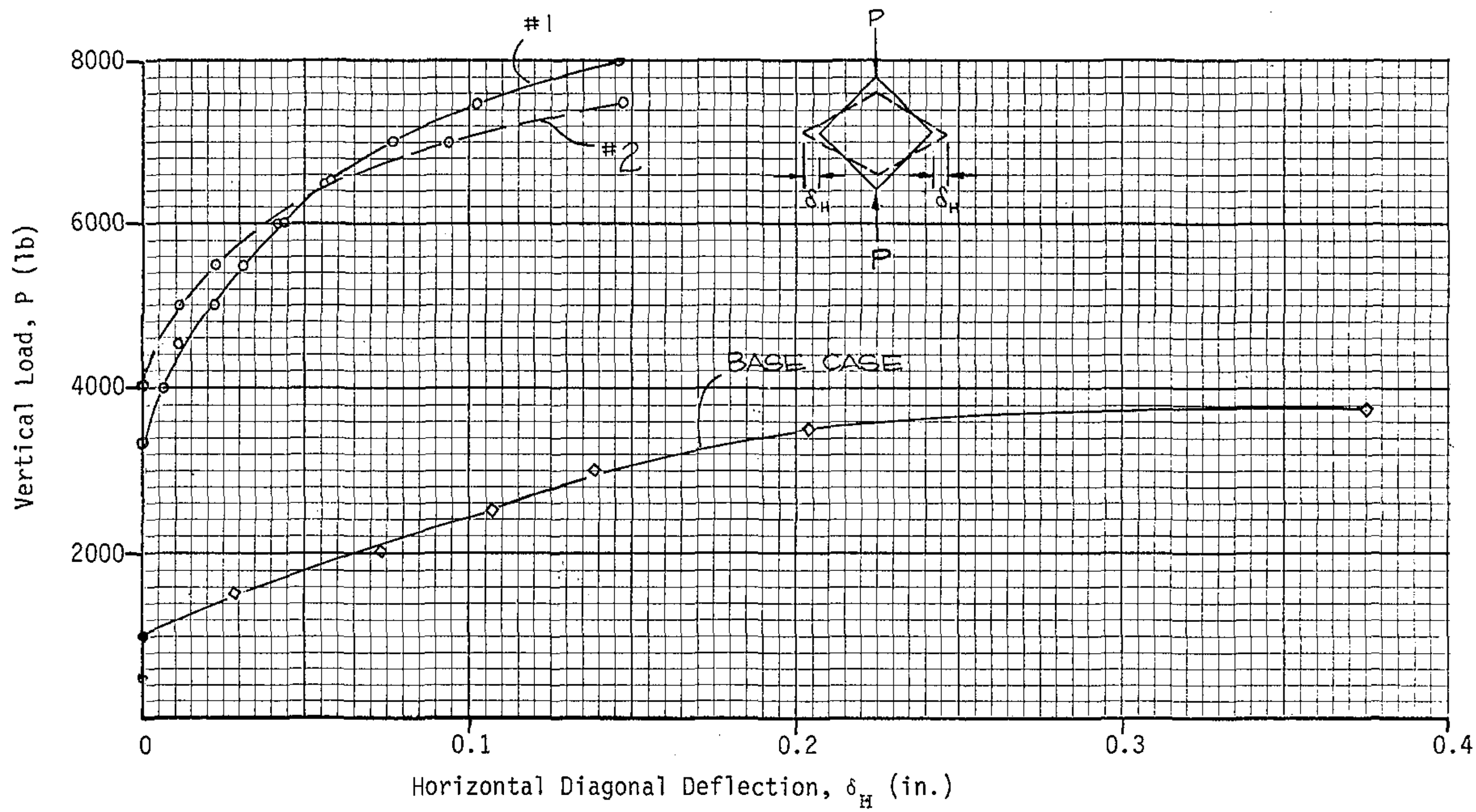


Fig. A-28. Horizontal Diagonal Deflection for Base Case Wall (Data for walls 1 & 2 also included).

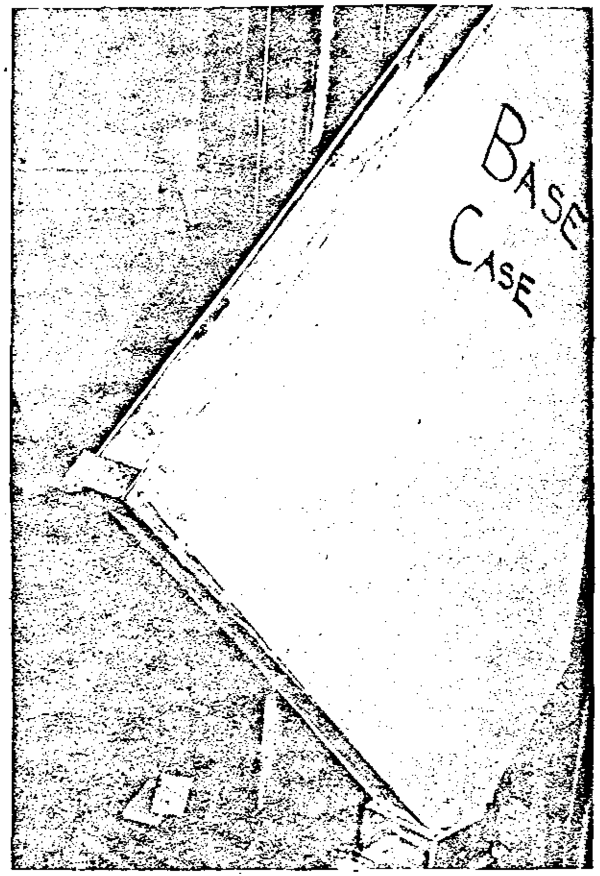


Fig. A-29. The Nails Along the Perimeter of the Sheetrock Torn Out.

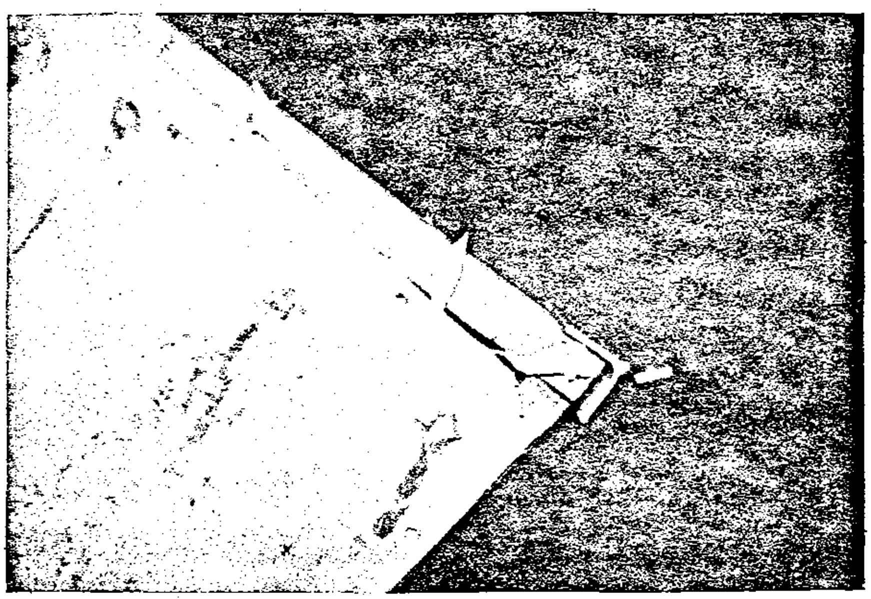
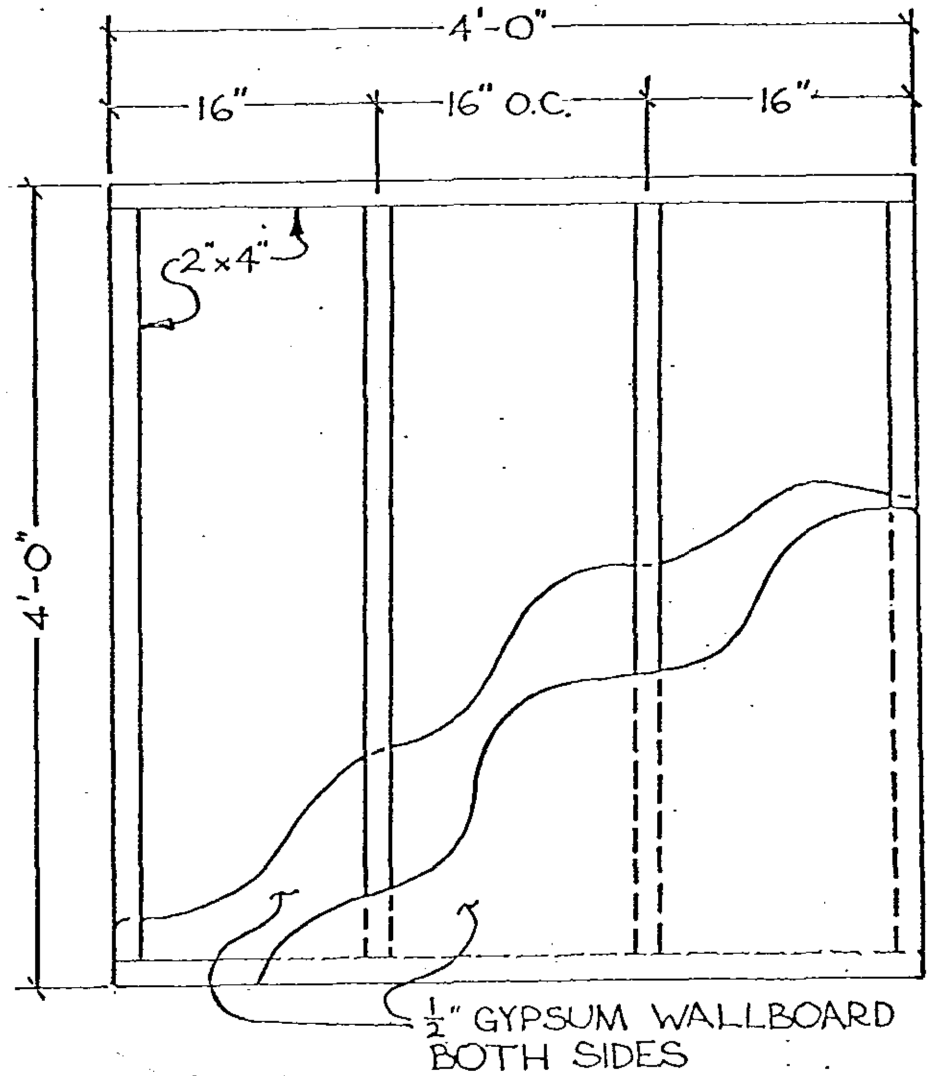


Fig. A-30. A Closeup of the Sheetrock Torn Away from the Nails.

INTERIOR 4' x 4' WALL NO. 1

Description



The wall was constructed indentically to that of the interior wall base case. The framing was made up of 2" x 4" Douglas Fir-Larch (Select Structural) studs, and one sheet of 4' x 4' gypsum wallboard was nailed to each side of the wall.

Test Procedure

Wall No. 1 was placed in the testing machine with one of its diagonals in the vertical position as shown in Figs. A-31 and A-32. The dial gauge used in measuring the horizontal diagonal deflection can be seen in Fig. A-32. The wall was then loaded slowly to failure. The load versus vertical diagonal deflection was monitored by the testing machine plotter; the resulting plot is shown in Fig. A-33. The horizontal diagonal deflector was also recorded at various load increments; these data have been plotted and are presented in Fig. A-28.

Test Data

Wall No. 1 weighed 86 lbs and 95 lbs, respectively, before and after the application of foam, resulting in a 0.56 lbs/sq ft (or a 10%) increase in weight due to the foam.

As shown on the plot of load versus vertical deflection (Fig. A-33), the ultimate load occurred at 8,200 lbs with the elastic region extending up to 6,750 lbs. The ultimate load represents an increase of more than 100% above the ultimate load obtained for the base case. The initial failure occurred due to the nails tearing out of the sheetrock along the perimeter of the wall.

Failure

Failure was initiated along the perimeter of the wall. The nails along the edges tore out sections of sheetrock along the horizontal tensile diagonal as shown in Fig. A-33. Along the vertical compression diagonal the nails produced local crushing or bearing failures in the sheetrock.

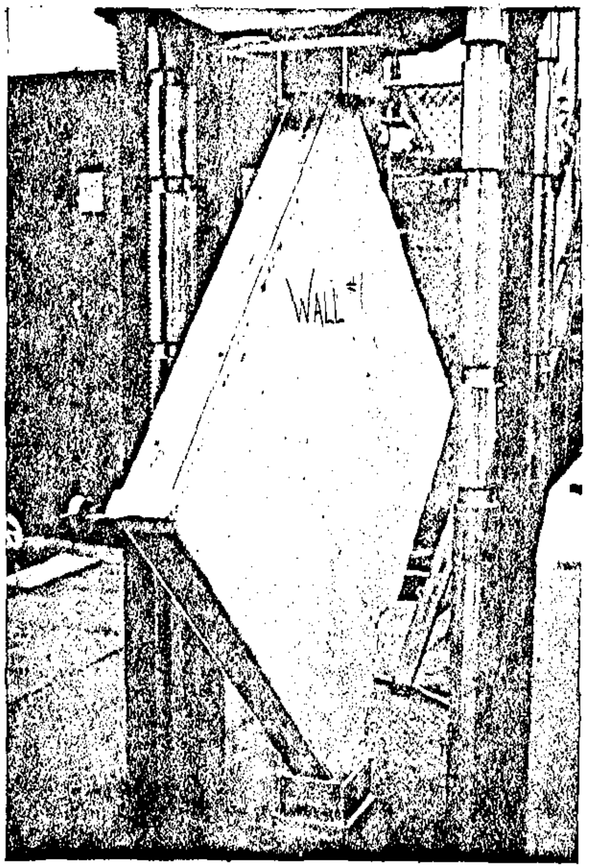


Fig. A-31. Test Arrangement for Wall Number 1.

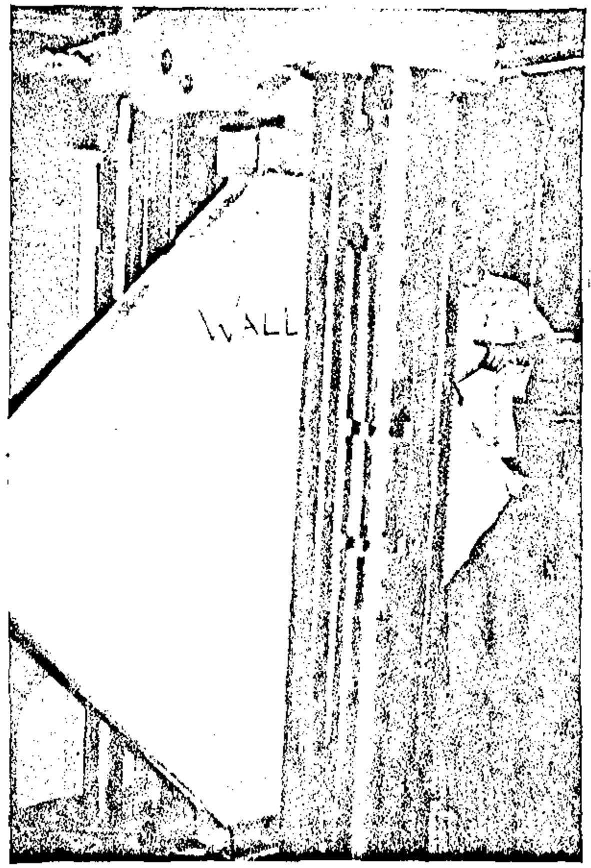


Fig. A-32. Failure of Sheetrock and Nails Can be Seen Along Perimeter of the Wall.

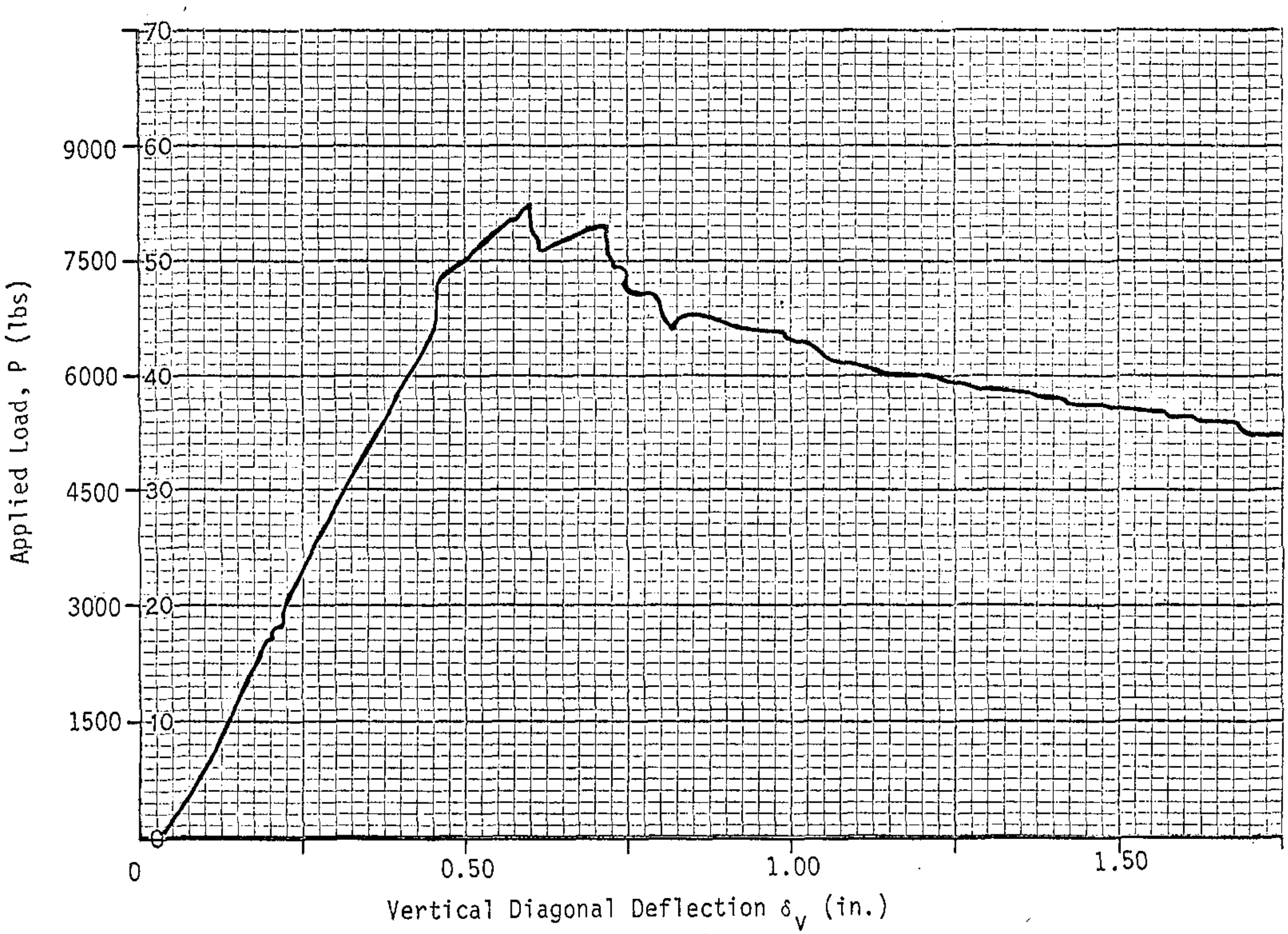
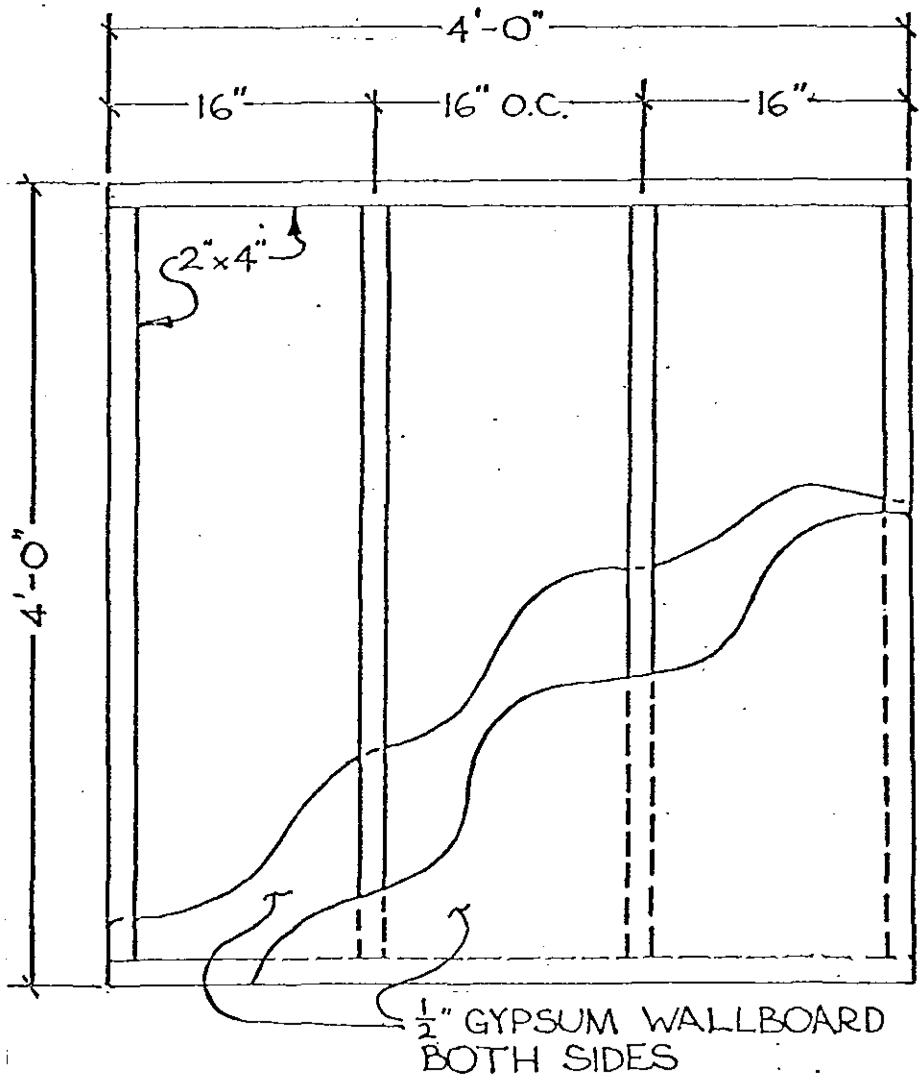


Fig. A-33. Load Versus Vertical Diagonal Deflection for Interior Wall No. 1.

INTERIOR 4' x 4' WALL NO. 2

Description



Wall No. 2 was constructed the same as Wall No. 1 and the base case. A sketch of this wall is shown above.

Test Procedure

Wall No. 2 was placed in the testing machine with one of its diagonals in the vertical position as shown in Fig. A-34. The wall was then loaded slowly to failure. The load versus vertical diagonal deflection was monitored by the testing machine plotter; the resulting plot is shown in Fig. A-35. The horizontal diagonal deflection was also recorded at various load increments; these data have been plotted and are presented in Fig. A-28.

Test Data

The wall weighed 86 lbs before and 96 lbs after foam was applied. This is equivalent to an 0.63 lbs/sq ft or 12% increase in wall weight due to the application of foam. Turning again to Fig. A-35, the load versus deflection plot for the vertical diagonal, the ultimate load was found to be 7,525 lbs for this wall. The elastic region extended up to an applied load of 5,500 lbs. The ultimate load represents an increase of 91% in applied load over the base case. The initial failure was due to the nails along the perimeter of the wall pulling out of the sheetrock. The rigidity of Walls 1 and 2 in the elastic region is 13,968 lbs, representing an increase of 168% over the base case.

Failure

As with Wall No. 1 and the base case, the sheetrock pulled away from the nails along the perimeter of the wall as shown in Figs. A-36 and A-37. Along the horizontal tensile diagonal, the nails pulled out tearing out small sections of the sheetrock. Along the vertical compression diagonal, local crushing or bearing failures occurred between the nails and sheetrock.

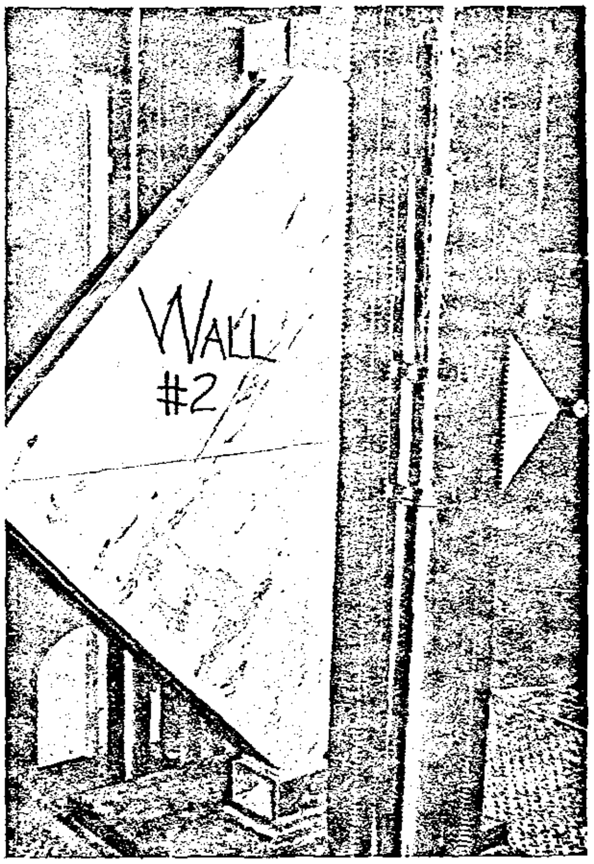


Fig. A-34. Test Arrangement for Wall Number 2.

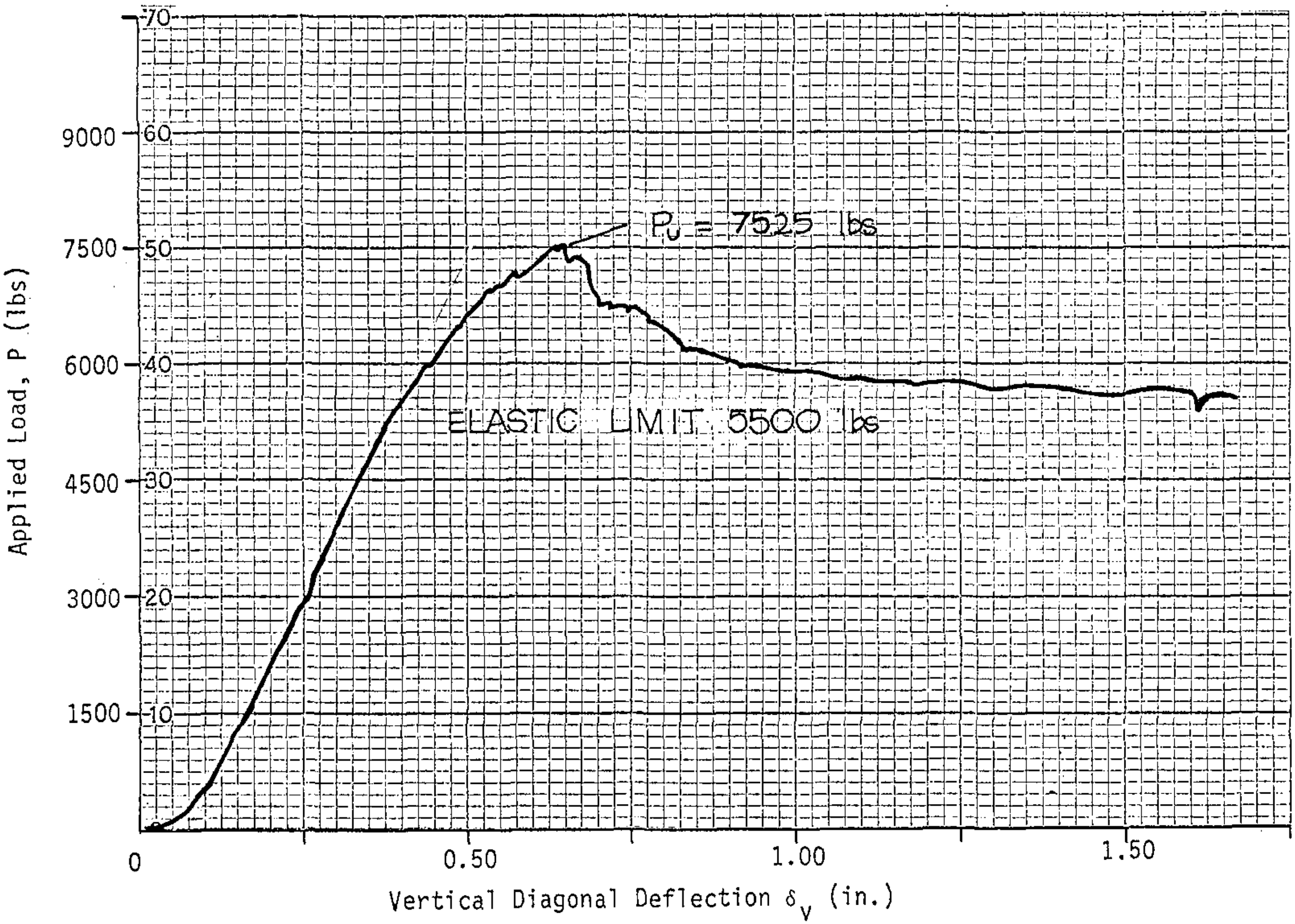


Fig. A-35. Load Versus Diagonal Deflection for Interior Wall No. 2.

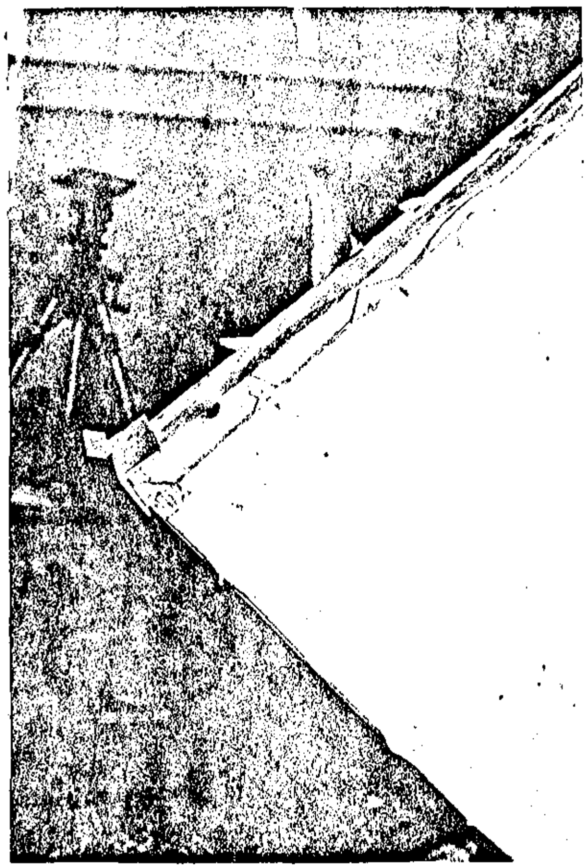


Fig. A-36. Failure of Sheetrock and Nails Along Perimeter of Wall.

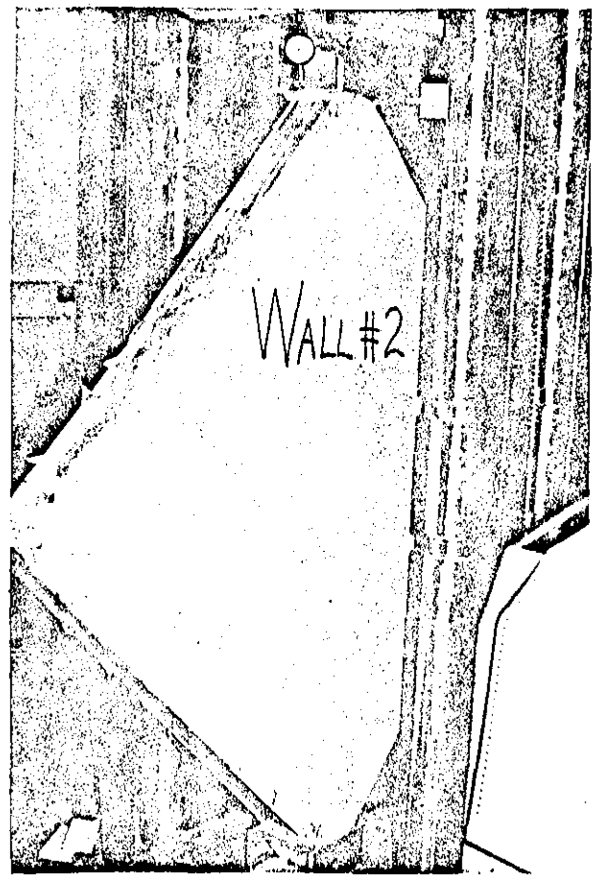
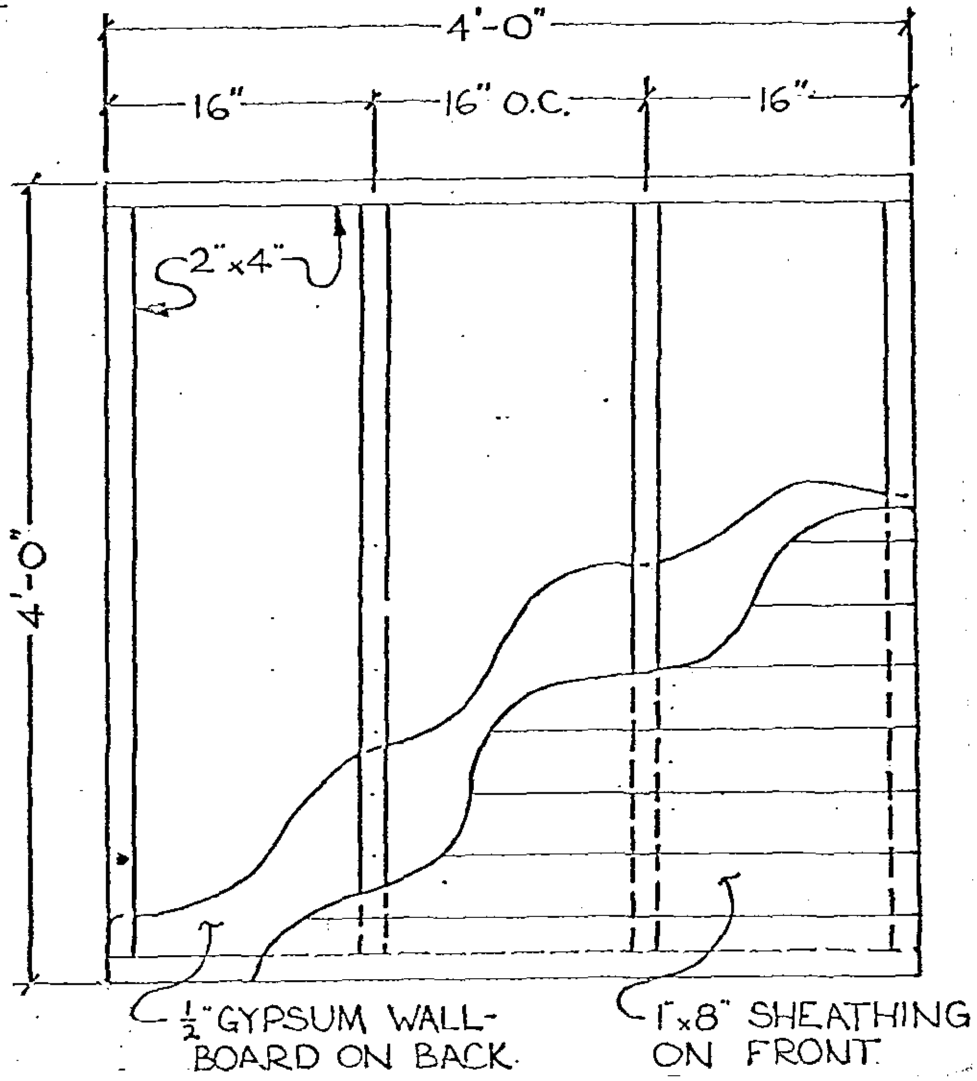


Fig. A-37. Closeup of Failure of Sheetrock and Nails Along Perimeter.

EXTERIOR 4' x 4' WALL - BASE CASE

Description



This specimen was constructed of four 2' x 4' Douglas Fir-Larch (Select Structural) studs on 16-inch centers. On one side, 1/2-inch gypsum wallboard (sheetrock) was nailed, and to the other side, 1" x 8" sheathing running perpendicular to the studs was nailed. The nailing schedule is shown in the text. A sketch of the wall is shown above.

Test Procedure

Base Case No. 2 was placed in the testing machine with one of its diagonals in the vertical position as shown in Figs. A-38 and A-39. A dial gauge was used to measure the horizontal diagonal deflection. The wall was then loaded slowly to failure. The load versus vertical diagonal deflection was monitored by the testing machine plotter and the resulting plot is shown in Fig. A-40. The horizontal diagonal deflection was also recorded at various load increments and presented in Fig. A-41.

Test Data

The ultimate load for this wall occurred at 1,925 lbs. Upon examination of the load versus deflection curve in Fig. A-40, the elastic region can be seen to extend up to about 1,050 lbs. The rigidity of this wall in the elastic region is 3,148 lbs per inch of shear deflection.

Failure

Failure began at the corners of the wall. The nails holding the sheetrock in place began to tear out (see Figs. A-42 - A-44). Up until the failure of the sheetrock the wall began to buckle due to torsion along its horizontal axis. The sheetrock being much more rigid in shear than the sheathing caused the wall to bow along the horizontal diagonal axis into a concave shape on the sheetrock side. After the sheetrock failed the buckling reversed itself and took up a concave shape along the horizontal diagonal on the sheathing side. The ultimate load reported was for the sheetrock just prior to failure. Another higher peak occurred for the wall but it occurred at such a large deformation (about 10 times the deflection of the first peak) that it has been neglected. The second peak was due to the wall being deformed or racked enough to fully develop the shear strength of the sheathing.

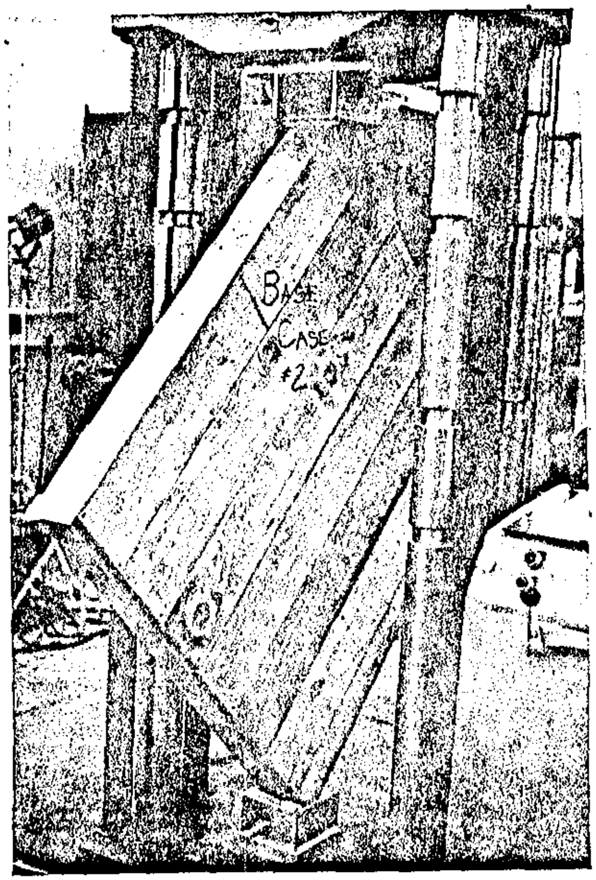


Fig. A-38. Front View of Base Case Exterior Wall in Testing Machine.

Fig. A-39. Back View of Base Case Exterior Wall in Testing Machine.

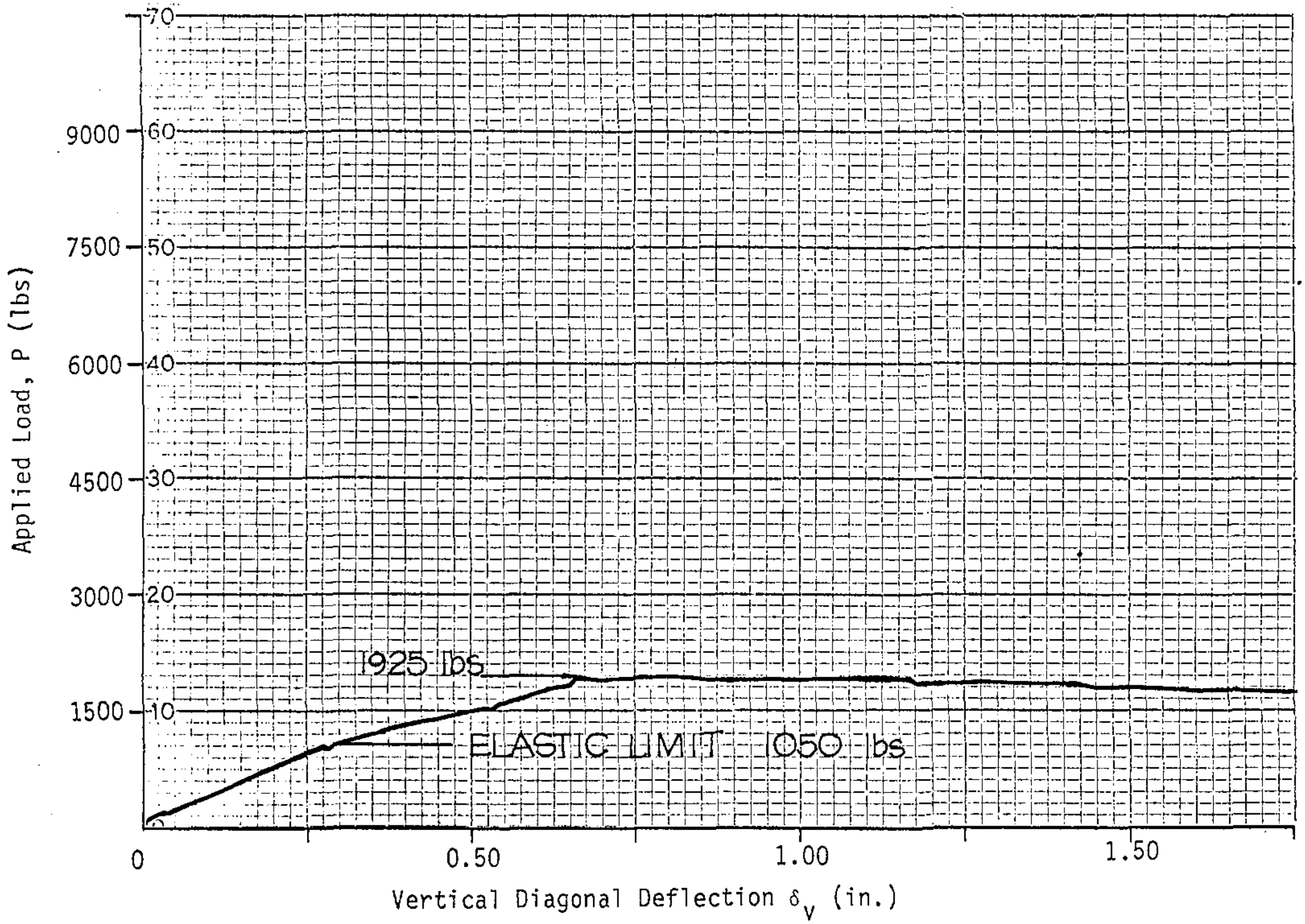


Fig. A-40. Load Versus Vertical Diagonal Deflection for Exterior Base Case Wall.

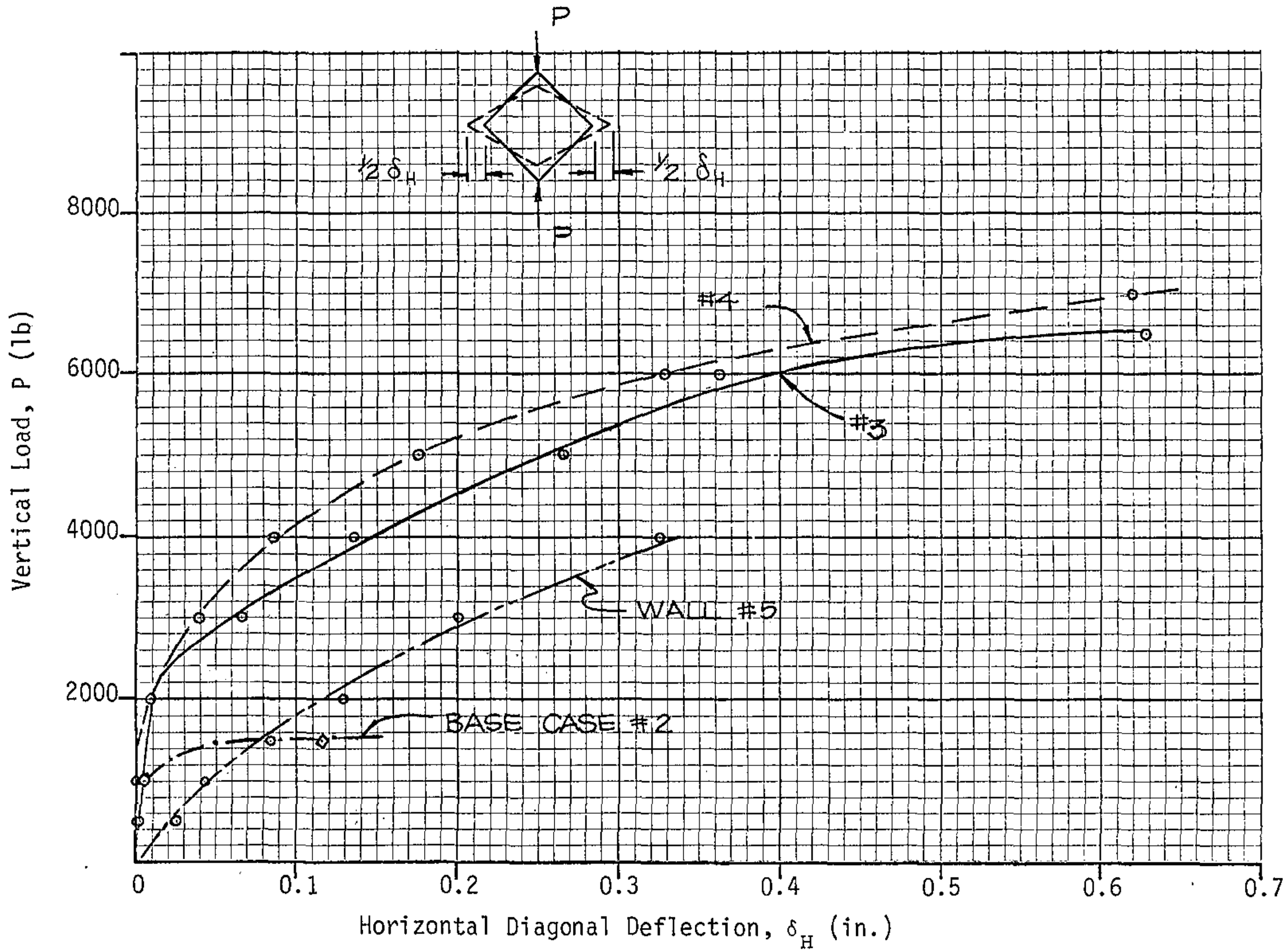


Fig. A-41. Horizontal Diagonal Deflection at Various Load Increments, Base Case and Walls 3, 4, and 5.

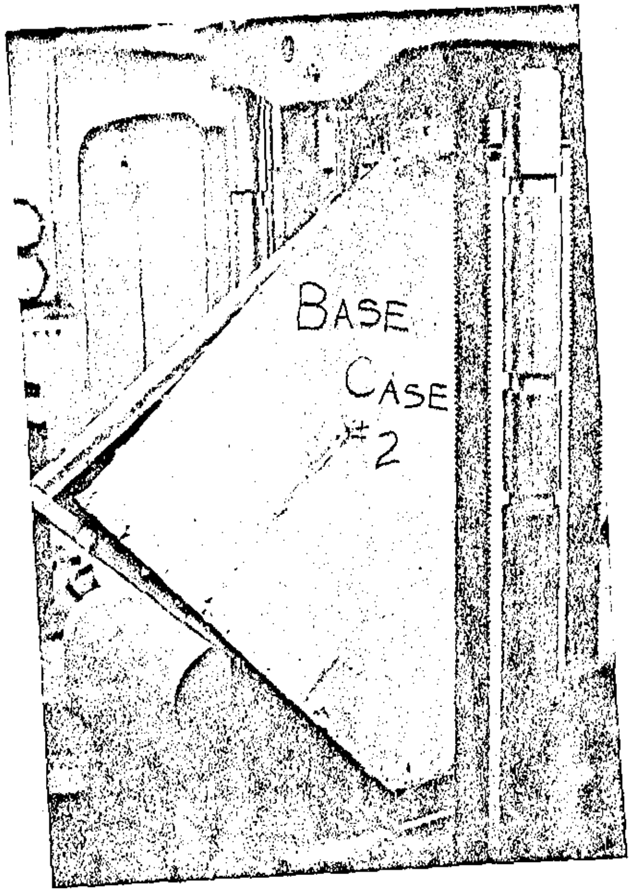


Fig. A-42. Failure of Base Case Wall Number 2, Sheetrock Side.

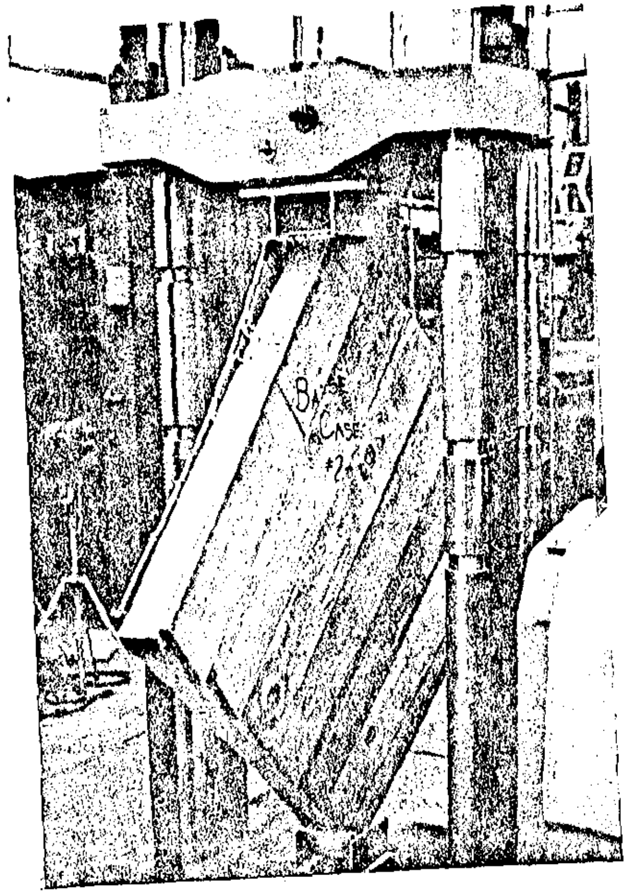
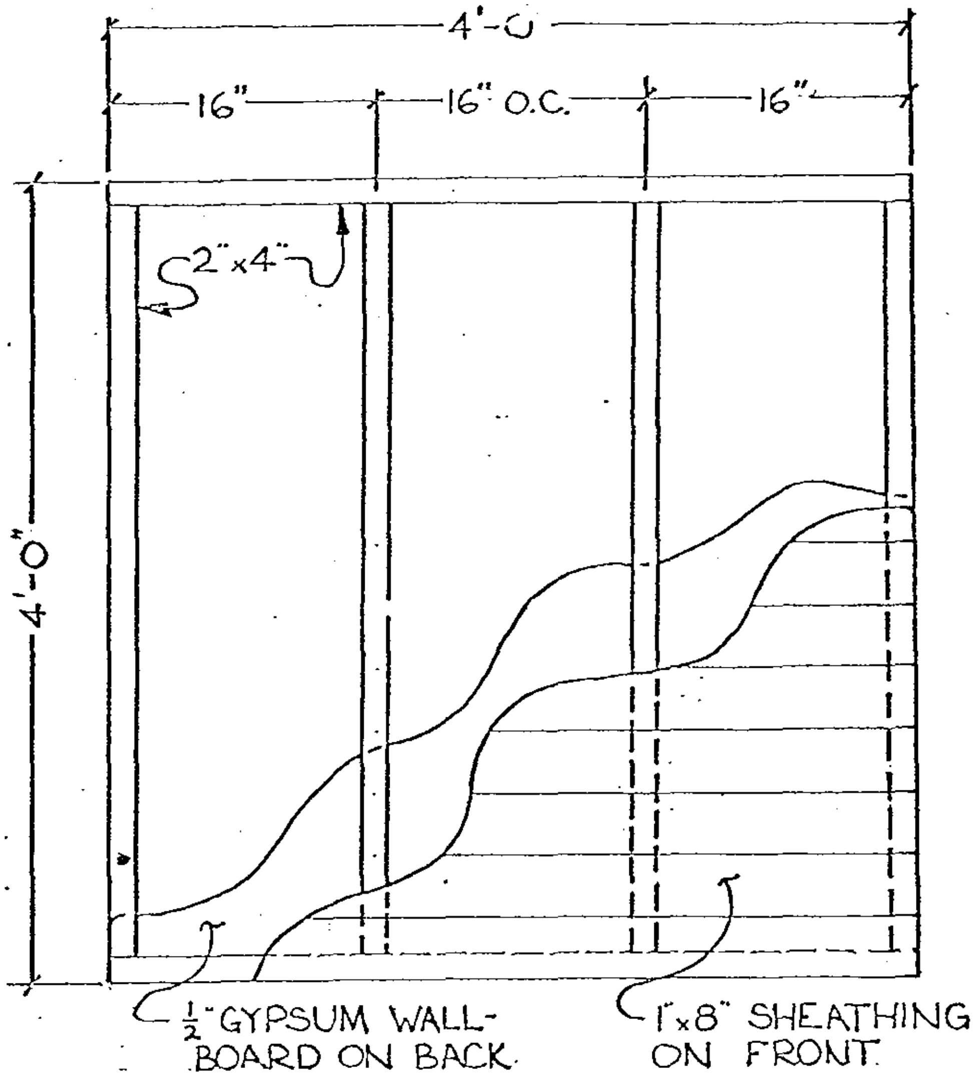


Fig. A-43. Failure of Base Case Wall Number 2, Sheathing Side.

Fig. A-44. Closeup End View of Failure of Base Case Wall Number 2.

EXTERIOR 4' x 4' WALL NO. 3

Description



Wall No. 3 was constructed identically to Base Case No. 2 with sheathing on one side and gypsum wallboard (sheetrock) on the other. The nailing schedule can be seen in the test. A sketch of this wall is presented above.

Test Procedure

Wall No. 3 was placed in the testing machine with one of its diagonals in the vertical position as shown in Figs. A-45 and A-46. The diagonal gauge used in measuring the horizontal diagonal deflection can be seen in Fig. A-45. The wall was then loaded slowly to failure. The load versus vertical diagonal deflection was monitored by the testing machine plotter and the resulting plot is shown in Fig. A-47. The horizontal diagonal deflection was also recorded at various load increments and plotted in Fig. A-41.

Test Data

The before and after foam application wall weights are 94 lbs and 101 lbs, respectively. This is equivalent to an increased dead load of 7% or 0.44 lbs/ft^2 due to the application of the foam. Turning again to Fig. A-47 (applied load versus vertical diagonal deflection), it can be seen that the ultimate load for this wall was 6,850 lbs and that the elastic region of the curve extends up to about 4,500 lbs. The ultimate load due to the application of foam has increased 155% above the base case ultimate load.

Failure

Failure of the wall was initiated by a buckling of the horizontal diagonal (see Fig. A-48). This is characterized by a bowing of the horizontal diagonal into a concave shape on the sheetrock side (see Fig. A-49). This is caused by the sheetrock being many times more rigid than the sheathing. The wall started buckling about the vertical diagonal which ultimately led to failure.

Fig. A-45. Front View of Wall Number 3 in Testing Machine.

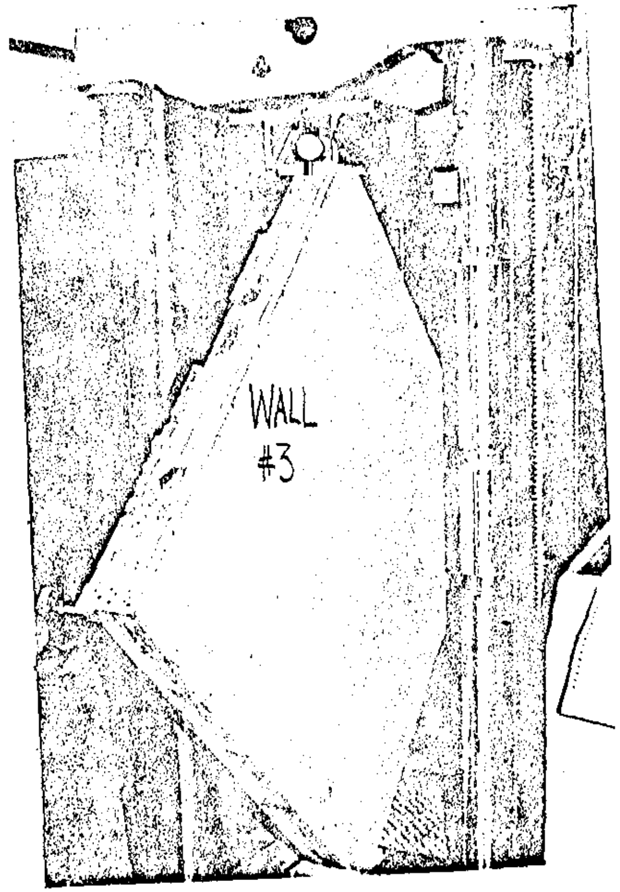


Fig. A-46. Back View of Wall Number 3 in Testing Machine.

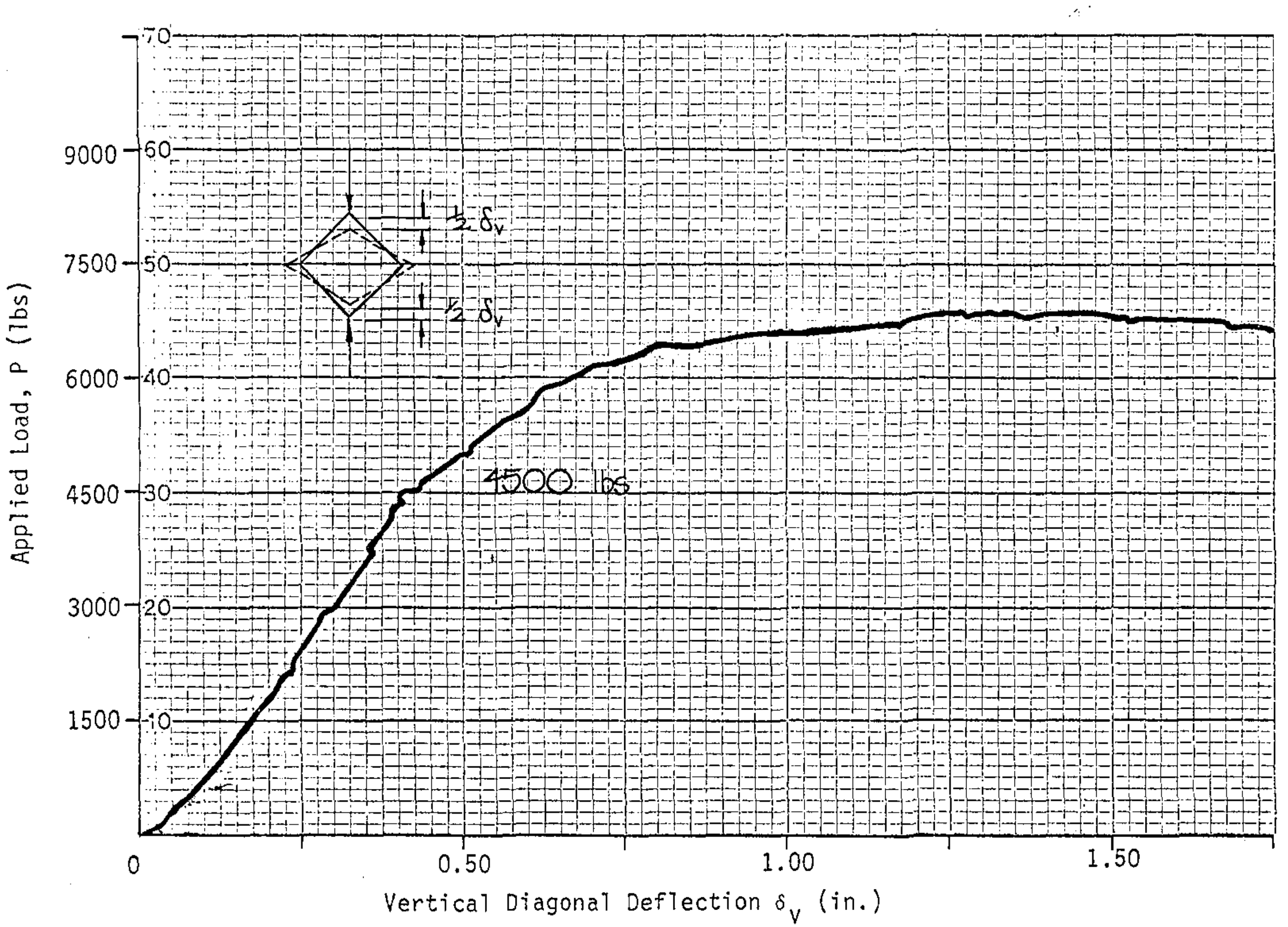


Fig. A-47. Load Versus Vertical Diagonal Deflection for Exterior Wall No. 3.

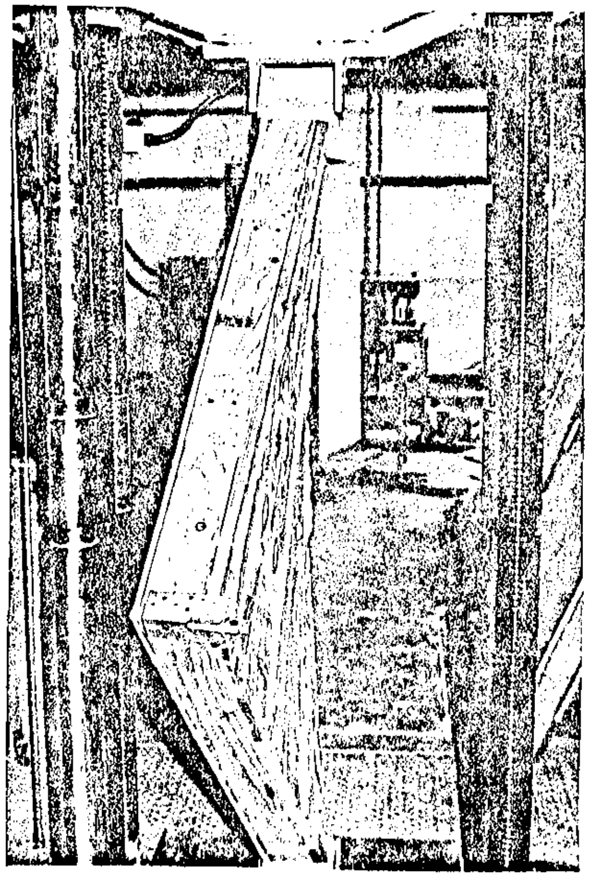


Fig. A-48. Failure of Wall Number 3.

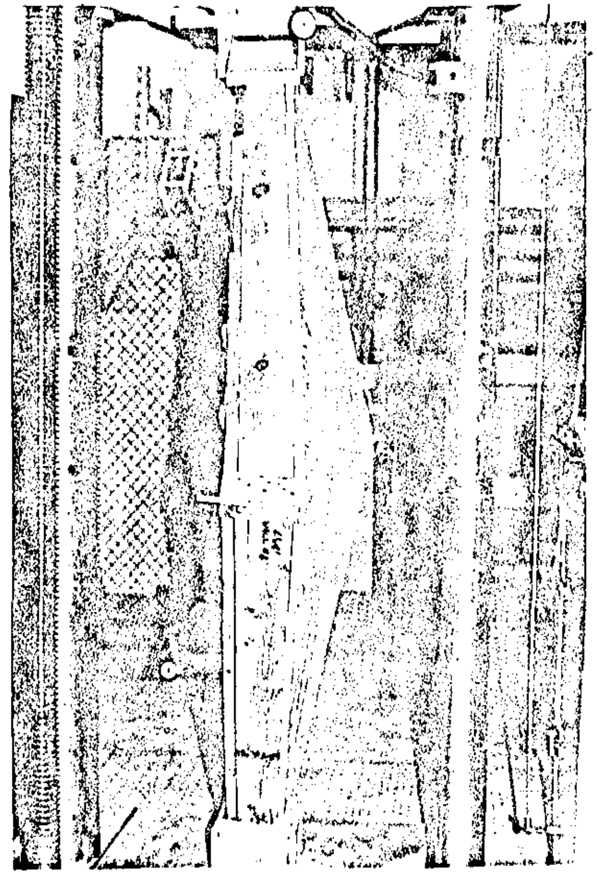
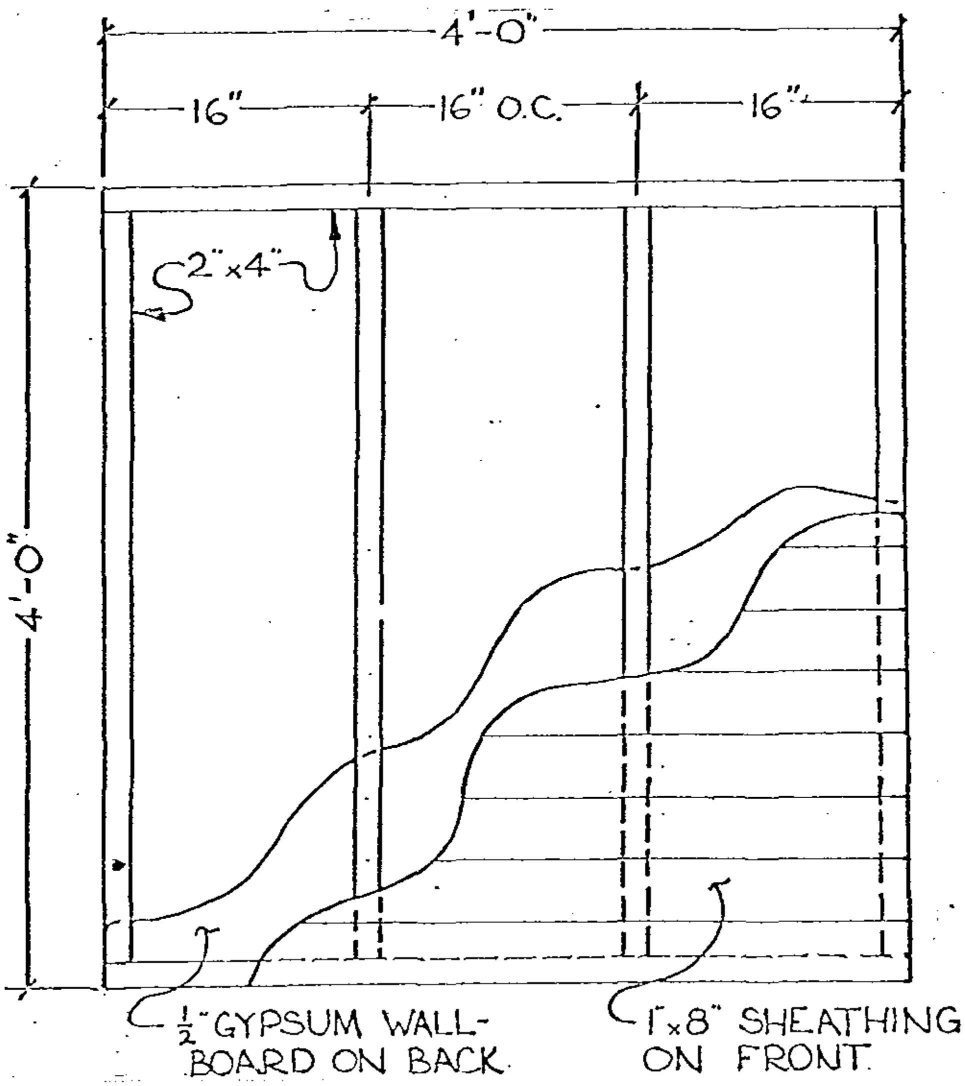


Fig. A-49. Failure of Wall Number 3.

EXTERIOR 4' x 4' WALL NO. 4

Description



Wall No. 4 was constructed identically to Wall No. 3 and Base Case No. 2, with 1" x 8" sheathing on one side and gypsum wallboard (sheetrock) on the other.

Test Procedure

Wall No. 4 was placed in the testing machine with one of its diagonals in the vertical position as shown in Figs. A-50 and A-51. The diagonal gauge used in measuring the horizontal deflection can be seen in Fig. A-50. The wall was then loaded slowly to failure. The load versus vertical diagonal deflection was monitored by the testing machine plotters and the resulting plot is shown in Fig. A-52. The horizontal diagonal deflection was also recorded at various load increments and plotted in Fig. A-41.

Test Data

The wall was weighed before and after foam application and the weights were 94 lbs and 101 lbs, respectively. This is equivalent to an 8% increase in dead load or 0.44 lbs/ft^2 due to the application of the foam. Referring again to Fig. A-51, the ultimate load is seen to be 7,275 lbs. The elastic region appears to extend up to about 4,800 lbs. The ultimate load due to the application of foam increased 149% over the non-foamed base case.

Failure

Wall No. 4 failed in an identical manner to Wall No. 3. Failure was initiated by a buckling about the horizontal diagonal (see Fig. A-53).

A concave shape along the horizontal diagonal formed on the sheetrock side of the wall. This caused the vertical diagonal to buckle in a more conventional manner (see Fig. A-54). The sheetrock and sheathing remained intact and exhibited few local failures for considerable deflection past the ultimate load.

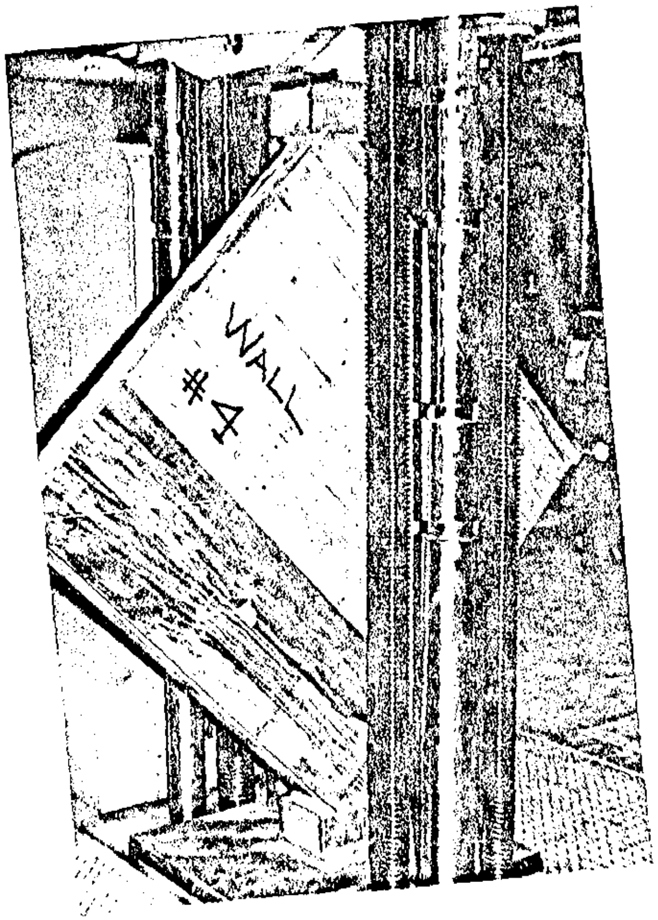


Fig. A-50. Front View of Wall Number 4 in Testing Machine.

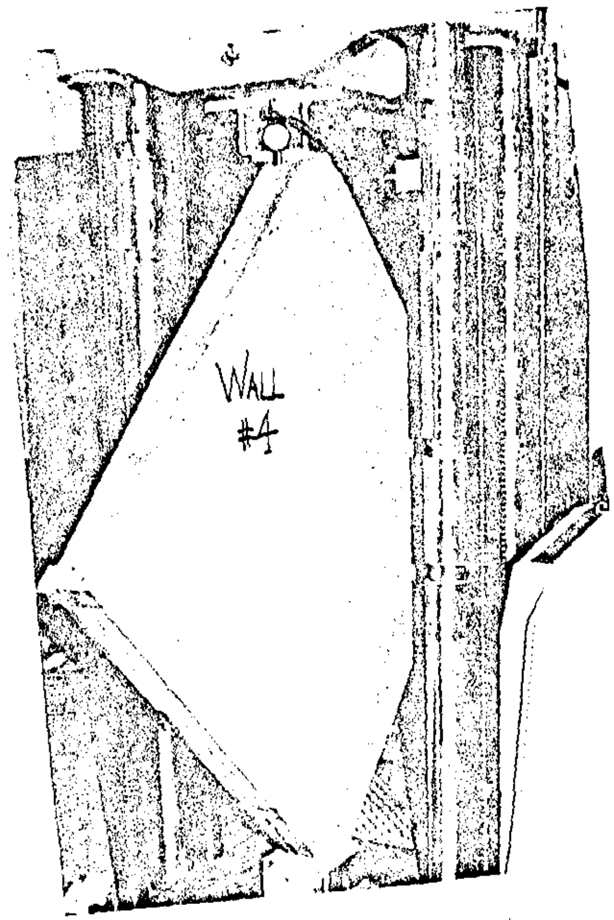


Fig. A-51. Back View of Wall Number 4 in Testing Machine.

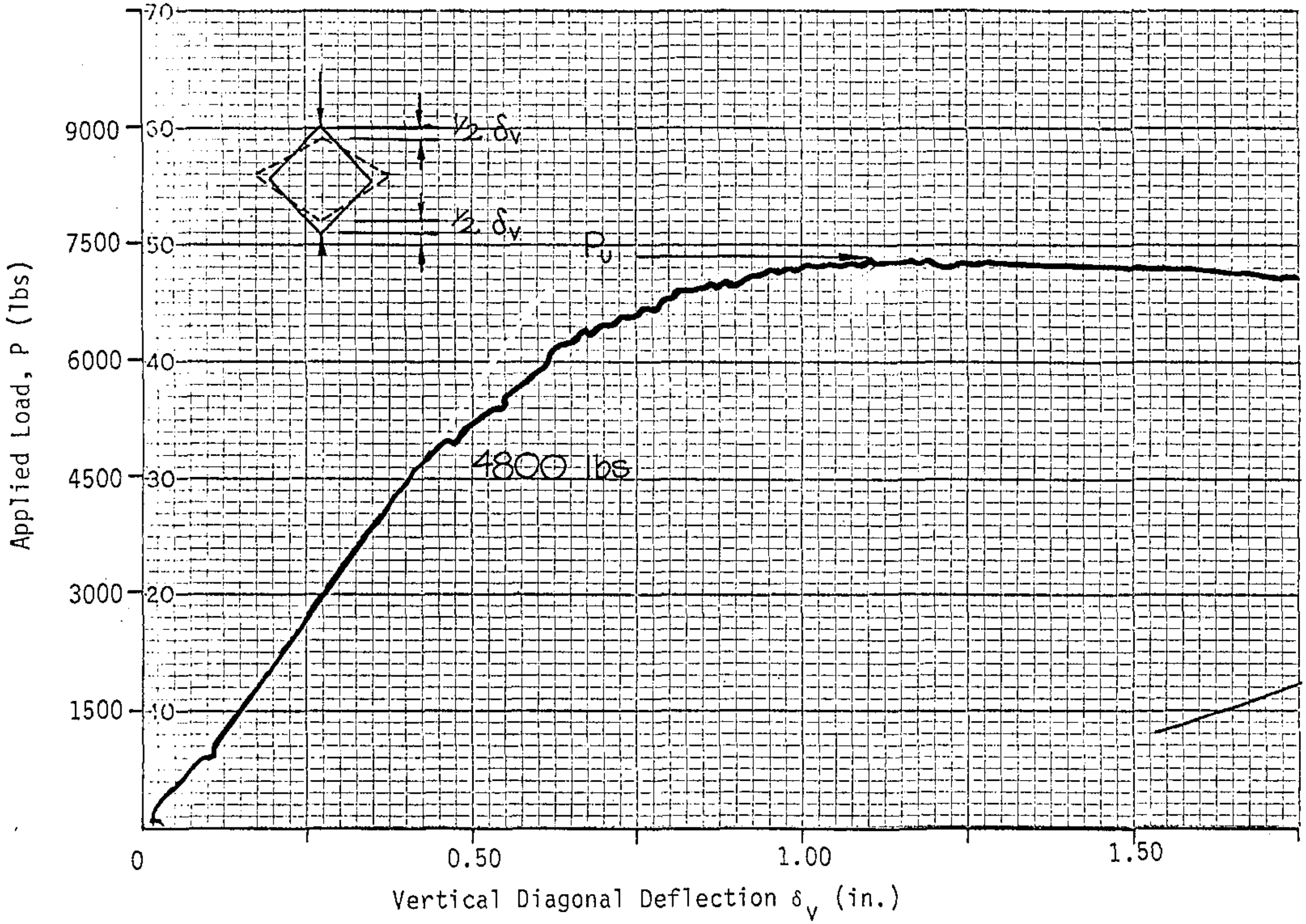


Fig. A-52. Load Versus Vertical Diagonal Deflection for Exterior Wall No. 4.

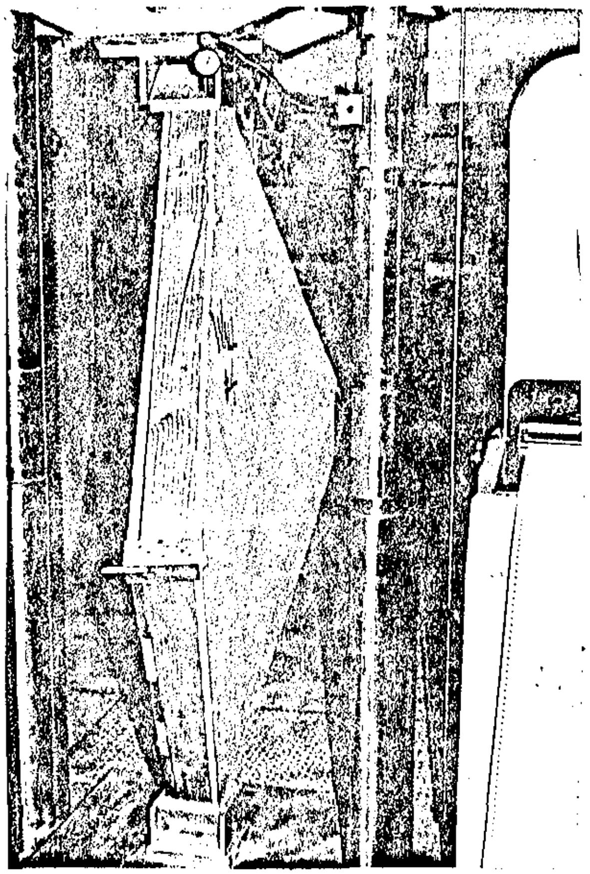


Fig. A-53. Failure of Wall Number 4.

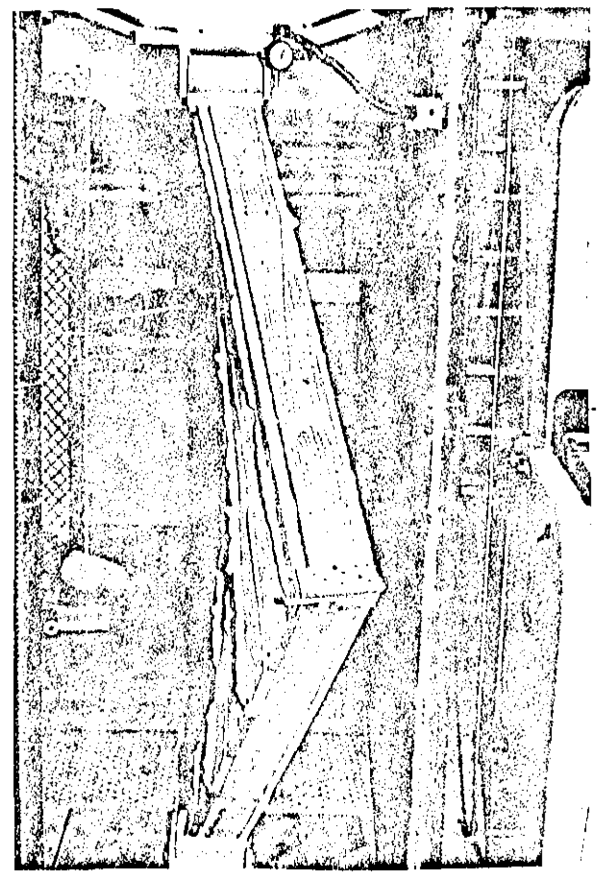
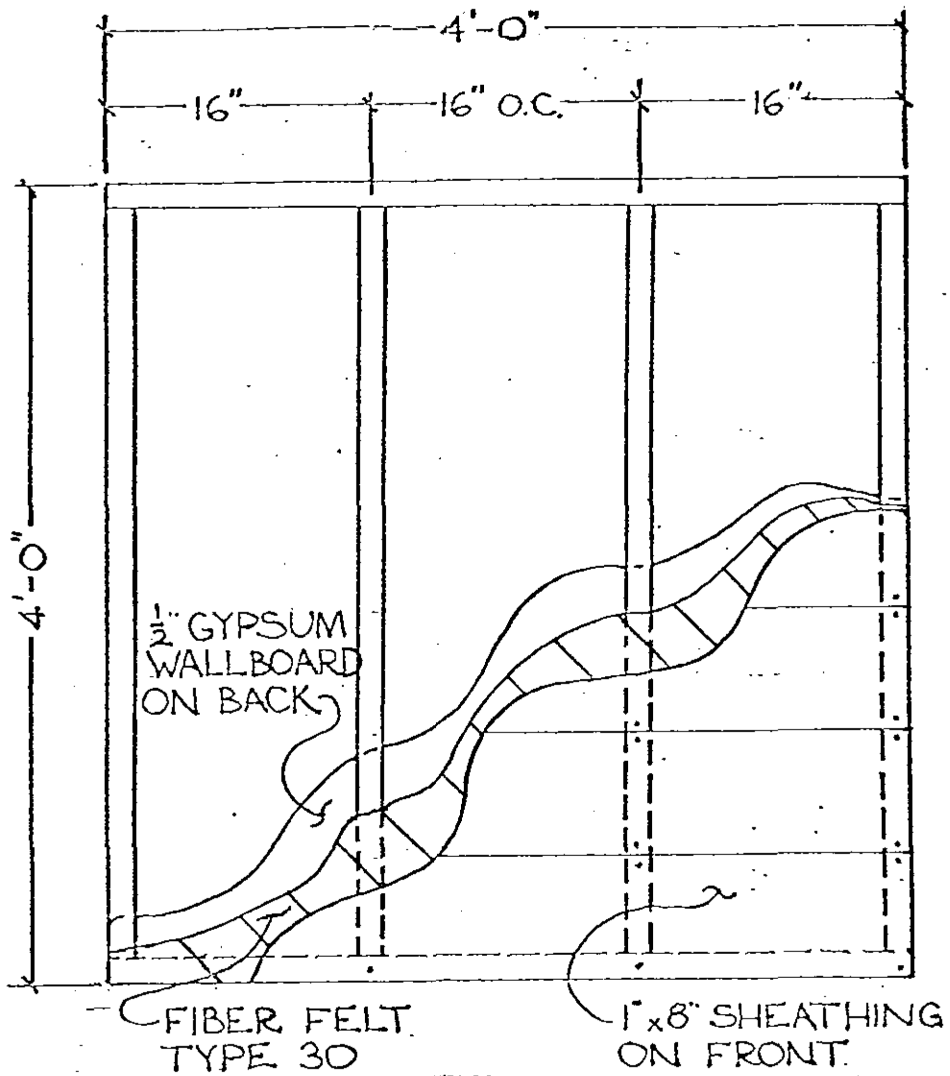


Fig. A-54. Failure of Wall Number 4.

EXTERIOR 4' x 4' WALL NO. 5

Description



The basic framing was used in the construction of this wall. It consisted of 2" x 4" Douglas Fir-Larch (Select Structural) studs on 16" centers as shown above, and 1/2" gypsum wallboard on one side and 1" x 8" sheathing nailed to the wall. A layer of asphalt impregnated felt paper serving as a moisture barrier was placed between the sheathing and wall.

Test Procedure

Wall No. 5 was placed in the testing machine with one of its diagonals in the vertical position as shown in Fig. A-55 A and B. The dial gauge used in measuring the horizontal diagonal deflection can be seen in Fig. A-55A. The wall was slowly loaded to failure.

The load versus vertical diagonal deflection was monitored by the testing machine plotted and the resulting plot is shown in Fig. A-56. The horizontal diagonal deflection was also recorded at various load increments and have been plotted in Fig. A-41.

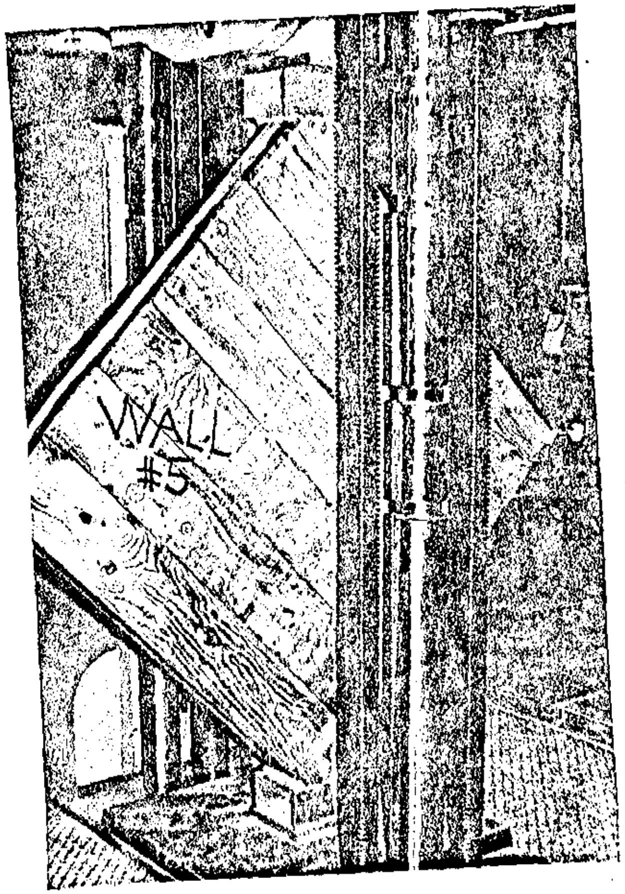
Test Data

The wall was weighed before and after the application of foam and the weights were 99 lbs and 105 lbs, respectively. This increased the dead load 6% or 0.38 lbs/ft^2 due to the application of foam. Referring to Fig. A-56, the ultimate load for this wall was 5,825 lbs. This is more than 200% greater than the non-foamed base case (Base Case No. 2). The elastic region extended up to 4,950 lbs.

Failure

Wall No. 5 failed due to buckling along its vertical diagonal as shown in Fig. A-57. Considerable deflection occurred but the sheathing and sheetrock remained relatively intact (see Fig. A-58).

A.



B.

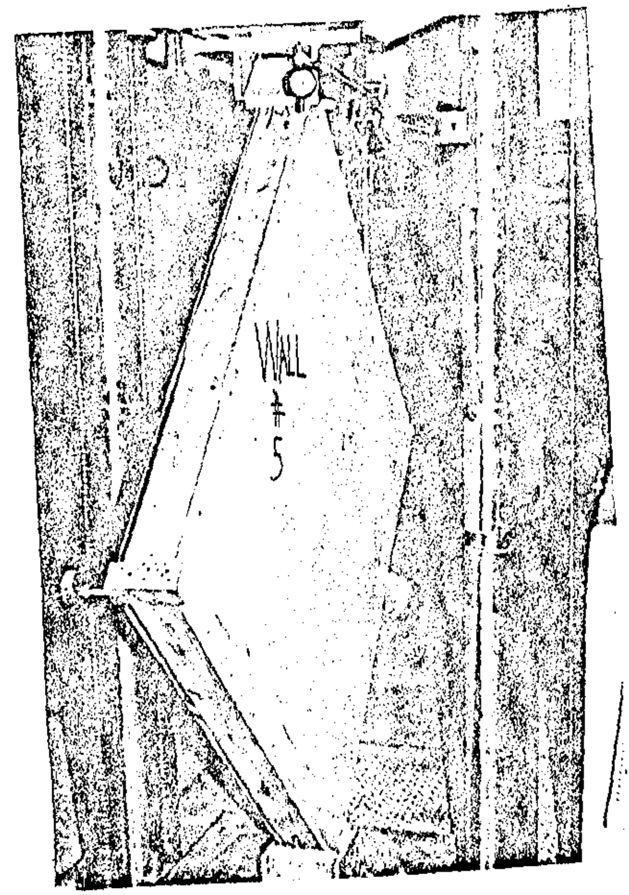


Fig. A-55. Wall Number 5 in the Testing Machine - Two Views.

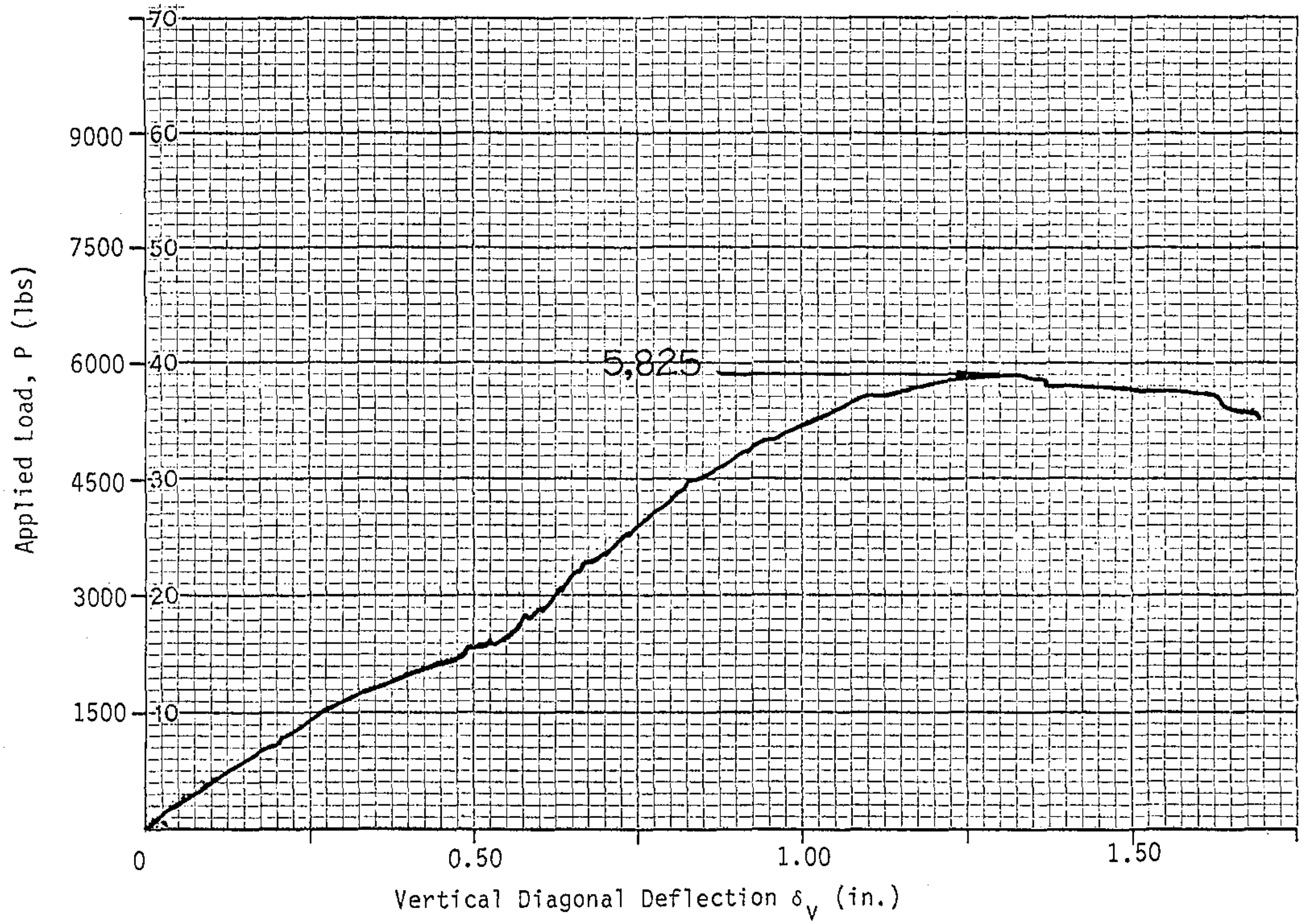


Fig. A-56. Load Versus Vertical Diagonal Deflection for Exterior Wall No. 5.

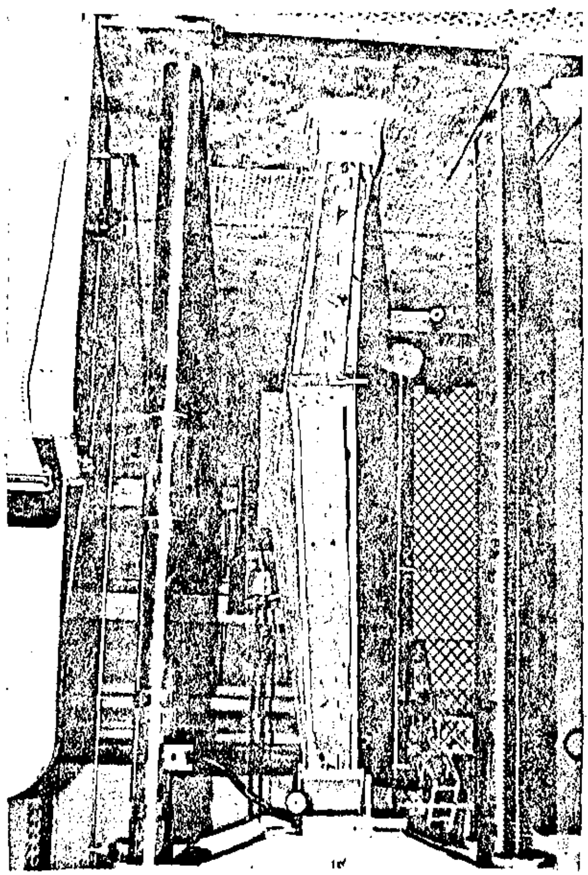


Fig. A-57. Failure of Wall Number 5 Due to Buckling.

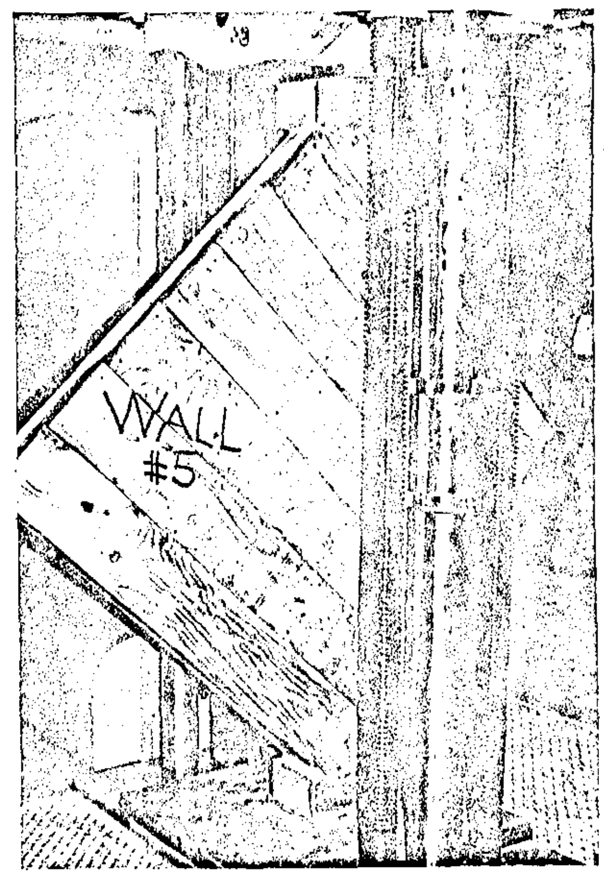
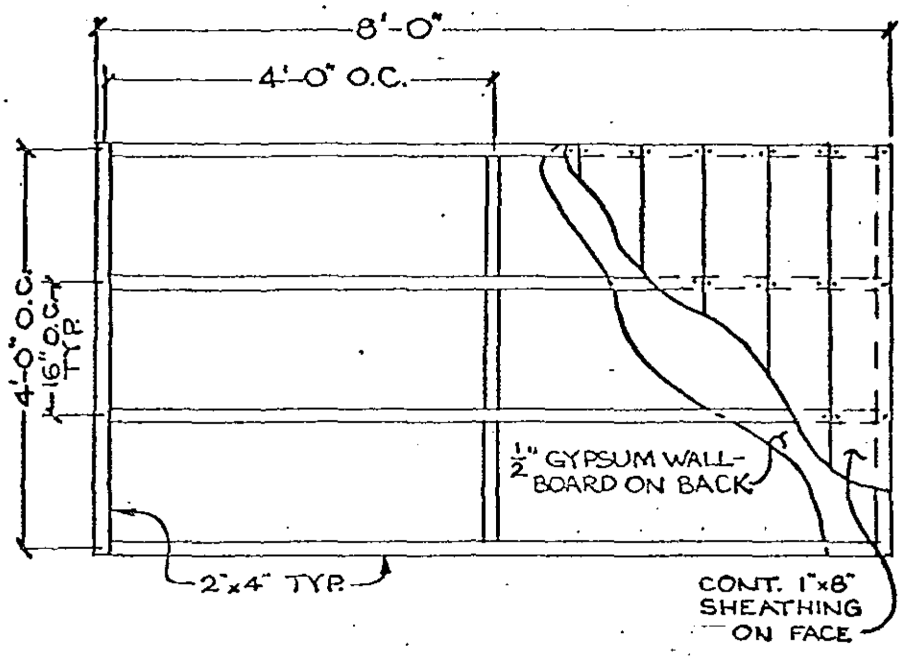


Fig. A-58. View of Sheathing of Wall Number 5 After Failure.

EXTERIOR 4' x 8' WALL - BASE CASE

Description



The above framed was constructed using Douglas Fir-Larch (Select Structural) lumber using the nailing schedule shown in the text.

Test Procedure

The base case wall was placed in the horizontal shear test and loaded slowly to failure (Fig. A-59).

Test Data

An electronic displacement gauge measured the center deflection of the wall while the load was increased. Fig. A-60 shows the resulting load versus deflection graph. The wall behaved somewhat linearly to about

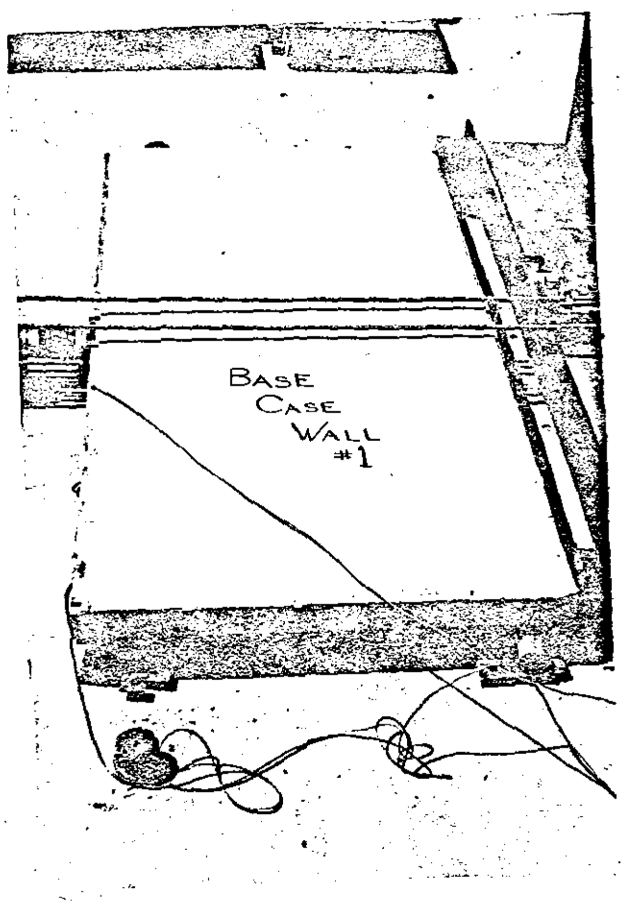


Fig. A-59. Base Case 4 ft x 8 ft Wall in Horizontal Shear Test.

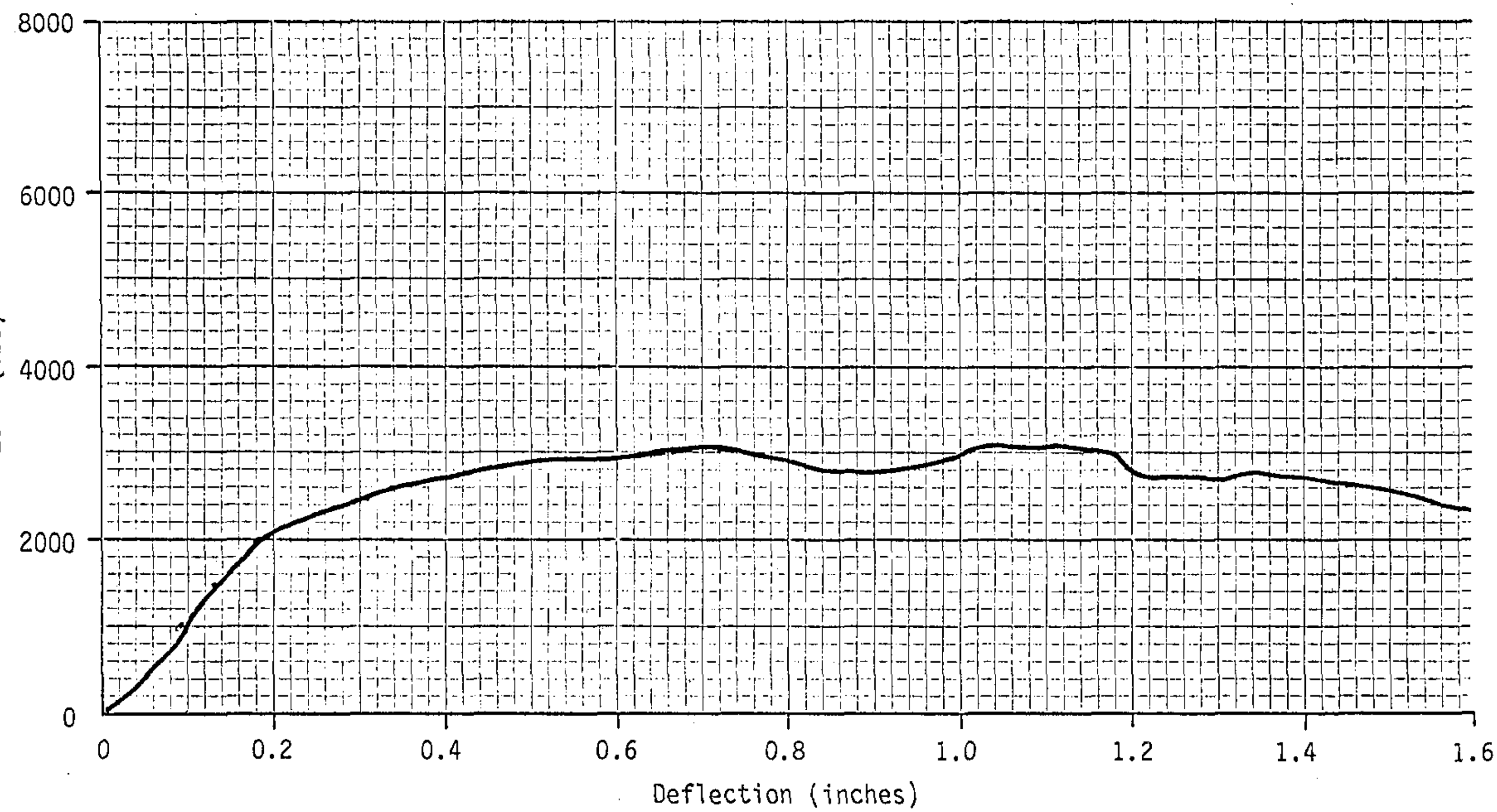


Fig. A-60. Test Results for Base Case Wall.

2,000 lbs and had an ultimate strength of about 3,100 lbs. The base case wall stiffness in the elastic range was approximately 11,000 lbs/in.

Failure

Fig. A-61 shows the deflected shape of the specimen at failure. From this photograph, you can see the sheetrock nails had torn the wallboard along both longitudinal edges and interior studs. Fig. A-62 shows the sheathing side where the relative dislocations of the 1 x 8 pieces are readily visible. Closer examination reveals cracks in various sheathing sections (Fig. A-63).

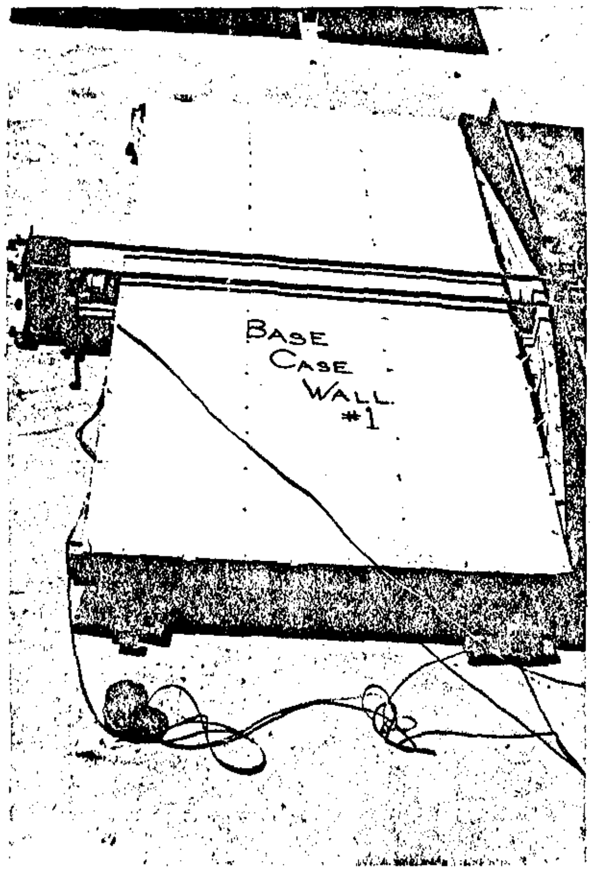


Fig. A-61. Base Case 4 ft x 8 ft Wall After Failure.

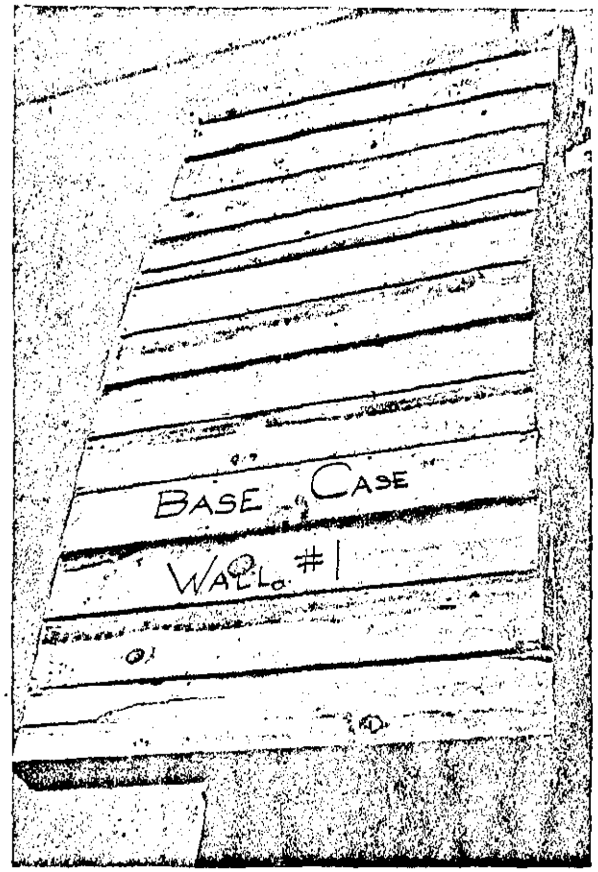
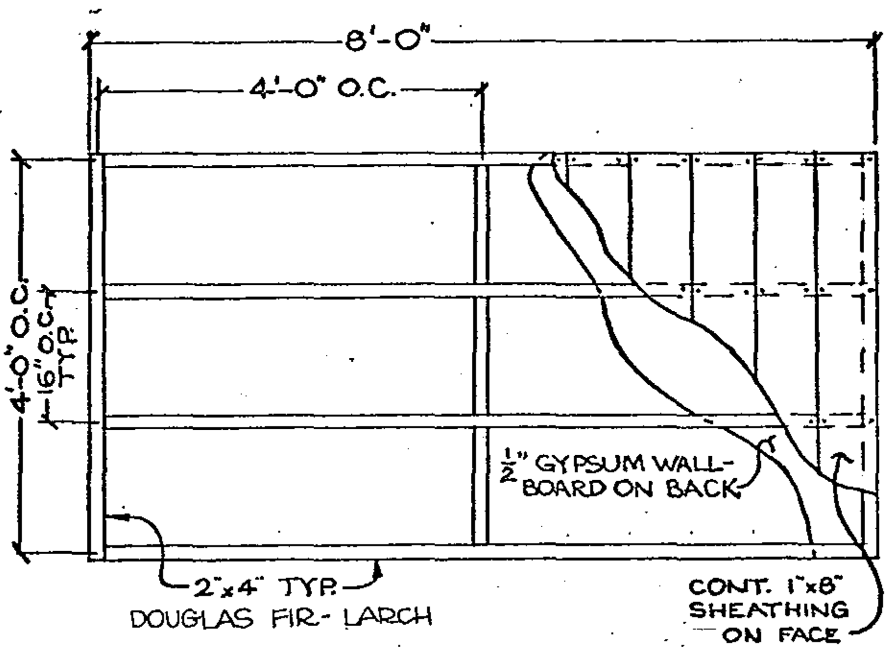


Fig. A-62. Sheathing Side of Base Case 4 ft x 8 ft Wall After Test.

Fig. A-63. Cracks in Sheathing of Base Case 4 ft x 8 ft Wall After Test.

EXTERIOR 4' x 8' WALL NO. 1

Description



Wall No. 1 was constructed in the same manner as the base case wall. The form was placed inside the wall using the techniques in Phase 1. The wall was completely filled causing some distress where the sheetrock was nailed (separated from studs).

Test Procedure

Wall No. 1 was tested in the same manner as the base case in the horizontal shear test (Fig. A-64). The load was slowly increased until failure occurred.

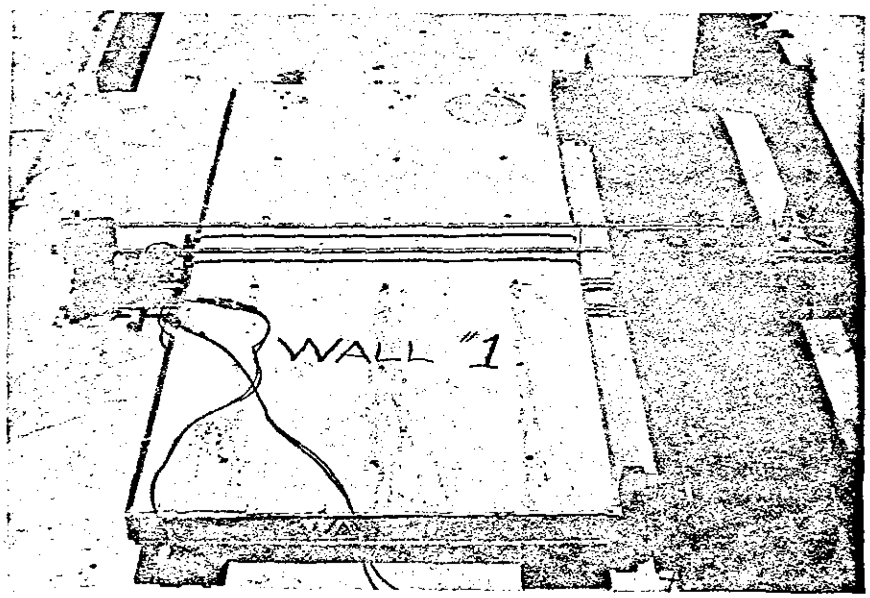


Fig. A-64. Wall Number 1 in Horizontal Shear Test Arrangement.

Test Data

The load versus deflection test results are shown in Fig. A-65. The load-deflection curve is approximately linear (i.e. straight) to 9,000 lbs for a stiffness of 64,000 lbs/in. The wall exhibited a yield point at 10,200 lbs with an ultimate strength of 12,000 lbs. Note the high load was maintained for considerable displacement showing remarkable energy absorption.

Failure

The first evidence of failure was cracking of the sheetrock. Fig. A-66 shows the deflected shape after failure and the extensive cracking. Fig. A-67 shows the major crack across the center penetrating into the foam. Failure in the foam occurred along the center line blocking and between pieces of sheathing. (Fig. A-68).

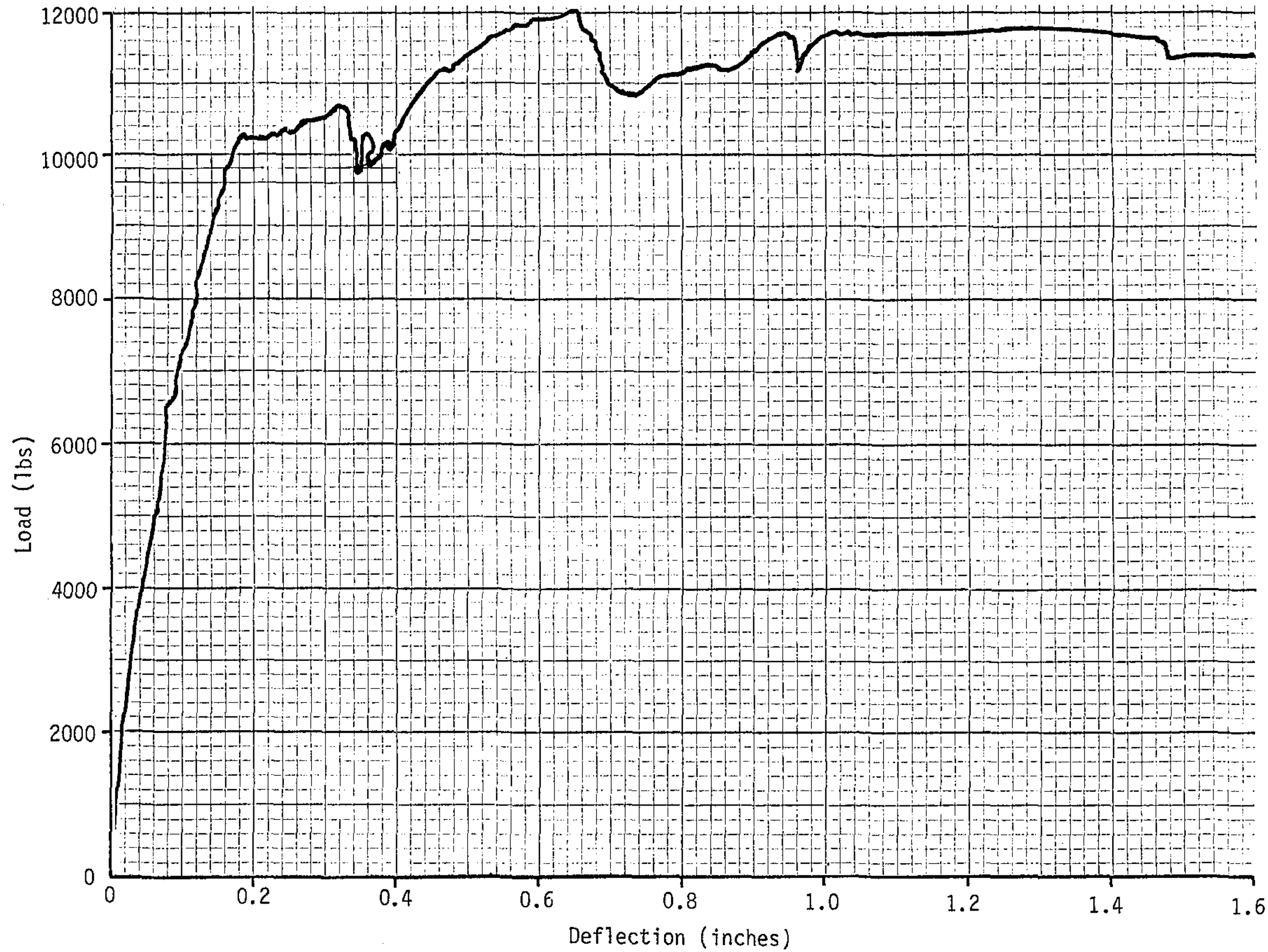


Fig. A-65. Wall Number 1, Load versus Deflection Curve.

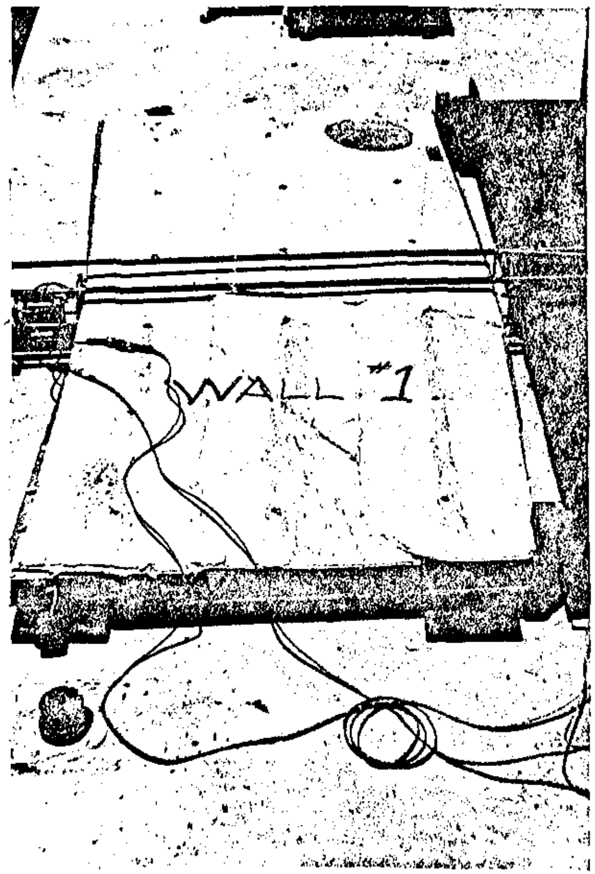


Fig. A-66. Wall Number 1 After Test.

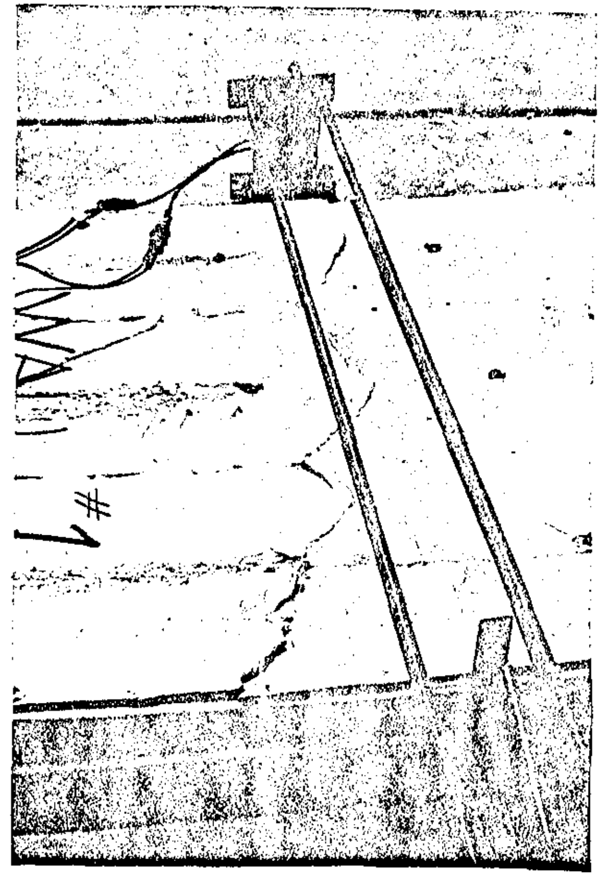
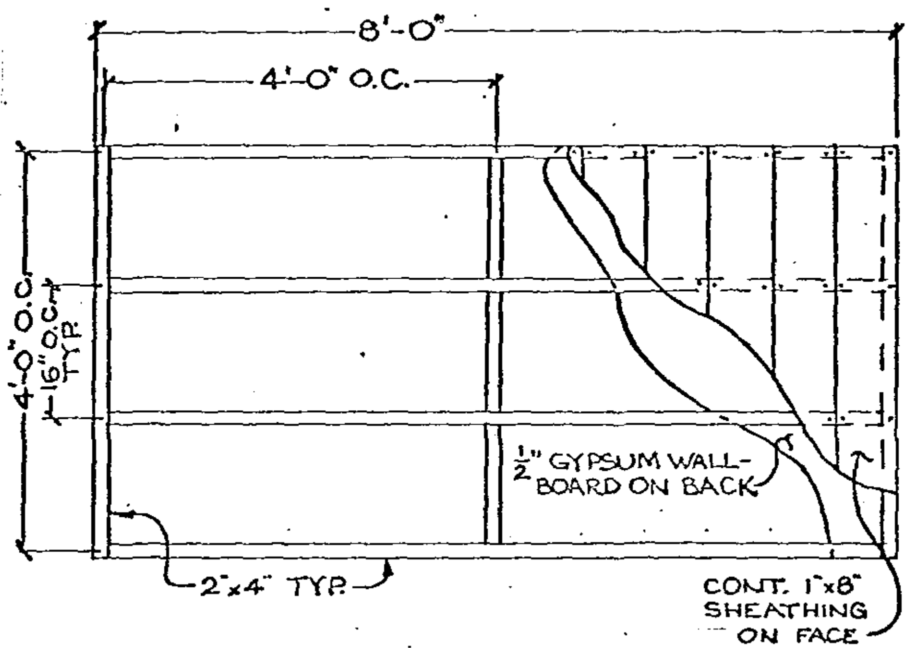


Fig. A-67. Crack Across Center Wallboard of Wall Number 1.

Fig. A-68. Shear Failure in Foam, Seen Between Sheathing.

EXTERIOR 4' x 8' WALL NO. 2

Description



Wall No. 2 was constructed the same as the base case wall. Foam was injected in Phase 1 through three holes at the same height in each cell using three lifts.

Test Procedure

Wall No. 2 was also subjected to the horizontal shear test similar to Wall No. 1 except the sheathing side was placed on top (Fig. A-69). As the load was increased, the resulting deflection at the center of the span was recorded.

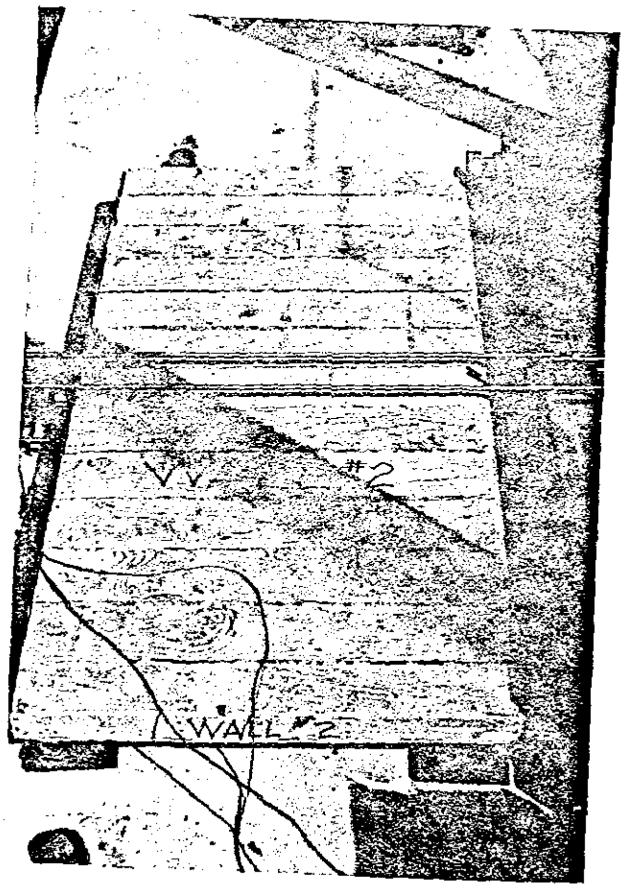


Fig. A-69. Wall Number 2 in Horizontal Shear Test Configuration.

Test Data

Fig. A-70 is the load-deflection curve for Wall No. 2. The elastic portion of the test extends to roughly 8,000 lbs for stiffness of 36,000 lbs/in. A central failure occurred at 11,800 lbs, but in subsequent displacement the wall decreased its strength to a maximum of 13,000 lbs.

Failure

Failure occurred in the top half of the wall apparently due to some voids along the top chord member. Fig. A-71 shows this failure by the large relative displacement between the two halves. In the top portion, foam failure was observed as large cracks between sections of sheathing (Fig. A-72). The sheetrock side shows extensive cracking in the failed half and virtually none in the bottom half (Fig. A-73).

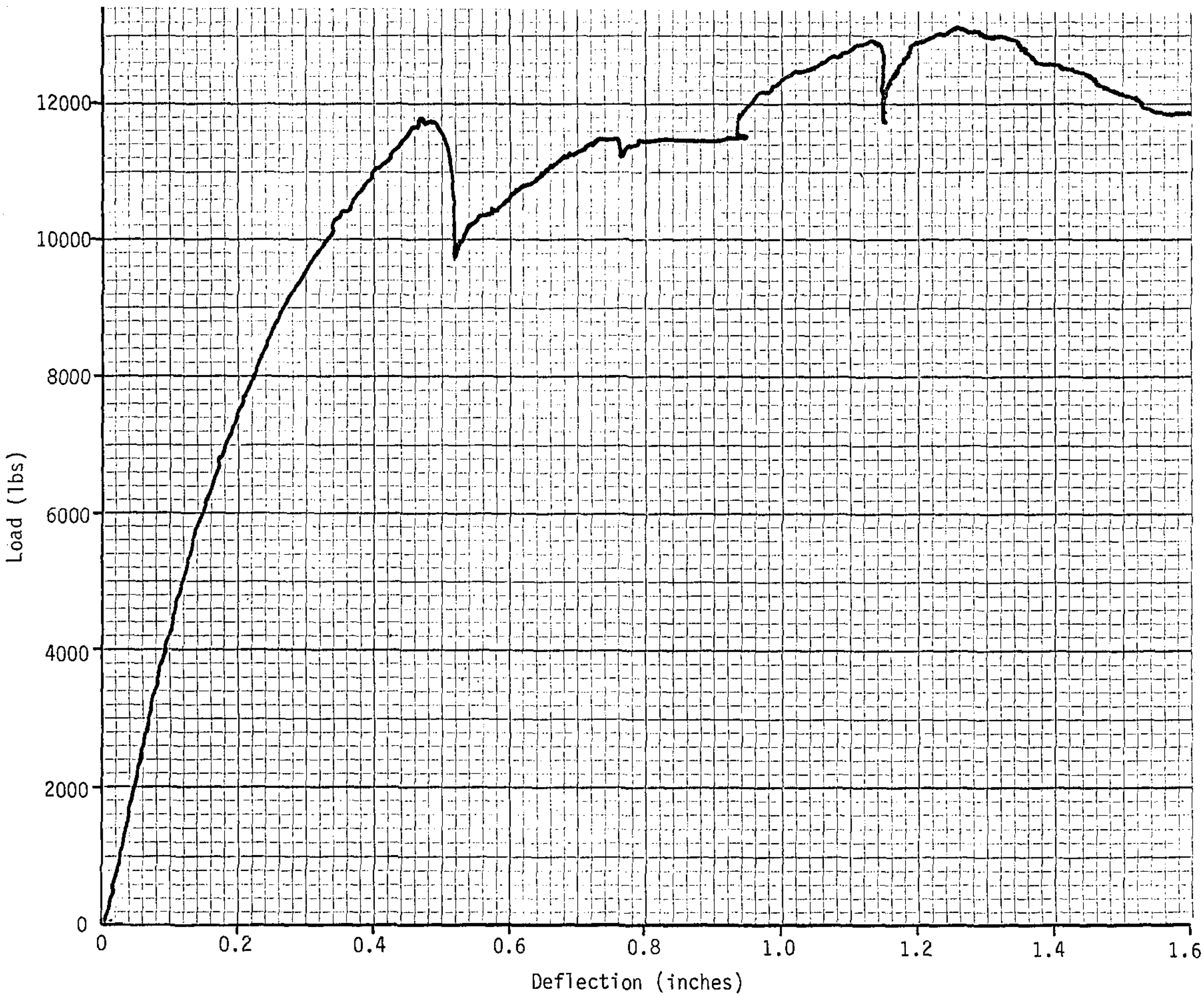


Fig. A-70. Exterior Wall No. 2 Load Deflection Curve.

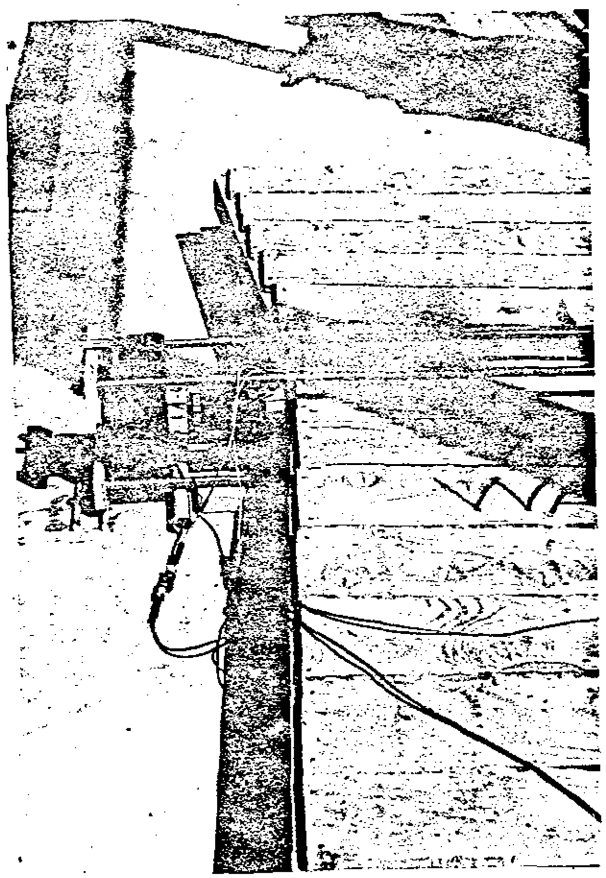


Fig. A-71. Relative Displacement Between Upper and Lower Half at Failure of Wall Number 2.

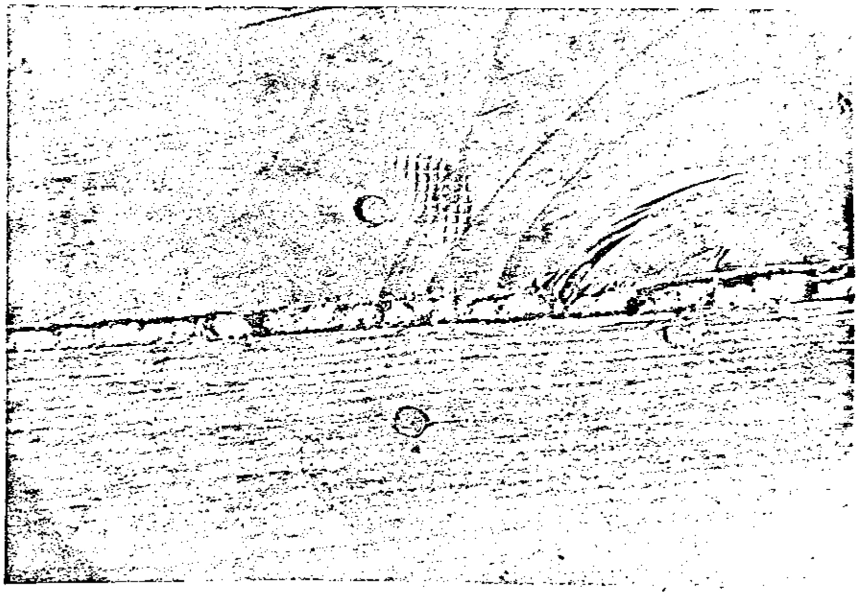


Fig. A-72. Shear Failure of Foam Between Sheathing Sections of Wall Number 2.

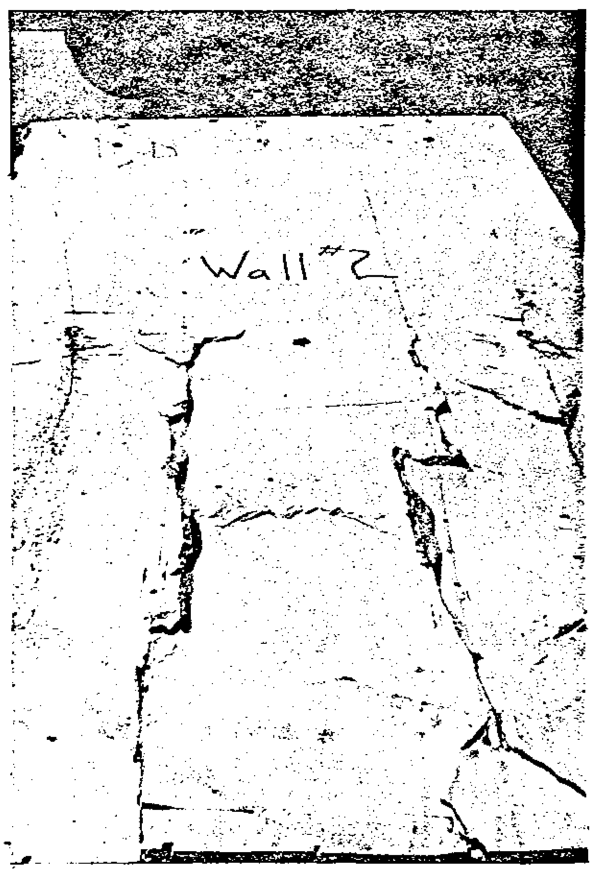
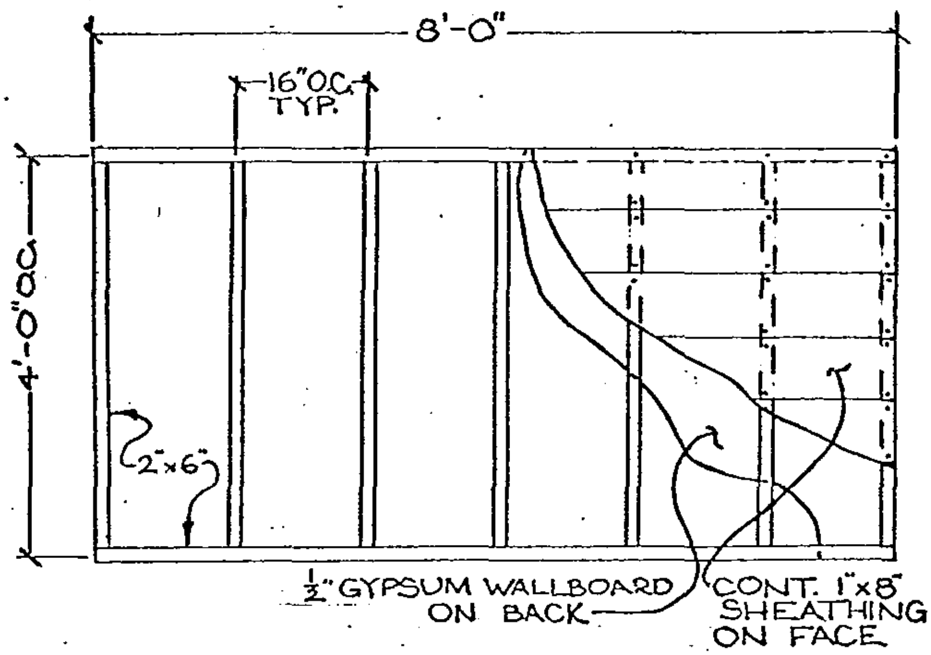


Fig. A-73. Extensive Cracking of Sheetrock at Failure at Top of Wall Number 2.

FLOOR TEST DATA

FLOOR - BASE CASE

Description



The base case floor was constructed as shown above using Douglas Fir-Larch (Select Structural) lumber and the nailing schedules shown in the text.

Test Procedure

This specimen was subjected to the horizontal shear test as shown in Fig. A-74 and loaded to failure.

Test Data

A load deflection curve was recorded and can be seen in Fig. A-75. As the graph shows, the floor base case did not behave elastically and required

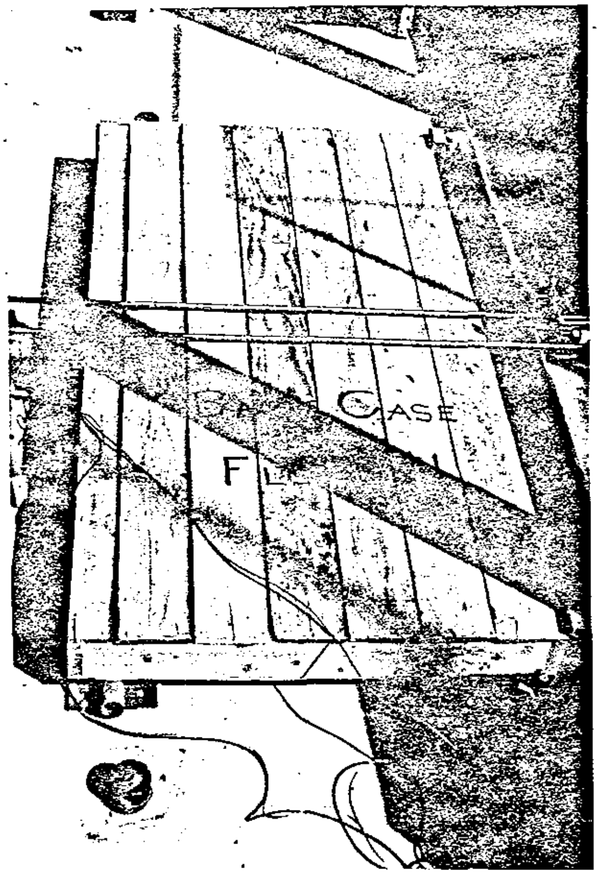


Fig. A-74. Floor Base Case in Horizontal Shear Test Frame.

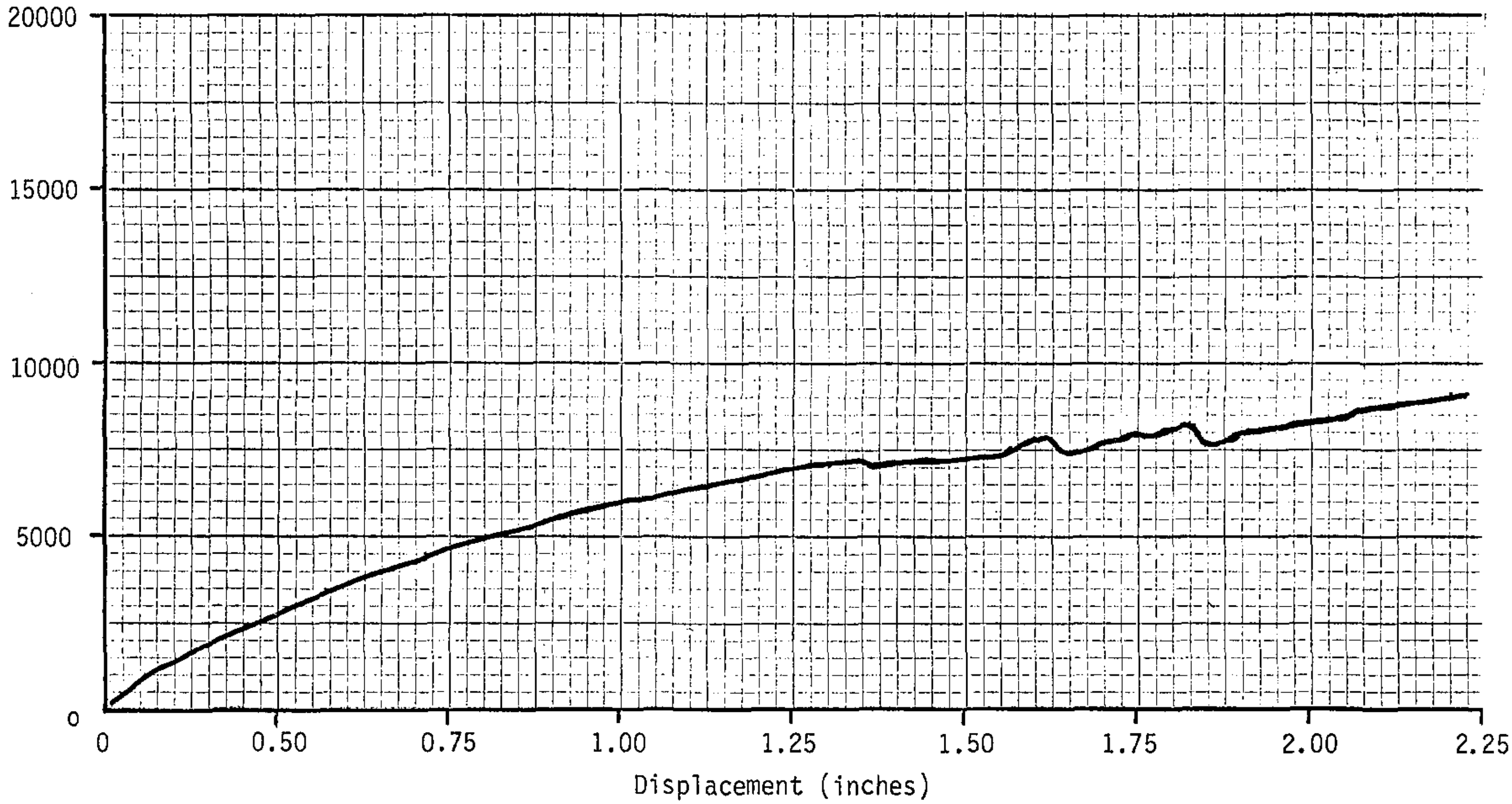


Fig. A-75. Floor Base Case Test Results.

large deflection to develop significant load restraint. The ultimate load before failure was about 9,000 lbs.

Failure

The test specimen after failure is shown in Fig. A-76. At the start of the test, the nails holding the sheetrock tore through along all four sides (Fig. A-77). As the deflection increased, more load was transferred to the sheathing at about 9,000 lbs and 1.5 inches of deflection bending failure occurred in the sheathing at the center of the panel (Fig. A-78).

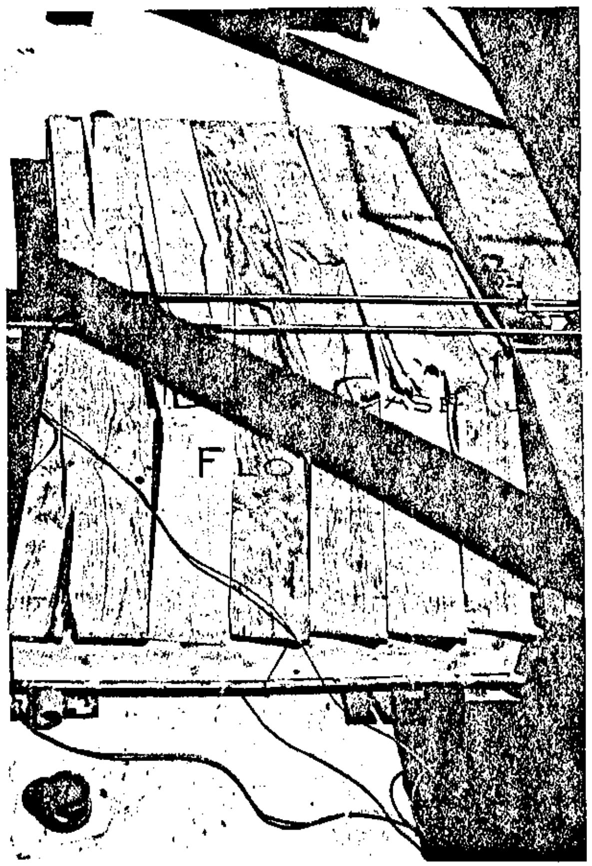


Fig. A-76. Floor Base Case After Test.

Fig. A-77. Wallboard Side of Floor Base Case After Test.

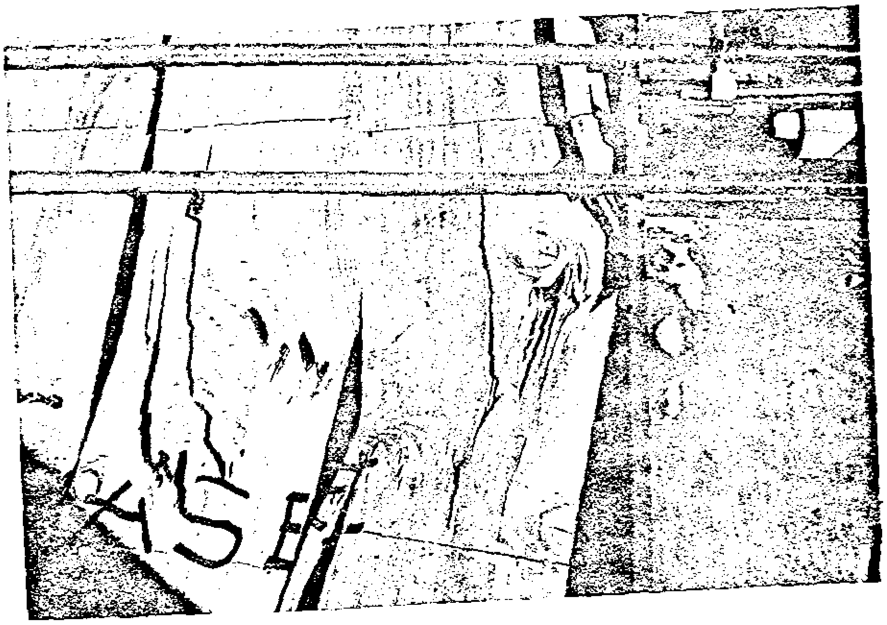
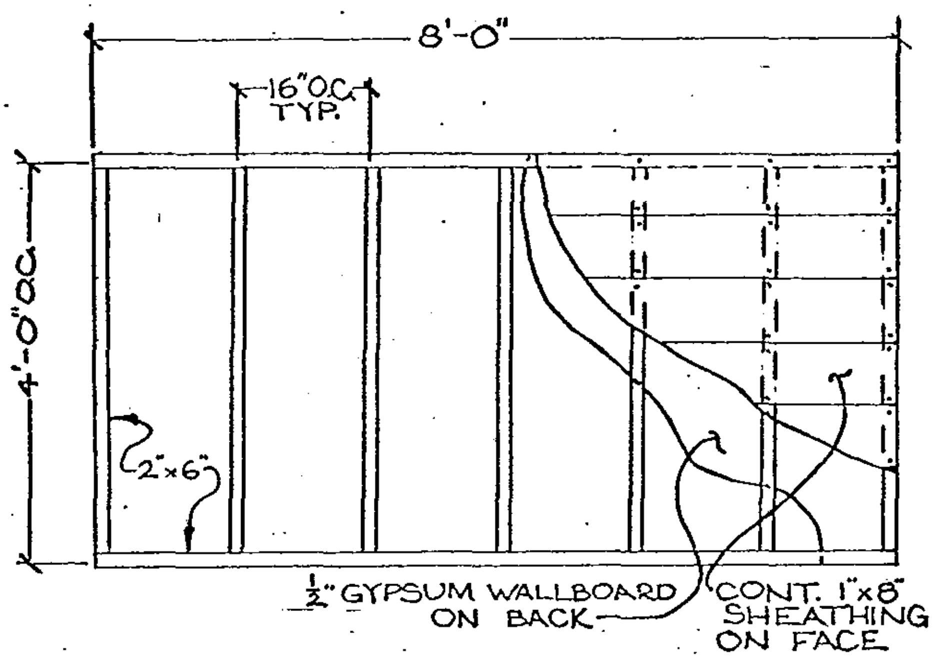


Fig. A-78. Sheathing Failure in Floor Base Case.

FLOOR NO. 1

Description



Floor No. 1 was constructed similar to the base case and filled with foam in Phase 1. In some areas, as the result of overflowing, the sheetrock cracked or separated from the framework.

Test Procedure

Floor No. 1 was placed in the horizontal shear test frame and tested to failure (Fig. A-79).

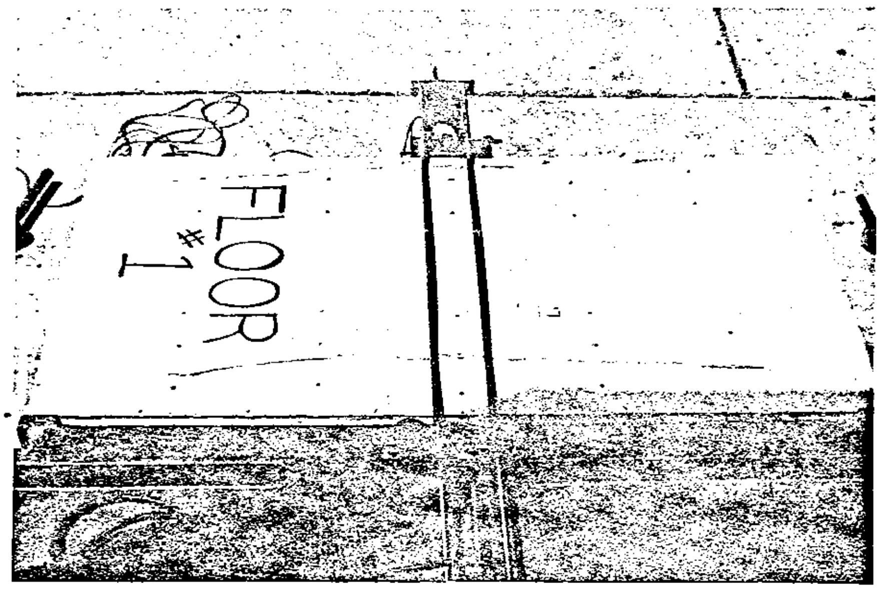


Fig. A-79. Floor Number 1 in Horizontal Shear Test Arrangement.

Test Data

The graph in Fig. A-80 shows elastic behavior to almost 10,000 lbs with a slope of 30,000 lbs/in. The maximum or ultimate load was 18,000 lbs at 1.25 inches of deflection.

Failure

Failure occurred when the foam separated from the perimeter cord member (Fig. A-81). A section cut through the floor shows cracks extending into the sheetrock and sheathing (Figs. A-82 and A-83).

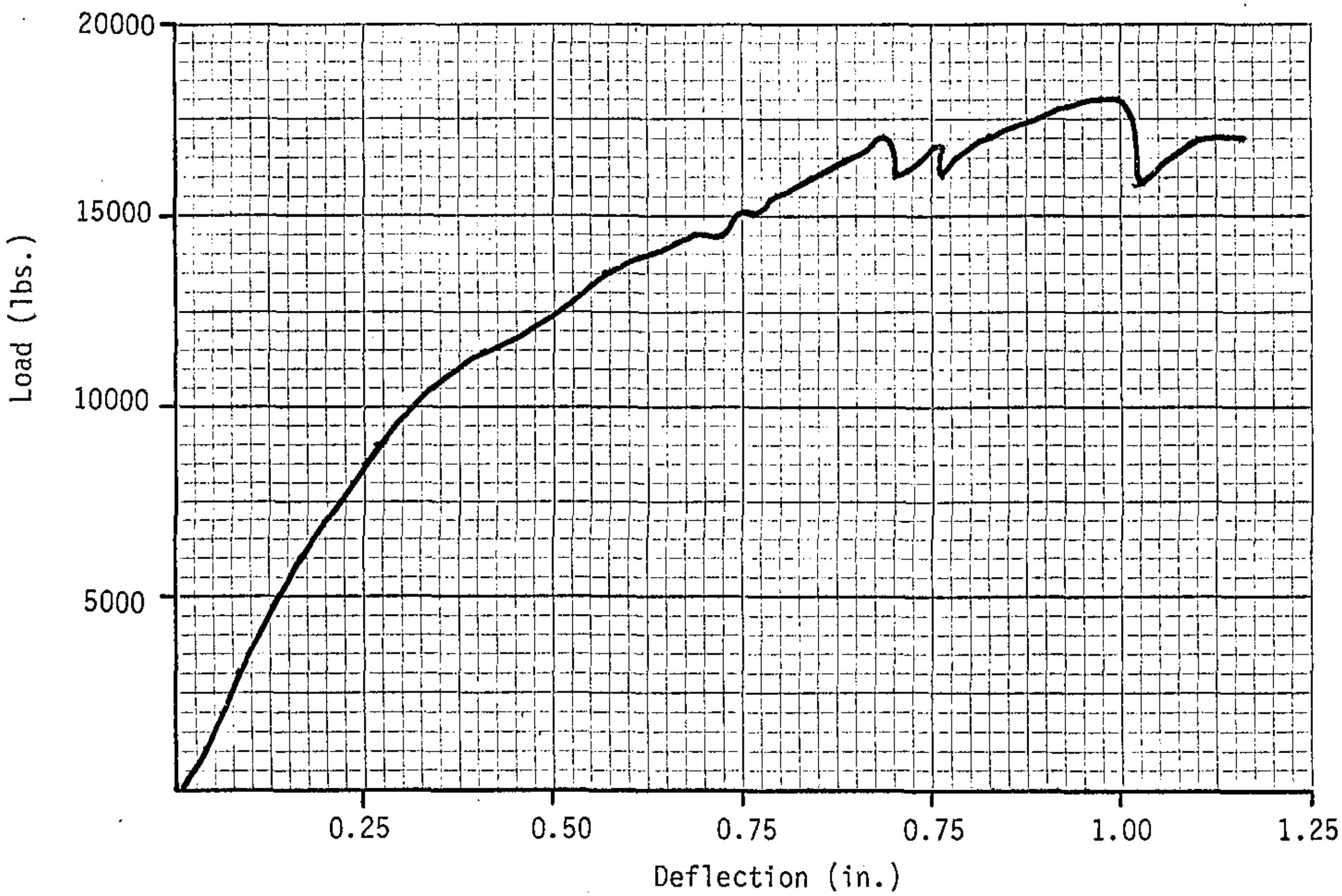


Fig. A-80. Load vs. Deflection Plot for Floor No.1.

Fig. A-81. Separation of Sheetrock and Foam from Longitudinal Member of Floor Number 1.

Fi.g A-82. Foam Failure Along Cord of Floor Number 1.

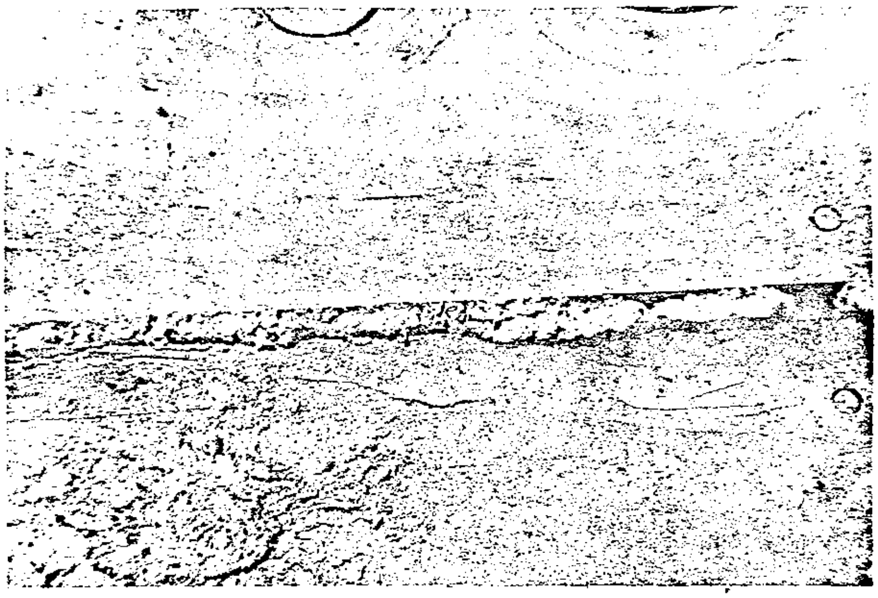
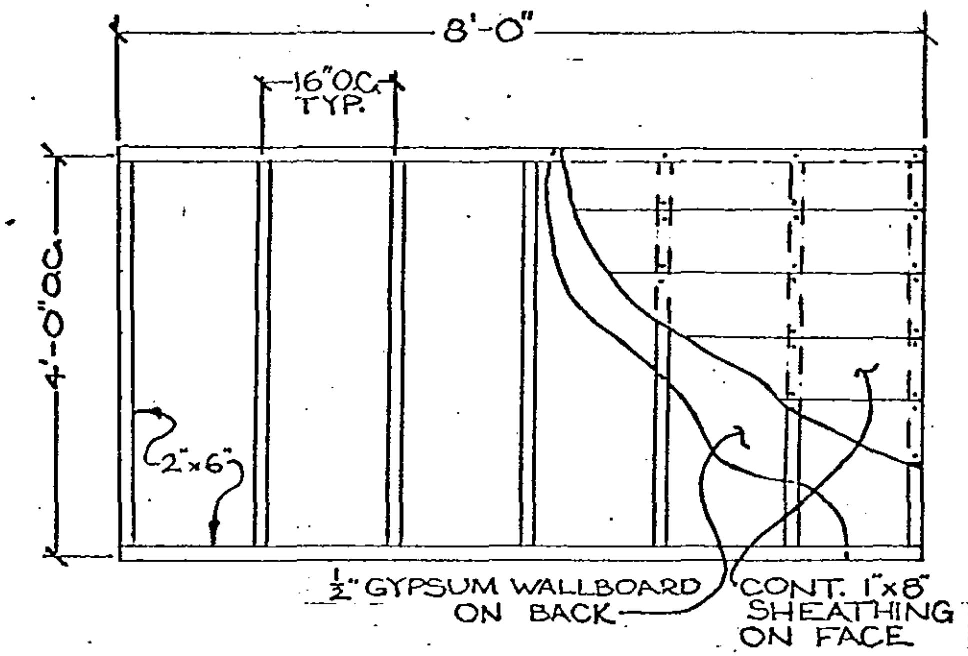


Fig. A-83. Crack in Foam Between Sheathing of Floor Number 1.

FLOOR NO. 2

Description



This floor was constructed the same as Floor No. 1 and the base case. Foam was placed inside the panel during Phase 1.

Test Procedure

Fig. A-84 shows the specimen on the horizontal shear test frame. The floor was loaded statically until failure occurred.

Test Data

The test results for Floor No. 2 are shown in Fig. A-85. The load-deflection curve is fairly linear to 12,000 lbs. A loud crack at failure occurred at the ultimate load of 16,500 lbs.

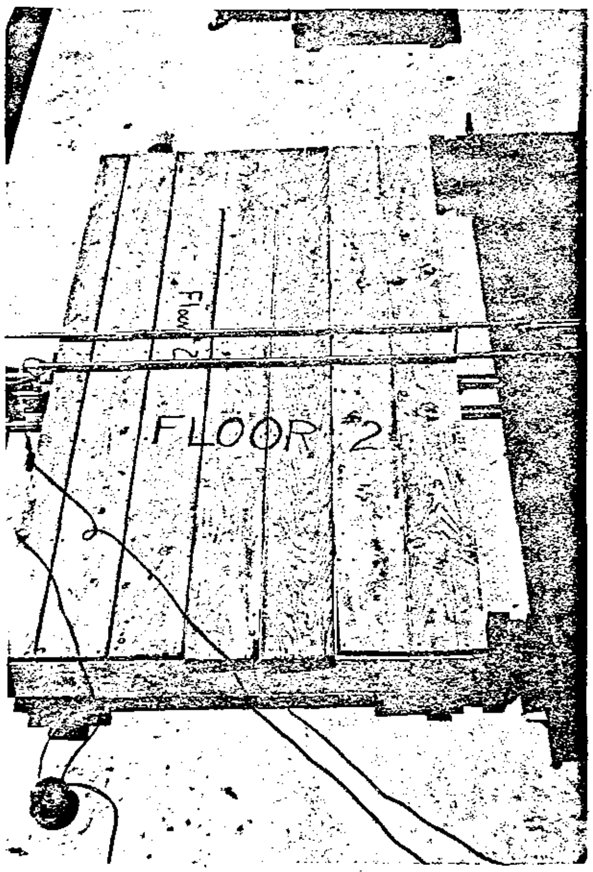


Fig. A-84. Floor Number 2 in Horizontal Shear Test Confirguration.

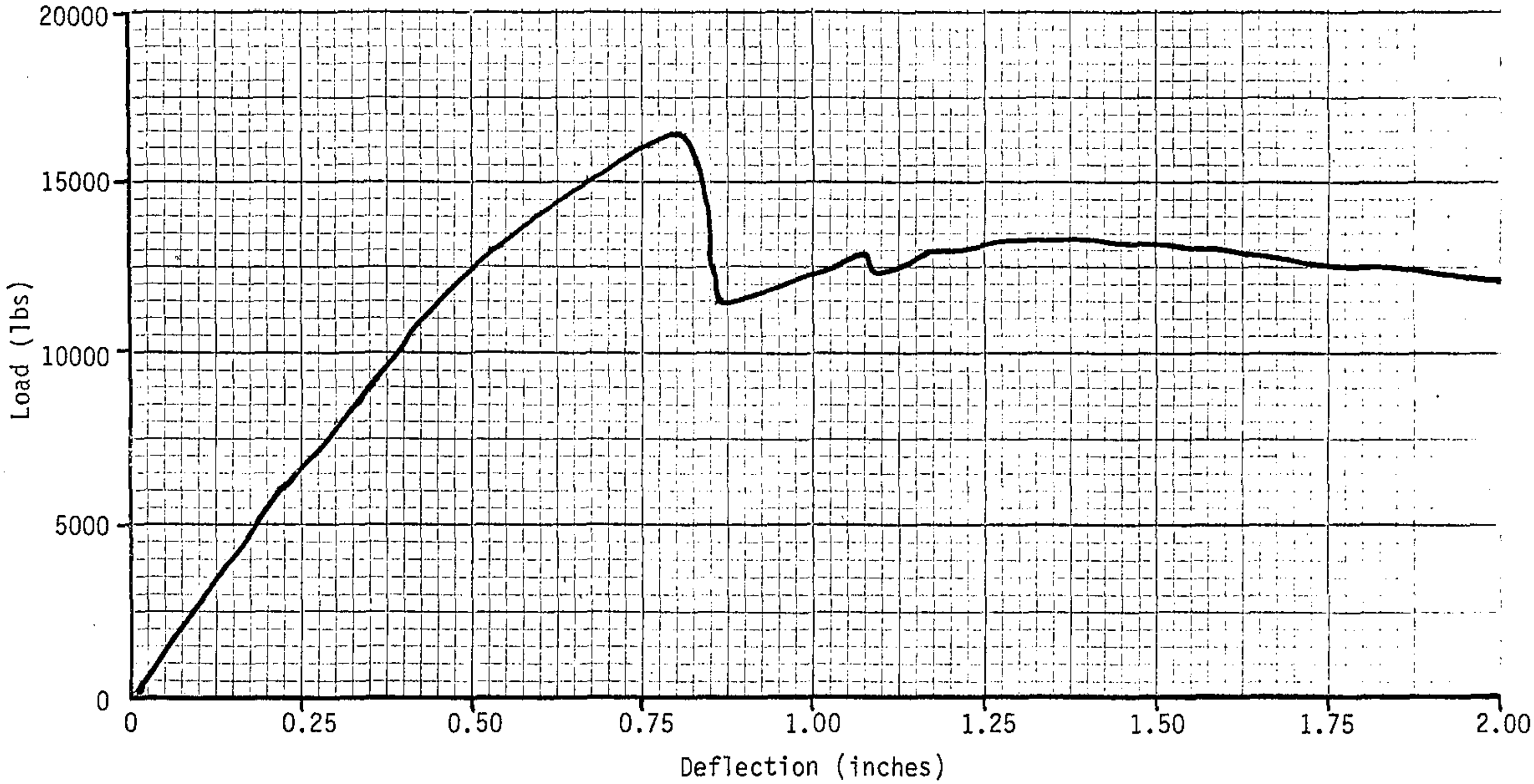


Fig. A-85. Floor Number 2 Test Results.

Failure

The failure of Floor No. 2 was very similar to that for Floor No. 1. After the foam separated from the center joists, the side member was seen protruding from the sheathing (Fig. A-86). A section through the floor system showed complete separation of the foam from the side member (Fig. A-87).

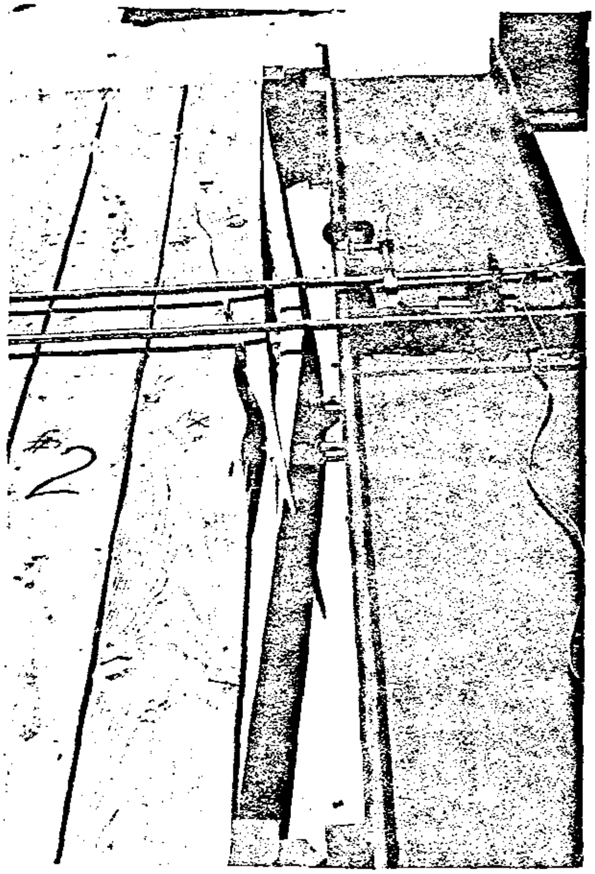


Fig. A-86. Floor Number 2 After Test.

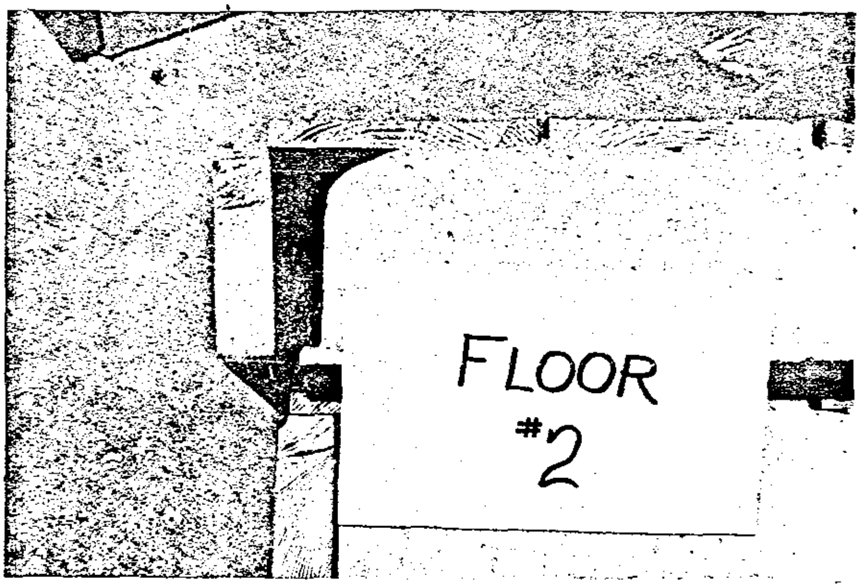
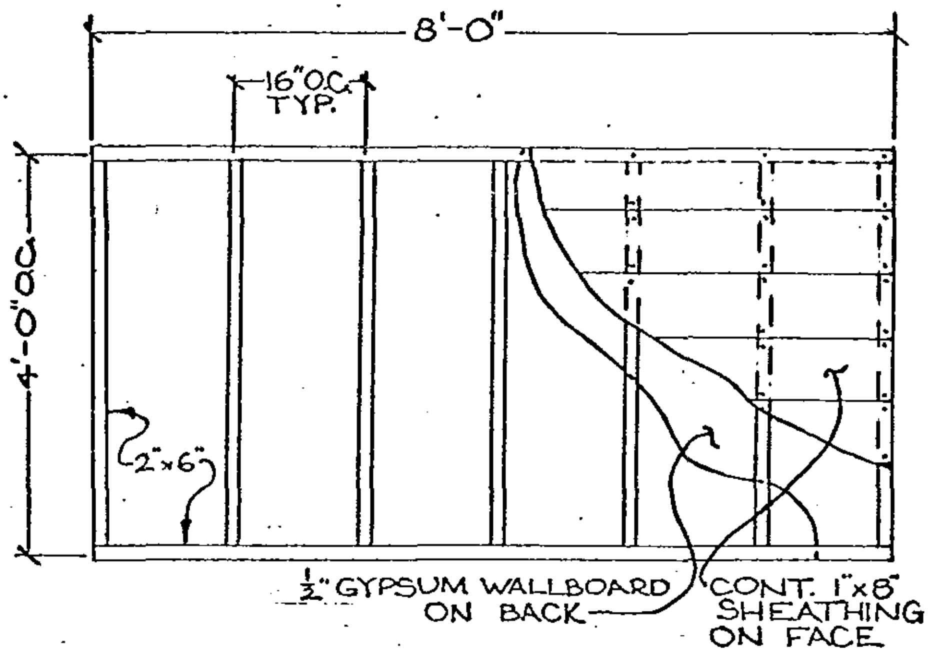


Fig. A-87. Floor Number 2 Section Showing Separation from Perimeter Member.

FLOOR NO. 3

Description



Floor No. 3 was constructed similar to Nos. 1 and 2 and the base case floor. This floor was injected with foam in Phase 3.

Test Procedure

The floor was tested in the horizontal shear test arrangement by slowly increasing the applied load until failure occurred (Fig. A-88).

Test Data

Fig. A-89 presents the test results and indicates a linear slope (elastic portion) to about 9,000 lbs. The elastic stiffness of this

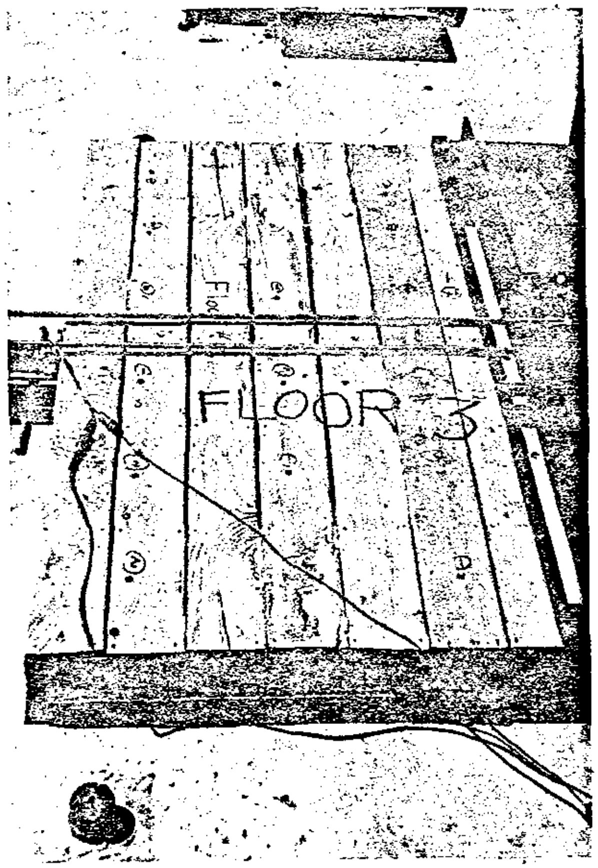


Fig. A-88. Floor Number 3 in Horizontal Shear Test Frame.

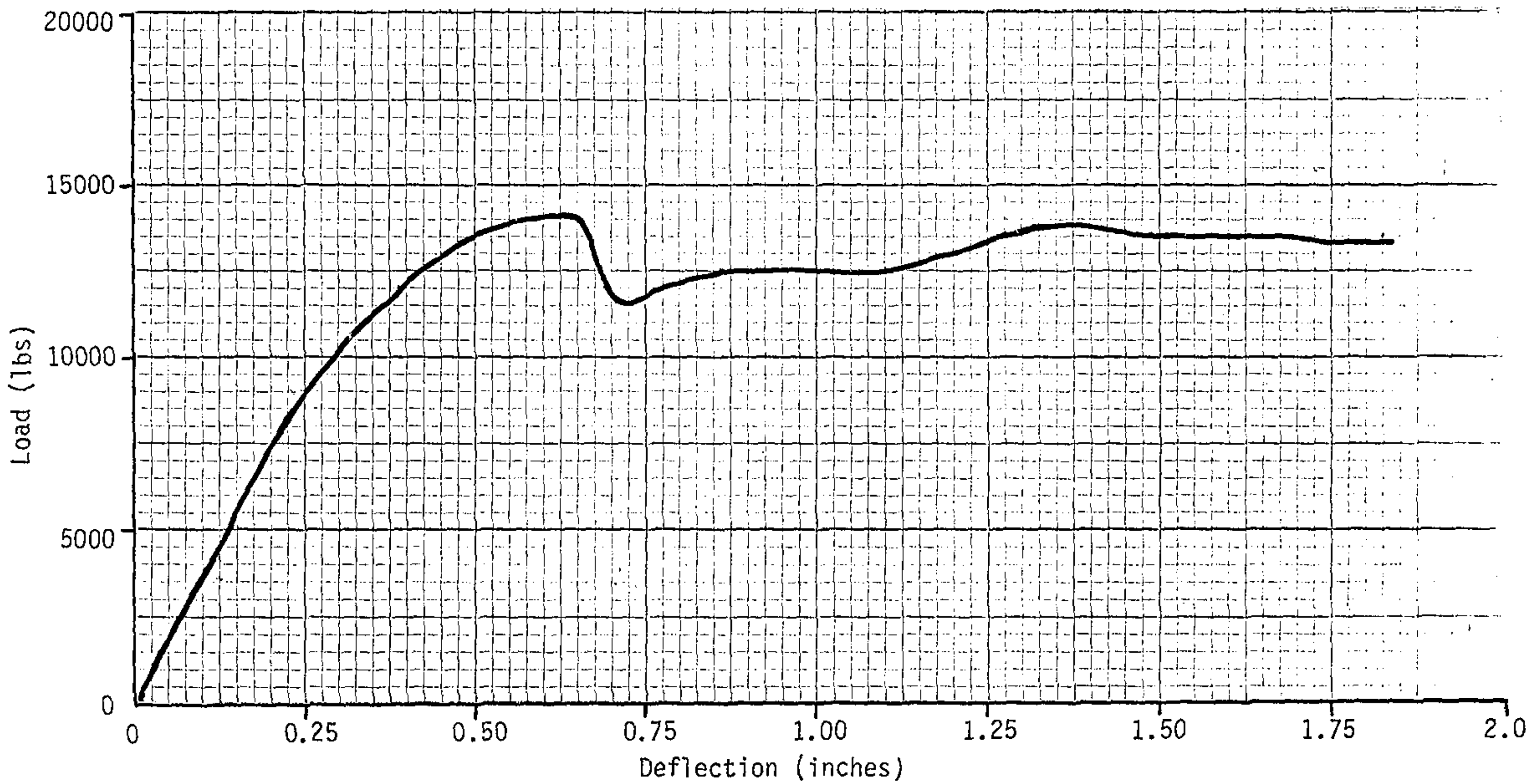


Fig. A-89. Floor Number 3, Load versus Deflection Graph.

specimen was 36,000 lbs/in. A definite failure occurred at 14,000 lbs, however, the test panel continued to sustain a high load.

Failure

The mode of failure was the same as in Floors Nos. 1 and 2. Fig. A-90 shows a bending failure in the sheathing after the foam had separated. Fig. A-91 shows the connection failure to the center joist.

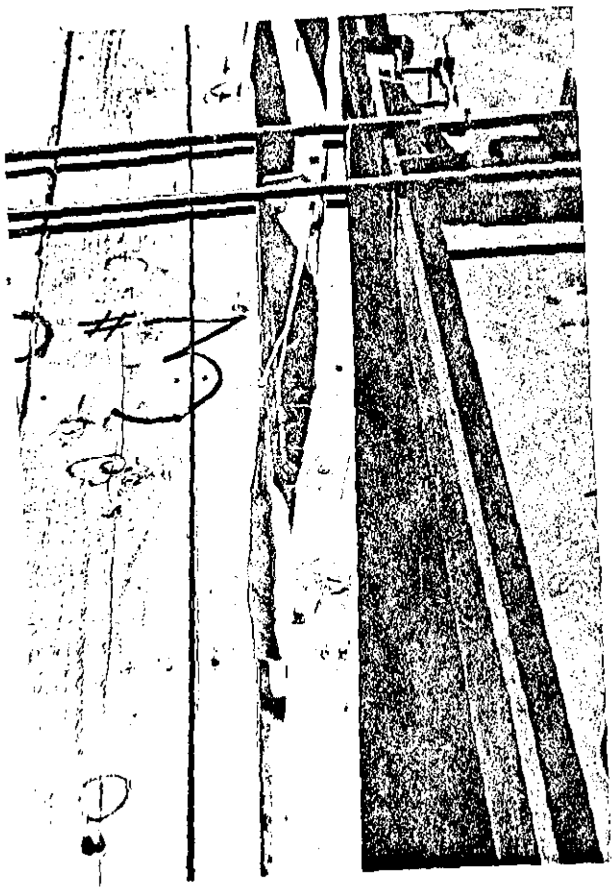


Fig. A-90. Floor Number 3 Failure of Foam-to-Wood Bond in Center Portion.

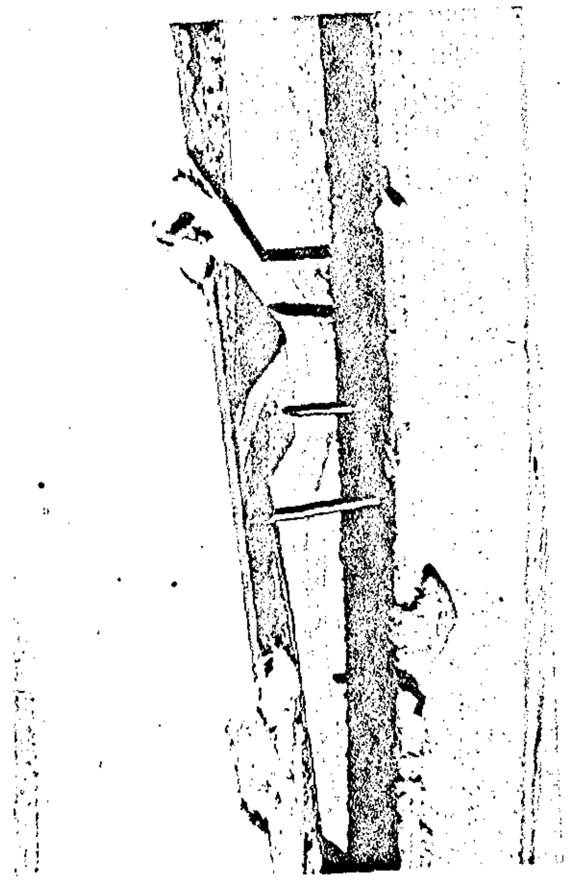
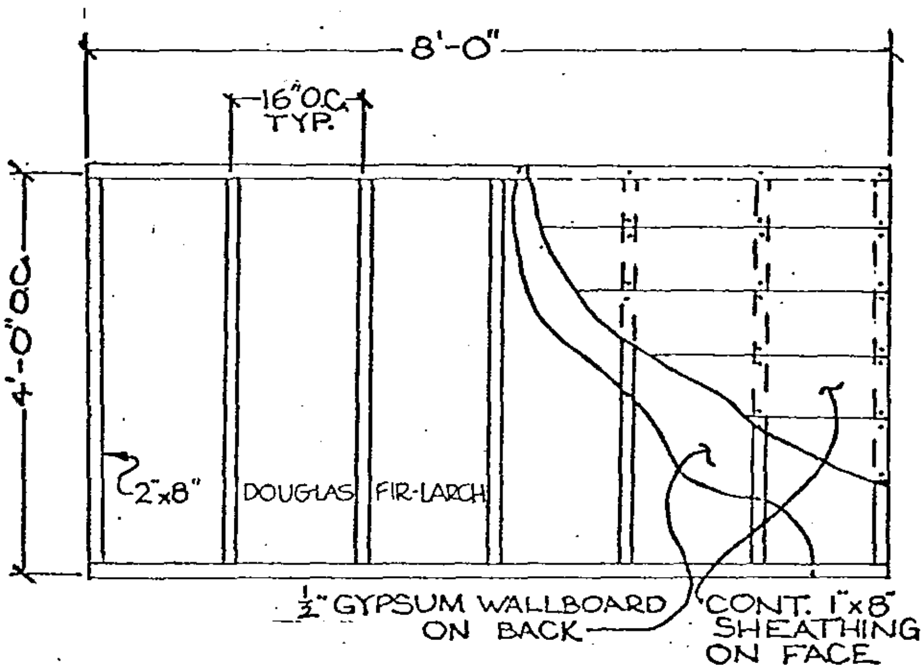


Fig. A-91. Nails Pulled Away from Joists in Floor Number 3.

FLOOR NO. 4

Description



Floor No. 4 was constructed as shown above with 2 x 8 joists of Douglas Fir-Larch. Foam was injected using the technique developed in Phase 3 to 90% volume.

Test Procedure

This specimen was subjected to the horizontal shear test as shown in Fig. A-92. The applied load and resulting deflection was recorded on an x-y plotter. The load was increased slowly until failure occurred.

Fig. A. 92. Floor Number 4 in Horizontal Shear Test Frame.

Test Data

The panel showed considerable plastic behavior for more than 2.0 inches at an average load of about 19,000 lbs (see Fig. A-93). The maximum load resisted was 21,000 lbs.

Failure

There was no distinct failure, just increasing signs of stress in the sheathing observed as cracking and splitting around nailing. Fig. A-94 shows the panel after testing. A closer examination revealed extensive cracking of the foam underneath the sheathing (Fig. A-95). The foam had also separated from center and perimeter frame members. Fig. A-96 shows a broken section of sheetrock and separation along the perimeter.

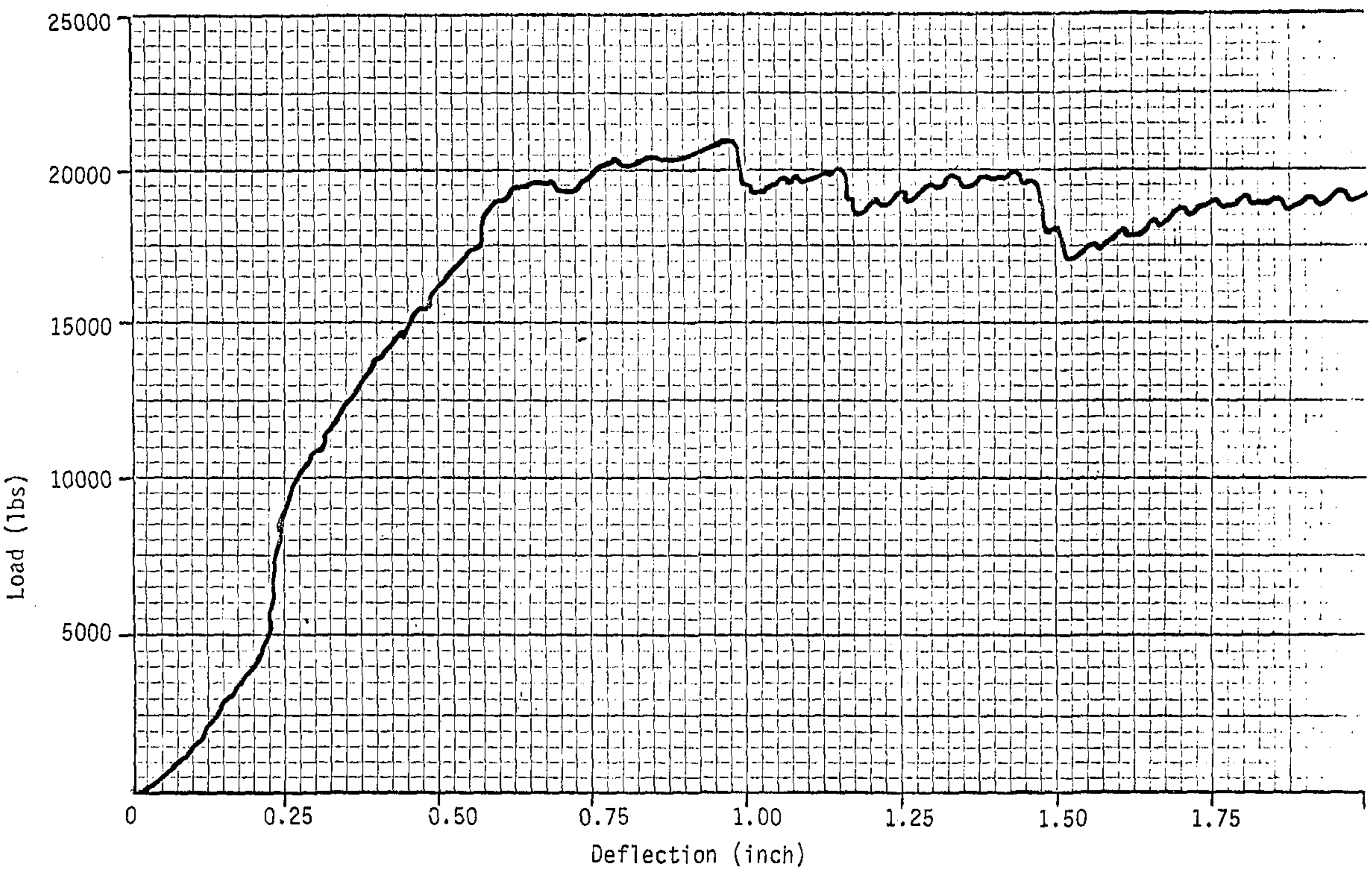


Fig. A-93. Floor No. 4 Test Results.

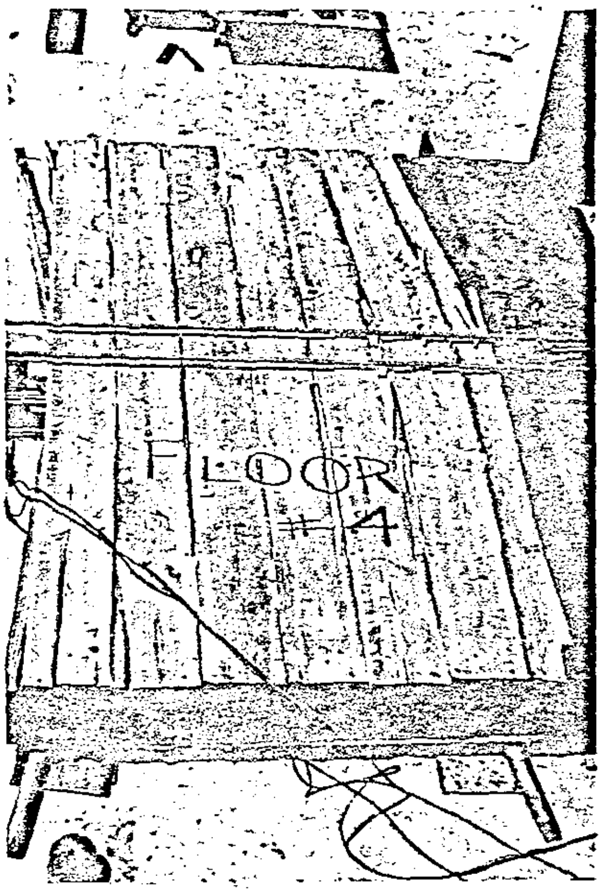


Fig. A-94. Floor Number 4 After Failure.

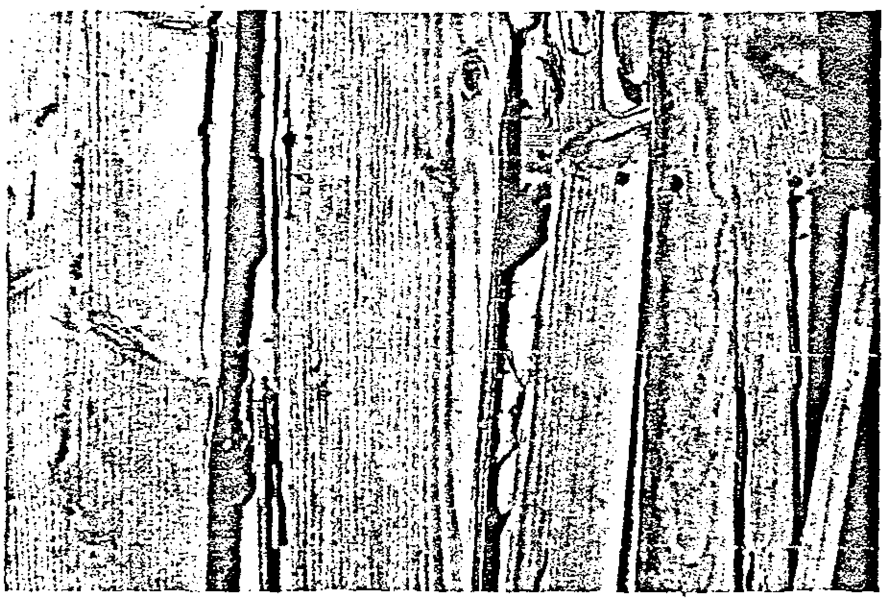
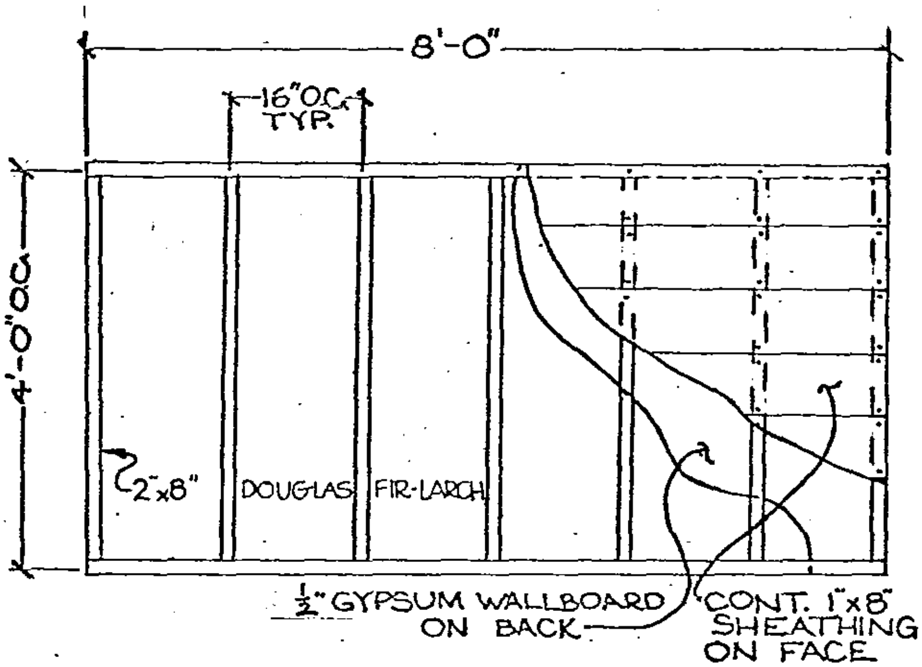


Fig. A-95. Splitting of Sheathing and Foam of Floor Number 4.

Fig. A-96. Gypsum Wallboard Side of Floor Number 4.

FLOOR NO. 5

Description



This test specimen was constructed as shown above using Douglas Fir-Larch. Floor No. 5 was not injected with foam; it was used for a base case comparison to Floor No. 4.

Test Procedure

This floor was subjected to the horizontal shear test as shown in Fig. A-97 and tested in the same manner as Floor No. 4 being slowly loaded to failure.

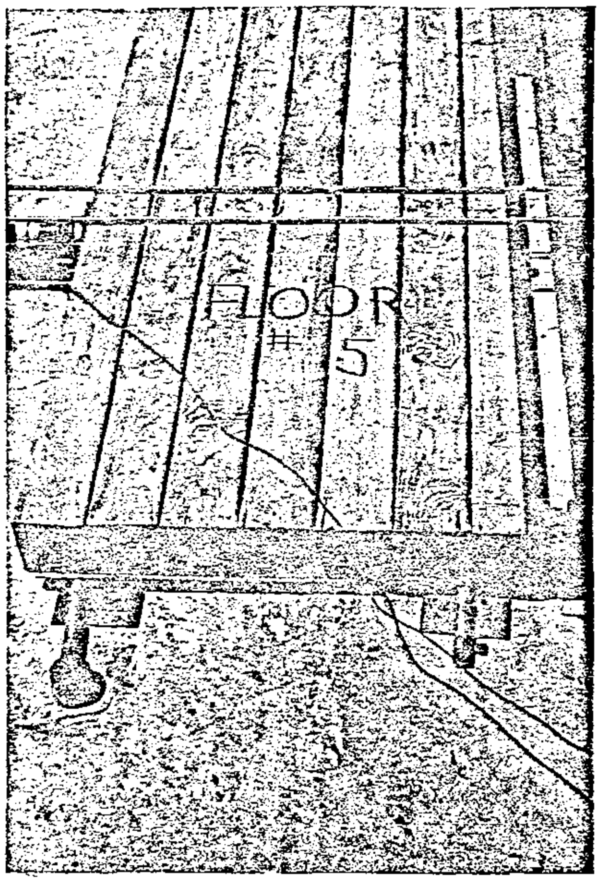


Fig. A-97. Floor Number 5 Placed in Horizontal Shear Test Frame.

Test Data

The slope of the load-deflection curve shown in Fig. A-98 decreases with increasing load to about 1.25 inches of deflection. From there, the floor behaved plastically with a maximum load restraint of 10,000 lbs.

Failure

Bending failure occurred in the center of the test panel in the sheathing (Fig. A-99). Fig. A-100 shows the gaps between the sheathing had closed, transferring a portion of the load to an adjacent board.

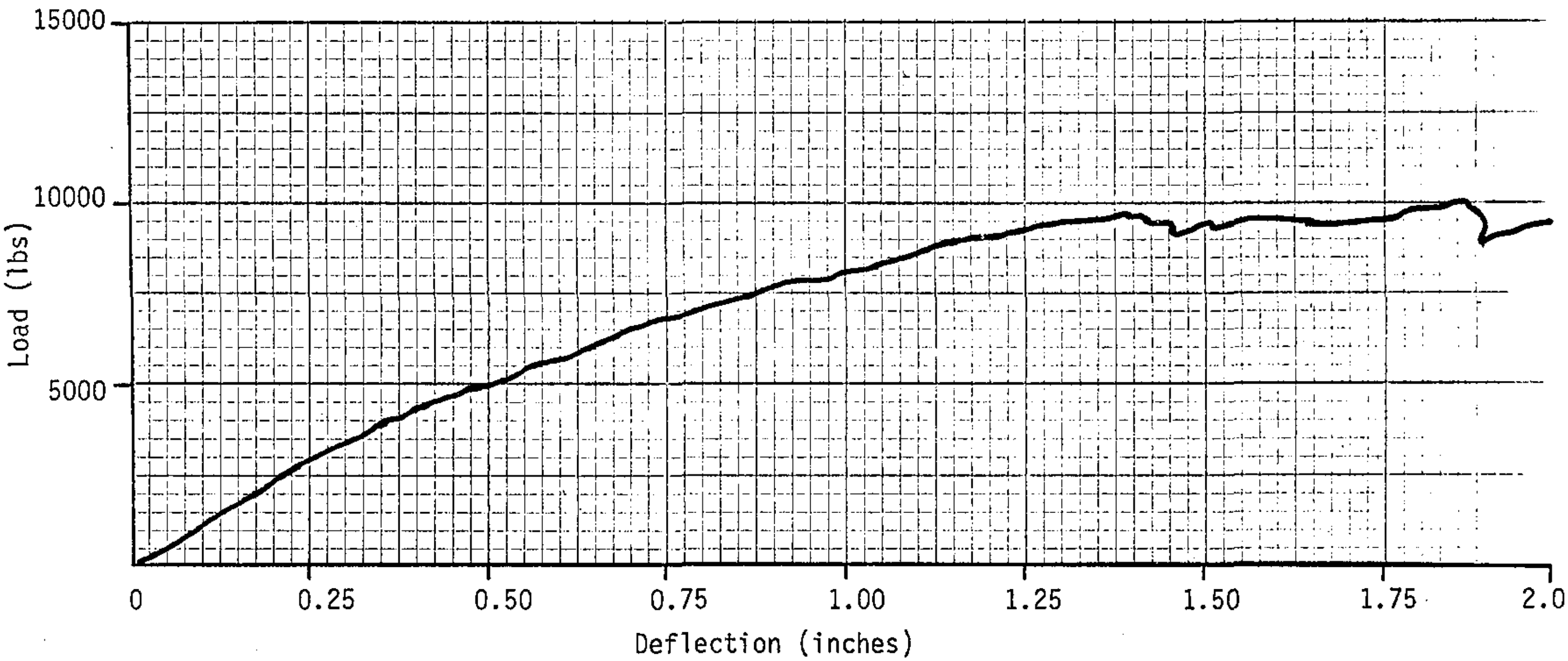


Fig. A-98. Floor No. 5 Test Results.

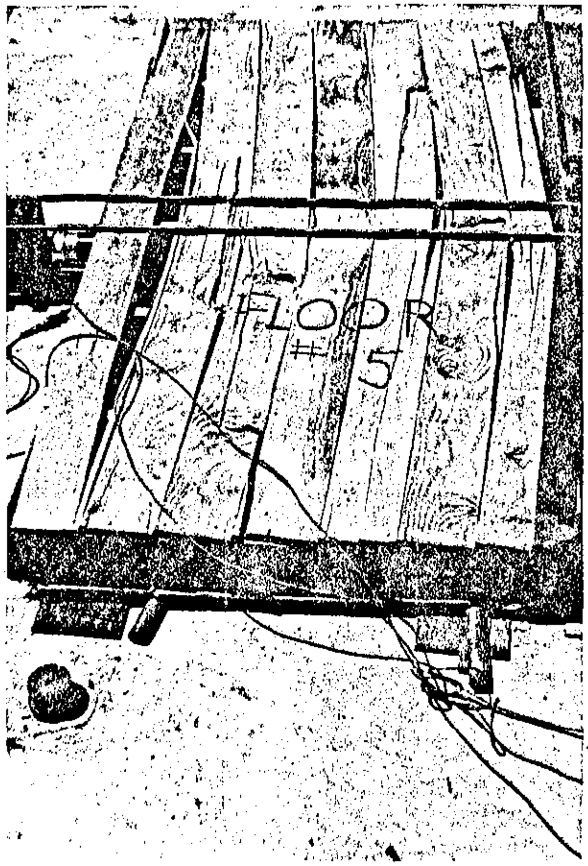


Fig. A-99. Floor Number 5 After Testing.

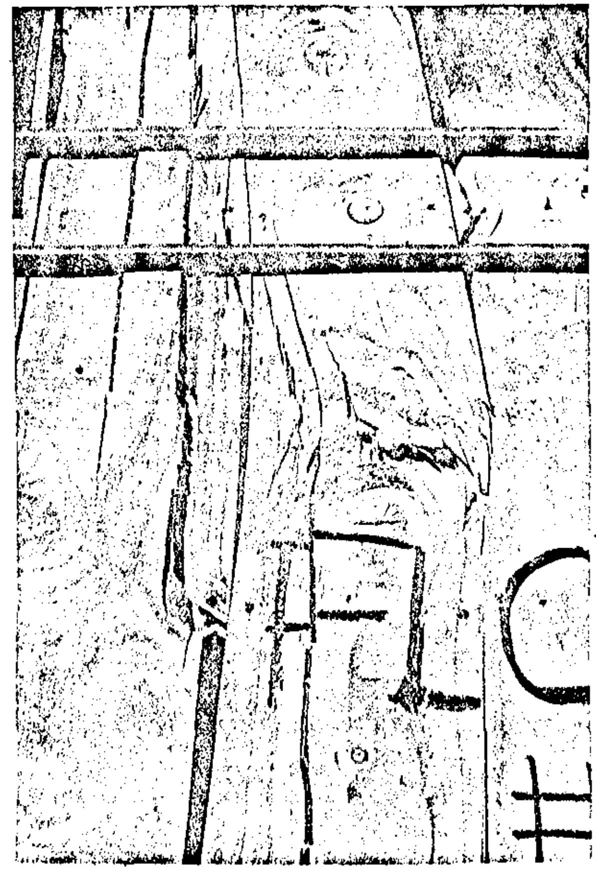
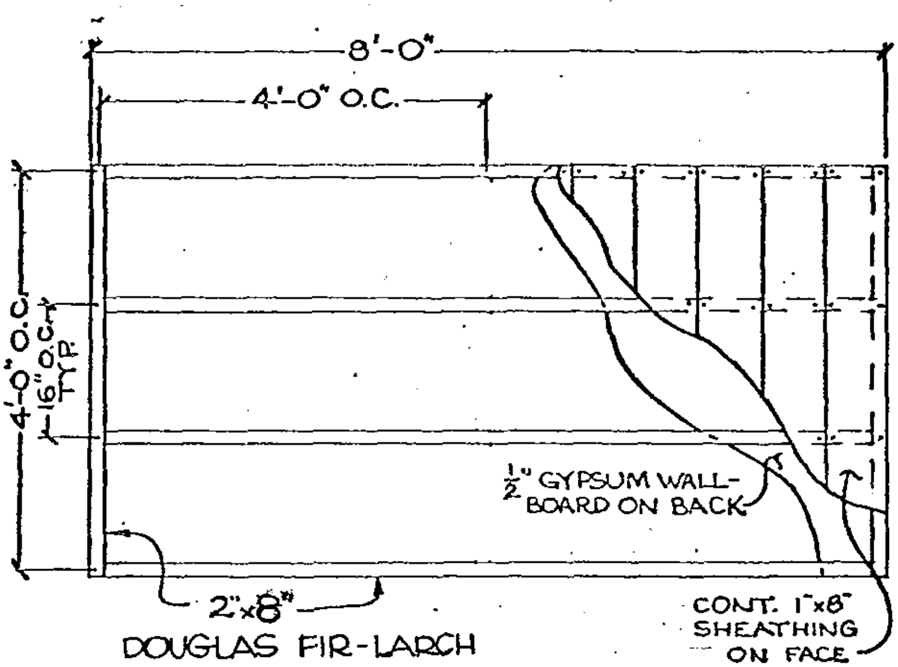


Fig. A-100. Bending Failure in Sheathing of Floor Number 5.

FLOOR NO. 6

Description



Floor No. 6 was constructed as shown above using Douglas Fir-Larch lumber nailed together as shown in the text (Section 3). This floor was foamed using the techniques of Phase 3 to 90% by volume.

Test Procedure

The floor was weighed before and after foam placement and subjected to the bending test before and after foaming (Fig. A-101). Before foaming, three bending tests at service load were conducted and the last test

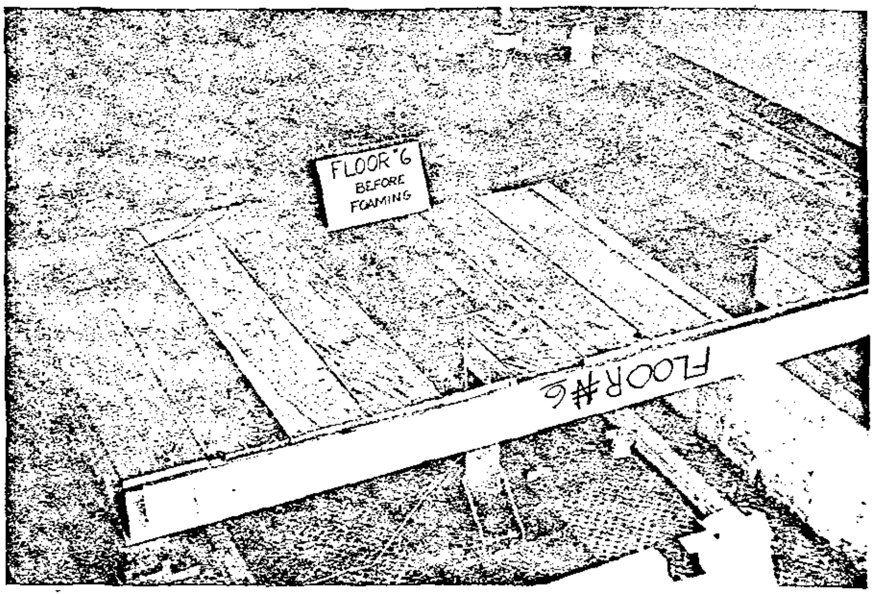


Fig. A-101. Floor Number 6 in Bending Test Arrangement.

recorded. After foaming, a bending test was conducted to failure using a 20-second ramp displacement input to the servo actuator. A load-deflection plot was obtained from each test.

Test Data

The floor weighed 189 lbs and 216 lbs after foaming for a 114% increase in panel weight due to foam placement. Fig. A-102 shows a change in stiffness from 8,000 lbs/in. to 10,000 lbs/in. for a 25% increase. In the bending test to failure (Fig. A-103), a maximum of 11,600 lbs was obtained.

Failure

A bending failure occurred in the outer joist between the load points as shown in Fig. A-104.

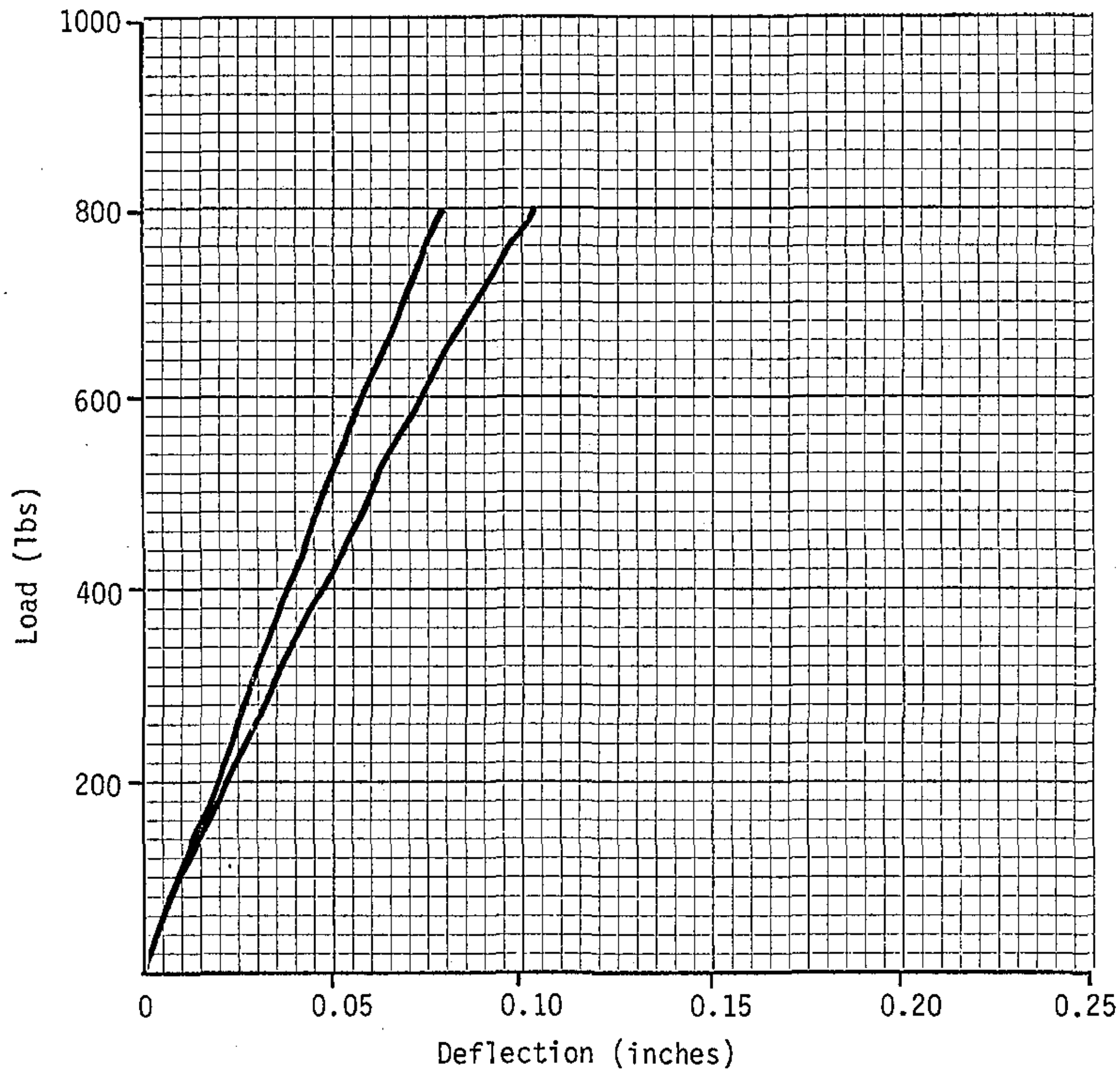


Fig. A-102. Floor No. 6 Bending Test Results Before and After Foam Placement.

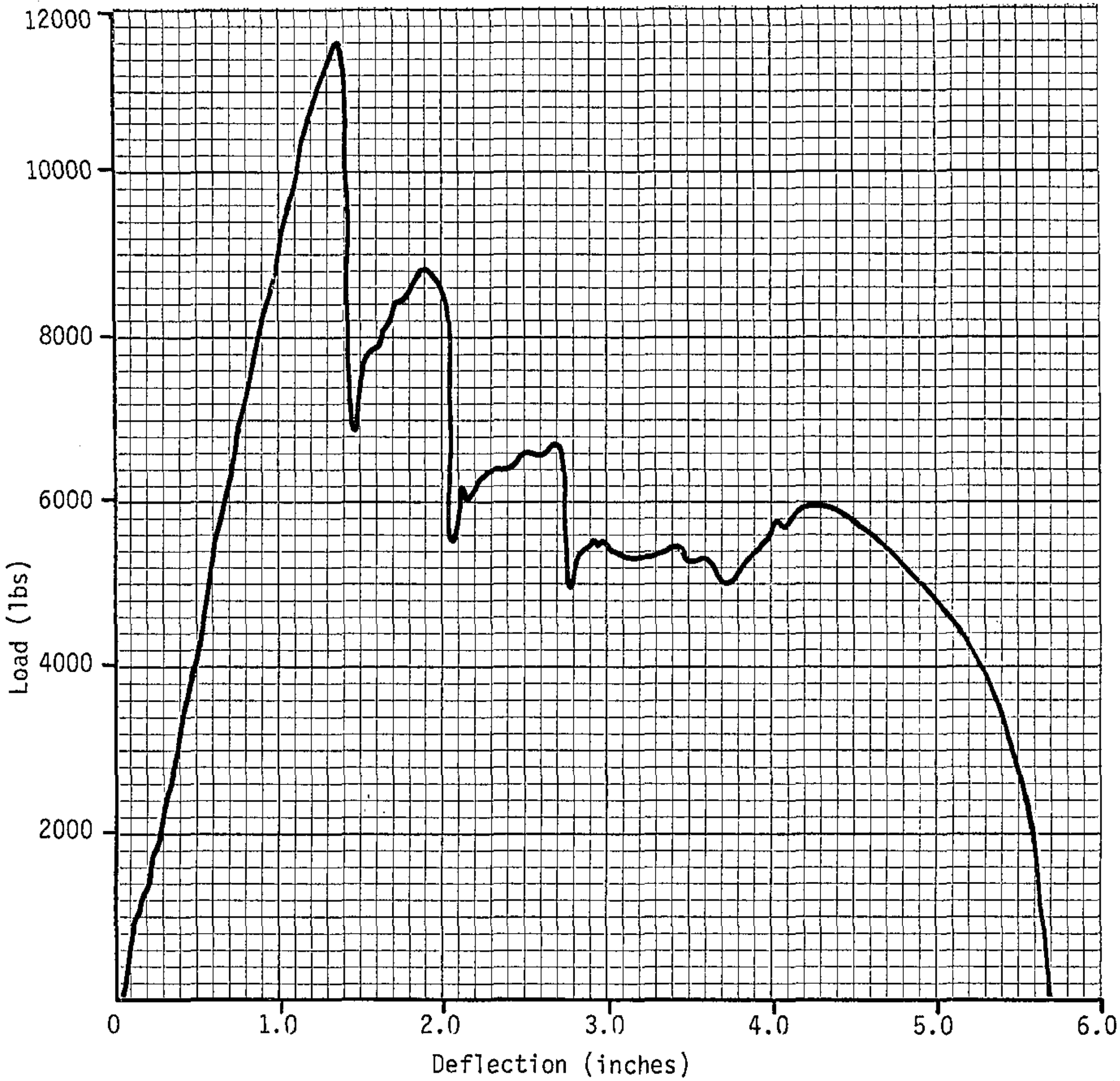


Fig. A-103. Floor No. 6 Bending Test to Failure Test Results.

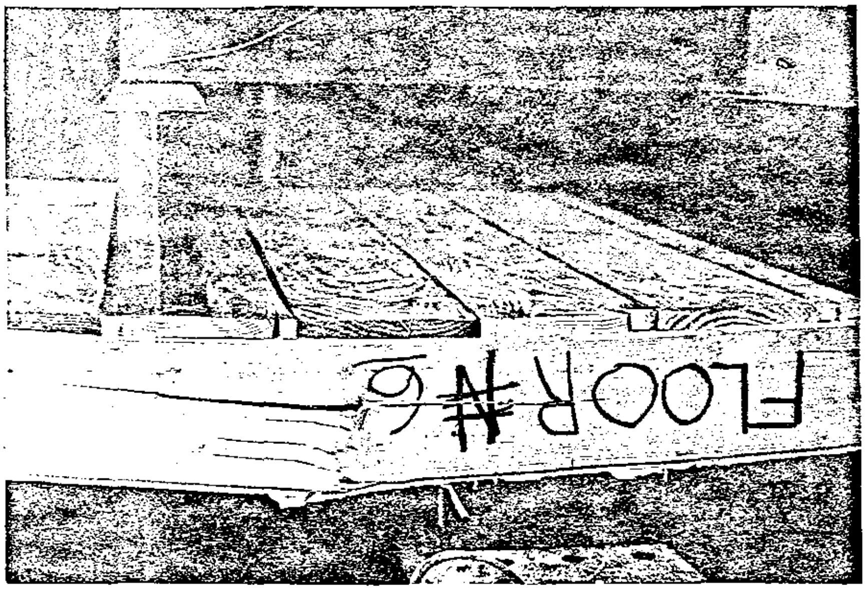
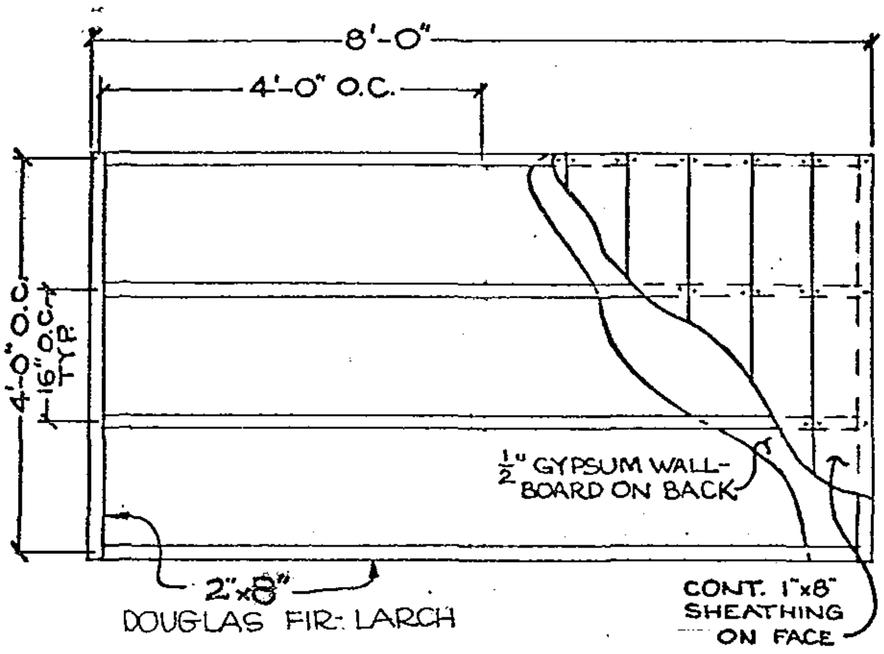


Fig. A-104. Floor Number 6 Failure in Joist Between Load Points.

FLOOR NO. 7

Description



This floor was constructed in the same manner as Floor No. 6 with Douglas Fir-Larch. The foam placement was completed in Phase 3 with 90% volume injections.

Test Procedure

The floor was weighed before and after foam placement and subjected to several bending tests (Fig. A-105). Three bending tests to service loads were conducted before and after foaming. The third test results were recorded and plotted. A bending test to failure was conducted using a 20-second ramp displacement input to the servo actuator loading the specimen.

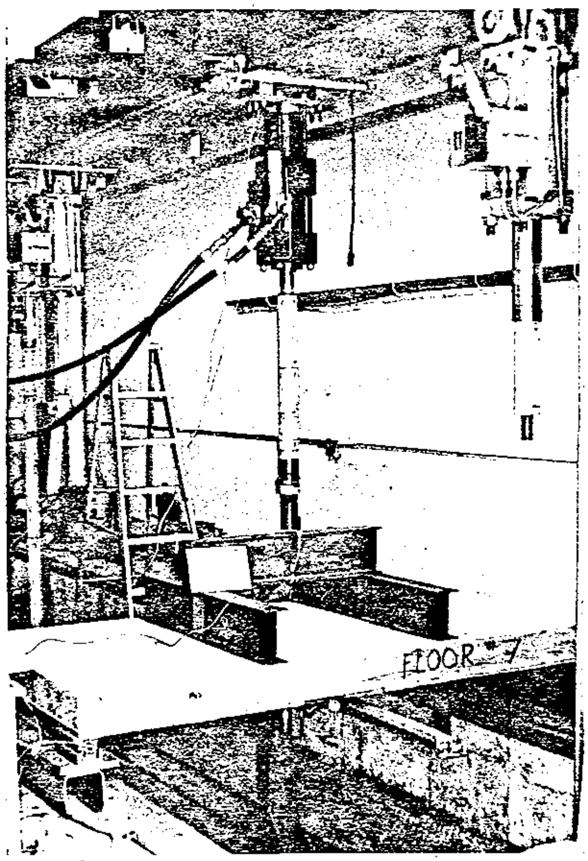


Fig. A-105. Floor Number 5 in Bending Test Frame.

Test Data

Floor No. 7 weighed 194 lbs before and 221 lbs after foaming for a 12% weight increase. Fig. A-106 shows the bending stiffness increase after foam placement from 8,500 lbs/in. to 12,300 lbs/in for a 44% increase. The floor failed at a maximum load of 11,200 lbs (Fig. A-107).

Failure

The center joist in Floor No. 7 failed between the load points as shown in Fig. A-108. The bottom layer of sheetrock and foam also failed in this zone with the foam separating from the joists and remaining attached to the sheetrock (Fig. A-109).

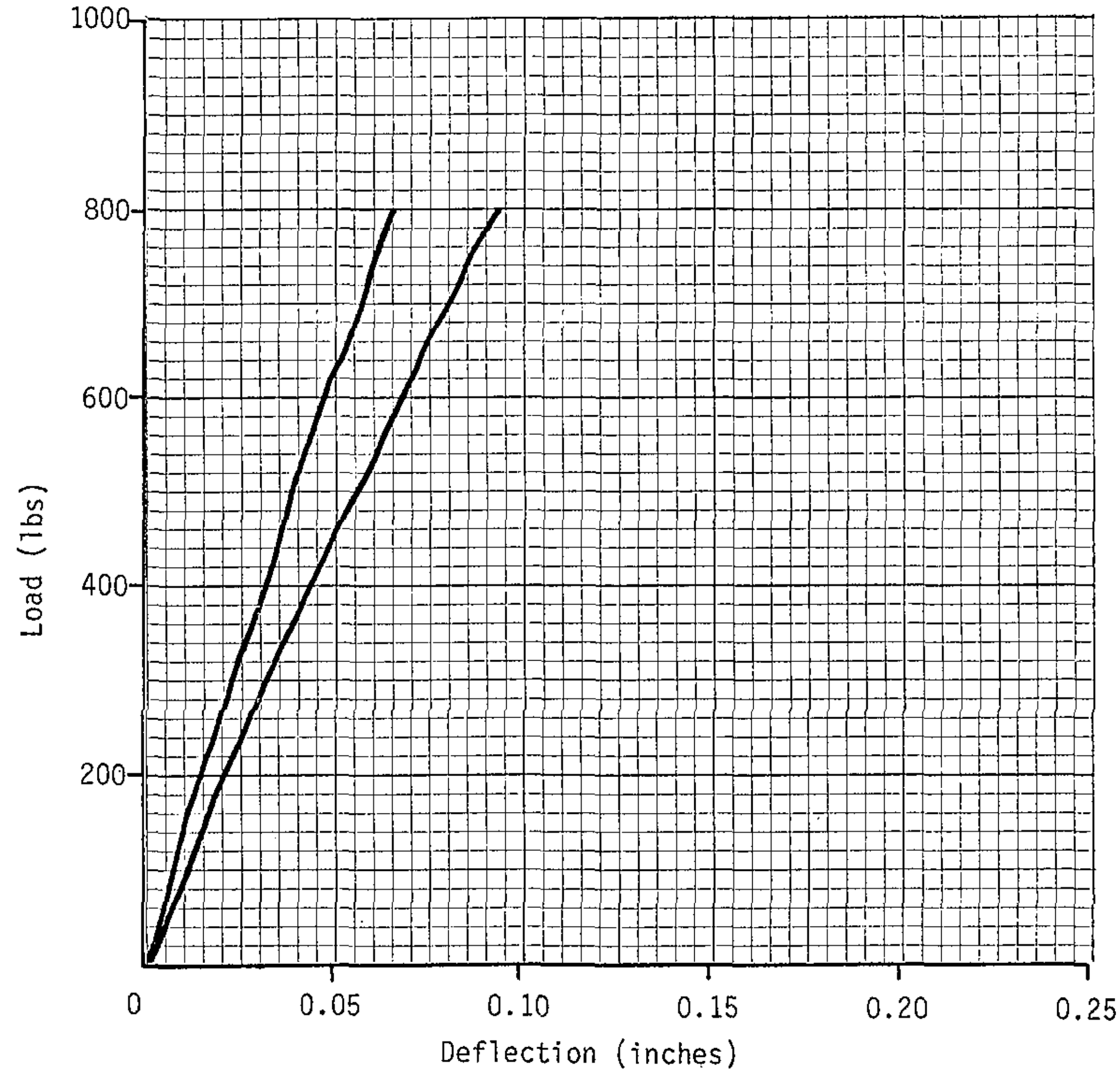


Fig. A-106. Floor No. 7 Bending Test Results Before and After Foam Placement.

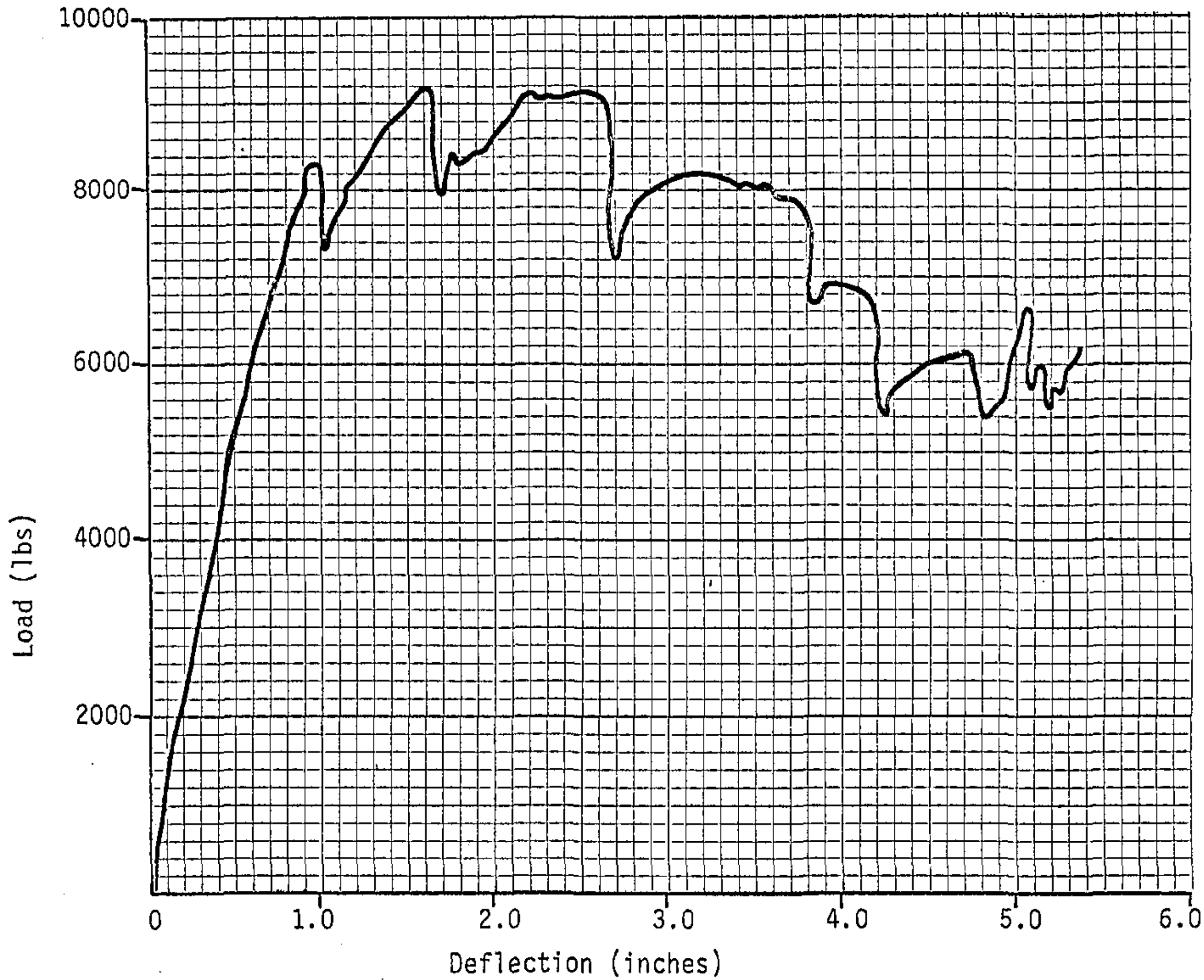


Fig. A-107. Floor No. 7 Test Results.

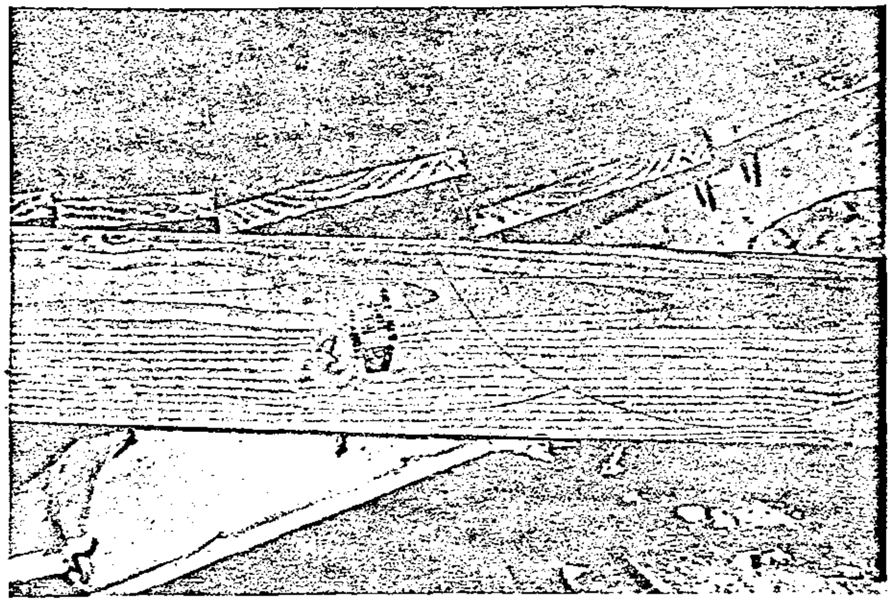


Fig. A-108. Floor Number 7 Bending Failure in Center Joist.

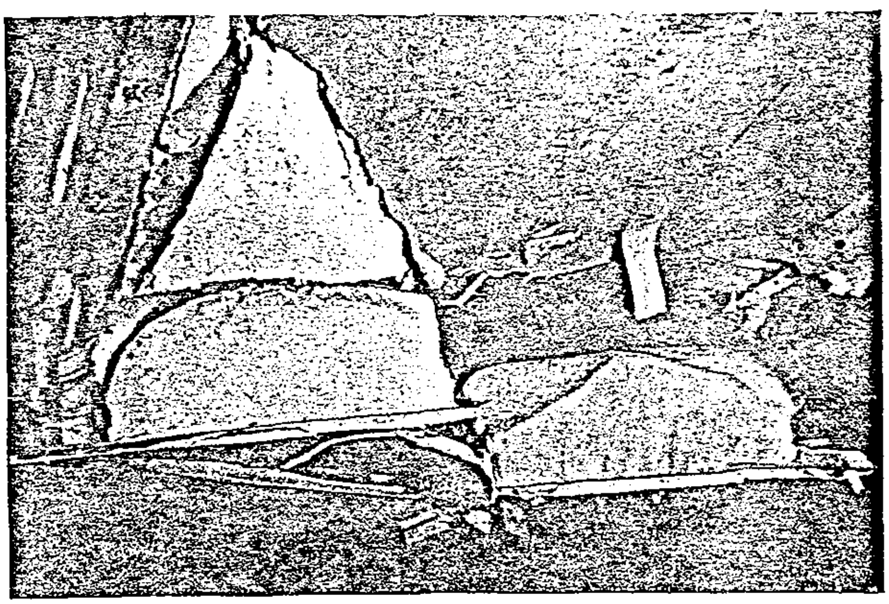


Fig. A-109. Floor Number 7 Sheetrock and Foam Failure After Test.

APPENDIX B

TEST DATA (SUPPLEMENTAL TEST PROGRAM)

Appendix B

TEST DATA (SUPPLEMENTAL TEST PROGRAM)

INTRODUCTION

This appendix presents the data from the supplementary test program. This program consisted of the following tests:

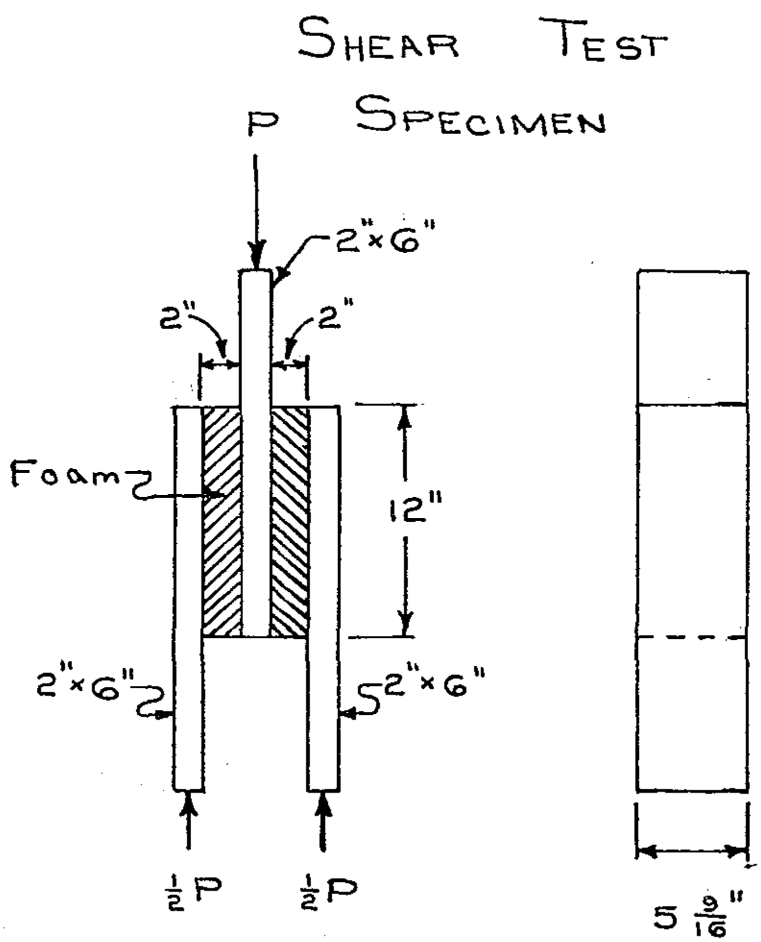
- o Foam Shear Tests
- o Foam Tensile Tests
- o Foam Compression Tests
- o Foundation Shear Tests

The test results for each test series have been summarized in Section 3 of this report. This section presents a description, test procedure, test data, and failure mode for the foam shear, tensile, and compression tests. (The test data for the Foundation Shear Tests have been presented in sufficient detail in Section 3 and are not reproduced here.)

SHEAR TESTS

Description

Six shear test specimens were built for this series. Each specimen consisted of three pieces of 2" x 6" Douglas Fir-Larch (Select Structural) lumber, 1½ feet in length and bonded together with a strip of rigid urethane foam, 12 in. in length, 5½ in. wide, and 2 in. thick (see sketch below).



Test Procedure

Each of the test specimens were placed in the testing machine as shown in Fig. B-1, and slowly loaded to failure.

Test Data

The testing machine was equipped with a load versus deflection plotter. The resulting graphs for each of the specimens are presented in Figs. B-2 through B-7. A summary plot is shown in Fig. B-8 and test data summarized in Table B-1.

The average ultimate applied load was 1,825 lbs which represents an ultimate shearing stress of 13.8 psi. The modulus of rigidity for the elastic region has also been calculated for each of the test specimens and the mean value is 756 psi. An average load-deflection curve is shown in Fig. B-9. In this curve it can be seen that the elastic region extends up to a load of 1,300 lbs.

Failure

The specimens all failed in the same manner. Post test photographs of Specimen No. 2 can be seen in Figs. B-10, A and B and is typical of the other test specimens. Failure was due to a separation at the foam to wood interface. Fig. B-11, A and B, show a close-up of this type of failure.

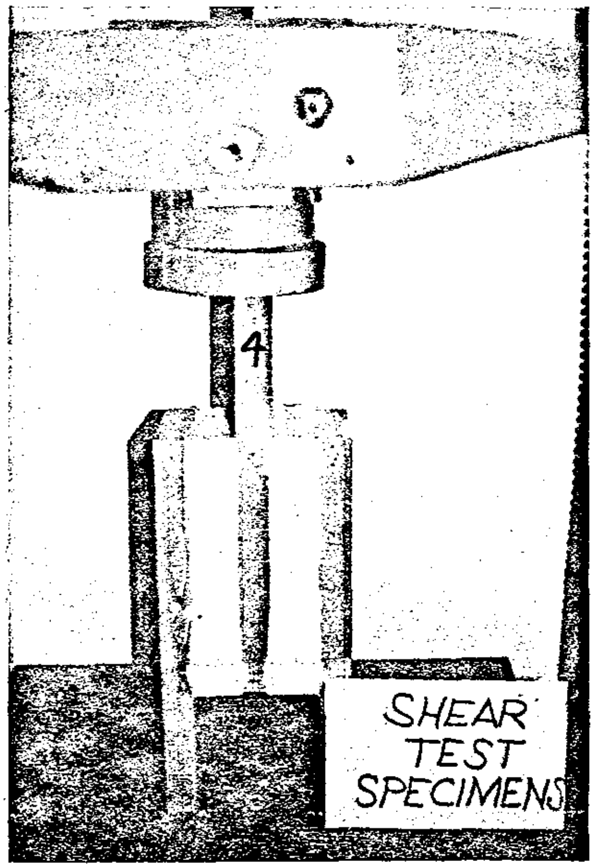


Fig. B-1. Testing Arrangement for the Shear Test Specimens.

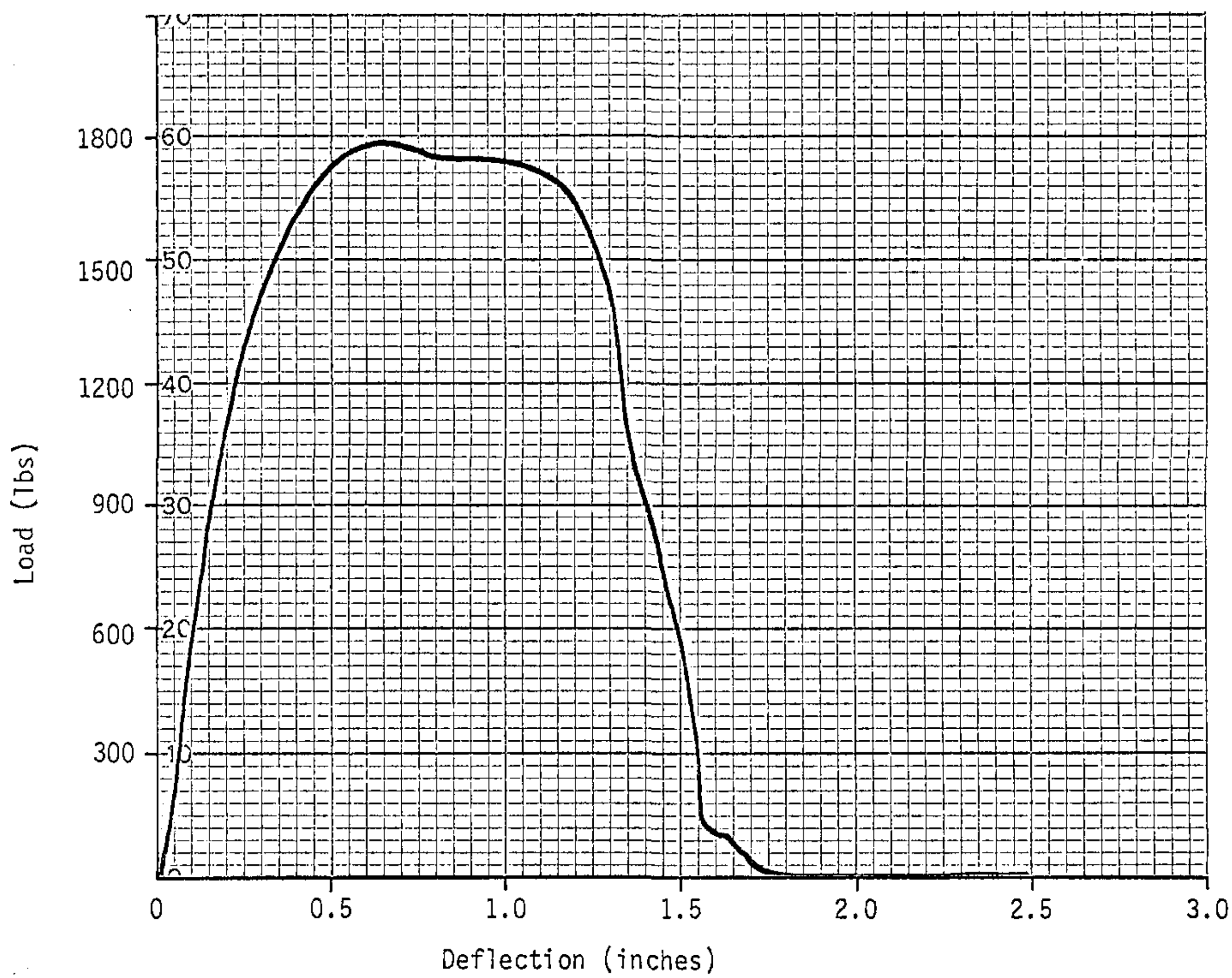


Fig. B-2. Shear Test Number 1

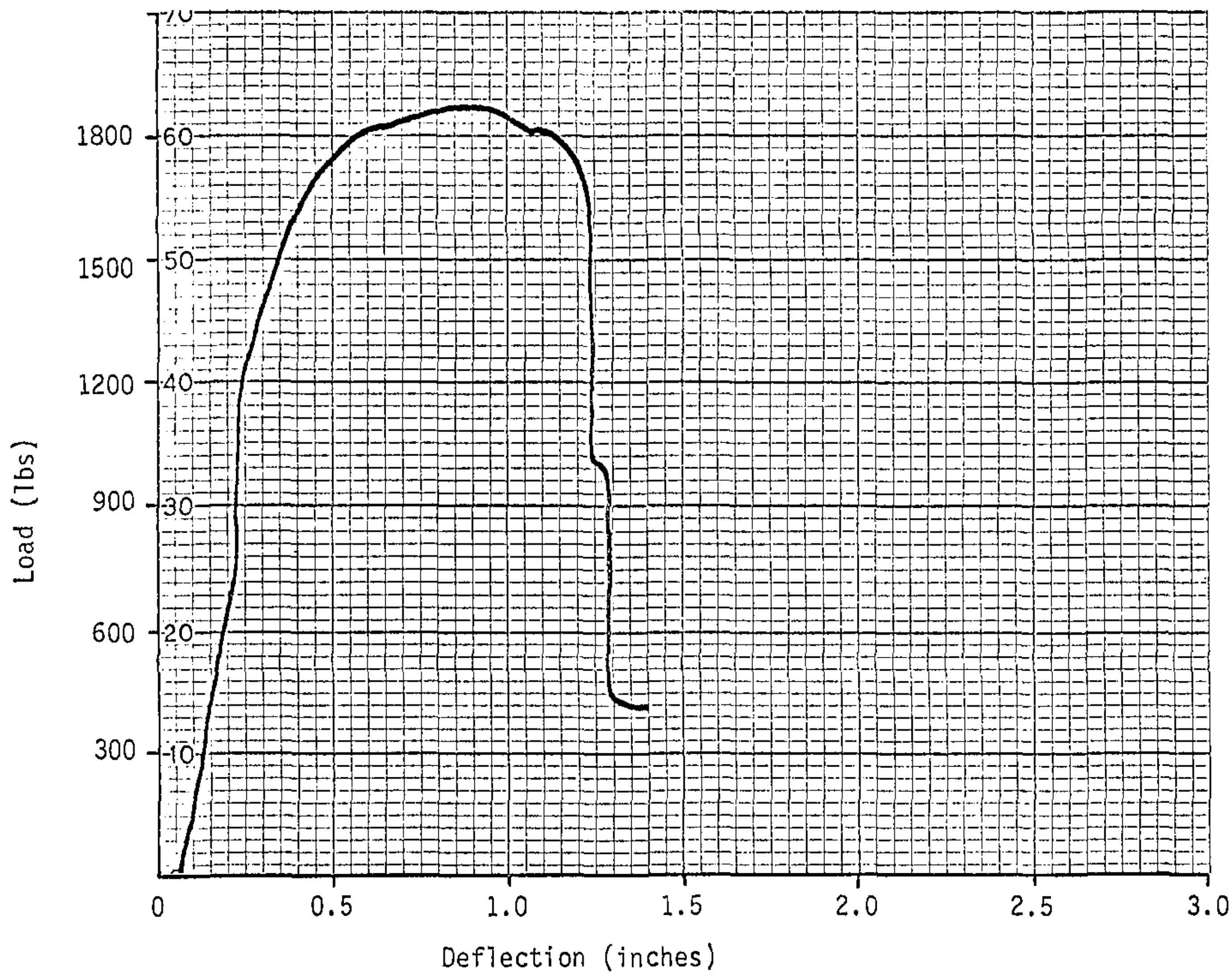


Fig. B-3. Shear Test Number 2

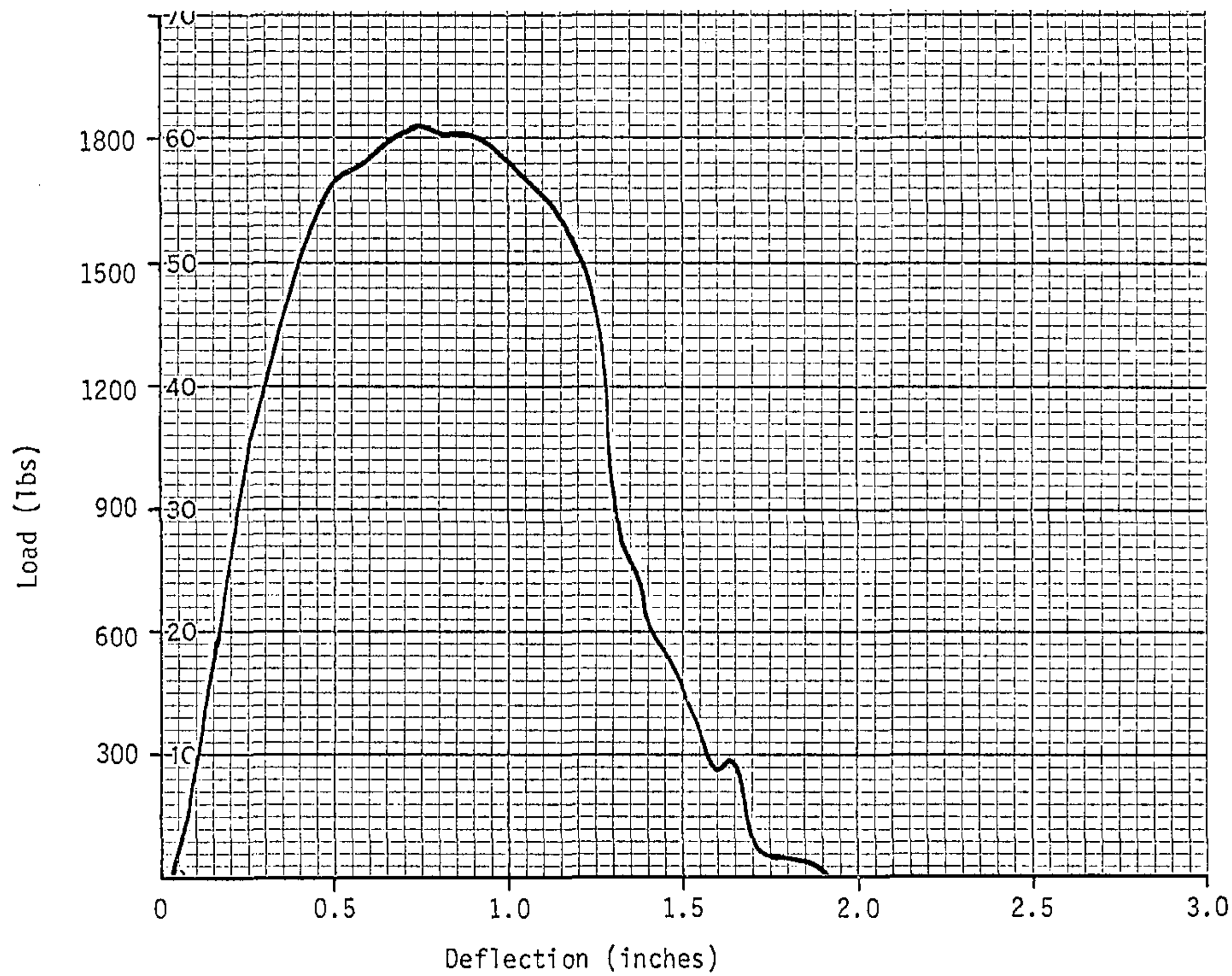


Fig. B-4. Shear Test Number 3

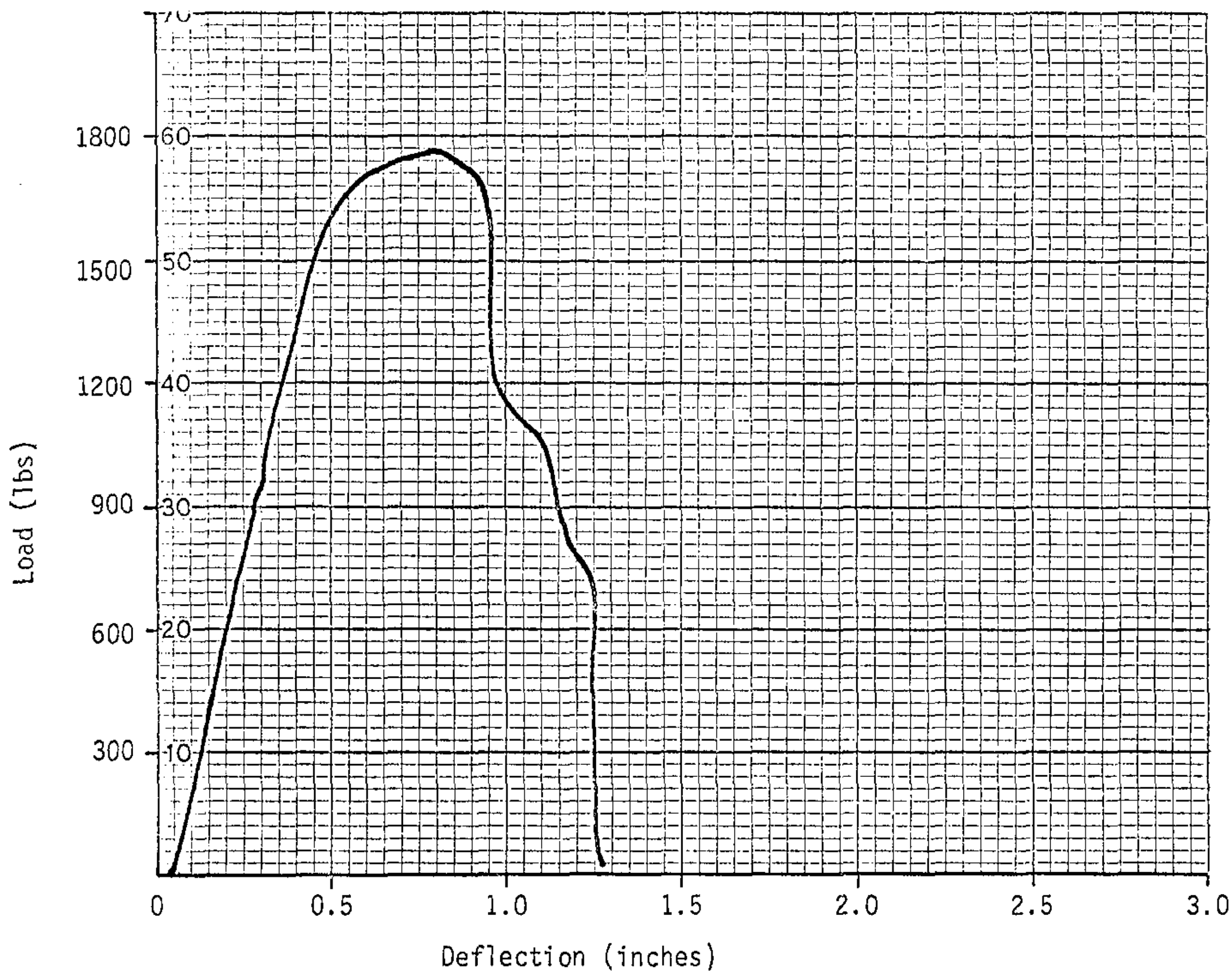


Fig. B-5. Shear Test Number 4.

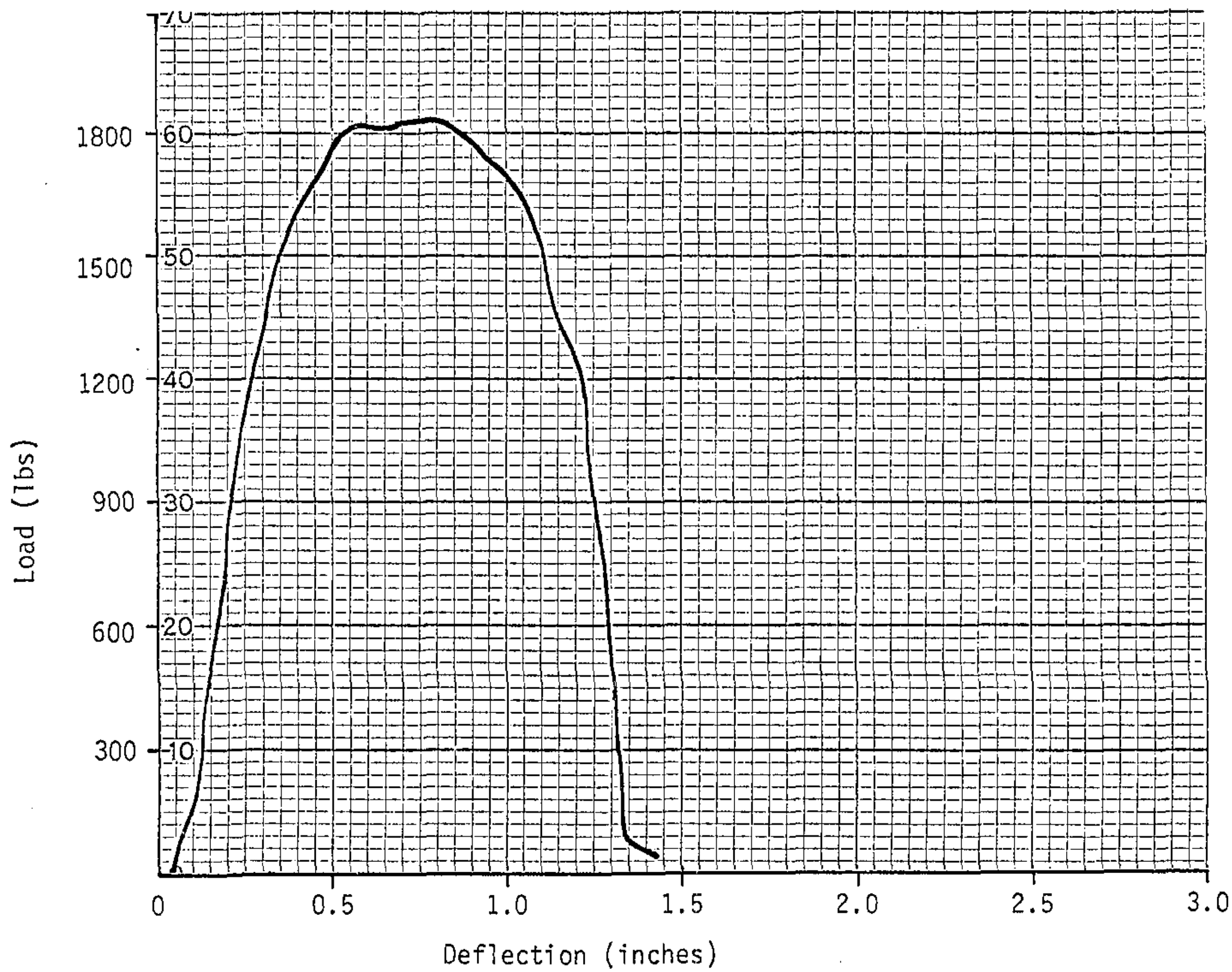


Fig. B-6. Shear Test Number 5.

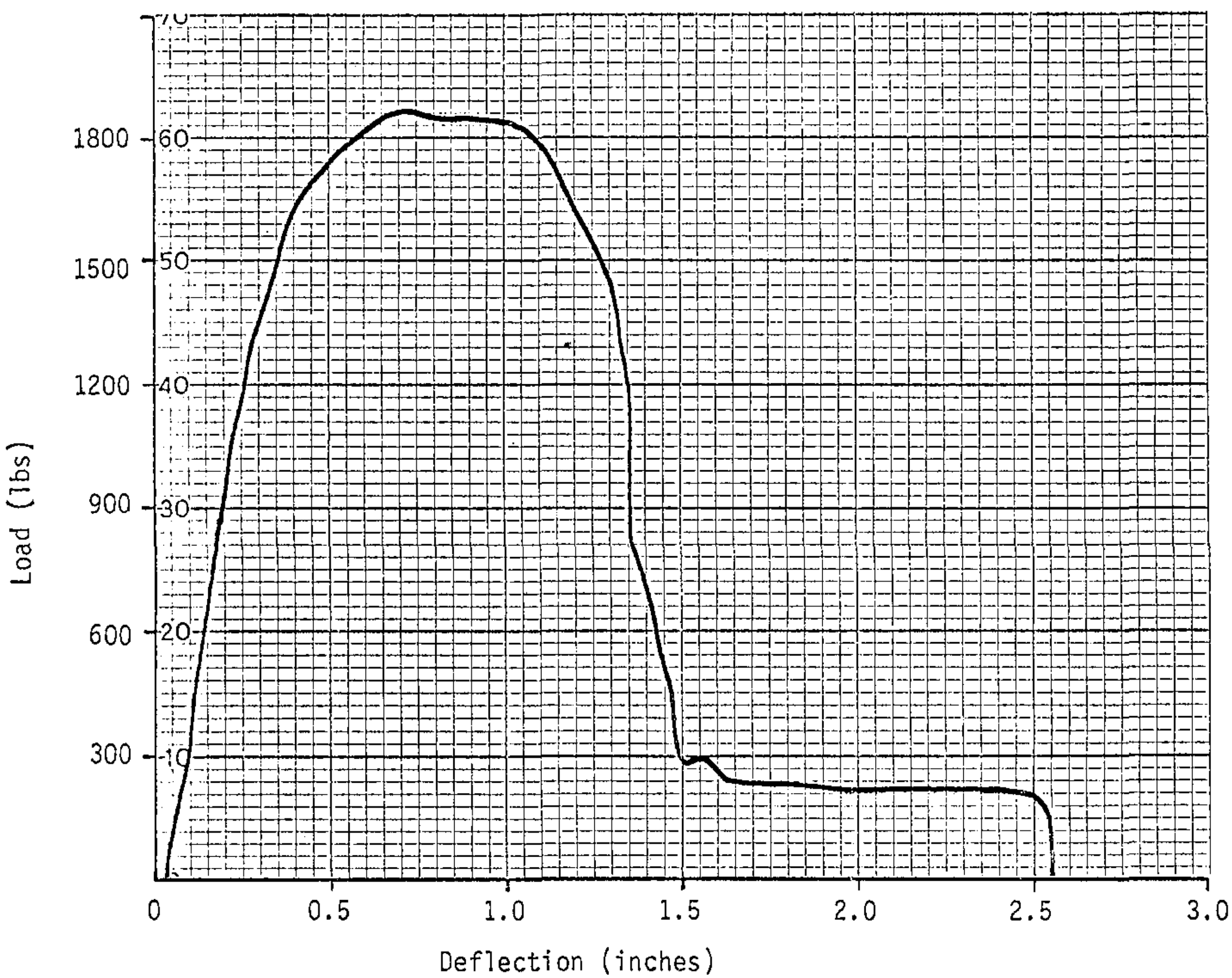


Fig. B-7. Shear Test Number 6.

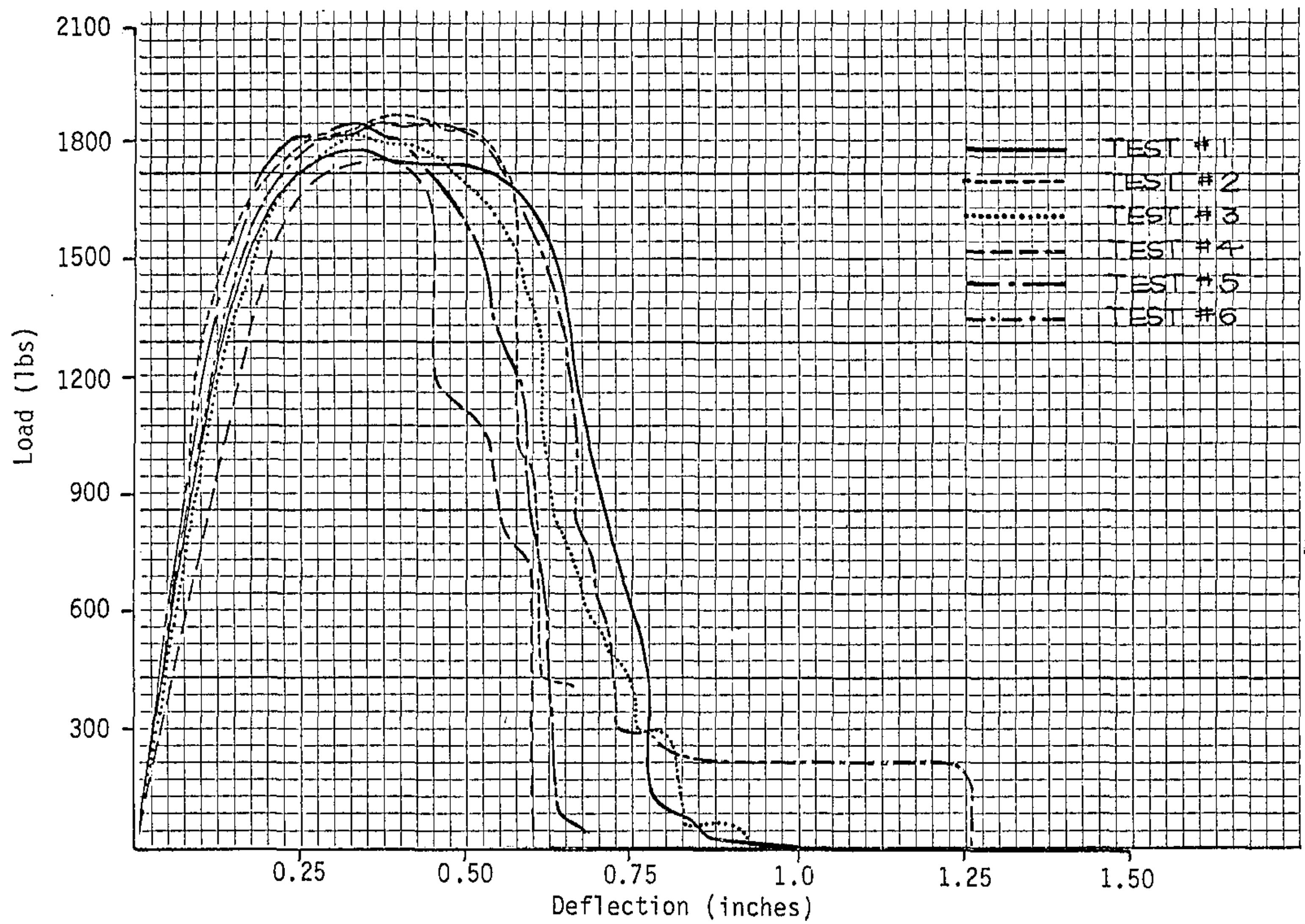


Fig. B-8. Summary of Foam Shear Test Data.

TABLE B-1: SHEAR SPECIMEN TESTS

TEST NO.	ULT. APPLIED LOAD (lbs)	ULT. SHEAR STRESS (psi)	MOD. OF RIGIDITY, G (psi)
1	1,799	13.93	795.9
2	1,865	14.13	849.4
3	1,820	13.79	544.4
4	1,760	13.33	860.6
5	1,865	14.13	774.6
Mean $\bar{x}$	1,825	13.83	756.0
Std. Dev.	40.9	0.31	117.2

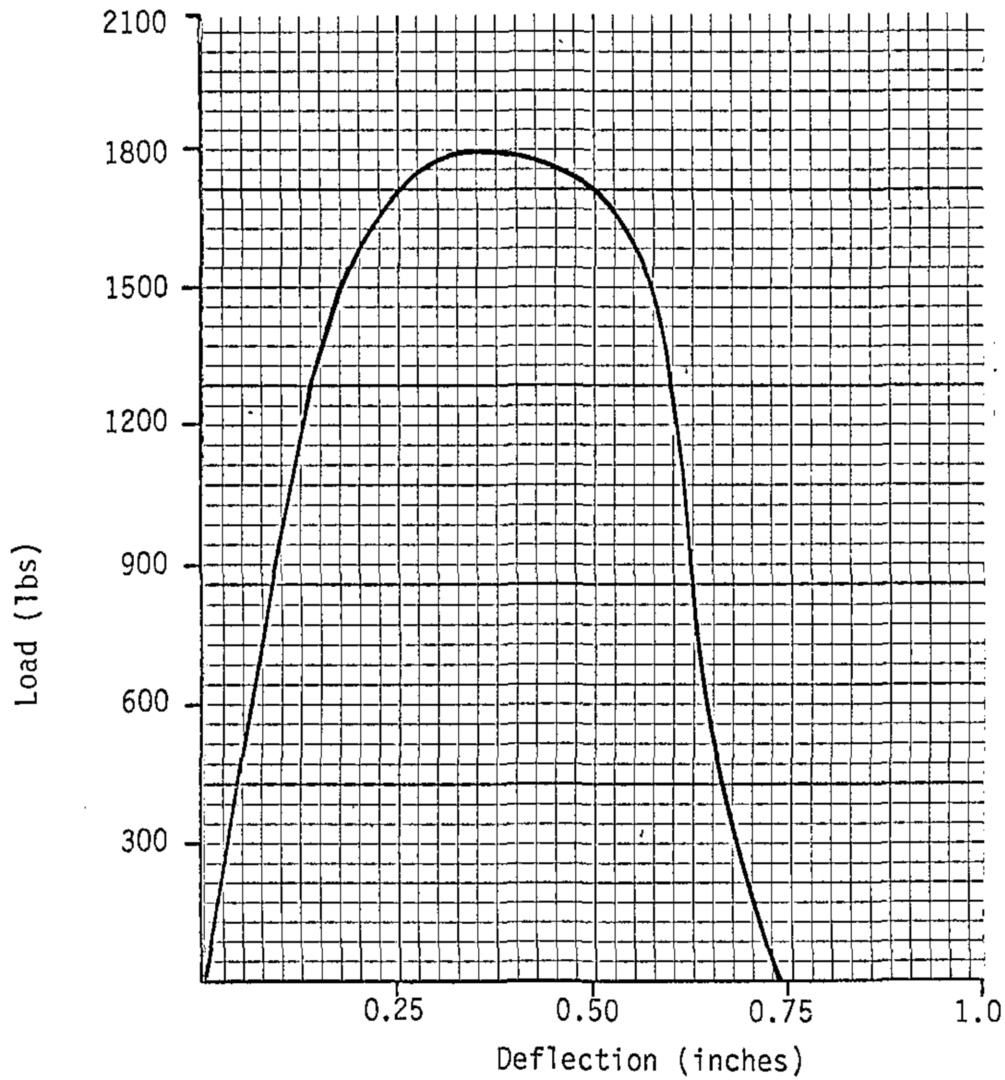
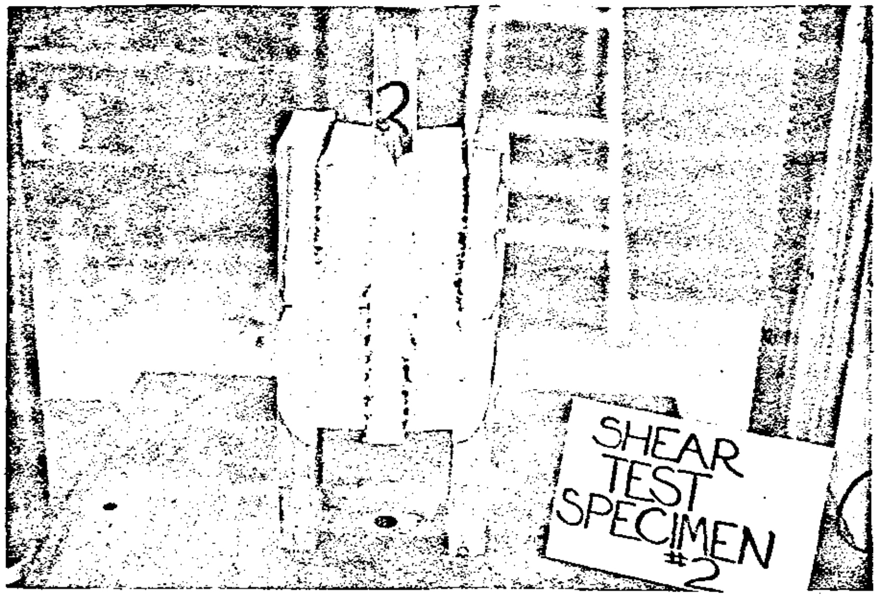


Fig. B-9. Average Load-Deflection Curve - Foam Shear Tests.

A



B

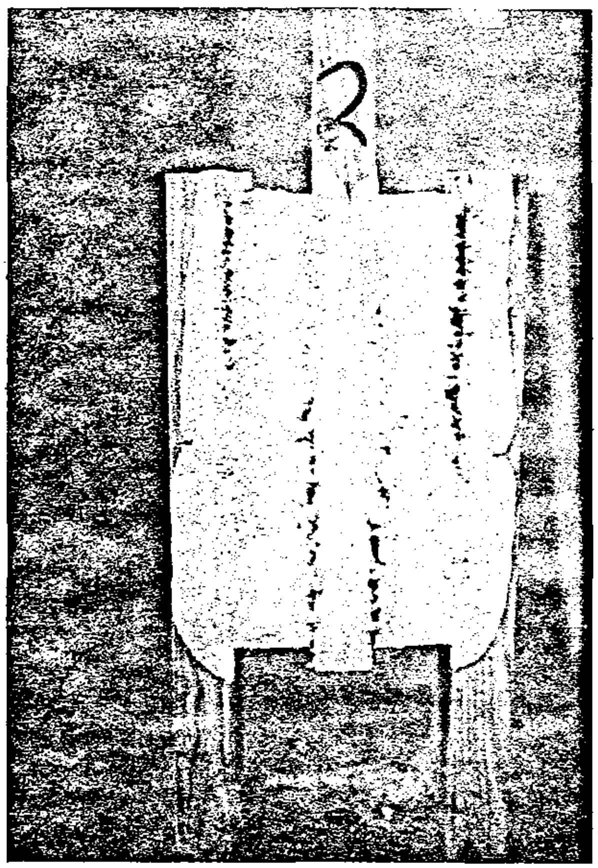
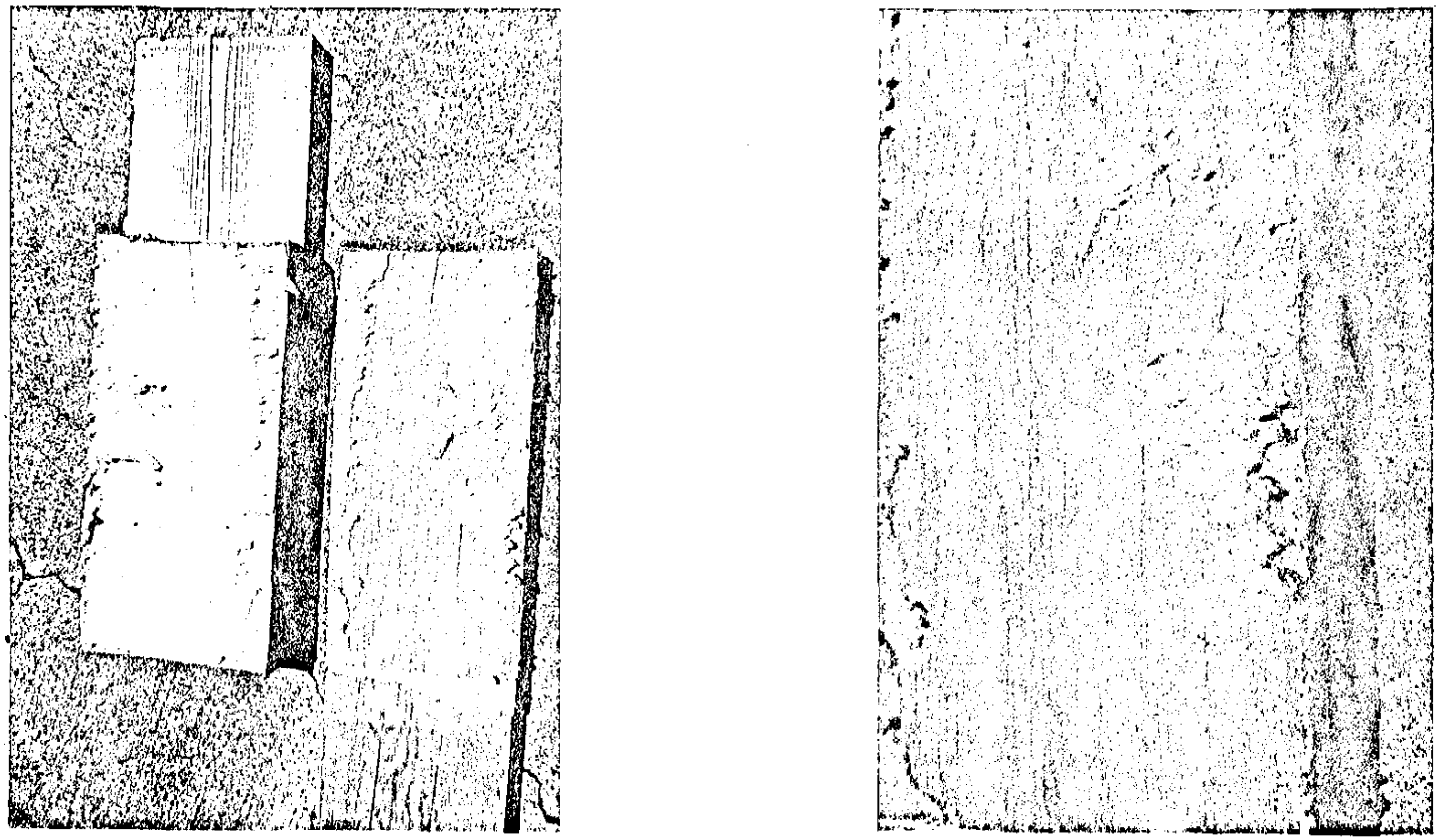


Fig. B-10. Post-Test Photographs of Specimen No. 2.



A

B

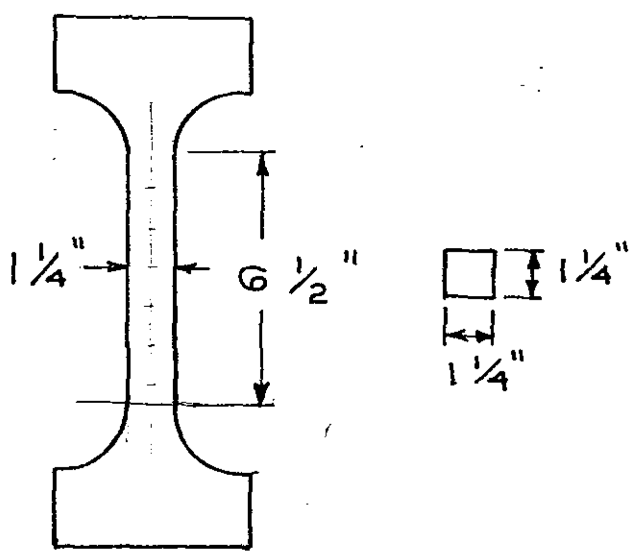
Fig. B-11. Closeup Photographs of Shear Test Specimen.

TENSILE TESTS

Description

A total of eight test specimens were cut from several blocks of rigid urethane foam. These specimens were cut in two directions, four parallel to the direction of rise in the foam, and four perpendicular to the direction of rise. The two types of specimens can be seen in Fig. B-12. A sketch of the test specimen is shown below.

TENSILE TEST SPECIMEN



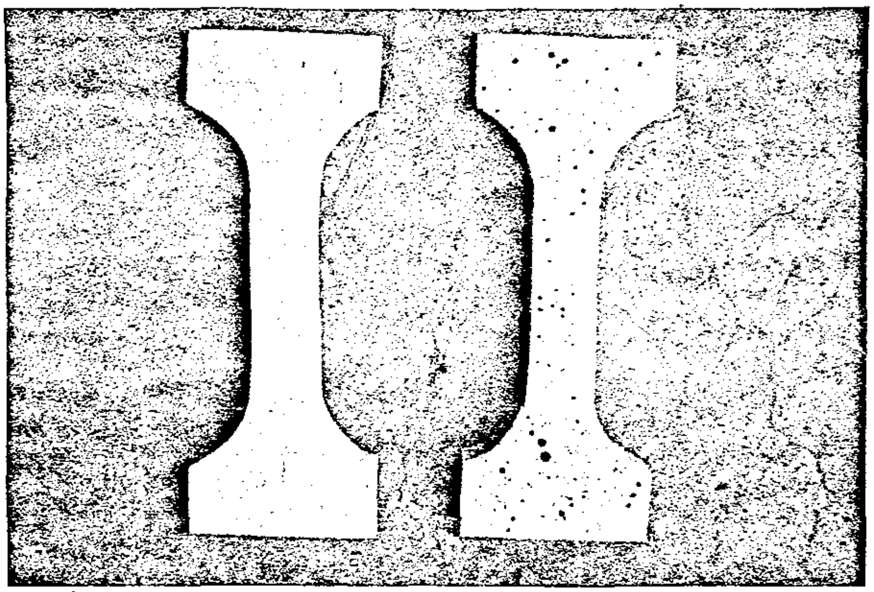


Fig. B-12. Tensile Test Specimens.

Test Procedure

Each of the specimens were placed in the testing machine as shown in Fig. B-13 and slowly loaded to failure.

Test Data

The ultimate tensile load for each of the test specimens was recorded and the results are presented in Table B-2 and B-3. From the results it appears that foam has an ultimate tensile stress of about 29 psi. The test results indicate very little difference between the ultimate loads of the two types of test specimens. Due to the small sample size tested it is believed that the specimens cut perpendicular to the direction of rise in the foam are significantly weaker in tension than those cut in the other direction. The standard deviations seem to bear this out, also in the perpendicular direction one standard deviation is 12% of the mean tensile stress whereas in the parallel direction one standard deviation is only 4.8%.

Failure

Both specimens failed as expected, breaking about mid-specimen height. The failures are shown in Fig. B-14.

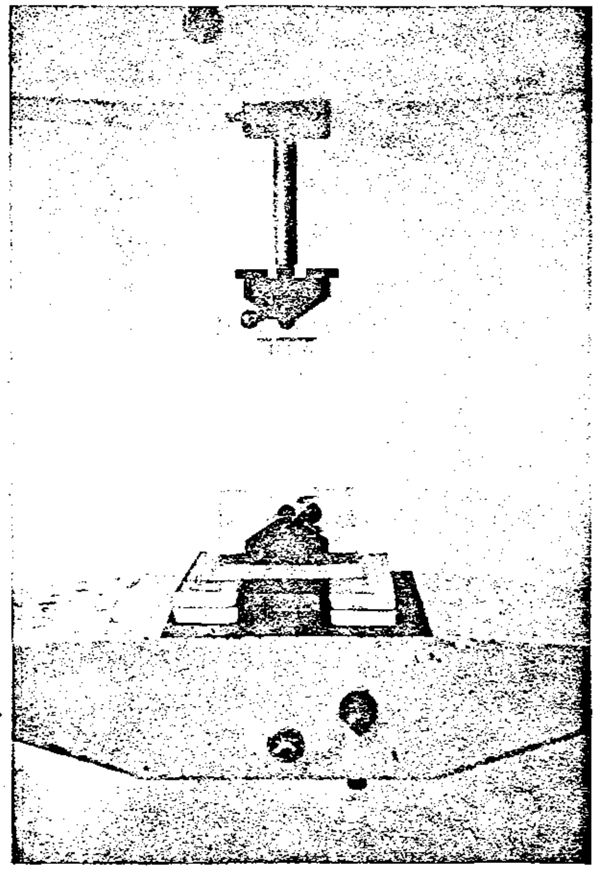


Fig. B-13. Tensile Test Specimen in Testing Machine.

TABLE B-2: TEST SPECIMENS CUT PARALLEL TO THE DIRECTION OF RISE OF THE FOAM

TEST NO.	FAILURE LOAD (lbs)	TENSILE STRESS (psi)
1	48	31
2	44	28
3	46	29
4	44	28
Mean $\bar{x}$	45.5	29.0
Std. Dev.	1.98	1.4

TABLE B-3: TEST SPECIMENS CUT PERPENDICULAR TO THE DIRECTION OF RISE OF THE FOAM

TEST NO.	FAILURE LOAD (lbs)	TENSILE STRESS (psi)
1	38	24
2	50	32
3	44	28
4	47	30
Mean $\bar{x}$	44.8	28.5
Std. Dev.	5.1	3.4

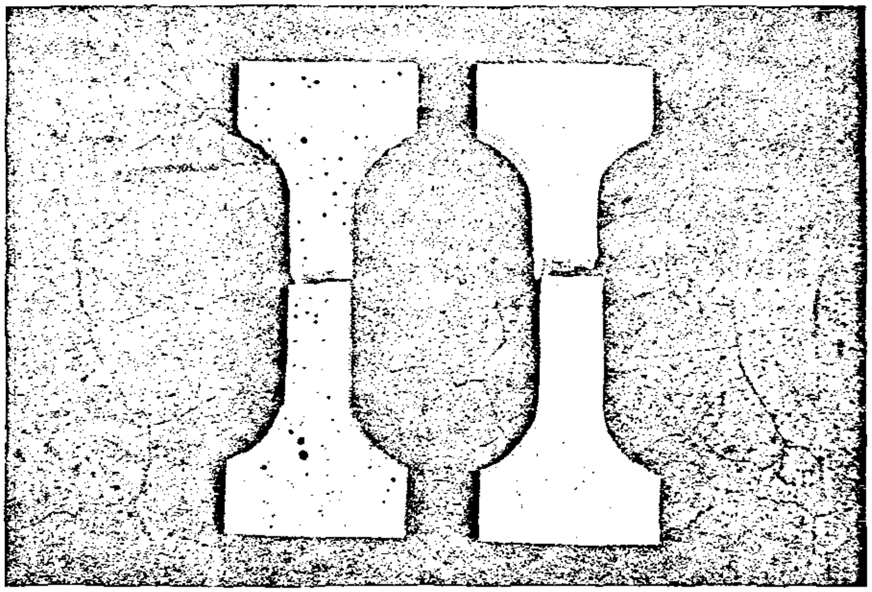


Fig. B-14. Typical Tensile Test Specimen Failure.

COMPRESSION TEST

Description

Six cylindrical foam specimens were made up for this test. Foam was injected into 6-in. diameter by 12 in. long sauna tubes and allowed to freely expand. Specimens 1, 2 and 3 were laid with the central axis in the vertical direction, and the foam was injected and allowed to cure in that orientation. For specimens 4, 5, and 6, the cylinder was laid on its side and the foam was allowed to cure with the bubbles forming perpendicular to the central axis.

Test Procedure

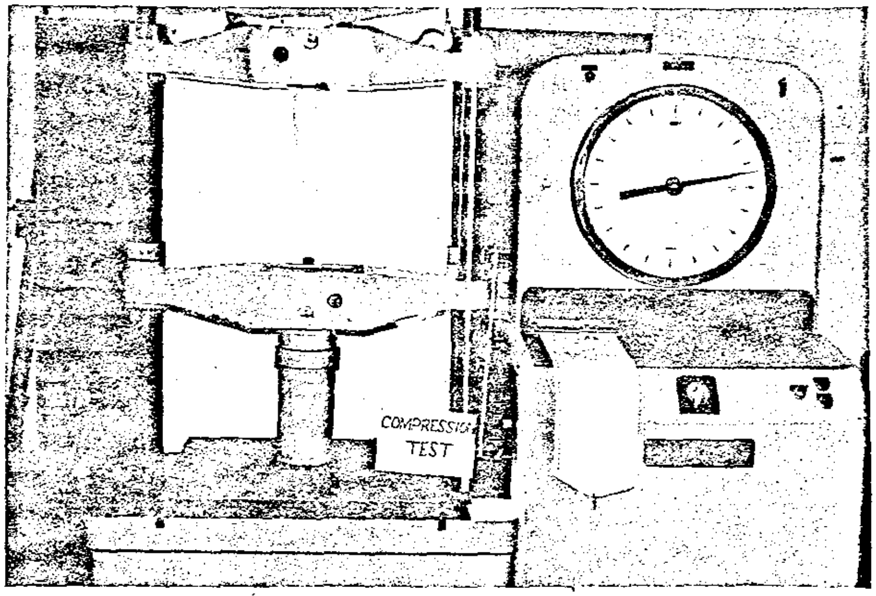
The test specimens were placed in the testing machine with the cylinder axis in the vertical position (see Fig. B-15, A and B) and slowly loaded to failure.

Test Data

The testing machine was equipped with a load vs deflection plotter. A plot of load vs deflection was made for each of the test specimens. These are presented in Figs. B-16 through B-21. The data are summarized in Tables B-4 and B-5.

It appears that the foam is 9% stronger when loaded parallel to the foam rise direction than when loaded perpendicular to the foam rise direction. The modulus of elasticity is 27% larger when loaded parallel rather than perpendicular to the direction of foam rise.

It might also be noted that the ultimate strength of foam in compression (approximately 32 psi) is almost the same as its strength in tension (approximately 29 psi), i.e., it acts very much like an isotropic material.



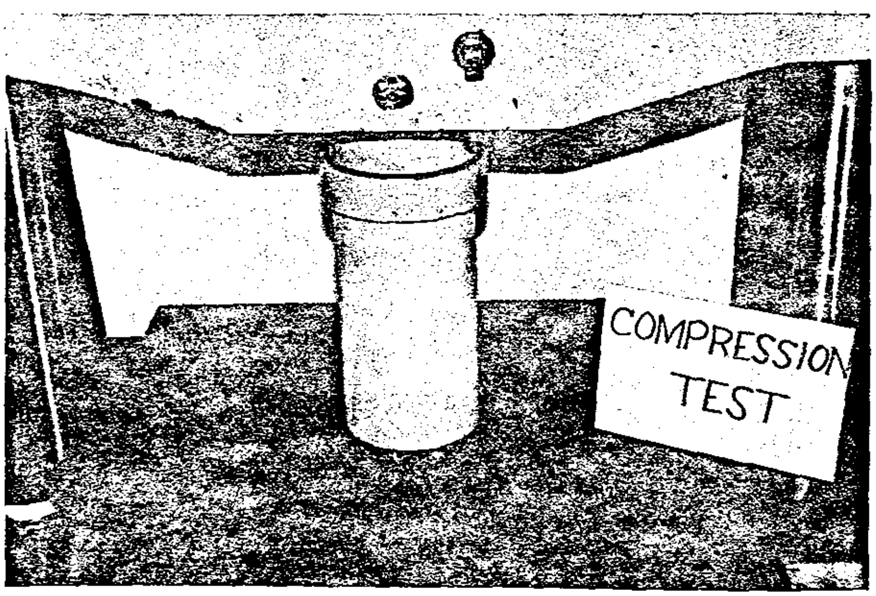


Fig. B-15. Pre-Test Photographs of the Compression Test Arrangement.

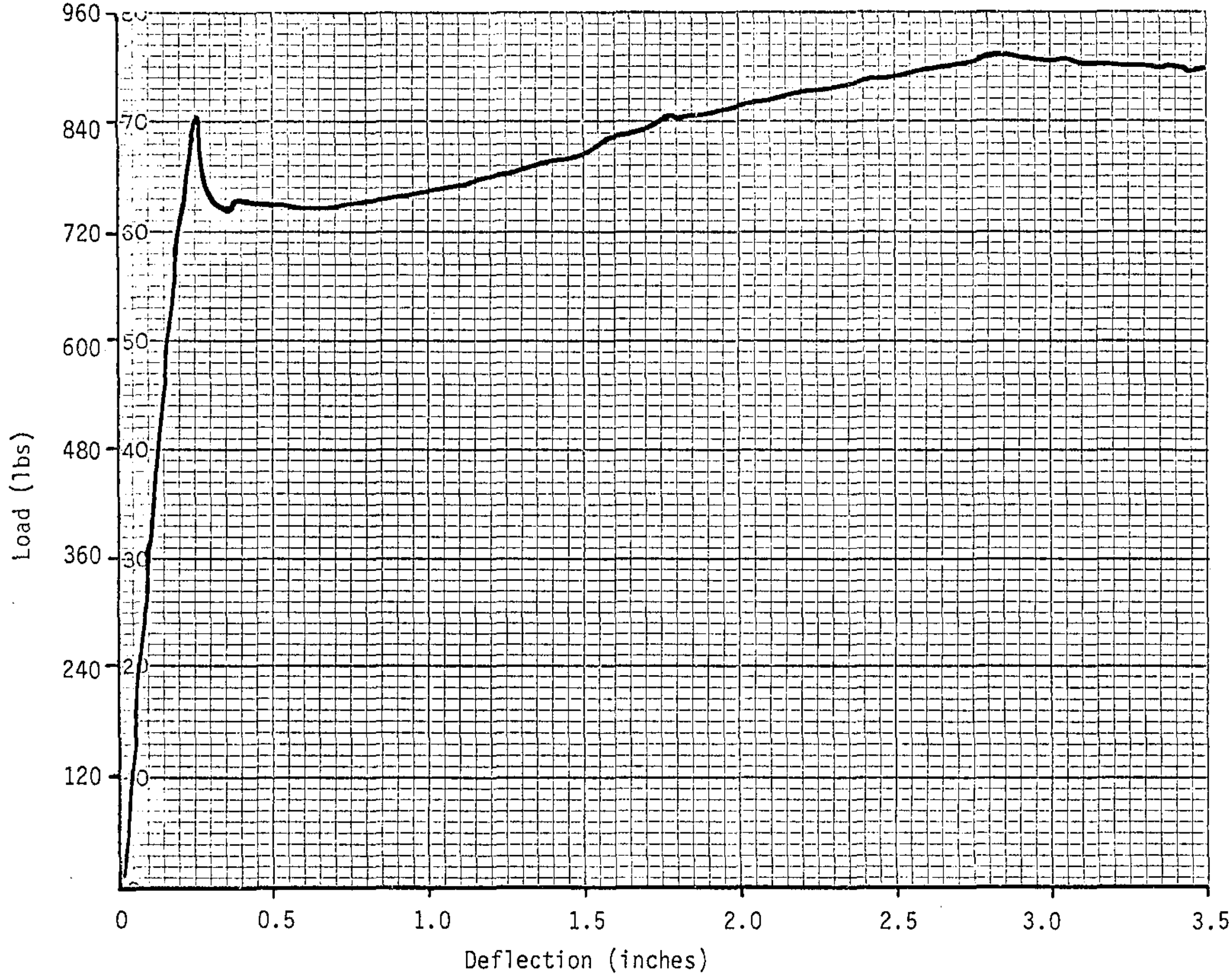


Fig. B-16. Compressive Test Number 1.

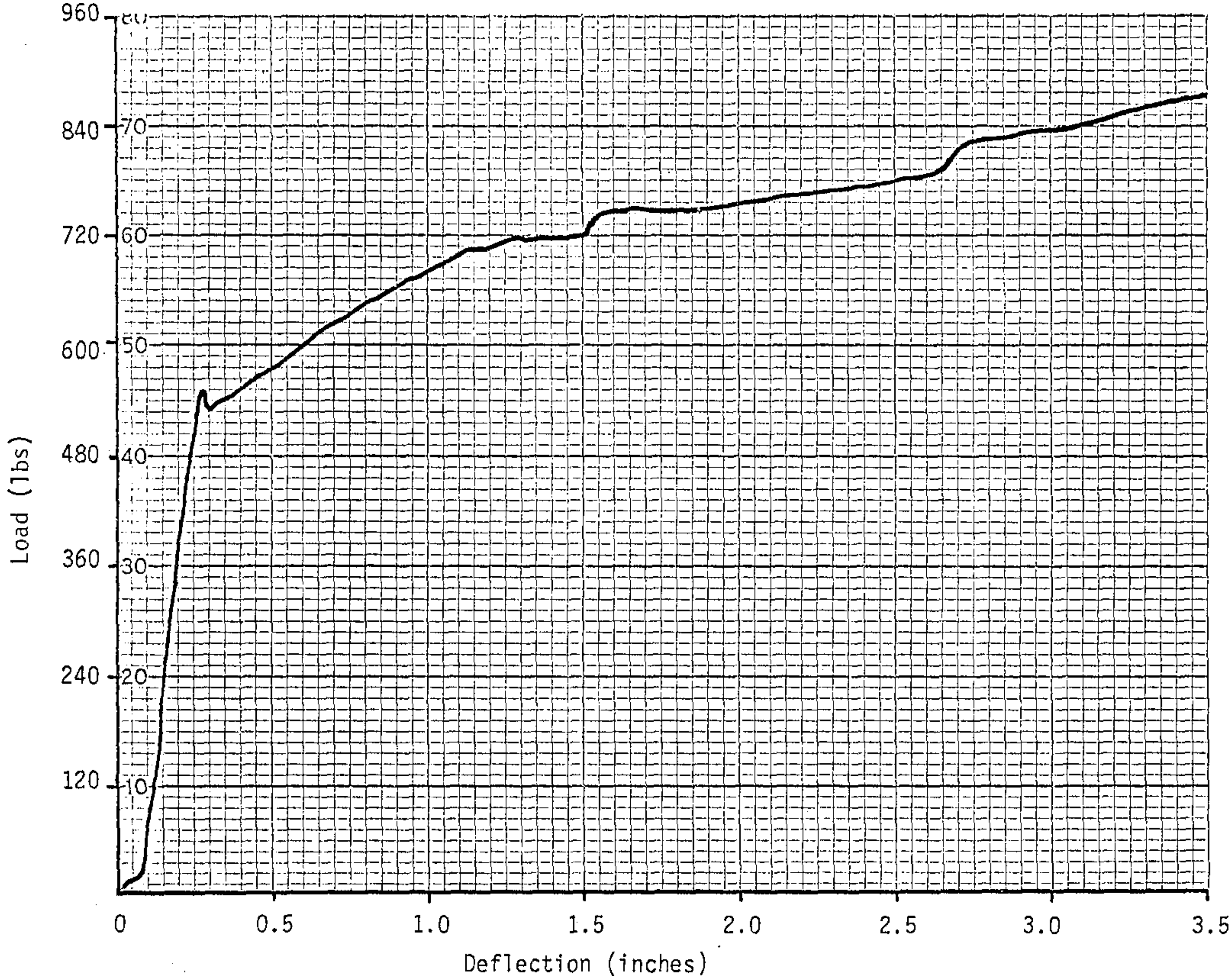


Fig. B-17. Compressive Test Number 2.

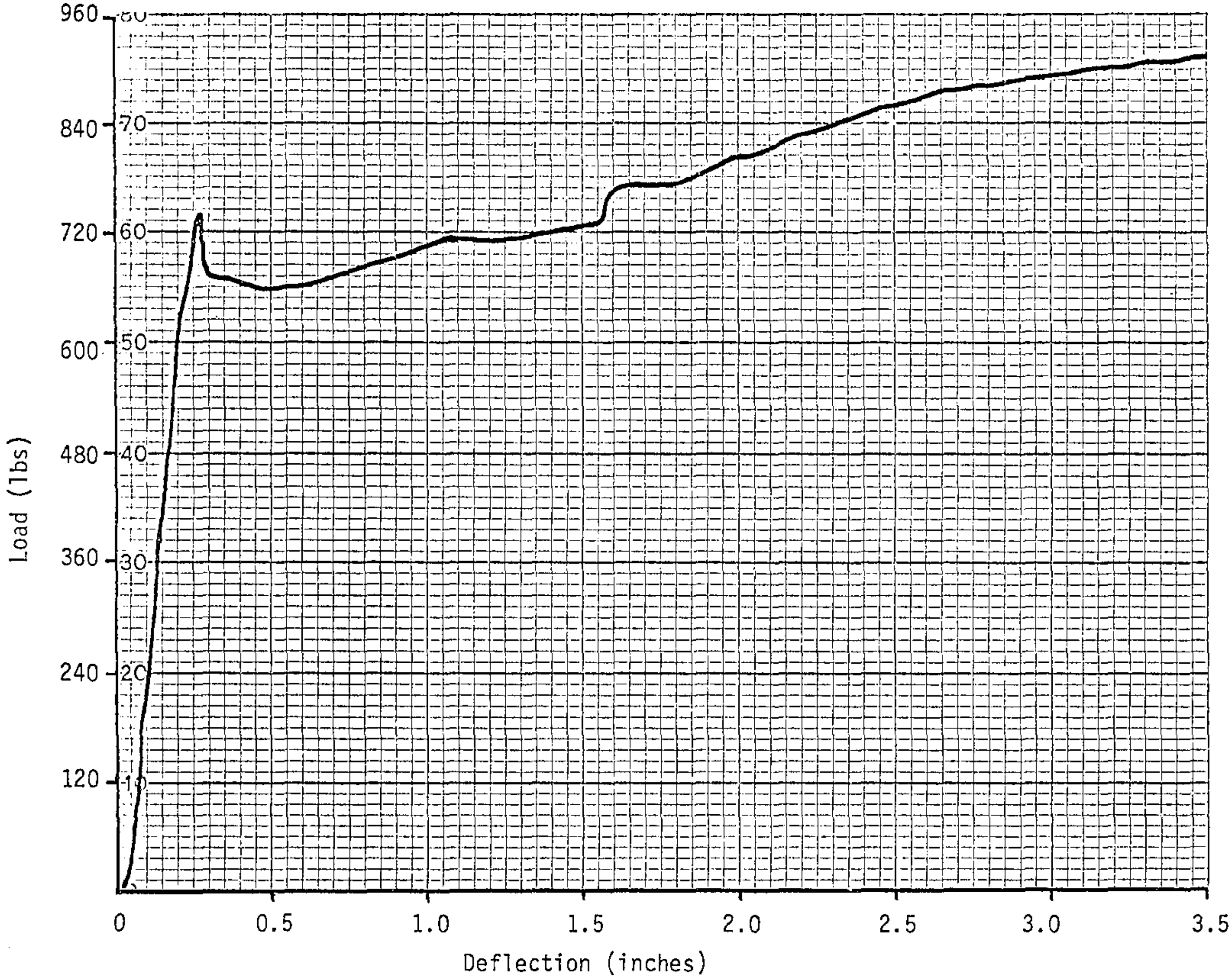


Fig. B-18. Compressive Test Number 3.

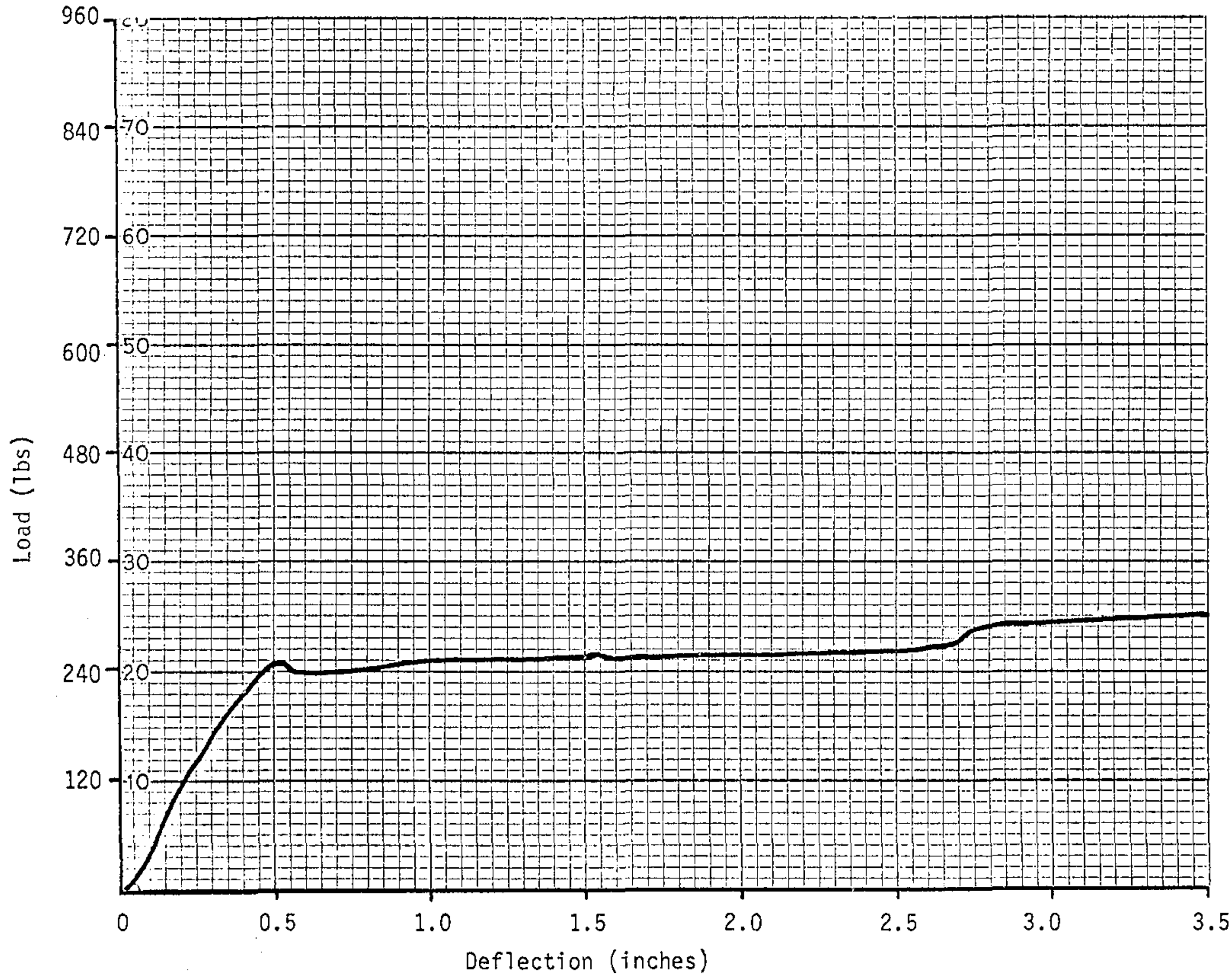


Fig. B-19. Compressive Test Number 4.

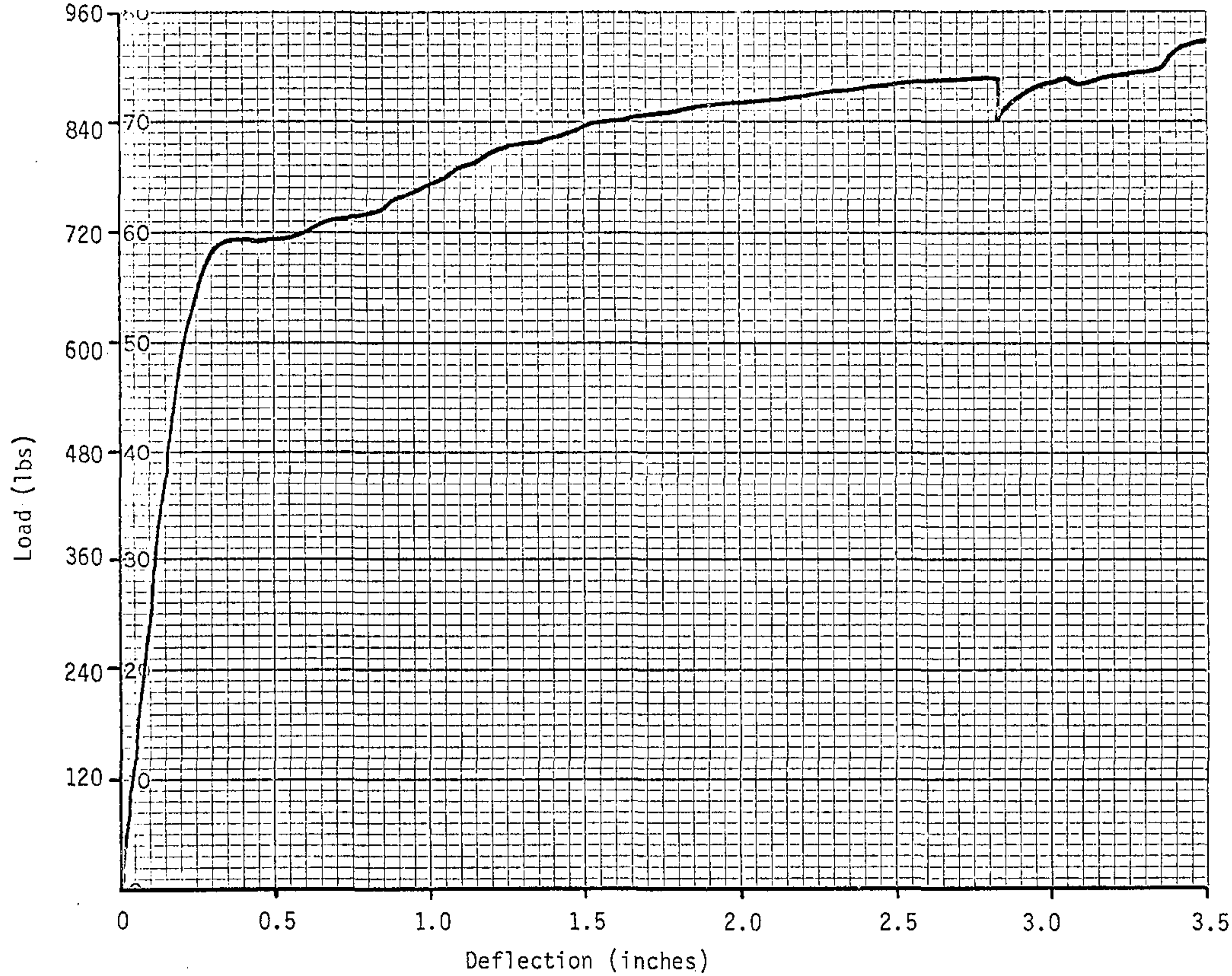


Fig. B-20. Compressive Test Number 5.

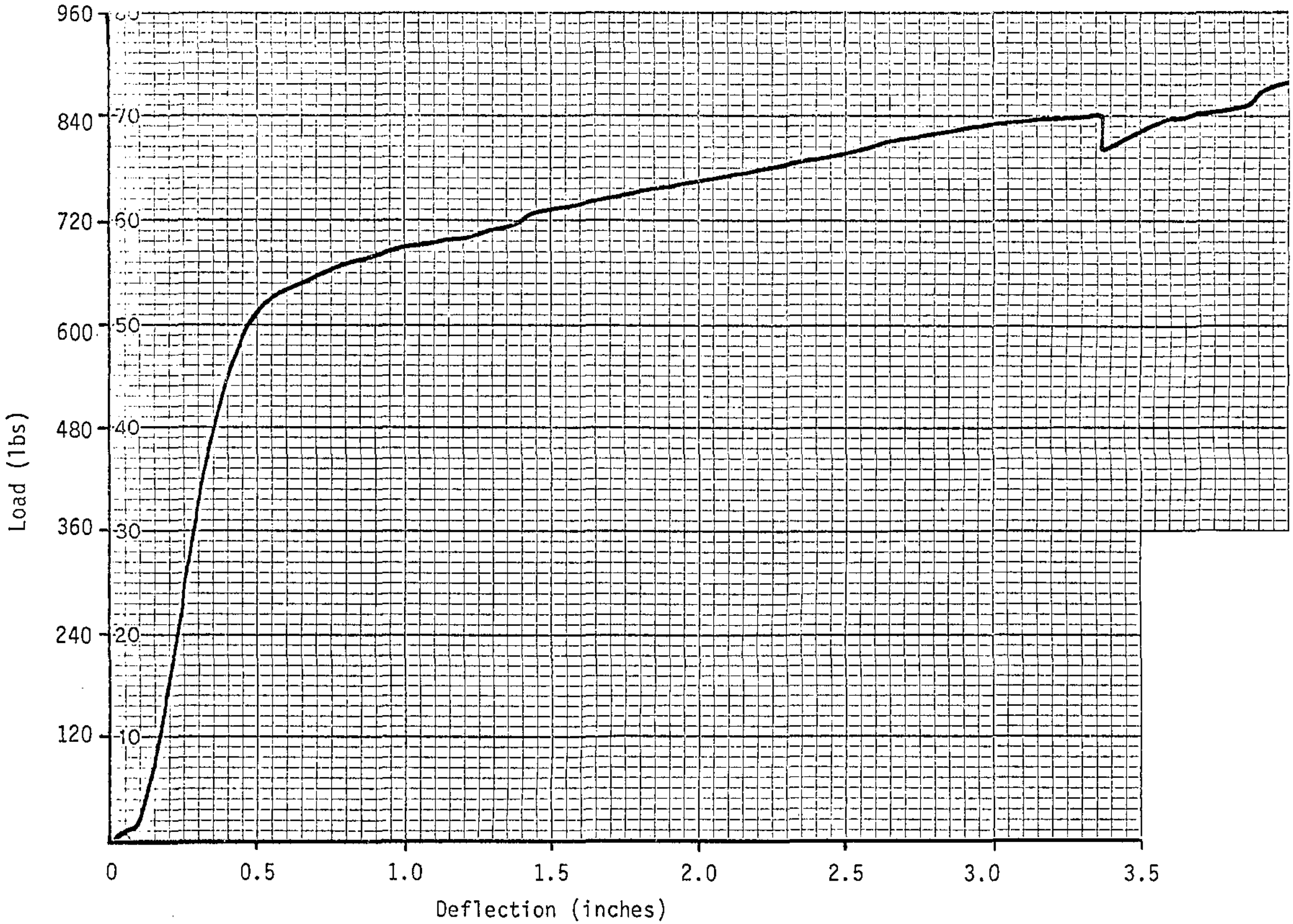


Fig. B-21. Compressive Test Number 6.

TABLE B-4: LOADING DONE PARALLEL TO CYLINDER AXIS AND PARALLEL TO FOAM RISE DIRECTION

Test No.	Yield Point Stress (psi)	Ultimate Stress (psi)	Proportional Limit Stress (psi)	Modulus of Elasticity (psi)
1	30.1	32.3	22.5	1,538
2	19.6	32.0	17.4	1,209
3	26.1	33.5	19.5	1,376
Mean $\bar{x}$	25.3	32.6	19.8	1,374.3
Std. Dev.	5.3	0.8	2.6	164.5

TABLE B-5: LOADING DONE PARALLEL TO CYLINDER AXIS AND PERPENDICULAR TO THE FOAM RISE DIRECTION

Test No.	Yield Point Stress (psi)	Ultimate Stress (psi)	Proportional Limit Stress (psi)	Modulus of Elasticity (psi)
4	22.2	28.3	14.9	1,251
5	25.1	33.2	19.9	1,051
6	21.7	31.2	16.6	709
Mean $\bar{x}$	23.1	30.9	17.1	1,004
Std. Dv.	1.8	2.5	2.5	274.1
	≈9% Weaker		27% Lower	

Failure

All six specimens ultimately failed due to localized buckling failures. For Specimens 1, 2, and 3, where the load was applied in the direction of rise of the foam, the specimens exhibited considerable symmetry in their buckling failures, as seen in Fig. 22, A and B.

Specimens 4,5, and 6 with loads applied perpendicular to the direction of the rise of the foam, exhibited unsymmetrical localized buckling failures, as shown in Fig. B-23.

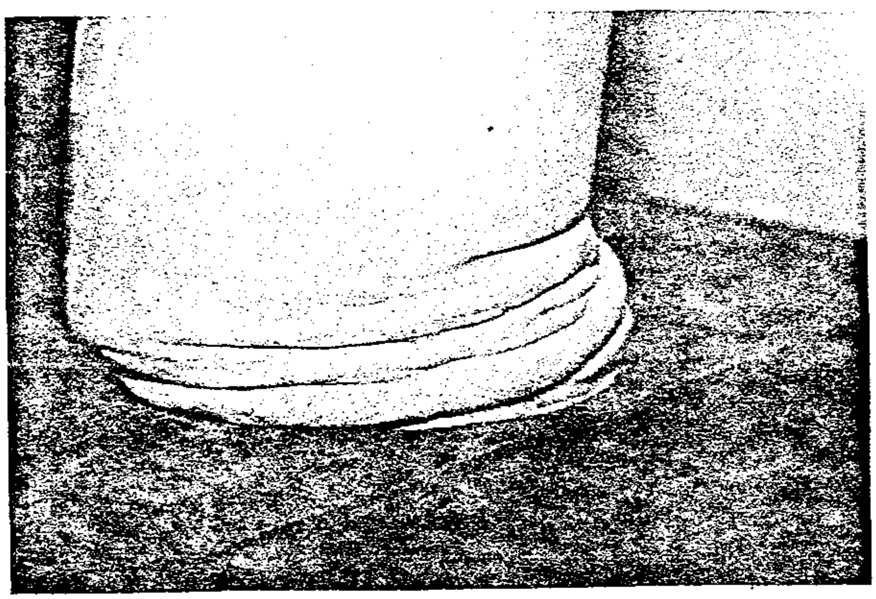


Fig. B-22. Compression Test. (Load Applied in Direction of Rise)

Fig. B-23. Compression Test. (Load Applied Perpendicular to Rise)

APPENDIX C
TEST EQUIPMENT

Appendix C
TEST EQUIPMENT

The load cells and readouts used in the horizontal shear, bending, and foundation shear tests were first calibrated on a Riehle model FH-60 testing machine (Fig. C-1). This machine, which was also used for the tensile, compression, and shear tests conducted on urethane foam specimens, is calibrated periodically traceable to the National Bureau of Standards. The most recent calibration certification is attached.

All of the tests conducted on the 4' x 4' size wall specimens were done on a Riehle model FS-300 testing machine (Fig. C-2). This machine is also calibrated periodically, traceable to the National Bureau of Standards. The certificate of calibration is attached.

The other instruments used for monitoring displacement, such as dial gauges, LVDT, etc., were calibrated using micrometers of dial gauges whose calibration is traceable to the National Bureau of Standards.

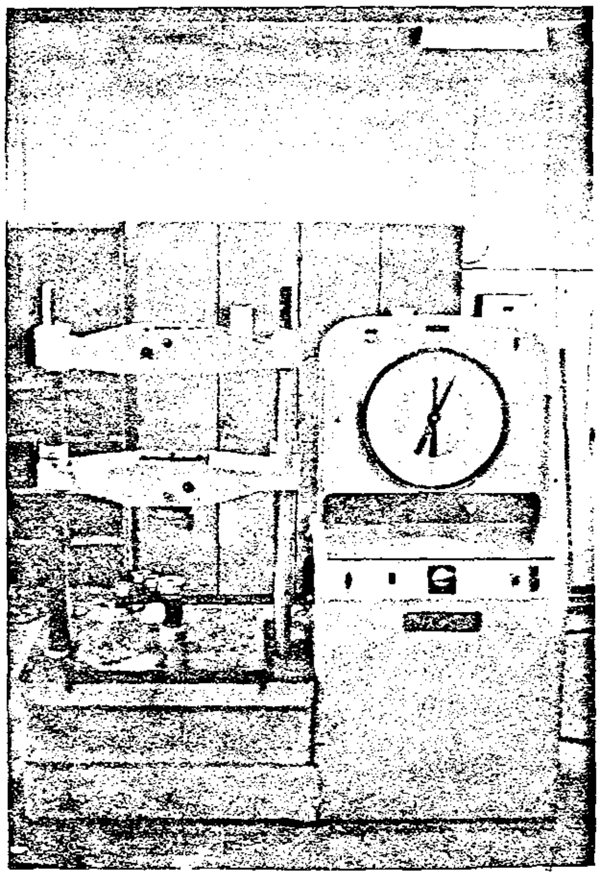


Fig. C-1. Riehle Model FH-60 Universal Testing Machine.

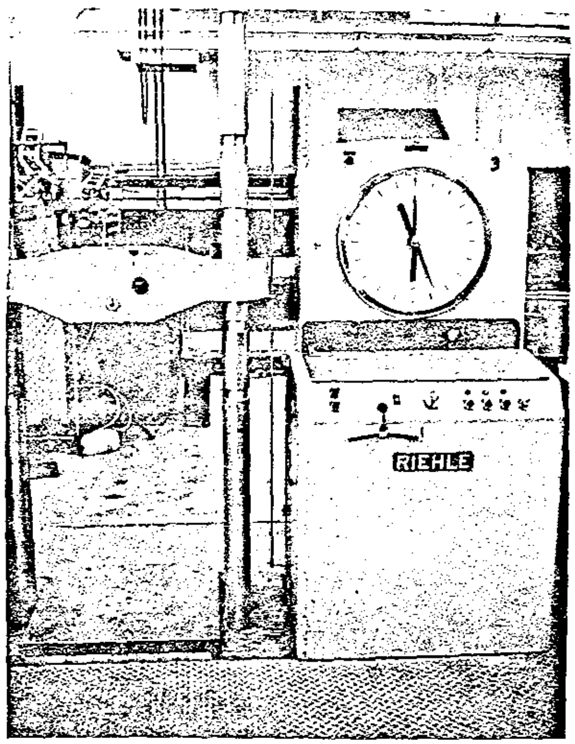


Fig. C-2. Riehle Model FS-300 Universal Testing Machine.

AGCO

Wilson Instrument Division

929 CONNECTICUT AVENUE, BRIDGEPORT, CONNECTICUT 06602 • (203) 335-2511

AMERICAN CHAIN & CABLE COMPANY, INC.

RIEHLE
Testing Machines

Certificate of Calibration

Calibration Date August 23, 1977 Machine Description Riehle Model FH-60

Customer San Jose State University Serial No. R84937

Wilson Instrument Division of Acco certifies that the machine described above has been calibrated to ASTM designation E4 using calibrated weights and/or proving rings calibrated to National Bureau of Standards Specification.

Machine Range 60,000 lbs.

Machine reading	% Error
12,000	0
24,000	+.11
36,000	+.10
48,000	-.04
60,000	+.14

Machine Range 6,000 lbs.

Machine reading	% Error
1,200	+.20
2,400	+.20
3,600	+.13
4,800	-.05
6,000	0

Machine Range 30,000 lbs.

Machine reading	% Error
6,000	0
12,000	0
18,000	0
24,000	+.04
30,000	0

Machine Range 3,000 lbs.

Machine reading	% Error
600	-.11
1,200	0
1,800	-.13
2,400	0
3,000	-.16

Machine Range 12,000 lbs.

Machine reading	% Error
2,400	+.20
4,800	+.10
7,200	-.03
9,600	-.02
12,000	0

Machine Range 1,200 lbs.

Machine reading	% Error
240	+.14
480	0
720	-.04
960	-.03
1,200	-.03

Calibrating apparatus used Morehouse Proving Rings

Capacity	Serial no.	Cal. date	Lab. no.
60,000	645	2/6/76	SJT.01/100893
10,000	710	6/22/77	SJT.01/101140
2,000	1810	2/9/76	SJT.01/100893

R Hegberg

Standards Manager

ACCO

Wilson Instrument Division

929 CONNECTICUT AVENUE, BRIDGEPORT, CONNECTICUT 06602 · (203) 335-2511

AMERICAN CHAIN & CABLE COMPANY, INC.

RIEHLE
Testing Machines

Certificate of Calibration

Calibration Date August 23, 1977

Machine Description Riehle Model FS-3(

Customer San Jose State Univ.

Serial No. R84939

Wilson Instrument Division of Acco certifies that the machine described above has been calibrated to ASTM designation E4 using calibrated weights and/or proving rings calibrated to National Bureau of Standard Specification.

Machine Range 300,000 lbs.

Machine reading	% Error
60,000	-.07
120,000	-.03
180,000	-.07
240,000	-.07
300,000	-.04

Machine Range 30,000 lbs.

Machine reading	% Error
6,000	0
12,000	+.08
18,000	+.05
24,000	-.04
30,000	-.09

Machine Range 150,000 lbs.

Machine reading	% Error
30,000	+.28
60,000	+.14
90,000	+.09
120,000	+.07
150,000	0

Machine Range 15,000 lbs.

Machine reading	% Error
3,000	-.08
6,000	0
9,000	-.10
12,000	+.08
15,000	0

Machine Range 60,000 lbs.

Machine reading	% Error
12,000	0
24,000	0
36,000	-.03
48,000	-.06
60,000	-.06

Machine Range 3,000 lbs.

Machine reading	% Error
600	-.05
1,200	0
1,800	0
2,400	+.10
3,000	0

Calibrating apparatus used Morehouse Proving Rings

Capacity	Serial no.	Cal. date	Lab. no.
300,000	789	3/31/76	SJT.01/100920
60,000	645	2/6/76	SJT.01/100893
10,000	710	6/22/77	SJT.01/101140
2,000	1810	2/9/76	SJT.01/100893

R Hefberg

Calibration Engineer

Standards Manager