NATIONAL BUREAU OF STANDARDS REPORT

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Study of

THE BEHAVIOR OF CONVENTIONAL PLYWOOD FLOORS UNDER CONCENTRATED LOAD

A Report
prepared for the
Office of Research and Technology
Department of Housing and Urban Development

NBS

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

NATIONAL BUREAU OF STANDARDS

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by

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Study of the Behavior of Conventional Plywood Floors Under Concentrated Load

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Summary

Five conventional plywood floor systems, constructed in accordance with minimum requirements of FHA "Minimum Property Standards" were tested under concentrated loads in order to determine compliance with evaluation criteria.

In 24 out of 26 tests the performance of the floor systems exceeded that required by the criteria. Data on failure loads, load-deflection characteristics and failure modes are presented and discussed.

Key Words: Concentrated-Load Capacity, Evaluation Criteria, Floors, Hardboard, Housing, Load Capacity, Performance Criteria, Plywood, Plywood Floors, Subflooring, Underlayment, Wood Frame Construction.

I. Introduction

1.1 Purpose of Study

This study was conducted as part of an effort to develop and improve evaluation criteria for housing. The criteria will be used to guide the development and evaluation of prototype housing for the Department of Housing and Urban Development's OPERATION BREAKTHROUGH.

The subject of this study are requirements for the resistance of floors to concentrated load. The objective of the study is to determine the level of performance of conventional floor systems and compare their performance with that required in the evaluation criteria for Operation Breakthrough[1][1].

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[1] Figures in brackets indicate literature references

1.2 Background Information

1.2.1 The Need to Evaluate the Structural Performance of Floors Under Concentrated Load

Present U.S. building codes and design standards for residential construction provide for floor capacity under distributed load. The only U.S. recommendation related to concentrated loads acting on floors is contained in a performance standard by HHFA [2] which is advisory and not enforceable. The standard recommends deflection limitations under a 250-lb concentrated load, and an "extended-load capacity" of 450 lb with a residual deflection not to exceed 25 percent of the maximum deflection. The concentrated loads are to be applied over a 1-inch diameter area.

The lack of enforceable provisions for concentrated-load capacity is not attributable to a lack of necessity for such provisions. It is merely brought about by the fact that codes are based on conventional building systems, which by and large tend to perform in a manner acceptable to the user under conditions of normal use. On the other hand it is envisioned that some innovative systems may comply with code provisions for distributed loads, but exhibit insufficient strength under other types of occupancy load. It is therefore necessary to evaluate these innovative systems under various types of loading generated by occupancy, including critical concentrated loads.

1.2.2 Occupancy-Generated Concentrated Loads Acting on Floors

Concentrated loads on floors may be caused by heavy furniture or by human activity. Two critical conditions are identified:

1. A concentrated load of critical magnitude that may cause damage to the entire floor, or more likely to a section of the floor, by exerting excessive bending moments and/or excessive shear.
2. A load that is concentrated over a very small area, thereby causing failure by excessive compressive stress and/or excessive punching shear.

Typical heavy concentrated loads have been studied by Boyd [3] and are summarized below:

1.	A person carrying a heavy load	350-450 lb
2.	A crowded sofa (per front caster)	300-350 lb
3.	An upright piano (1 caster)	200 lb
4.	A grand piano (1 caster)	280 lb
5.	Transportation of an upright piano (per wheel)	250-350 lb
6.	Transportation of a grand piano (per wheel)	350-450 lb

Boyd concluded that since the use of grand pianos is relatively rare, the following design-loads should be used:

(a) 400 lb for several seconds
(b) 350 lb for 1/2 hour
(c) 200 lb indefinitely.

In extreme cases these loads may be spread over an area as small as 0.5 in^2.

Critical loading caused by load concentration over a small bearing area is caused by stiletto heels. Even though these heels are no longer fashionable, their future use cannot be ruled out.

A study of typical stiletto-heel pressures [4] indicates a range of compressive stresses from 550 psi to 1390 psi, and one extreme value of 2,260 psi. Values of punching shear computed from these data range from 80 lb/in to 117 lb/in. The case that produced the 2260-psi compressive stress produced a punching shear of 156 lb/in.

1.2.3 Discussion of the Evaluation Criterion for Concentrated Load on Floors

The following criterion has been adopted as a guide for OPERATION BREAKTHROUGH [1]:

> "The structural floor should resist a 400-lb load, applied on a circular area of 5/8-in diameter and sustained for one hour, without causing a residual indentation of the structural surface in excess of 1/16 in, measured 1 hour after removal of the load, and a 280 lb long-term sustained load, applied on a circular area of 5/8-in diameter.
>
> If the wearing surface is of non-durable material, or if there is a possibility that this surface may be removed during the useful life of the structure, the floor should satisfy this criterion with the wearing surface removed."

This criterion is intended to test the structural floor and not the wearing surface. However, permanent-type wearing surfaces are left in place, so that the beneficial effect of such surfaces on the load capacity of structural floors can be relied upon.

The criterion requires reasonable deflection recovery under a 400-lb concentrated load sustained for one hour and a 280-lb long-term sustained-load capacity. The term "sustained-load" capacity is not defined in the criterion. In this investigation it is assumed that the intent of the criterion is that a 280-lb load applied over a 5/8-in diameter area continuously during the useful life of the structure should not cause serious distress or structural failure.

The 400-lb requirement would be in many cases associated with the capacity to support a higher short-term load; however, the relationship between the short-term capacity, the one-hour capacity, and the long-term capacity would depend on the material of the structural floor. As an example, this relationship is considered for the case of wood.

The following approximate capacities can be calculated using the information in Reference [5] and assuming that the 400-lb one-hour load does no damage and that the capacity is related to flexural strength:

30-second capacity	485 lb
1-hour capacity	400 lb
1-year capacity	290 lb

On the other hand, for another material, instantaneous and long-term capacities may differ very little from the one-hour capacity.

The compressive stress caused by the 400-lb load required in the criterion is 1300 psi and the punching shear is 203 lb/in.

If we compare the concentrated load, the compressive stress and the punching shear with the data in section 1.2.2, it is evident that the criterion represents reasonable minimum requirements with little or no margin with respect to extreme occupancy loads. However, it should be noted that some of the extreme loads, caused by the moving of heavy furniture, could be modified or avoided by simple precautions.

The loading requirements in the criterion differ from existing techniques, such as the ASTM E72 test [6] and the ASTM D 2394 test [7]. Both of these test methods use a 1-in diameter disc to transmit the load, while the criterion requires a 5/8-in diameter loading area.

The E72 test is intended to measure the structural capacity of the system, and the D2394 tests measure the strength of the finished flooring. These tests, with proper choice of load levels, could adequately evaluate most floor systems. A problem, however, arises with floor systems that consist of a thin structural skin supported by stiffening elements. In this case the system may perform satisfactorily under the D2394 test, while under different support conditions the structural skin may fail by punching shear. On the other hand, in order to generate adequate stress under a 1-in diameter disc, the concentrated load would have to be increased to over 1000 lb, and in order to generate adequate punching shear the load would have to be increased to at least 500 lb. These heavier concentrated loads would be higher than the extreme concentrated loads that actually act on the floor in service.

2. Scope of Testing Program

Seven different kinds of plywood subflooring were tested, representing typical minimum construction standards presently used. Most of the subflooring specimens tested were supported by wooden joists of 2 x 4-in nominal size, spaced 16 in on center. In a small number of specimens joist spacings of 24 in, 20 in, 10 in and 6 in were used in order to investigate failure modes. The small 4-in joist depth was selected, since in all cases the joists were fully supported, and joist - deflection and hence, joist size, was not a variable considered in this investigation. Test loads were concentrated loads which were increased until failure occurred. For part of the specimens loads were applied in several cycles of unloading and reloading. Deflections were measured near the point of load application. The test loads were applied over circular areas of 1 in, 5/8 in, and in a limited number of tests, 1/2 in diameter. Table 2.1 shows the test variables and the scope of the testing program.

3. Test Specimens

3.1. Materials

All materials were purchased from local suppliers and were typical of those presently used in building construction. Plywoods met the requirements of Product Standard PS1-66 [8] for softwood plywood. Dimensions and physical properties of the different plywoods used are shown in table 3.1.

Hardboard underlayment satisfied Federal Standard LLL-B-810a, Type VI [9]. Dimensions and physical properties of the hardboard used are shown in table 3.2.

Wooden joists were Construction Grade Douglas Fir. Moisture content was 9.7 percent[2/] and specific gravity was 0.41.[3/]

3.2 Description of Specimens

All the standard specimens were constructed in accordance with the provisions in "Minimum Property Standards" [14], Sections 817.3 and 817.4.

[2/] Determined in accordance with ASTM D2016 [10]

[3/] Determined in accordance with ASTM D2395 [11]

Standard specimens were constructed in small widths compared to the size of plywood sheets actually used in construction. This provided simulated conditions representing the least strength and stiffness that the floors may be expected to develop in service.

3.2.1 Standard Specimens without Underlayment

Figure 3.1 shows a typical specimen. The 2 x 4 joists were 16 in long and were spaced 16 in on center. Plywood sheets, nominally 1/2 in thick, 14 in wide, and 48 in long, were nailed to both narrow sides of the joists. The plywood sheets were oriented with the grain of the outer plies perpendicular to the axis of the joists. The joists were 2 in longer than the width of the plywood sheet to give the specimens stability under concentrated load, applied at the long edge of the plywood. The plywood sheets were nailed to the joists with 8d common nails. Three nails, spaced 6 in on center, were used for the two outside joists. The inside joists were nailed with two nails, spaced 10 in on center.

Standard specimens, as described in this section, were made for three different floor systems:

System A, using plywood a[4/]

System B, using plywood b

System C, using plywood c

3.2.2 Standard Specimens with Underlayment

Figure 3.2 shows a typical standard specimen with underlayment. The two 48 in long 2 x 4 joists were spaced 16-in on center. Four 12-in long and 16-in wide sections of nominally 1/2-in thick plywood were nailed to each of the narrow sides of the joists. Each 12 x 16-in plywood section was nailed on each side by three 8d common nails, spaced 5 in on center. This spacing was less than the 6-in spacing required in "Minimum Property Standards." The reduced nail spacing was chosen in order to compensate for the fact that this specimen was only 16 inches wide, while in an actual building an 8 ft sheet would be used, providing continuity at least at one of the two joist supports. The 1/2-in plywood sheets were oriented with the grain of the outer ply perpendicular to the axes of the joists. A continuous sheet of underlayment, 16 in wide and

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[4/] For description of plywoods refer to Section 3.1 and table 3.1

48 in long, was nailed to the outer face of the 1/2 in plywood sheets. This underlayment consisted of either 7/32-in thick hardboard or 1/4-in thick plywood. The underlayment was nailed to the 1/2-in plywood sheets by 4d annular-thread nails spaced 6-in on center.

Standard specimens with underlayment were made for four different floor systems:

System D, using plywood d with 7/32-in hardboard underlayment;

System E, using plywood d with 1/4-in plywood underlayment;

System F, using plywood c with 7/32-in hardboard underlayment;

System G, using plywood c with 1/4-in plywood underlayment.

3.2.3. Specimens With Other Than 16 in Joist Spacing

Several Specimens were made with other than 16 in joist spacing. These specimens were all without underlayment and were similar to the specimens described in Section 3.2.1 except that the joist spacing was different.

4. Testing Procedure

The specimens were built and stored in the laboratory at approximately 73°F and 50 percent relative humidity. The tests were performed in the same laboratory.

The load was transmitted from the head of a 60,000-lb capacity testing machine. The test setup is shown in figure 4.1. The specimen rested on the platten of the testing machine. Load was applied to the specimens through the end of a 6.5-in long steel rod. The end of this rod was sharp edged and machined to the required diameter. This steel rod was connected to a load cell which was inserted between the upper end of the rod and the head of the testing machine.

Deflection[5/] was measured by a displacement transducer (LVDT). The transducer was connected to a base, made of a 2 x 4 in wooden member, 18 in long, that rested on three adjustable

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[5/] The term "indentation" used in the criterion was interpreted as a deflection of localized nature which was measured relative to two points on the surface of the floor, spaced 16 in apart and which in some cases included a well defined indentation of the floor surface, as well as a localized deflection between two adjacent supporting joists. In the case of the standard specimens, the measured deflections at the critical locations were referenced to two points at the floor surface located above the centerlines of two adjacent supporting joists.

bolts. These bolts were so spaced, that the base could be supported on the centerline of two joists on 16 in centers. Deflections were measured to the face of a bracket, which was connected to the upper end of the load cell. Thus deflections were measured by measuring the downward movement of the loading device, relative to points, spaced 16 in apart and located at the surface of the specimen. The distance between the centerline of the displacement transducer and the centerline of the loading rod was 4 in.

Deflections thus measured also included shortening of the loading rod and the load cell. To determine the magnitude of this effect, the shortening of the rod and the load cell was measured for loads up to 1000 lb. It was determined that the effect of this shortening on test results was of second order magnitude and corrections for this effect were therefore unnecessary.

Data were recorded electronically, by transmitting the output from the displacement transducer and the load cell to an X-Y recorder. The X-Y recorder plotted loads on the Y axis to a scale of 100 lb per 1 in, and deflections on the X axis to a scale of 0.1 in per 1 in. This produced a graphical record of the data which had adequate resolution.

The load was applied at a rate of 1/2 lb/sec. Most specimens were loaded continuously to failure, but several specimens were subjected to cycles of unloading and reloading. After each load increment of 100 lb these specimens were completely unloaded and reloaded to a load 100 lb greater than the previous load or to failure, whichever came first. This procedure left a record of instantaneous deflection recovery for each specimen. On two specimens, a 400-lb load was maintained for one hour, and the specimens were then unloaded and deflection recovery was measured after one hour. In some tests failure occured at loads higher than 1000 lb. In these cases the load cell which had a 1000-lb capacity, was removed prior to the completion of the test and loads were measured by the testing machine. For these tests, only failure loads were recorded since the deflections at failure were not measured.

5. Test Results

The test data, which consist of a plotted load-deflection curve for each specimen tested are summarized in table 5.1. The first column in the table identifies the floor system, in accordance with the list of floor systems in table 2.1. The diameter of the loaded area is shown in the second column, the joists spacing in the third column, and the location of the test load in the fourth column. Testload locations are identified as shown in figure 5.1. The other three columns identify failure load, load causing initial structural damage, and deflection at failure load, respectively.

The method by which these values were determined is illustrated in figure 5.2 which shows a typical load-deflection curve. In general specimens could be loaded to a certain level without any sign of distress. First signs of distress, which were usually associated with some cracking sound, can be identifed on the load-deflection curves as a drop in the applied load which is not associated with a change in deflection. Such a drop in load is associated with a residual deflection which is roughly proportional to the magnitude of the drop in load. The load level at which this first distress occurred is identified in column 6 of table 5.1, and is shown in figure 5.1. If loading was subsequently continued, most specimens were able to support additional load increments without an appreciable change in the slope of the load-deflection curve, until an additional drop in load occurred at a higher load level.

The failure load in column 5 of table 5.1 identifies the lowest load level at which a load drop of 30 lb or more occurred. This point does not always represent the highest load that the specimen can support. The definition of failure load is based on the observation that a load drop of 30 lb was associated with irrecoverable deflections of 1/20 in or less. It is reasonable to assume that after such a drop in load most specimens would not meet the deflection-recovery requirements in the criterion, which specifies a residual deflection of less than 1/16 in, and that a clearly identifiable residual deflection would remain on all specimens after removal of the load.

Other information that can be derived from the test data, together with plots of typical load-deflection curves, is presented in Section 6 where test results are interpreted.

6. Interpretation of Test Results

6.1. Compliance with the OPERATION BREAKTHROUGH Criterion

6.1.1 Concentrated-load capacity

Figure 6.1 is a plot showing the range of load capacities and average load capacities. The test data are for test locations 1 and 1u in figure 5.1, since these locations are considered critical. Actually tests at locations 3, 4, and 2u yielded lower results, but in accordance with good construction practice free edges of plywood sheets should be blocked when 1/2-in thick plywood is used, or tongue and groove joints should be provided for thicker plywood sheets.

Compliance with the criterion at test locations 3, 4 and 2u is therefore not required.

The shaded rectangles in figure 6.1 show the range of the failure loads and the unshaded rectangles show the range of loads that caused initial distress. The solid and hollow circles[6/] show the average loads at failure and initial distress, respectively. Test results are plotted for loaded areas of 5/8 in, as well as 1 in diameter. The heavy, horizontal line shows the load level required by the criterion.

The following conclusions can be derived from figure 6.1:

1.) All specimens tested failed at load levels equal to, or higher than that required by the criterion.
2.) Except for floor system E, all specimens tested showed first signs of distress at load levels equal to or higher than that required by the criterion. For system E, two out of the three specimens tested showed first signs of distress at load levels higher than that required by the criterion.

[6/] In some cases the test results do not cover a significant range, or only one single test was performed. In these cases only the solid and hollow circles are shown.

3.) In all cases, specimens tested by the 1-in diameter disc had significantly greater load capacity than specimens tested with the 5/8-in diameter disc.

The overall conclusion is, that except for one specimen in system E, all specimens satisfied the criterion and most specimens exceeded the capacity required in the criterion by a substantial margin. It should be noted that this conclusion is based on a test setup which uses specimens of 14 in and 12 in width, respectively. This is a simulation representing the least strength that a floor may be expected to develop. In an actual building, where floors are continuous over much larger areas, load capacities may be somewhat higher.

6.1.2 Deflection Recovery

Figure 6.2 shows the load-deflection curve for a test in which floor system C was loaded in accordance with the requirement of the criterion. Deflections are plotted along the abscissa, and loads along the ordinate.

Note that the instantaneous deflection under the 400-lb load was approximately 0.178 in. When the load was sustained for an hour, this deflection increased by 0.012 in and when the load was removed, there was an instantaneous deflection recovery to a residual deflection of 0.02 in. One hour after unloading, the remaining residual deflection was 0.01 in. This should be compared with the 1/16-in (0.0625 in) residual deflection permitted by the criterion. Thus this specimen exceeded the performance required by the criterion by a substantial margin.

Figures 6.3 through 6.7 show deflection-recovery characteristics for floor systems A,B,C,F, and G, respectively. In all cases the residual deflection, measured immediately after removal of the 400-lb load, was less than 1/20 in. This is an indication that all these floor systems have deflection-recovery characteristics which would satisfy the criterion.

6.1.3 Sustained-Load Capacity

No long-term tests were conducted to determine the sustained-load capacity of the specimens. Some indication of the magnitude of that capacity can be derived using the data presented in reference [5]. In accordance with these data, a 1-hour capacity of 400 lb would correspond to a 1-year capacity of 290 lb and to a 30-year capacity of 265 lb.

If we define the 30-year capacity as the required sustained-load capacity, a one-hour capacity of 422 lb would satisfy the 280-lb requirement in the criterion. Of the 26 specimens tested at load locations 1, 2, and 1u, 24 exceeded this capacity.

Thus it can be concluded that the floor systems tested satisfy the requirement for sustained-load capacity.

6.2 Failure Modes

Figures 6.8 and 6.9 illustrate two typical modes of failure. Figure 6.8 shows a typical failure of a specimen of floor system A loaded over a 1-in diameter area and gives the appearance of a flexural tensile crack. Figure 6.9 shows the failure mode of a specimen of floor system B, loaded over a 5/8-in diameter area, which is typical for most specimens under this loading, except for specimens that were loaded over the joists support at locations 5 and 3u. This mode of failure has the appearance of a combination of a local shear failure (punching shear) in the upper four plies with a flexural tensile failure in the lowest ply.

When test results are interpreted, some conclusions could be drawn from a theoretical consideration of the effects of the variation of the loaded area, the joists spacing, and the location of the applied load. The following theoretical considerations apply to loads acting at locations 1, 2 and 1 u.

1.) Flexural stress would vary with joist spacing, but the diameter of the loaded area would have relatively little effect. Flexural failure would probably occur under the loaded area.
2.) Local (punching) shear would vary with the diameter of the loaded area and would not vary with joist spacing. Failure by local shear would occur close to the perimeter of the loaded area.
3.) Vertical compression would vary with the diameter of the loaded area and would be independent of the location of the loaded area and of joist spacing.

Indentations caused by vertical compression were determined in the testing program by applying concentrated loads over the joists, at locations 5 and 3u. On this basis it was determined, that vertical compression would not be critical for the 1-in and the 5/8-in diameter loading discs. The 1/2-in diameter disc was ruled out on the basis of tests performed at location 5 on floor system C. Data for these tests are shown in table 5.1.

Some conclusions about the failure mode can be drawn by considering the effect of joist spacing and of the diameter of the loaded area. It has already been noted in section 6.1.1 that load capacity increased with an increase in the diameter of the loaded area. This effect, and the effect of joist spacing are illustrated in figures 6.10 and 6.11.

Figure 6.10 shows the effect of joist spacing on failure loads and load levels at which initial damage occurred in system A. Note that there was considerable variation in strength between individual specimens. The average values therefore only represent approximate trends since the number of samples used was small.

For the 1-in diameter test load, there was no difference in strength between the 6-in and the 10-in joist spacing. At these spacings, failure probably occurred by punching shear. For larger joist spacing, the failure load dropped with increasing spacing. This drop, together with the characteristics of the typical failures which is shown in figure 6.8, leads to the conclusion that these specimens probably failed by flexural compression and tension.

For the 5/8-in diameter test load, the failure load tends to decrease with increasing joist spacing between the 6-in and the 16-in spacing. Then the failure load tends to increase. This inconsistency may be attributable to the strength variability. The dashed curve, which shows loads causing initial damage, shows a consistent decrease of load with increasing joist spacing. Since for flexural failure the failure load would be independent of disc-size, and for local shear the load would be independent of joist spacing, it is concluded from figure 6.10 that for the 5/8-in loading diameter failure probably was caused by a complex combination of flexural stresses and local shear.

Figure 6.11 shows the relationship between load capacity and joist spacing for floor system B, loaded over a 5/8-in diameter area. In this case capacity only slightly decreased with joist spacing. The dominant failure mode for these specimens was probably local shear.

6.3 Effect of the Test Location on Load Capacity and Stiffness

6.3.1 Floor Systems Without Underlayment

Floor systems A, B and C were tested at 5 different locations. Locations 1 and 2 were between joists and 6 in from the free edge of the plywood sheet. These locations only differed in the fixity of the plywood sheet at the joist support. At location 1 the edge of the plywood was nailed to one joist support, and the plywood was continuous over the other joist support. At location 2, the plywood was continuous over both joist supports. It was reasoned that location 1 should be weaker than location 2, since there was less fixity at the joist that supported the edge of the plywood sheet. However, comparison of the average test results in table 5.2 indicates, that the strength at location 2 was similar to that of location 1 in systems A and B. Only system C had greater strength at location 2. Locations 3 and 4 were at the edge of the plywood sheet between joists and represented points of least strength. This can be seen from the data in table 5.2. Location 5 was over the joist support, and as expected supported much higher loads.

A comparison of load-deflection characteristics for the various loading points is shown for system A in figure 6.12. As expected, location 5 is the stiffest. There is little difference in stiffness between locations 2 and 1, and locations 3 and 4 have also comparable stiffness. This is consistent with the observation that there was no significant difference in strenth between locations 1 and 2, as well as between locations 3 and 4.

Location 1 is considered to represent the most critical condition, since in a properly constructed floor, the free edge at locations 3 and 4 should be supported by blocking.

6.3.2 Floor Systems With Underlayment

Floor systems D, E, F and G were tested at three locations. Location 1u is halfway between joists and at a point, where two free edges of the plywood sheet are covered by underlayment. Location 2 u is at a free, unsupported edge, midway between joists, and location 3u is over a joist. The test results at these locations are shown in table 5.2. As expected, location 3u is the strongest and location 2u the weakest.

The load-deflection characteristics for these loading points are compared in figure 6.13 for floor system E.

Location 1 u is considered to represent a simulation of the most critical condition, since the free edge at location 2 u should be blocked.

6.4 Relative Stiffness of the Floor Systems

The stiffnesses of the floor systems without underlayment, loaded at location 1, are compared in figure 6.14. System A was the least stiff. This system also had the least strength. It should be noted, that system A does not meet the minimum requirements set by FHA [14], since the thickness of the plywood was reduced by 1/32 of an inch by the sanding of one surface.

The stiffnesses of floor systems with underlayment, loaded at location 1u, are compared in figure 6.15. Again, the least stiff system (E) developed the least strength.

7. Conclusions

1.) Out of 26 tests performed on the specimens at the weakest location likely to be encountered in a built floor, 24 exceeded the one-hour load capacity requirement in the OPERATION BREAKTHROUGH criterion for concentrated-load capacity by a substantial margin, 1 test exactly satisfied the criterion and 1 test did not pass the criterion.
2.) For those tests that exceeded the one-hour load capacity requirement, residual deflections were generally smaller than the 1/16-in maximum permitted in the criterion.
3.) On the basis of the data presented in reference [5], it can be concluded that 24 out of the 26 points tested satisfied the sustained-load requirement of the criterion.

4.) The observed mode of failure under the 5/8-in diameter loaded area was punching shear, or a complex combination of flexural tension and punching shear. Vertical compressive stresses developed under the concentrated load were not critical.

5.) Load capacity under a 1-in diameter loaded area exceeded the capacity under a 5/8-in diameter loaded area by a substantial margin. Under a 1/2-in diameter loaded area vertical compressive stresses caused by a 400-lb concentrated load exceeded the material strength.

References

[1] National Bureau of Standards, Building Research Division, Guide Criteria for the Design and Evaluation of Operation Breakthrough Housing Systems, revised October 1970. (unpublished)

[2] Housing and Home Finance Agency, Performance Standards, Structural and Insulation Requirements for Houses, Washington, D.C., June 1947.

[3] Boyd, J.D., Minimum Strength and Stiffness Necessary for Wooden Floors in Houses, Paper No. 34, CSIRO, Division of Forest Product Technology, Melbourne, Australia, 1964.

[4] Thorburn, H.T., Flooring Damage by Heels, Materials Research Standards, ASTM, Vol.2, No. 9, Philadelphia, Pa., September 1962.

[5] Wood, Lyman W., Relation of Strength of Wood to Duration of Load, Forest Products Laboratory, Madison, Wis., December 1951.

[6] ASTM Designation E72-68, Conducting Strength Tests of Panels for Building Construction, American Society for Testing Materials, Philadelphia, Pa., 1968.

[7] ASTM Designation D 2394-69 Tests for Simulated Service Testing of Wood and Wood-Base Finish Flooring, American Society for Testing Materials, Philadelphia, Pa., 1969.

[8] National Bureau of Standards, Voluntary Product Standard PS 1-66, Softwood Plywood, Construction and Industrial, U.S. Government Printing Office, Washington, D.C., July 1970.

[9] General Service Administration, Federal Specification, LLL-B-810 a, Building Board, (Hardboard) Hard Pressed, Vegetable Fiber, Washington, D.C., July 7, 1965.

[10] ASTM Designation D 2016-65, Tests for Moisture Content of Wood, American Society for Testing Materials, Philadelphia, Pa., 1965.

[11] ASTM Designation D 2395-65 T Tests for Specific Gravity of Wood and Wood-Base Materials, American Society for Testing Materials, Philadelphia, Pa., 1965.

[12] ASTM Designation D 805-63 Veneer, Plywood, and other Glued Veneer Construction Testing, American Society for Testing Material, Philadelphia, Pa., 1963.

[13] U.S. Department of Commerce, Commercial Standard CS 251-63, Washington, D.C., April 1967.

[14] Federal Housing Administration, Minimum Property Standards for One and Two Living Units., Washington, D.C., Nov. 1966, as subsequently amended.

TABLES

TABLE 2.1

Number of Tests Performed

Joist Spacing, in		16			24		20		10		6		
Diameter of Loaded area, in		1	5/8	1/2	1	5/8	1	5/8	1	5/8	1	5/8	TOTAL
Subflooring System	A	12	18			6	6	6	6	6	6	6	72
	B		18			12		6		11		6	53
	C	5	6	2									13
	D	14	7										21
	E	14	7										21
	F		6										6
	G		7										7
Total No. of Tests													193

SUBFLOORING SYSTEMS:

A: 15/32-in-thick underlayment grade Southern Pine interior-type, 5-ply plywood.

B: 1/2-in-thick standard grade Southern Pine interior-type with exterior glue, 5-ply plywood.

C: 1/2-in-thick standard grade Douglas Fir interior-type, 3-ply plywood.

D: 1/2-in-thick standard grade Douglas Fir interior-type, 3-ply [a/] plywood. under 7/32-in-thick hardboard underlayment.

E: 1/2-in-thick plywood as in D under 1/4-in-thick plywood underlayment.

F: 1/2-in-thick plywood as in C under 7/32-in-thick hardboard underlayment.

G: 1/2-in-thick plywood as in C under 1/4-in-thick plywood underlayment.

[a/] The core of this plywood was laminated giving the interior ply double thickness.

TABLE 3.1

Physical Properties of Plywoods[a]

Designation	Thickness in.	No. of plies	Species	Grade	Identification Index	Type	Moisture[d] Content %	Specific[d] Gravity
a [b]	15/32	5	Southern Pine	Underlayment	Plugged and Touch Sanded	Interior with Exterior Glue	7.1	0.60
b [b]	1/2	5	Southern Pine	Standard	32/16	Interior with Exterior Glue	7.3	0.54
c [c]	1/2	3	Douglas Fir	C-D	32/16	Interior with Exterior Glue	6.3	0.53
d [b]	1/2	3 [e]	Douglas Fir	Standard	32/16	Interior with Exterior Glue	9.5	0.47
Underlayment [b]	1/4	3	Douglas Fir	A-A		Interior	8.0	0.48

[a] Properties are defined in conformance with Product Standard PS1-66.

[b] Properties identified in DFPA Grade-Trademark except for species, moisture content and specific gravity.

[c] Properties identified in TECO Gradestamps, except for species, moisture content and specific gravity.

[d] Properties determined in accordance with ASTM designation D-805 [12].

[e] The core of this plywood was laminated, giving the interior ply double thickness.

TABLE 3.2

Physical Properties of the Hardboard a/

Thickness	Modulus of Rupture	Water Absorption	Thickness Swelling	Specific Gravity	Average Moisture Content
0.215 in	4,500 psi	13.73%	7.08%	0.998	5%

a/ Tested by manufacturer in accordance with Commerical Standard CS 251-63 [13]

TABLE 5.1. Test Results

Floor System	Diameter of Loaded Area in	Spacing of Joists in	Location of Test	Failure Load lb	Load Causing Initial Structural Damage lb	Deflection at Failure Load in
A	5/8	16	1	540	480	0.52
				700	670	0.54
				620	570	0.39
				400	400	0.30
			Average	565	530	
			2	450	450	0.34
				600	460	0.38
			Average	525	455	
			3	310	310	0.67
				210	210	0.51
				440	440	0.68
				490	460	0.84
			Average	363	355	
			4	300	300	0.61
				300	300	0.36
			Average	300	300	
			5	1000 b/	980	0.12 a/
				1000 b/	950	0.14 a/
				1000 b/	920	0.13 a/
				1000 b/	--- c/	0.08 a/
				1000 b/	--- c/	0.07 a/
				1000 b/	--- c/	0.08 a/
	5/8	24	1	670	460	1.20
				430	280	0.89
				820	590	1.32
			Average	640	343	
			2	1044	1044	1.22
				740	300	1.14
				600	600	0.75
			Average	795	648	

a/ Deflection readings were taken at 1000 lb.

b/ The test was discontinued at the load level indicated.

c/ No information is available.

Floor System	Diameter of Loaded Area in	Spacing of Joists in	Location of Test	Failure Load lb	Load Causing Initial Structural Damage lb	Deflection at Failure Load in
A	5/8	20	1	540	460	0.63
				610	610	0.64
				730	460	0.88
			Average	627	510	
			2	540	540	0.50
				740	450	0.80
				610	610	0.61
			Average	630	503	
		10	1	990	890	0.39
				910	710	0.41
			Average	950	800	
			2	1000	1000	0.37
				1138	1138	0.30 a/
				960	940	0.27
				1010	950	0.31 a/
			Average	1027	1007	
		6	1	1082	1082	0.25 a/
				1372	1372	0.18 a/
			Average	1227	1227	
			2	994	994	0.28
				1290	--- c/	0.22 a/
				1122	--- c/	0.22 a/
				1172	--- c/	0.22 a/
			Average	1145		
	1	16	1	1040	640	0.58 a/
				1208	1000	0.46 a/
				1482	1000	0.49 a/
				670	670	0.36
				1065	740	0.56 a/
				970	860	0.54
				795	700	0.43
				795	795	0.42
			Average	1003	801	
			2	1152	1000	0.48 a/
				590	590	0.31
				800	710	0.62
				590	590	0.32
			Average	783	723	

Floor System	Diameter of Loaded Area in	Spacing of Joists in	Location of Test	Failure Load lb	Load Causing Initial Structural Damage lb	Deflection at Failure Load in
A	1	20	1	845	845	0.64
				860	860	0.74
				530	370	0.51
			Average	745	558	
			2	850	660	0.66
				1242	1000	0.87 a/
				1264	560	0.84 a/
			Average	1119	740	
		10	1	1788	--- c/	---- c/
				1706	--- c/	---- c/
			Average	1747	---	
			2	1662	--- c/	---- c/
				1182	--- c/	---- c/
				1726	--- c/	---- c/
				1268	--- c/	
			Average	1460	---	
		6	1	1750	--- c/	---- c/
				1740	--- c/	---- c/
			Average	1745	---	
			2	1546	--- c/	---- c/
				1564	--- c/	---- c/
				1508	--- c/	---- c/
				1584	--- c/	---- c/
			Average	1551	---	
B	5/8	16	1	895	895	0.51
				860	660	0.61
				825	810	0.61
				600	600	0.40
			Average	795	741	
			2	730	700	0.43
				790	790	0.51
			Average	760	745	
			3	290	290	0.43
				480	470	0.68
				425	360	0.68
				590	590	0.79
			Average	446	428	

Floor System	Diameter of Loaded Area in	Spacing of Joists in	Location of Test	Failure Load lb	Load Causing Initial Structural Damage lb	Deflection at Failure Load in
B	5/8	16	4	440	440	0.57
				634	634	0.68
			Average	537	537	
			5	840	840	0.14
				1000 b/	--- c/	0.12 a/
				950	950	0.13
				1000 b/	630	0.14 a/
				1000 b/	--- c/	0.11 a/
				1000 b/	--- c/	0.11 a/
		24	1	890	780	1.29
				945	790	1.29
				730	640	1.20
				910	910	1.25
				652	360	1.06
				640	600	1.08
				600	600	0.94
				920	500	1.27
			Average	748	640	
			2	680	660	0.81
				670	670	1.07
				795	795	0.97
				770	770	0.92
			Average	729	724	
		20	1	785	785	0.79
				634	634	0.59
				800	630	0.90
			Average	740	683	
			2	990	890	0.78
				810	660	0.71
				810	810	0.61
			Average	870	787	
		10	1	940	690	0.39
				650	650	0.24
				830	550	0.31
				1126	570	0.44 a/
				900	900	0.25
			Average	889	672	

Floor System	Diameter of Loaded Area in	Spacing of Joists in	Location of Test	Failure Load lb	Load Causing Initial Structural Damage lb	Deflection at Failure Load in
B	5/8	10	2	660	620	0.36
				960	820	0.38
				660	660	0.23
				840	830	0.31
				800	800	0.27
				990	670	0.35
			Average	818	733	
		6	1	830	680	0.20
				1012	1012	0.28 a/
			Average	921	846	
			2	790	790	0.17
				810	810	0.18
				938	938	0.32
				975	830	0.29
			Average	878	842	
C	5/8	16	1	580	540	0.31
			2	770	770	0.37
			3	250	250	0.31
				380	380	0.62
			Average	315	315	
			5	1000 b/	520	0.12 a/
				1000 b/	470	0.13 a/
			Average		495	
	1/2	16	5	1000 b/	280	0.21 a/
				1000 b/	700	0.19 a/
			Average		490	
	1	16	1	710	620	0.59
				710	630	0.37
			Average	710	625	
			3	420	350	0.76
				660	460	0.85
			Average	540	405	
			4	400	350	0.45

Floor System	Diameter of Loaded Area in	Spacing of Joists in	Location of Test	Failure Load lb	Load Causing Initial Structural Damage lb	Deflection at Failure Load in
D	5/8	16	1u	780	570	1.21
				675	620	0.53
				695	660	0.57
				680	480	0.71
			Average	708	583	
			2u	568	330	---- c/
			3u	1000 b/	--- c/	0.18 a/
				1000 b/	--- c/	0.18 a/
	1	16	1u	1025	910	0.74 a/
				1006	730	0.70
				1002	1000	0.71
				1008	1008	0.70
				1064	1064	0.71
				985	960	0.80
			Average	1015	945	
			2u	800	570	1.32
				640	440	1.31
				700	570	1.50
				660	500	1.50
			Average	700	520	
			3u	1000 b/	--- c/	0.09 a/
				1000 b/	--- c/	0.09 a/
				1000 b/	--- c/	0.11 a/
				1000 b/	--- c/	0.11 a/
E	5/8	16	1u	410	360	0.51
				542	542	0.53
				540	540	0.52
			Average	497	481	
			2u	400	390	0.73
				450	420	0.96
			Average	425	405	
			3u	670	670	0.22
				880	810	0.18
			Average	775	740	

Floor Systems	Diameter of Loaded Area in	Spacing of Joist in	Location of Test	Failure Load lb	Load Causing Initial Structural Damage lb	Deflection at Failure Load in
E	1	16	1u	1002	1002	0.65
				1104	1000	0.63 a/
				890	890	0.63
				830	830	0.58
				670	500	0.50
				700	550	0.70
			Average	866	795	
			2u	820	630	1.31
				380	380	0.63
				670	530	1.48
				545	240	1.50
			Average	604	445	
			3u	1000 b/	--- c/	0.16 a/
				1000 b/	--- c/	0.16 a/
				1000 b/	--- c/	0.21 a/
				1000 b/	--- c/	0.21 a/
F	5/8	16	1u	950	950	0.55
				890	860	0.58
			Average	920	905	
			2u	420	420	0.66
				310	290	0.39
			Average	365	355	
			3u	1000 b/	--- c/	0.12 a/
				1000 b/	--- c/	0.12 a/
G	5/8	16	1u	720	670	0.43
				860	680	0.56
				770	690	0.56
			Average	783	680	
			2u	350	300	0.55
				370	370	0.53
			Average	360	335	
			3u	1000 b/	--- c/	0.20
				1000 b/	--- c/	0.19

TABLE 5.2

Summary of Average Test Results for Specimens with 16-in Joist Spacing

		5/8-in Diameter Area		1-in Diameter Area	
Floor Systems	Location of Test	Average Failure Load lb	Average Load Causing Initial Structural Damage lb	Average Failure Load lb	Average Load Causing Initial Structural Damage lb
A	1	565	530	1003	801
	2	525	455	783	723
	3	363	355		
	4	300	300		
	5	1000+	975+		
B	1	795	745		
	2	760	745		
	3	446	428		
	4	537	537		
	5	1000+	903+		
C	1	580	540	710	625
	2	770	770		
	3	315	315	540	405
	4			400	350
	5	1000+	495		
D	1u	708	583	1015	945
	2u	568	330	700	520
	3u	1000+		1000+	
E	1u	497	481	866	795
	2u	425	405	604	445
	3u	775	740	1000+	
F	1u	920	905		
	2u	365	355		
	3u	1000+			
G	1u	783	680		
	2u	360	335		
	3u	1000+			

FIGURES

FIGURE 3.1 STANDARD SPECIMEN WITHOUT UNDERLAYMENT

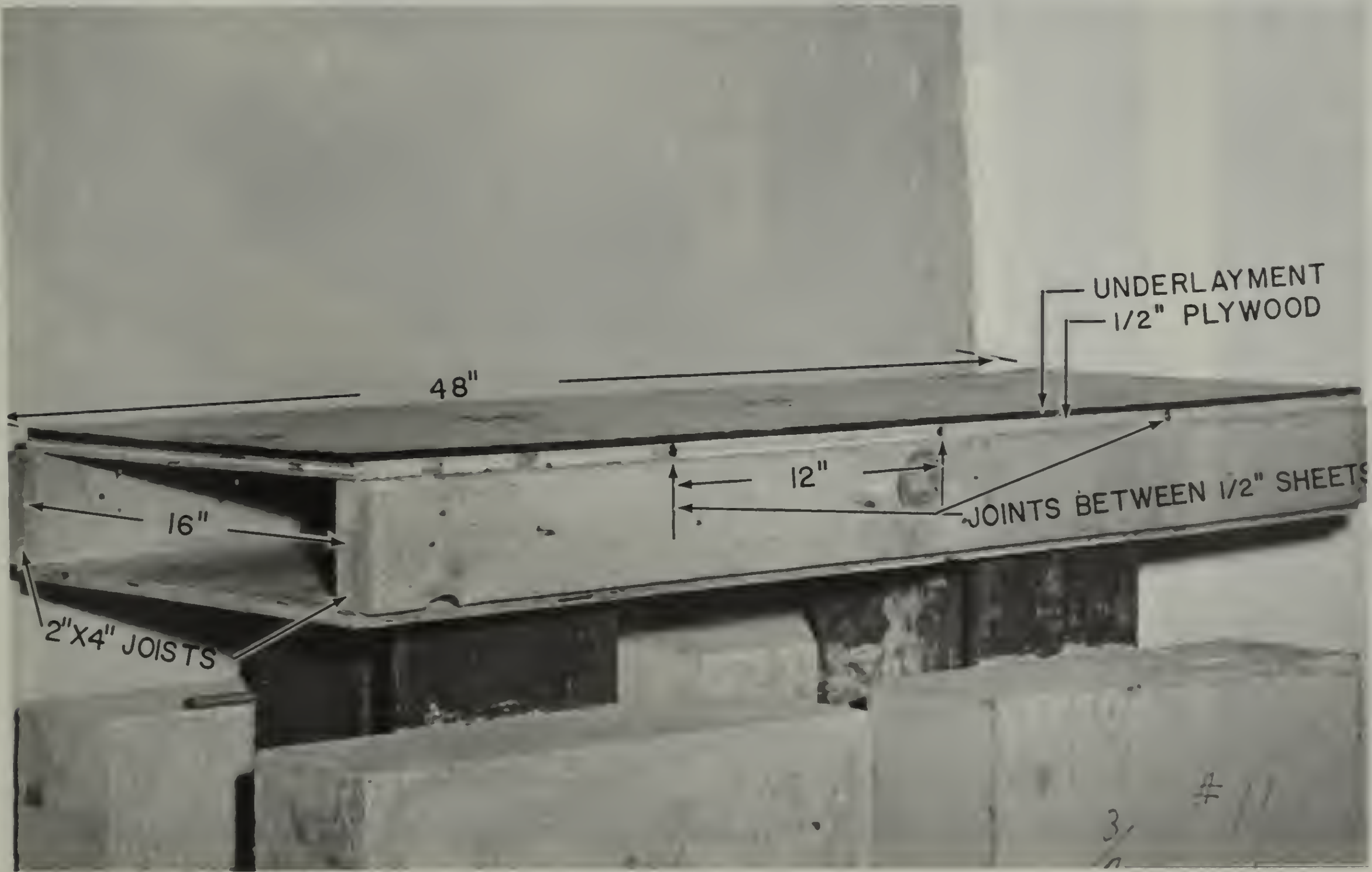


FIGURE 3.2 STANDARD SPECIMEN WITH UNDERLAYMENT

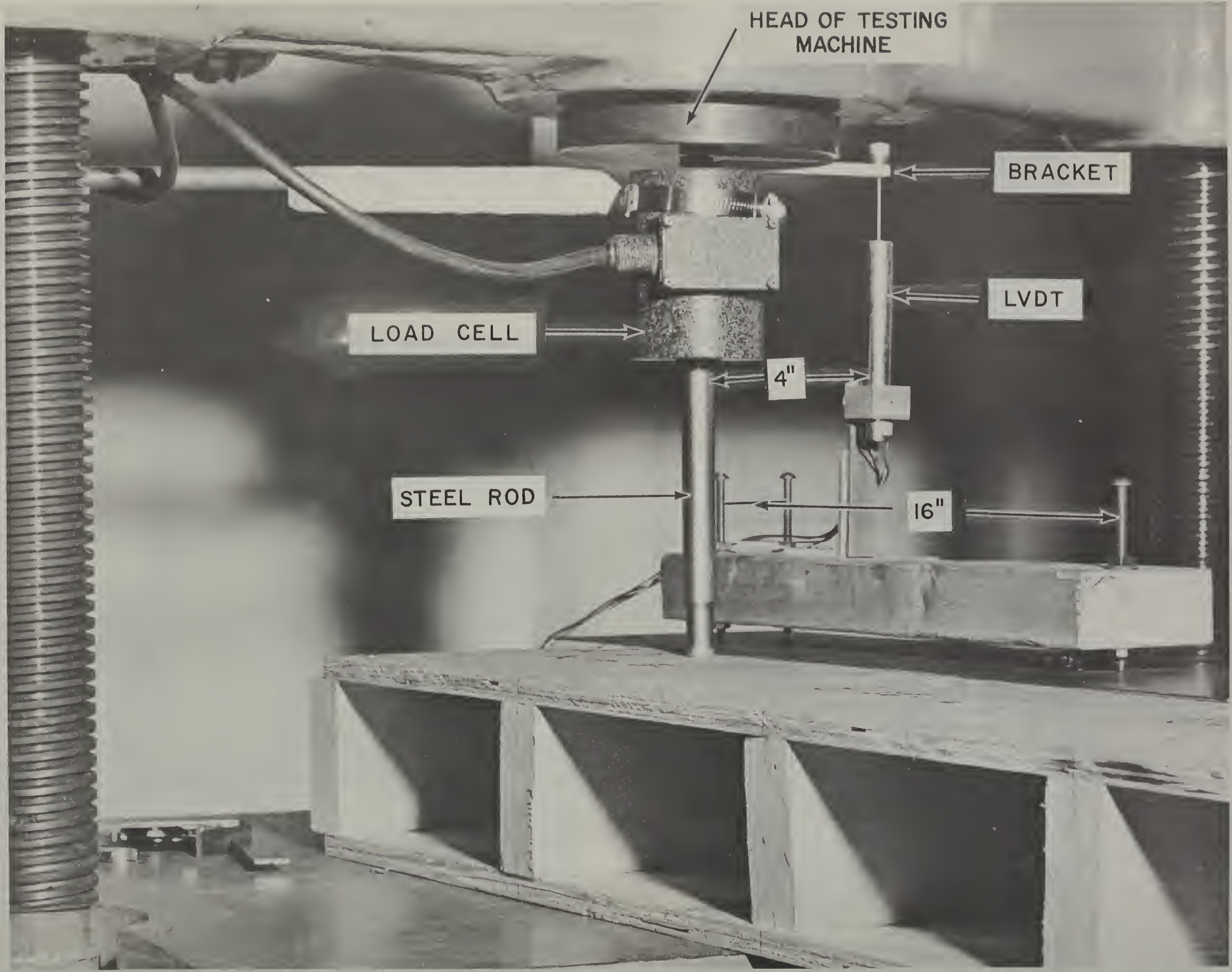
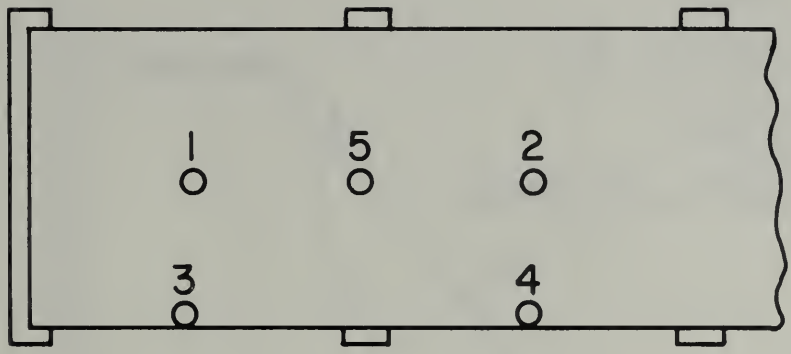
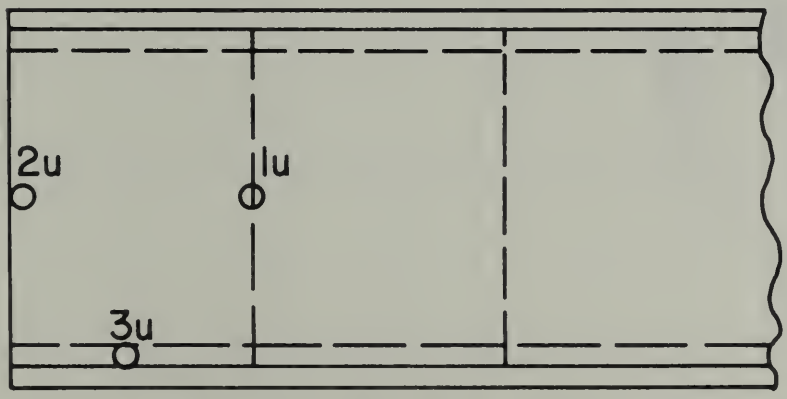


FIGURE 4.1 TEST SET UP



(a) SPECIMEN WITHOUT UNDERLAYMENT



(b) SPECIMEN WITH UNDERLAYMENT

FIGURE 5.1 LOCATION OF TEST POINTS

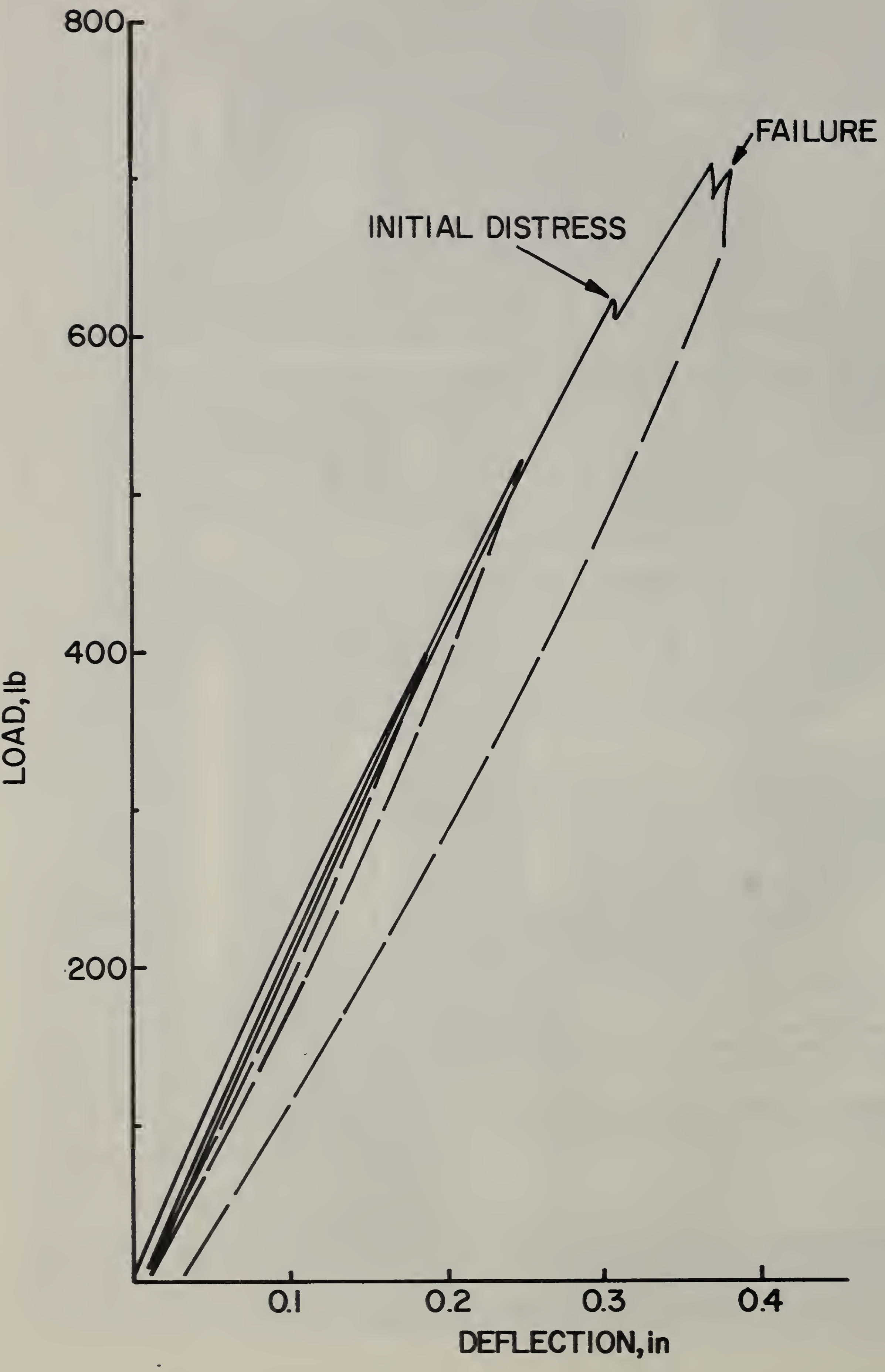


FIGURE 5.2 INTERPRETATION OF TEST RESULTS

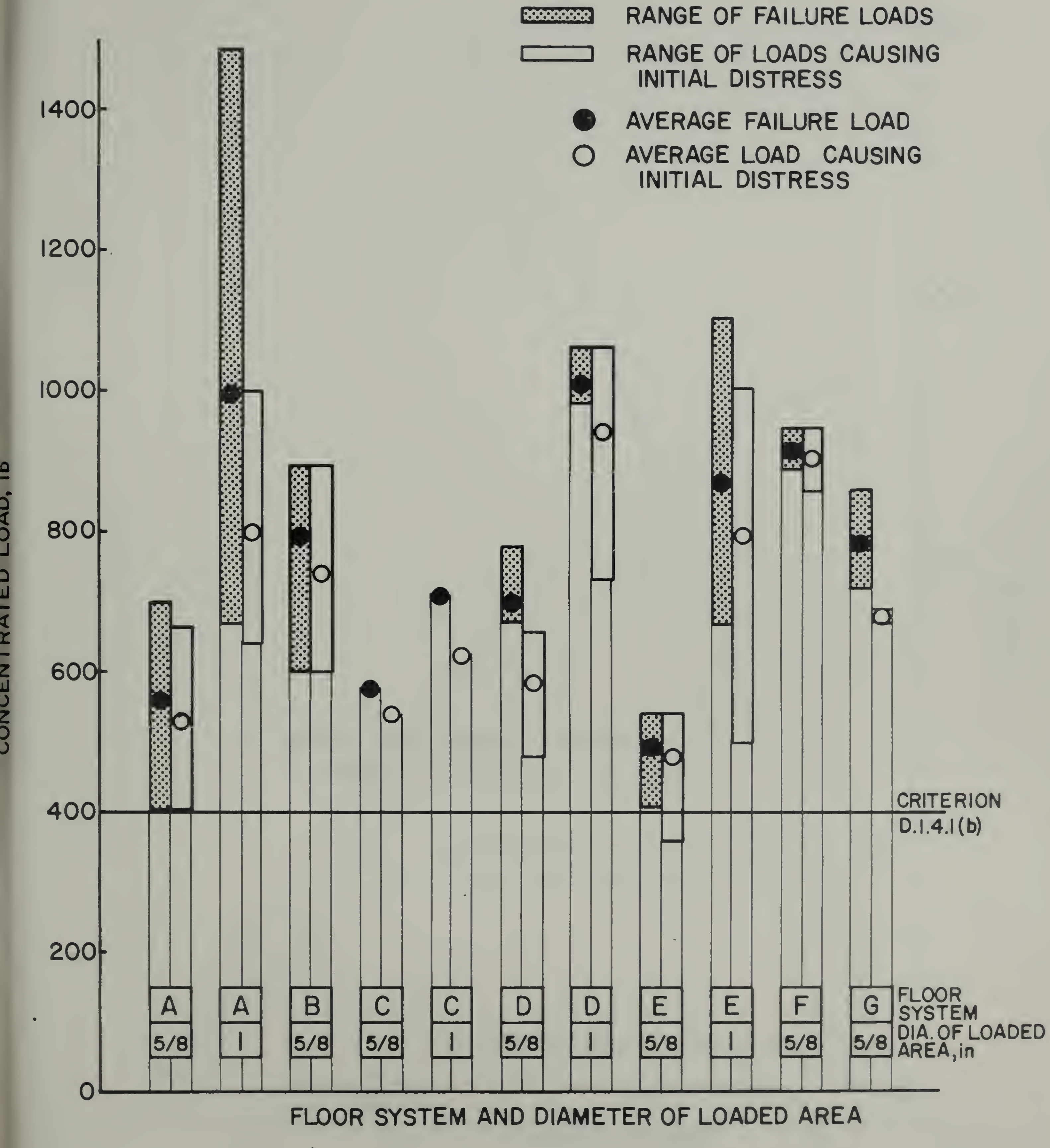


FIGURE 6.1 RANGE AND AVERAGES OF TEST RESULTS FOR TEST LOCATIONS 1 AND 1u

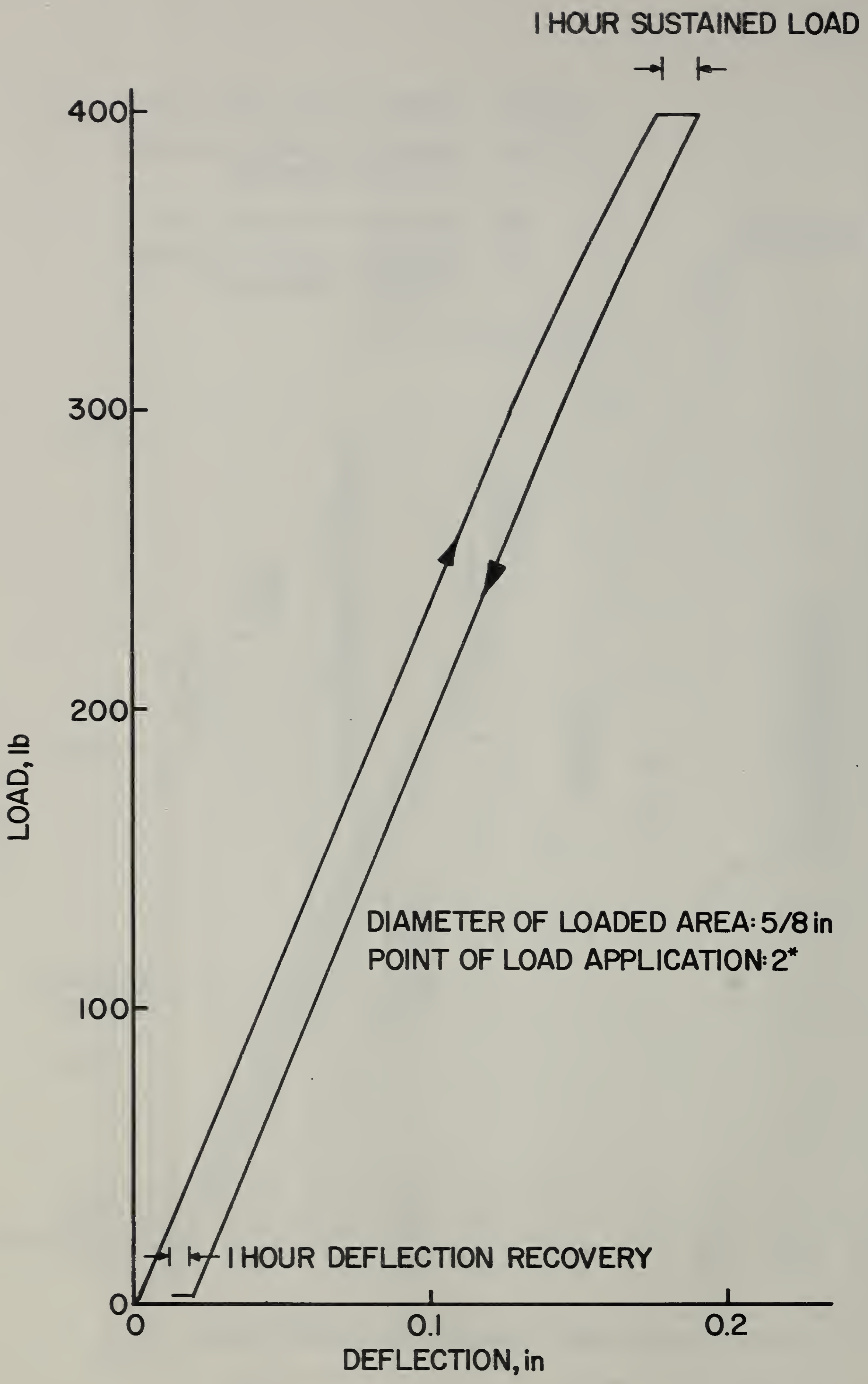


FIGURE 6.2 COMPLIANCE OF FLOOR SYSTEM C WITH BREAKTHROUGH CRITERION D.1.4.1(B)

* See Figure 5.1

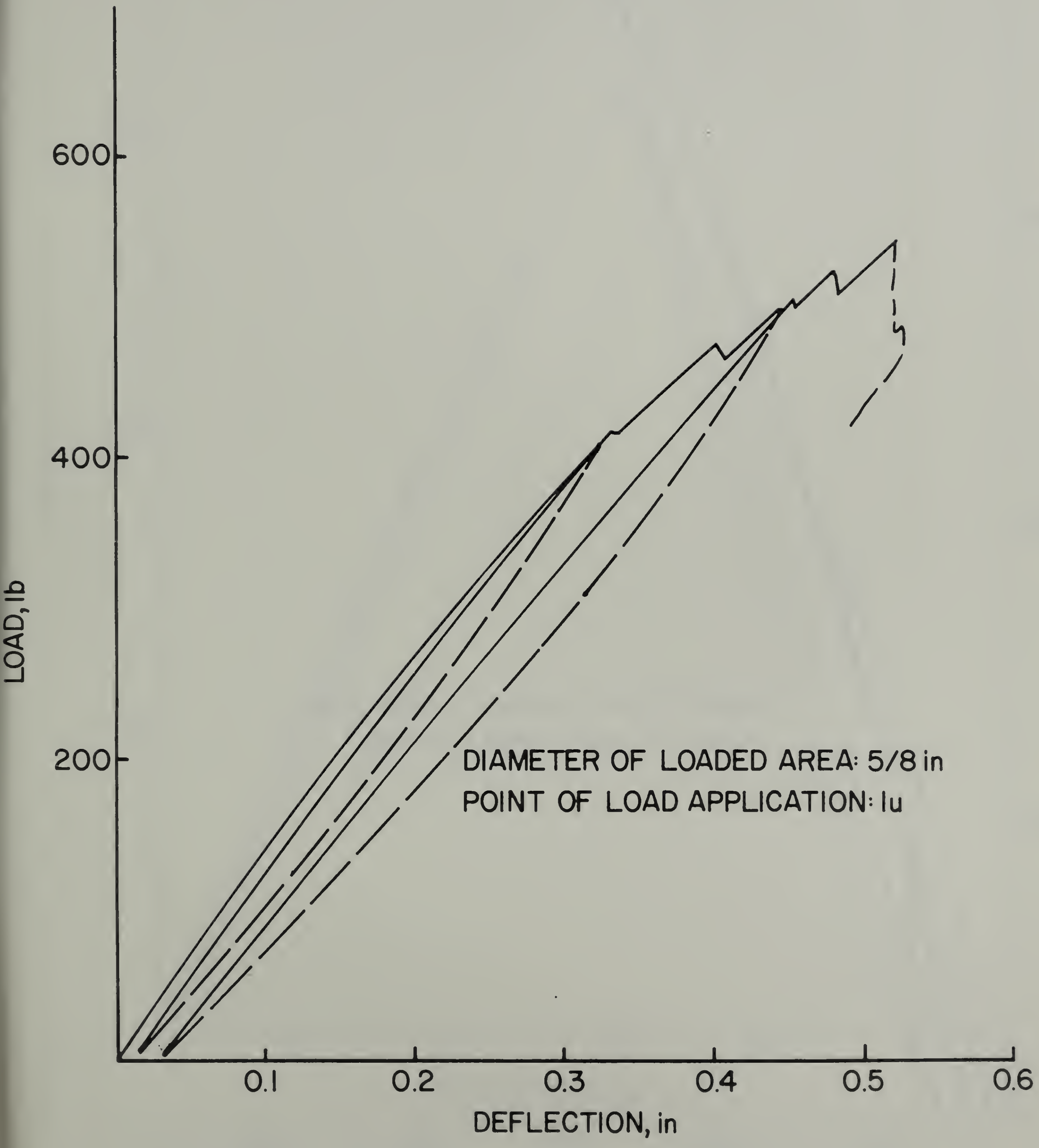


FIGURE 6.3 DEFLECTION RECOVERY CHARACTERISTICS OF FLOOR SYSTEM A

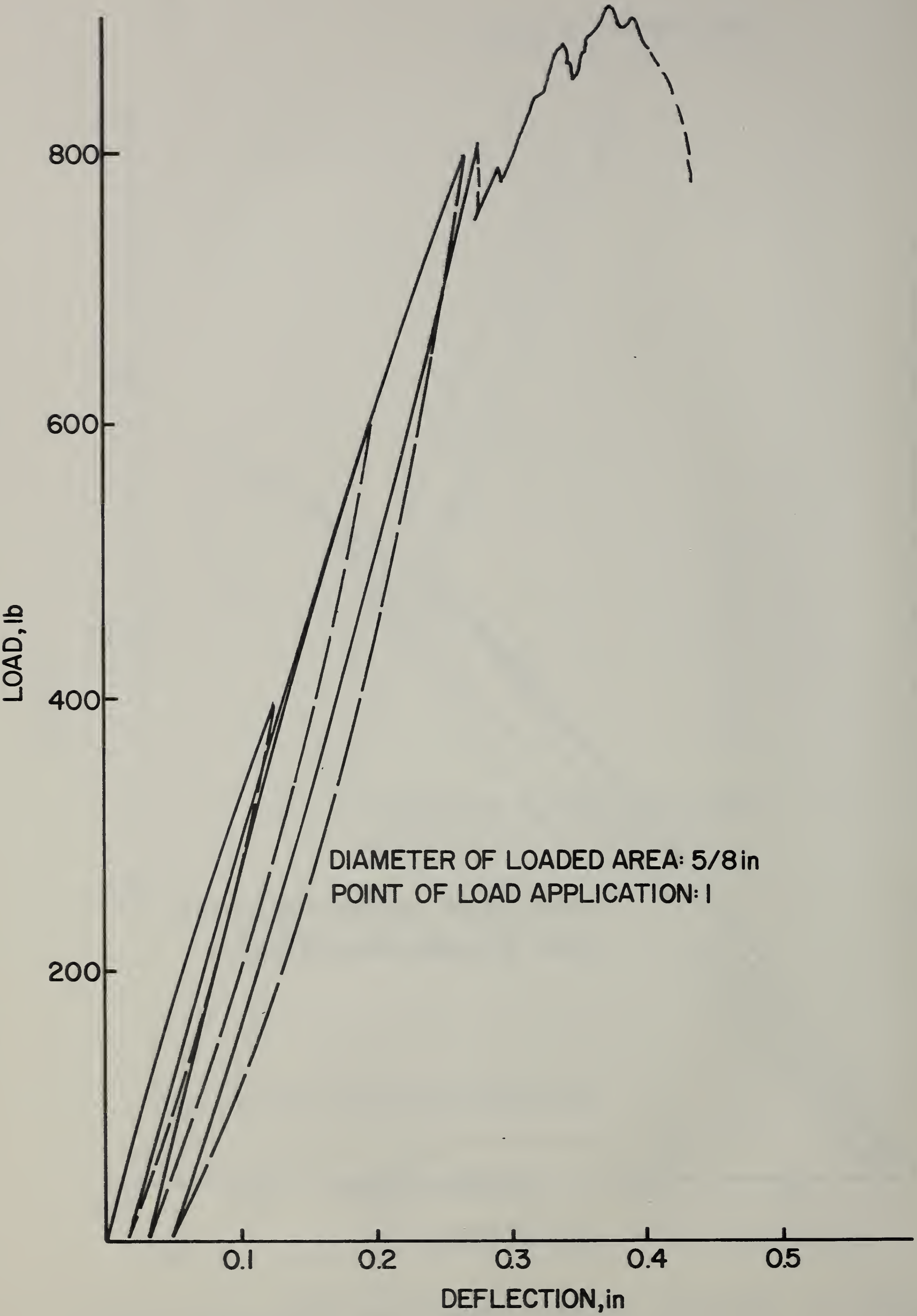


FIGURE 6.4 DEFLECTION RECOVERY CHARACTERISTICS OF FLOOR SYSTEM B

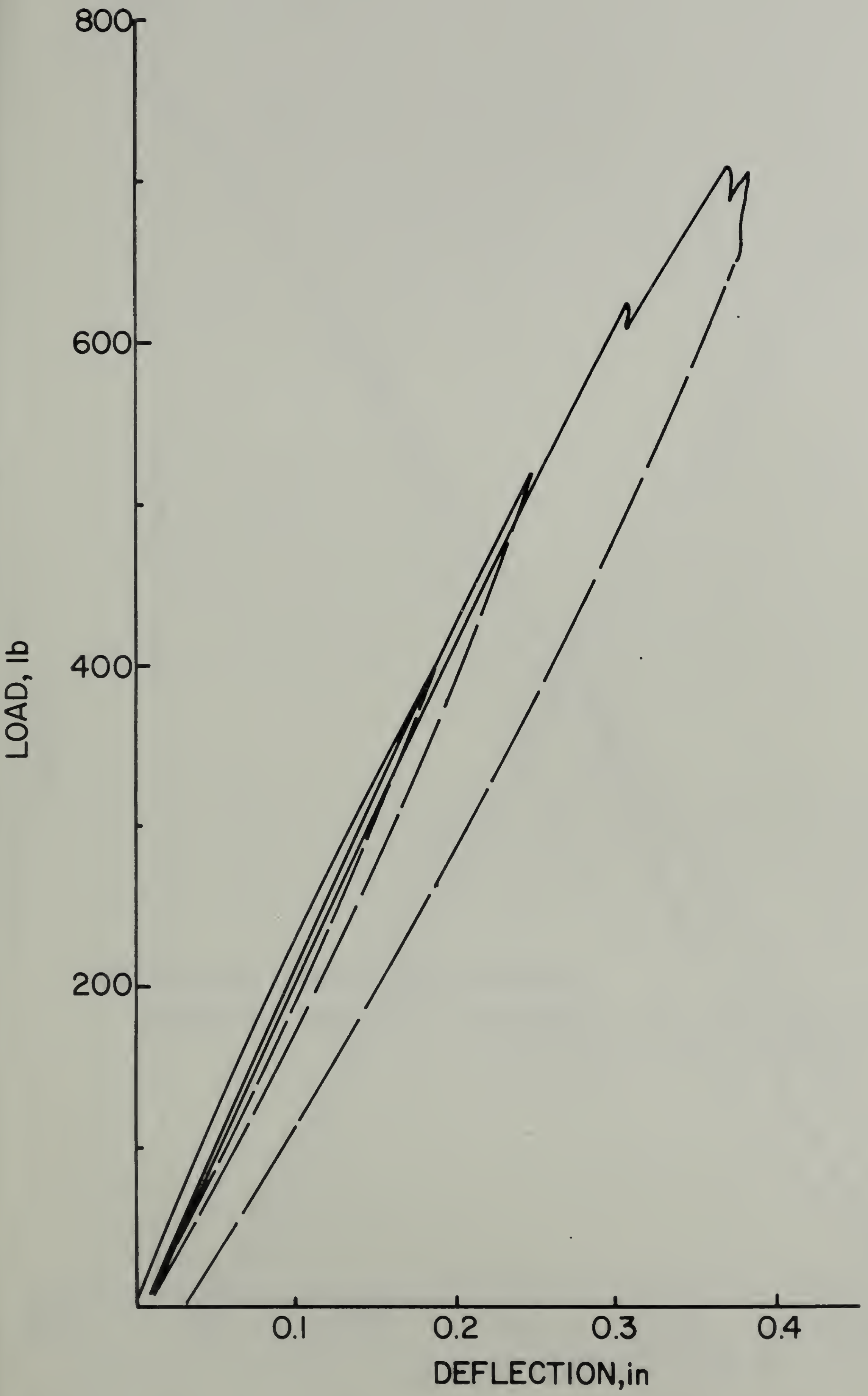


FIGURE 6.5 DEFLECTION RECOVERY CHARACTERISTICS OF FLOOR SYSTEM C

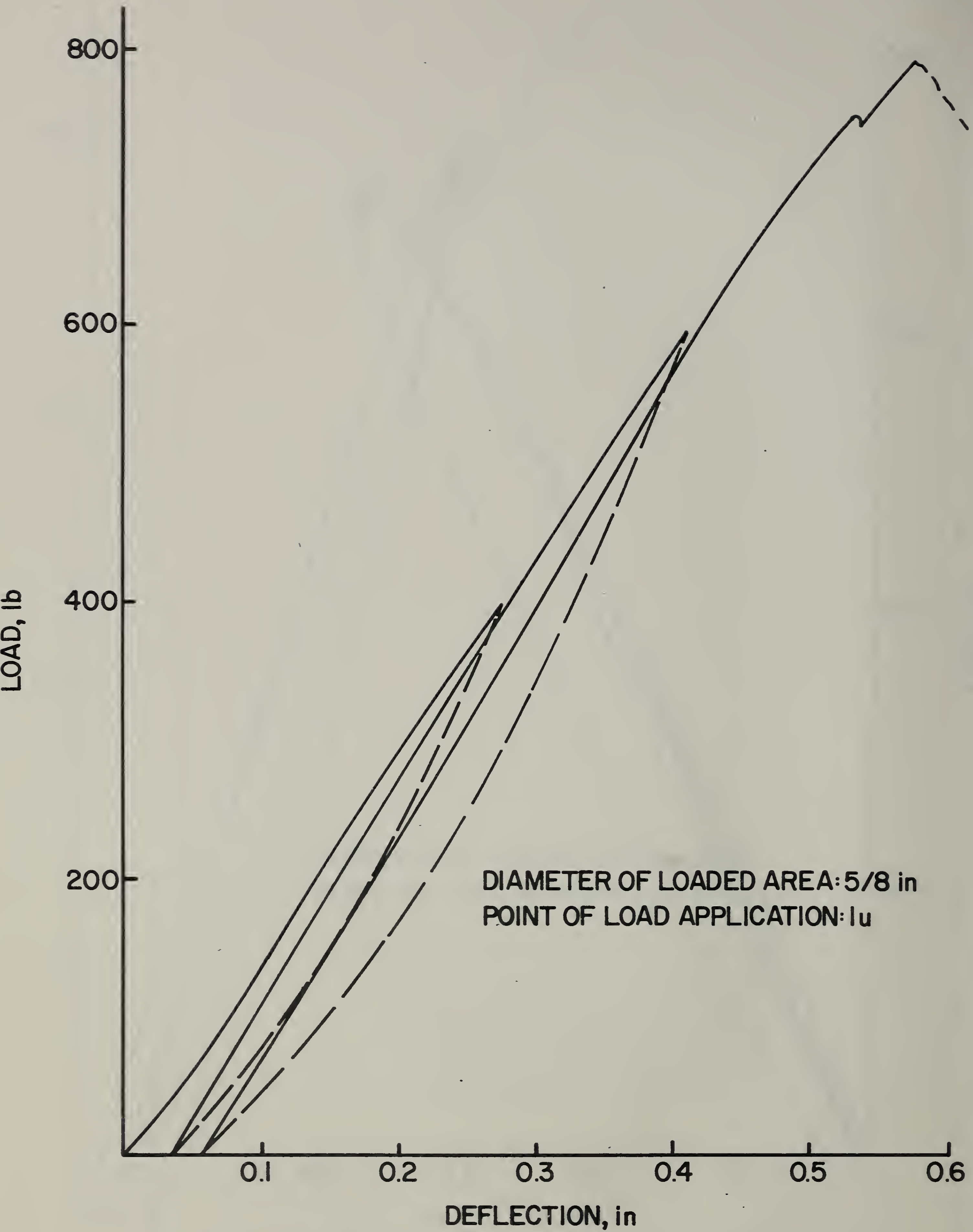


FIGURE 6.6 DEFLECTION RECOVERY CHARACTERISTICS OF FLOOR SYSTEM F

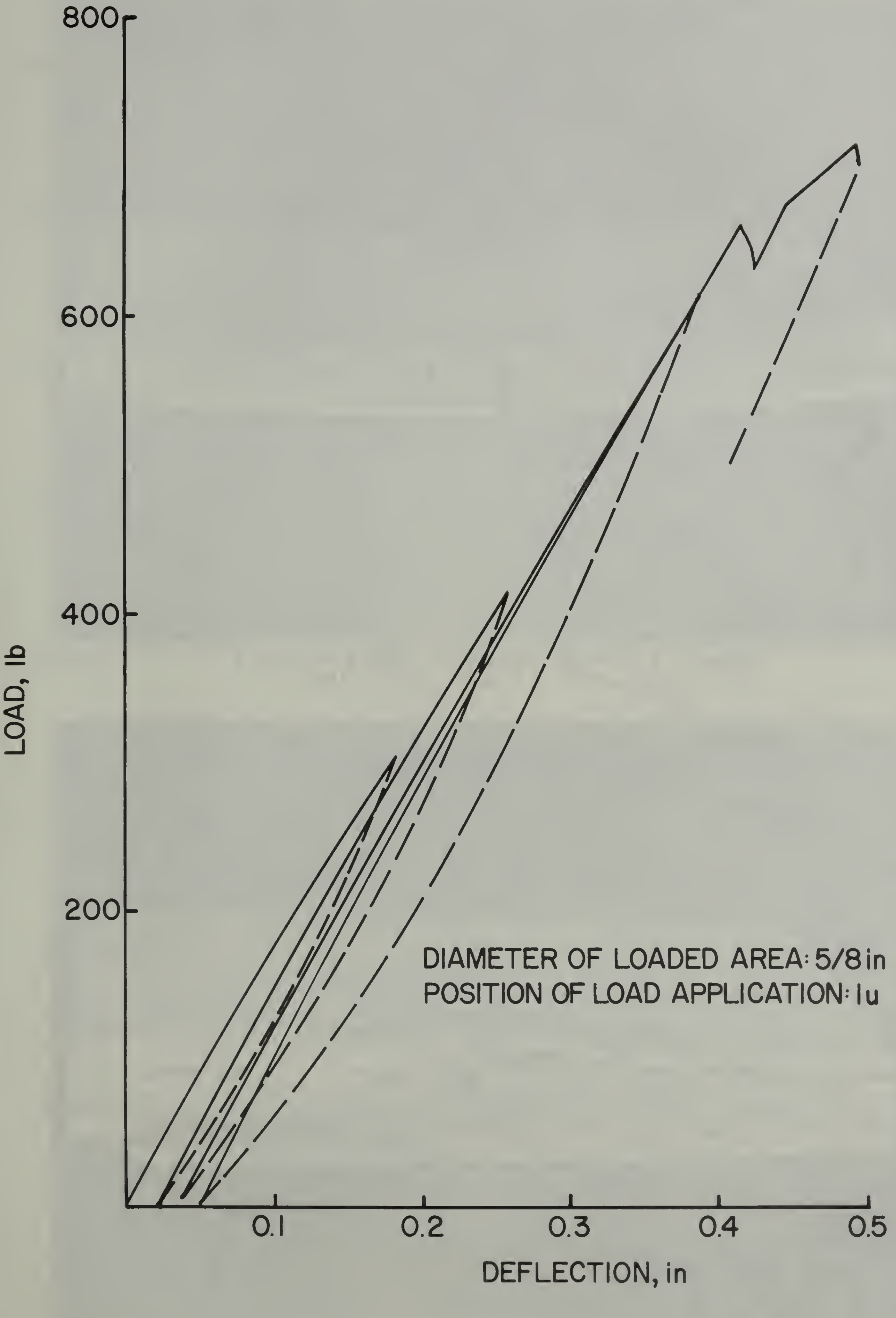


FIGURE 6.7 DEFLECTION RECOVERY CHARACTERISTICS OF FLOOR SYSTEM G

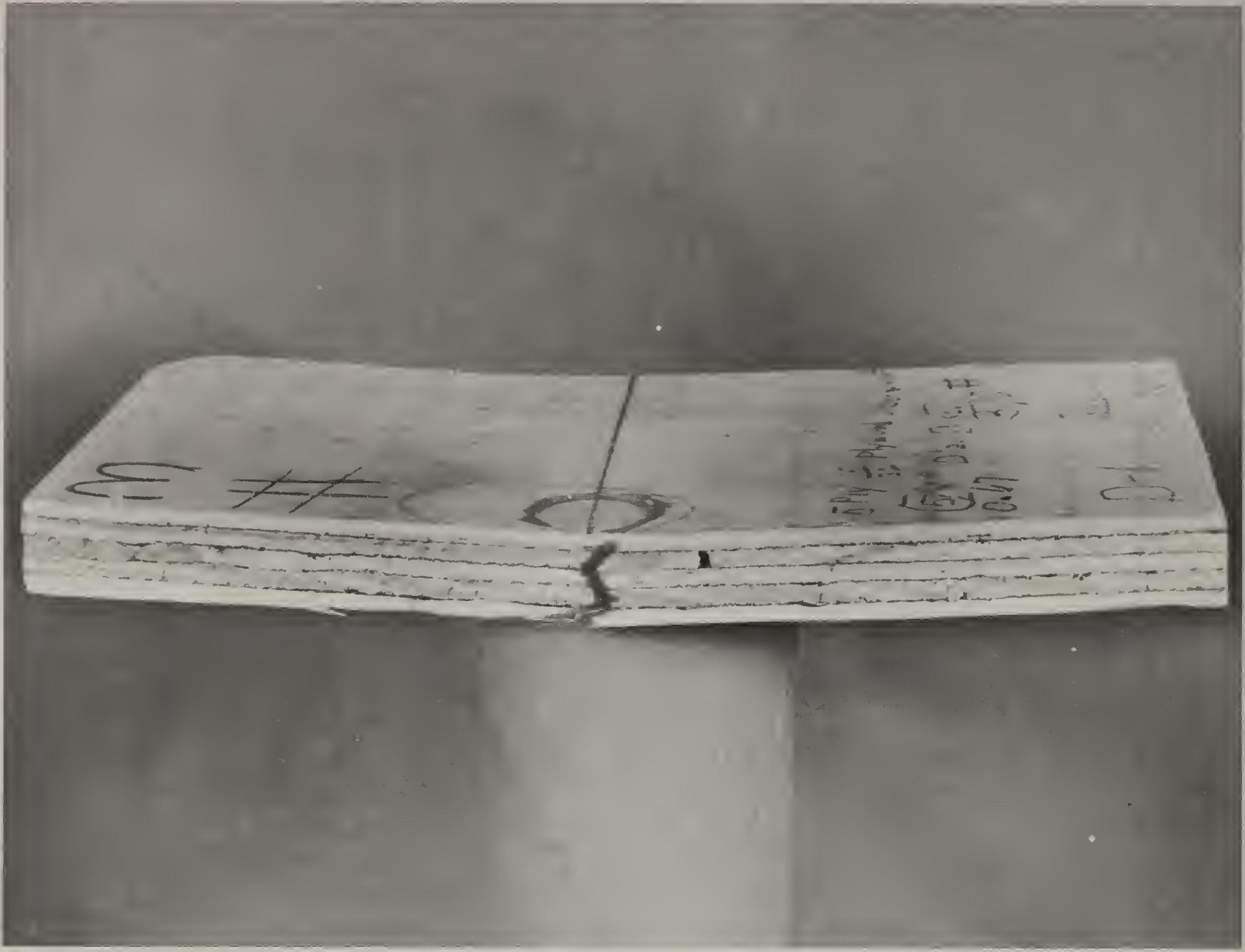


FIGURE 6.8 TYPICAL FAILURE OF FLOOR SYSTEM A LOADED OVER A 1-in DIAMETER AREA

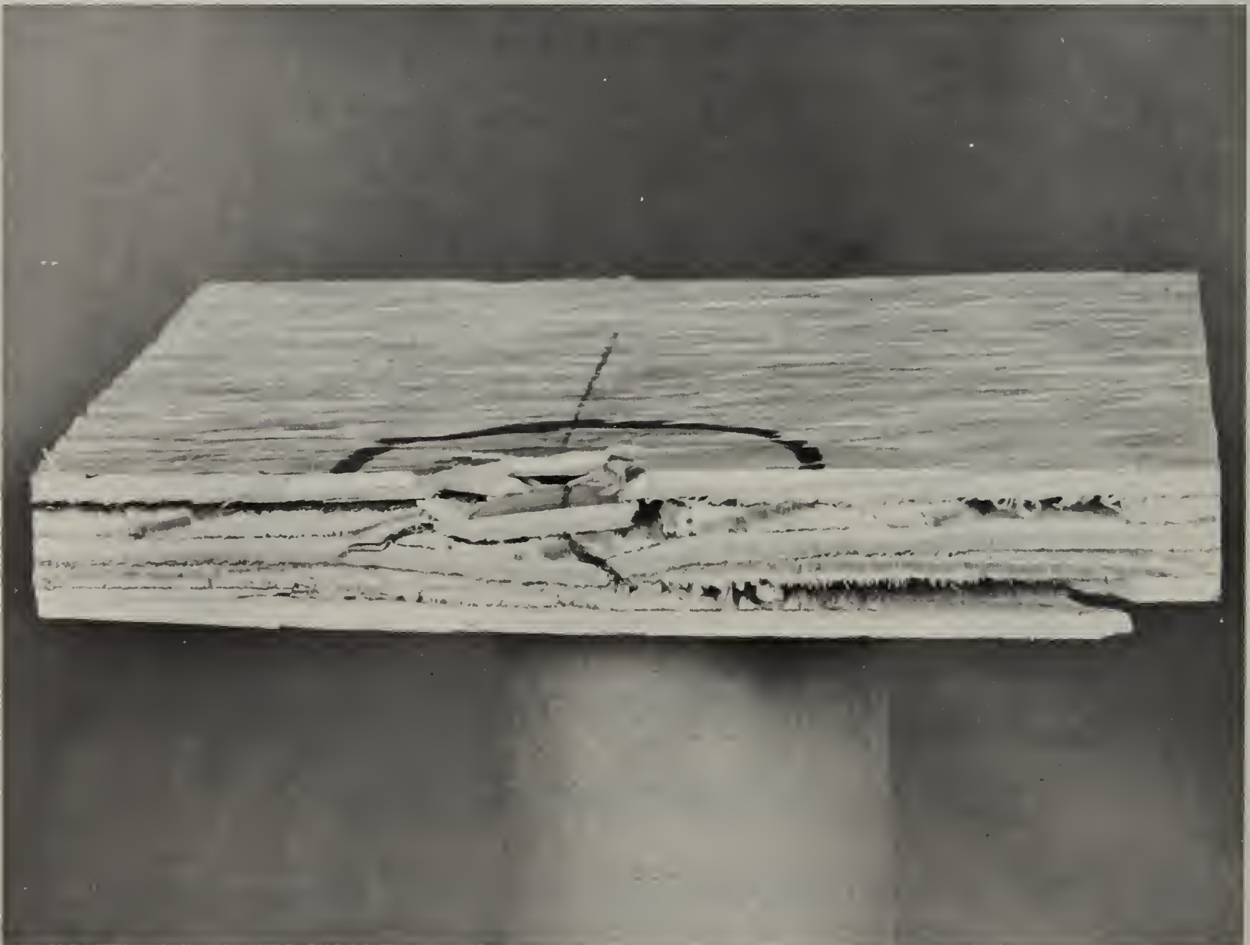


FIGURE 6.9 TYPICAL FAILURE MODE OF FLOOR SYSTEM B LOADED OVER A 5/8 in DIAMETER AREA

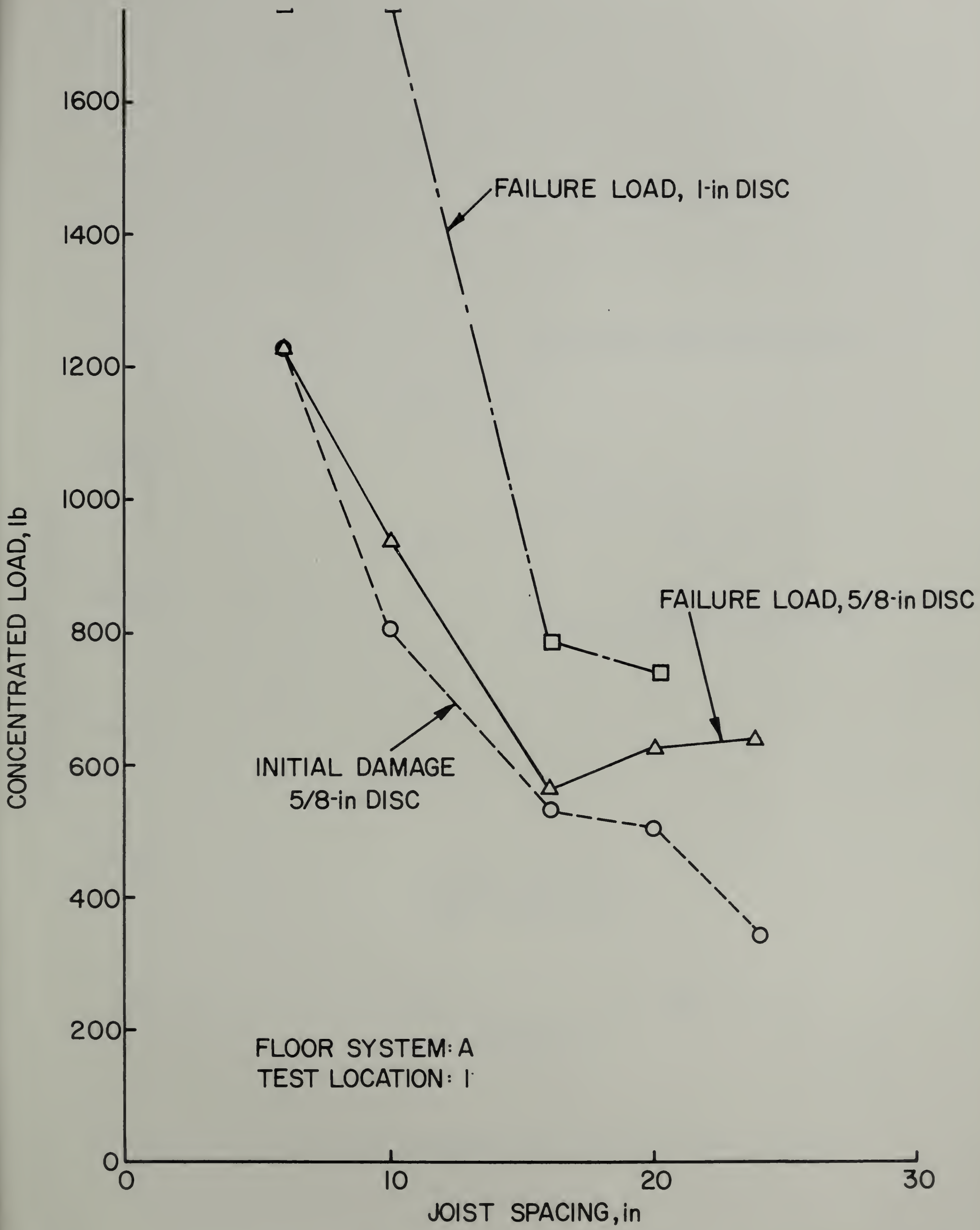


FIGURE 6.10 RELATIONSHIP BETWEEN JOIST SPACING AND STRENGTH

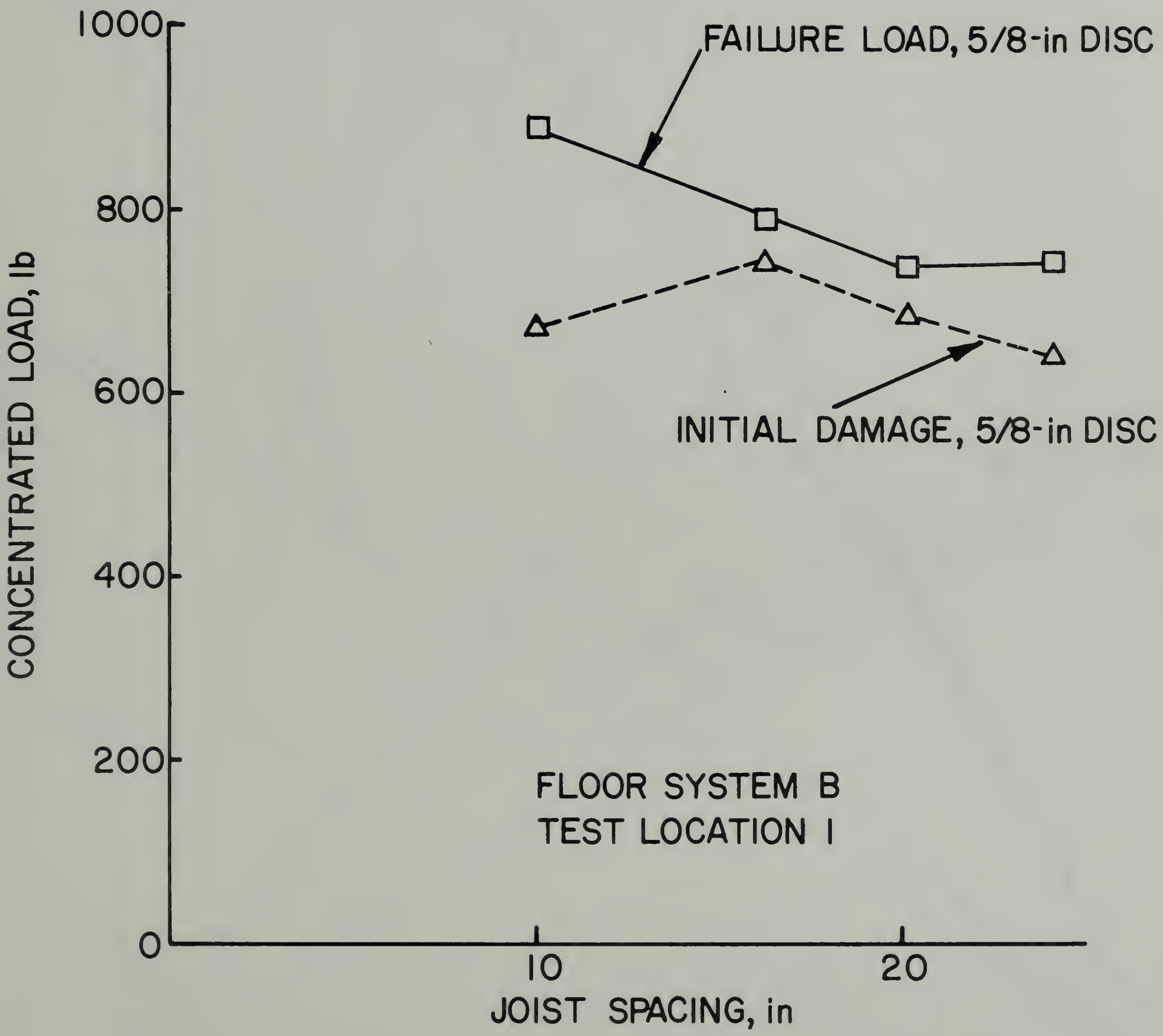


FIGURE 6.11 RELATION BETWEEN JOIST SPACING AND STRENGTH

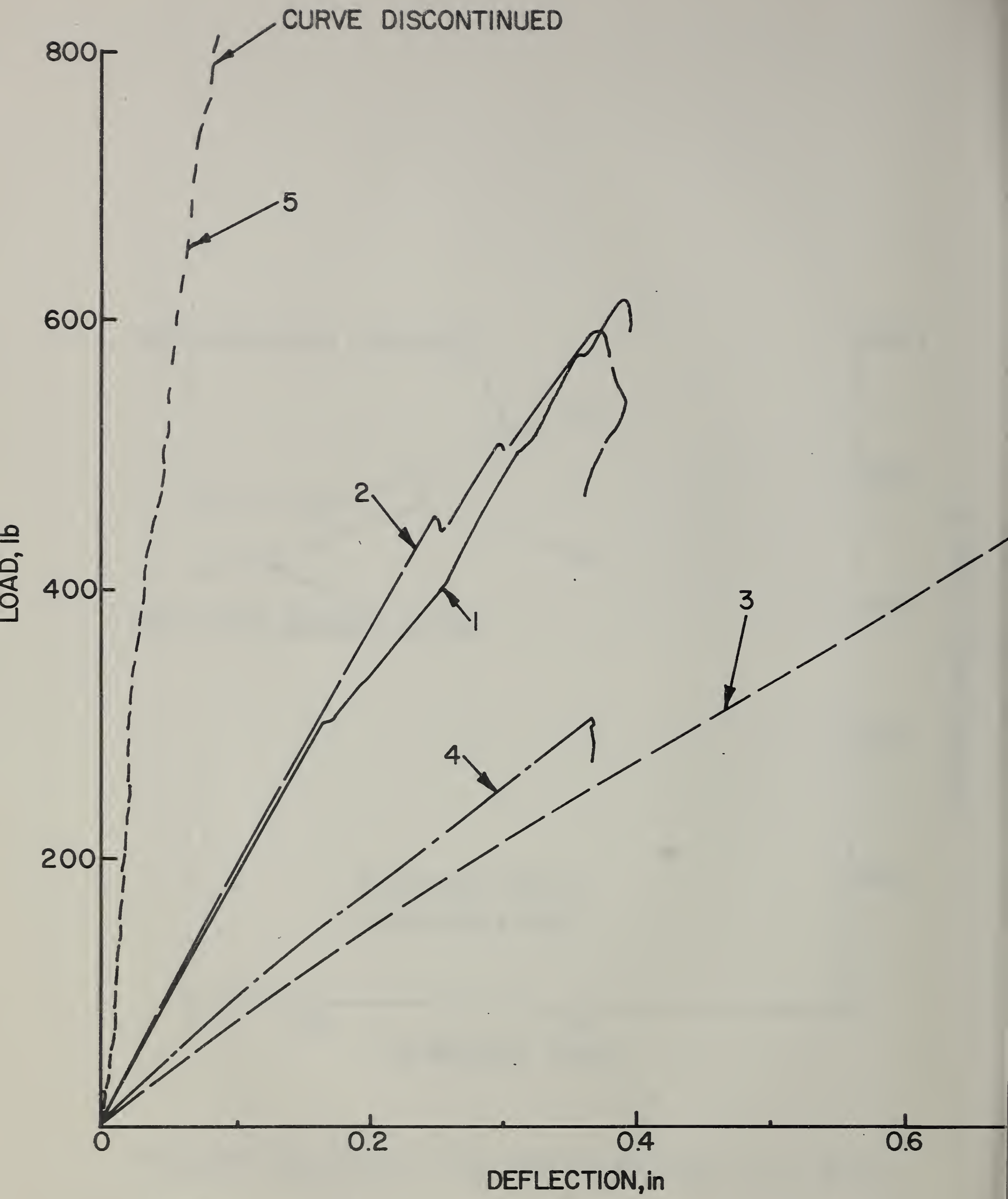


FIGURE 6.12 RELATIONSHIP BETWEEN THE LOAD-DEFLECTION CHARACTERISTICS AND THE POSITION OF THE CONCENTRATED LOAD FOR FLOOR SYSTEM A

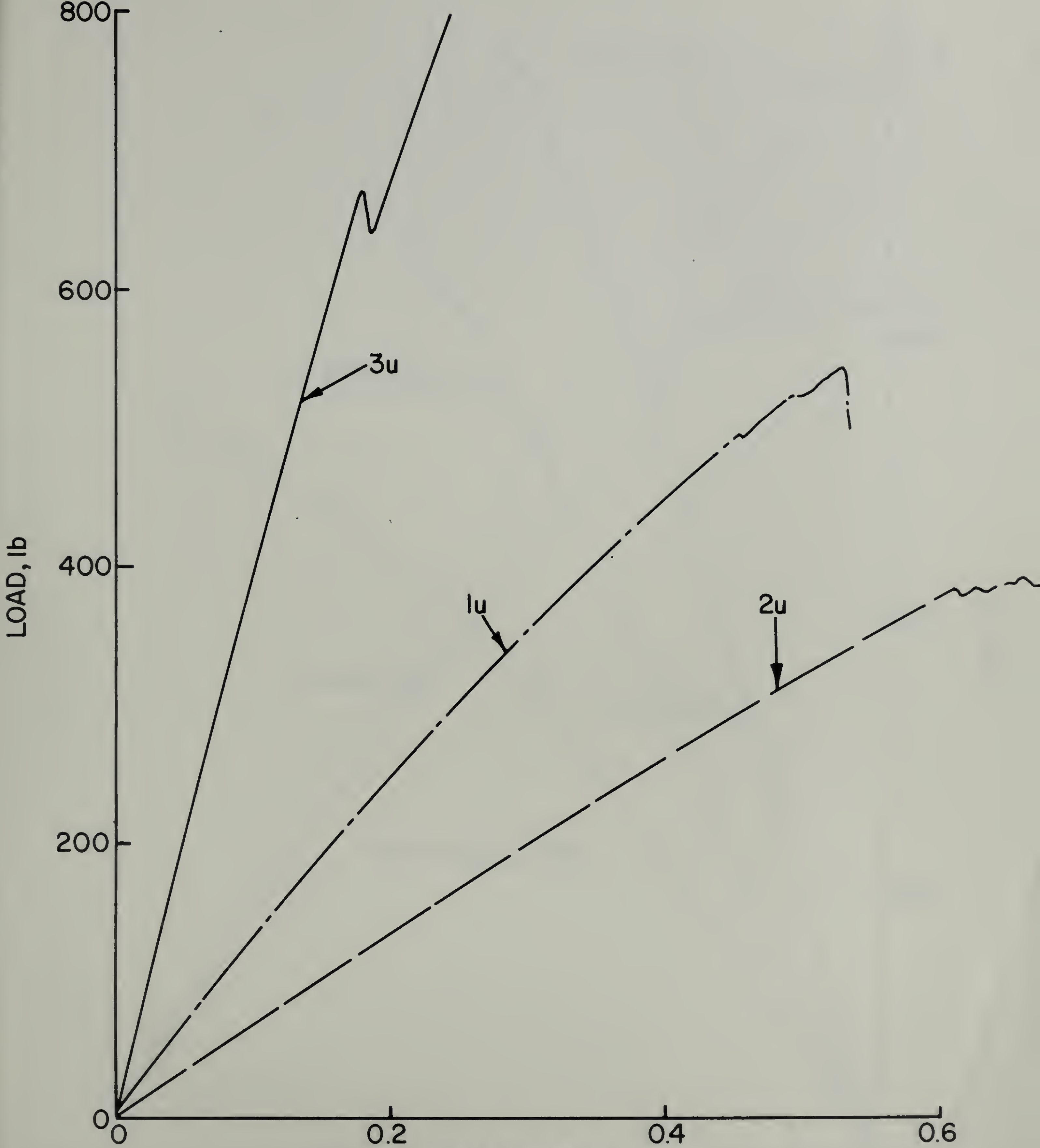


FIGURE 6.13 RELATIONSHIP BETWEEN LOAD-DEFLECTION CHARACTERISTICS AND THE POSITION OF THE CONCENTRATED LOAD FOR FLOOR SYSTEM E

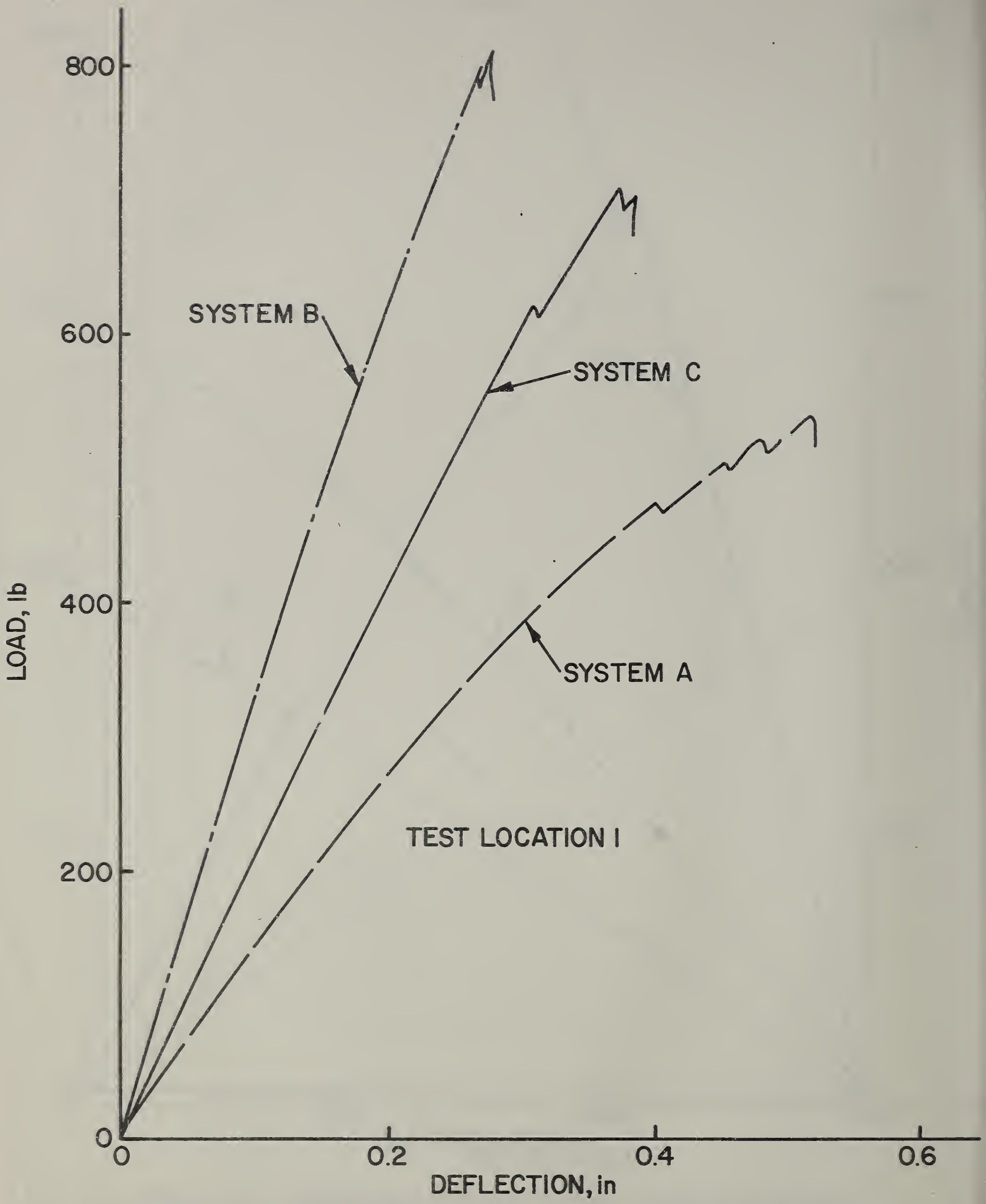


FIGURE 6.14 RELATIVE STIFFNESS OF FLOOR SYSTEMS WITHOUT UNDERLAYMENT

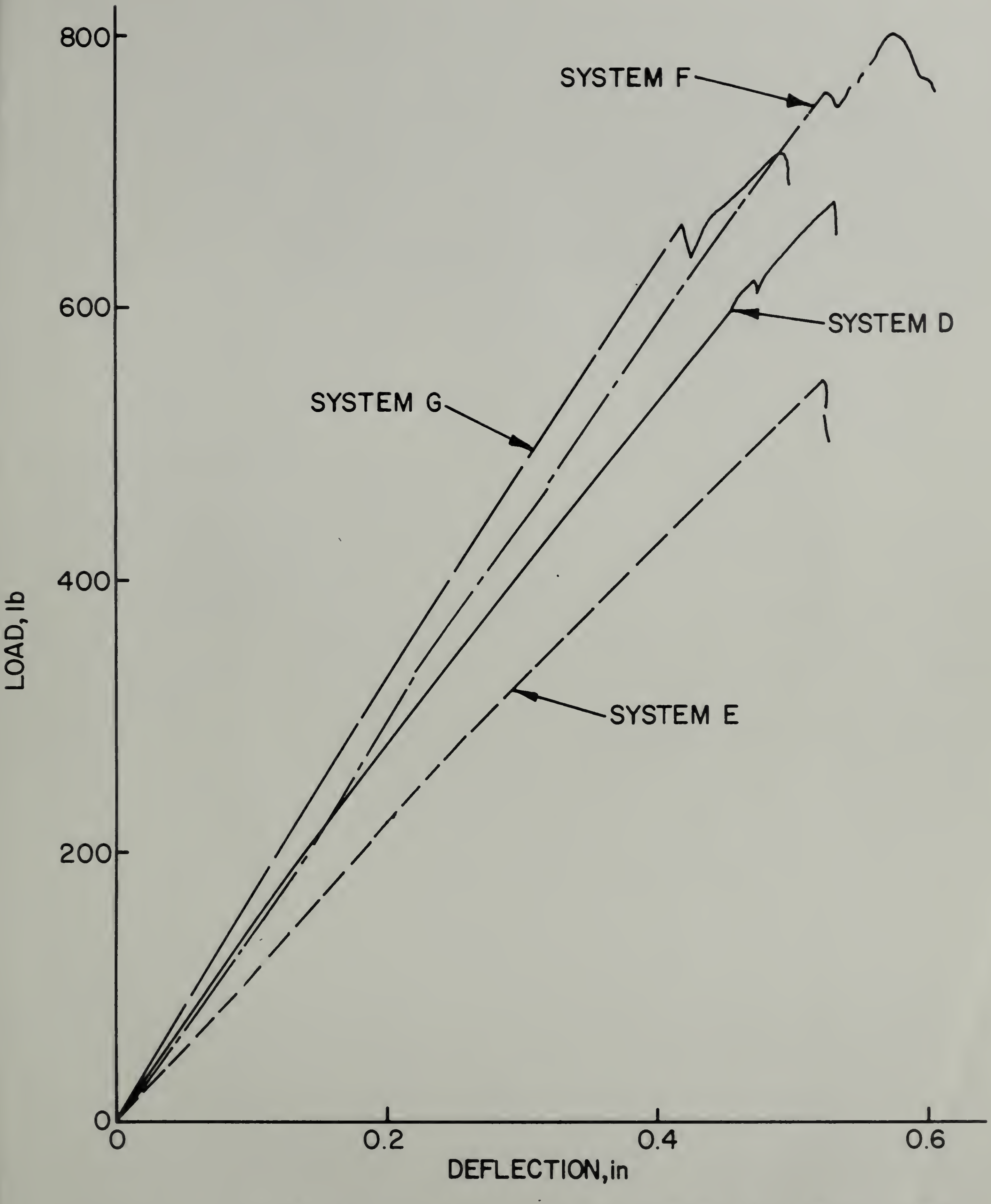


FIGURE 6.15 RELATIVE STIFFNESS OF FLOOR SYSTEMS WITH UNDERLAYMENT

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