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EVALUATION OF EXPEDIENT TECHNIQUES FOR STRENGTHENING FLOOR JOIST SYSTEMS IN RESIDENTIAL DWELLINGS

by

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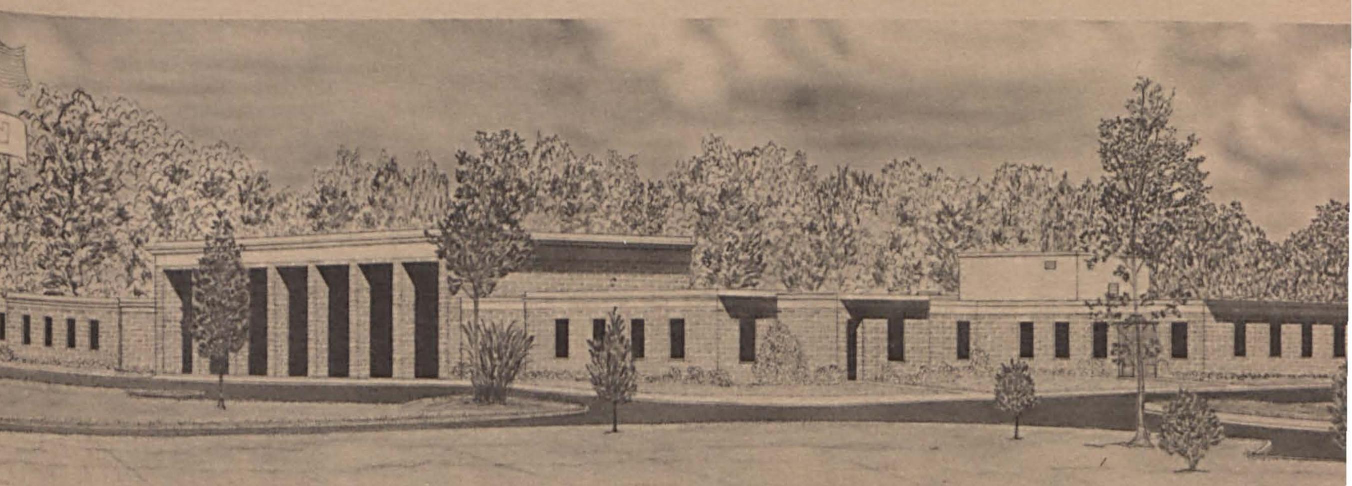
July 1975

Final Report



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Expedient techniques for reinforcing wood floor joist systems were evaluated by building 15 test specimens and subjecting them to static tests in a 200-kip loader. Each specimen consisted of three 2- by 10-inch by 16-foot floor joists (16 inches on center). Two sheets of 4- by 8-foot by 3/4-inch plywood and two sheets of 4- by 8-foot by 1/4-inch Masonite were centered and nailed to the joists. A 2- by 10-inch by 4-foot header board was nailed to each end of the floor specimen. Unreinforced and reinforced floor specimens were tested. The expedient techniques of joist reinforcement evaluated were: (Continued)

20. ABSTRACT (Continued).

(1) 1-1/2-inch by 16-foot by 1/8-inch steel strap nailed to the bottom of the joists, (2) 4- by 8-foot by 1/4-inch plywood nailed to the bottom of the joists, (3) U-shaped hanger straps bolted around the joists, (4) combination of the hanger straps and 1-1/2-inch by 16-foot by 1/8-inch steel strap, and (5) 22-gage galvanized steel strap nailed to the bottom of the joists. Five unreinforced specimens were tested to determine the degree of composite action developed between the subfloor and the floor joist and to serve as control specimens for comparison with the results of the tests on the reinforced specimens. Comparing the experimentally determined moments of inertia of three joists alone and that of the composite section showed that little composite action had developed. With the exception of the hanger-strap reinforced specimens, the reinforcing techniques tested required the development of composite action to increase the strength of the floor system. Comparison of the test moment of inertia and the calculated moment of inertia determined that only about 10 percent of the available composite action was developed during the test of the plywood, 1/8-inch-thick steel strap, and combination steel strap-hanger strap reinforced specimens. The 22-gage steel strap reinforced specimens developed nearly 80 percent of the available composite action. The strength increases observed during the test were within the limits of the normal variation of the mechanical properties of wood.

PREFACE

The study reported herein was conducted by the U. S. Army Engineer Waterways Experiment Station (WES) under contract DAHC 20-68-W-0192 the Defense Civil Preparedness Agency.

This work was accomplished during the period August 1973 through May 1974 under the general supervision of Messrs. W. J. Flathau, Chief, Weapons Effects Laboratory, and J. T. Ballard, Chief, Structures Division. This report was prepared by Mr. M. S. Black under the direct supervision of Messrs. W. L. Huff and T. E. Kennedy. Acknowledgment is made to Messrs. B. W. Benson, J. L. Scott, D. Reed, and N. J. Lavecchia, and Ms. Patricia Loy of the Structures Division for their support.

BG E. D. Peixotto, CE, and COL G. H. Hilt, CE, were Directors of WES during the preparation of this report. Mr. F. R. Brown was Technical Director.

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CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	2.54	centimetres
feet	0.3048	metres
kilotons (mass)	907.185	megagrams
megatons (mass)	907.185	gigagrams
pounds (force)	4.448222	newtons
kips (force)	4448.222	newtons
pounds (force) per square inch	6894.757	pascals
pounds (force) per square foot	47.88026	pascals

EVALUATION OF EXPEDIENT TECHNIQUES FOR STRENGTHENING FLOOR JOIST SYSTEMS IN RESIDENTIAL DWELLINGS

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

A large number of shelter spaces exist in the basements of family dwellings. In many cases the floor over the basement is constructed of timber consisting of cross-braced joists supported on beams and covered with a timber floor. Usually this first floor or basement roof is designed to deflect less than 1/360 of the span under a 40-psf[1] live load (Reference 1). Tests (Reference 2) have shown that wood basement roof systems of this type offer limited protection from the blast effects of nuclear weapons.

The blast protection potential of a basement shelter could be significantly increased if the basement roof joist system could be strengthened. This strengthening can be accomplished in two ways: (1) by shortening the span of the joists by shoring or placing additional supporting members at midspan, or (2) by reinforcing the joists to give them additional flexural strength. Either of these options can be accomplished at a relatively low cost and with little effort. However, the use of additional supporting members under the floor limits the utility of the basement area. As a result, homeowners may not be willing to use this technique. Also, material availability during an emergency may be a serious limitation and timber for the construction of additional supporting members may not be available. Joist strengthening is more desirable if the additional load-carrying capacity for practical systems can be achieved at small cost and effort.

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[1] A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 4.

1.2 OBJECTIVE

The general objective of this study was to test a series of five inexpensive and expedient techniques for reinforcing floor joist systems to give them additional flexural strength without placing additional supports at midspan. These data will be used as a basis for evaluating the ability of a floor system strengthened in such a manner to carry additional load.

CHAPTER 2

EXPERIMENTAL METHODS

2.1 DESCRIPTION OF TEST SPECIMENS

A review was made to determine current prevalent practices used by American home builders with respect to floor construction and materials. Contractors in the Midwest and Southern portions of the United States were contacted. The general consensus was that floor framing over a basement with a 14-foot span generally consists of 2- by 10-inch wooden joists 16 inches on center. Rough flooring is provided by 4- by 8-foot sheets of plywood with a thickness of 3/4 inch. On top of the plywood decking, a layer of 1/4-inch Masonite provides a smooth surface for the installation of carpet, floor tile, etc. Thickness of the plywood subfloor and underlayment may vary, but the composite thickness of the floor remains 1 inch.

Materials for the test specimens of this study consisted of 2- by 10-inch floor joists of Southern Yellow Pine. Southern Yellow Pine was chosen because of its prevalent use in construction in this area. Although the minimum grade of this wood acceptable (Reference 1) was No. 3, the decision was made to specify No. 2 medium grain, the grade commonly used in floor construction. Materials were obtained from a local lumber supplier in the same manner as would be done by a typical contractor. Upon receipt of the materials, it was realized that a supplier will ship the grade of lumber specified or better, depending on his inventory. Therefore, No. 1 and No. 2 dense and medium grain joists were obtained with rated working stresses of 1350 to 1900 psi. The material for the subfloor consisted of exterior plywood type A-C, Group 1.

Construction of the various specimens was the same and was based on the procedure set forth in Reference 1. Three 2- by 10-inch by 16-foot joists were spaced 16 inches on center and a 2- by 10-inch by 4-foot header was nailed to each end. Cross bridging conforming to standards in Reference 1 was nailed to the inside of the joists at midspan (see Figures 2.1-2.6). Two sheets of 4- by 8-foot by 3/4-inch plywood were centered and nailed to the joists with 8d nails 10 inches on center. The plywood joint was located at midspan of the floor joists. Masonite, 1/4 inch thick, was nailed to the plywood subfloor with 4d screw-type nails. The Masonite was placed on the plywood subfloor in two 4-foot-square sections and one 4- by 8-foot section so its joints would not correspond to those of the plywood subfloor (see Figures 2.1-2.7). Typical floor test specimens are shown in Figure 2.7.

Five expedient methods were used to increase the flexural strength of the joists. The first method was that of applying steel strap to the bottom of the joists (Figures 2.2 and 2.7). Holes were drilled in the strap to allow it to be nailed directly to the joist. Specimens II, VI, and IX were reinforced in this manner. Specimens III and IV were reinforced with 1/4-inch plywood nailed to the bottom of the joists. The plywood was applied in two 4-foot-square pieces and one 4- by 8-foot piece so the joints would not correspond to those of the plywood subfloor (Figure 2.3). Specimen VIII was reinforced with U-shaped steel hanger straps, fabricated by placing the flat steel strip in a vise and pounding it with a hammer. The hanger straps were then drilled and attached to the joist with 1/4-inch-diameter cap screws (Figure 2.4). The location of the hanger straps was determined by analyzing failures of previous test specimens. Specimens X and XI were reinforced with a combination of steel strap and hanger strap. Steel strap was first nailed to the test specimens; the hanger straps were placed over the steel strap, around the joist, and then fastened to the joist with 1/4-inch cap screws (Figure 2.5). The reinforcement for Specimens XII and XIII consisted of 22-gage galvanized steel, available in 4- by 10-foot sheets. This metal was readily cut with tin snips or an electric sabre saw equipped with a metal cutting blade. The sheet steel was cut into 1-1/2-inch by 10-foot strips and fastened to the joists with 12d annular grooved (screw-type) nails (Figure 2.6). The remaining specimens (I, V, VII, XIV, and XV) were unreinforced control specimens (Figures 2.1 and 2.7).

2.2 TEST PROGRAM

Fifteen specimens were tested statically in the U. S. Army Engineer

Waterways Experiment Station's 200-kip loader (Reference 3), a device capable of applying an almost immediate concentrated load over a maximum stroke of 6 inches. The loader was designed to apply forces varying from 10,000 to 200,000 pounds in either tension or compression and to allow loads as high as 400,000 pounds; however, the maximum load capability of the device is dependent upon the type of test being conducted.

Each specimen in this study was loaded to rupture. A load spreader was constructed and used (Figure 2.8a) to distribute equal, concentrated line loads at the quarter points of the test specimen. The load spreader consisted of two 8-inch-deep WF beams joined by 4-inch-inside-diameter steel pipe and was designed to deliver static loads up to an equivalent uniform load of 10 psi. The cross-member, a 12-inch-deep WF beam to which load cells were rigidly attached, transmitted the load from the loader ram of the 200-kip device to the load spreader. All the beams of the load spreader were strengthened with flange stiffeners.

The free span of the floor specimens was 14 feet, with a 1-foot overhang on each end, making the total specimen length 16 feet. The test specimens were supported on rollers. Of course, roller supports did not represent actual end conditions, but it was not the intention of the study to obtain qualitative data on the load-carrying ability of a floor system or to analyze possible failure conditions at the supports. Rather, the intent was to test a simplified system that would provide data on the flexural capabilities of a reinforced floor joist system as compared to that of an unreinforced joist system. Consequently, no attempt was made to support and tie the joist ends into a sill system such as would exist in typical house construction. It was recognized that a realistic end support would increase the moment capacity, but it is believed that this increase would be the same in all cases; hence, it would have no effect on the relation of one reinforcing technique to another. For the same reason, only 4-foot-wide strips of simulated floor were constructed and tested.

Load and deflection were recorded on analog magnetic tape during all the tests. Two deflection gages were located at midspan of the test specimens. Both gages were 12-inch, linear-travel, Collins linear variable differential transformers (LVDT) and were mounted above the floor specimen, rigidly attached to the frame of the loader (Figure 2.8a). Two Baldwin SR-4, 50,000-pound compression load cells were attached to the cross beam of the load spreader with 1/4-inch-diameter cap screws during the test. Figures 2.8a and b show the test setup for the floor structures tested.

2.3 TEST PROCEDURE AND RESULTS

In the event that airblast loading is experienced, it is usually assumed that a floor would undergo a uniformly distributed load. The maximum moment developed by a uniformly distributed load is $wL^2/8$. The maximum moment developed by point loads applied at the quarter points of the span is $PL/4$. If P is equal to $wL/2$, then the maximum moment developed by the point loads applied at the quarter points of the span closely approximates the maximum moment developed by the uniform load (Figure 2.8c). The end shears for both types of loading are equivalent. Since it was easier, from the experimental standpoint, to apply equal concentrated static loads to the test specimens rather than a static uniform load, quarter-point loading was chosen as the load configuration for this study.

Loading procedures for all the floor specimens were identical and were accomplished using the hydraulic ram of the 200-kip device. In some instances, a pause occurred in the loading to allow a secondary pump to increase the hydraulic pressure needed for specimen failure. This pause was slight and did not affect test data. During the test of Specimen IX, loading was stopped as the flange on one of the beams of the load spreader began to bend. The frame was slightly repositioned and the test continued. Test data were not affected by the unloading and subsequent reloading of the structure as yield had not been reached.

Each of the floor specimens was loaded until two of the three wood joists ruptured. Posttest photographs of all the test specimens are shown in Figures 2.9-2.23.

The data recorded from the load cells and deflection gages were digitized and plotted as load-deflection curves which appear in Figures 2.24-2.38. These curves represent the average of the two load cells and the average of the two deflection gages. Generally, the load-deflection curve for a test specimen increases to the elastic limit, at which time one of the joists fails, shown on the load-deflection curve as a peak followed by a sharp drop. At this point, the remaining joists carry the load and the load-deflection curve again increases until a second joist fails, shown as a second peak followed by another sharp drop in the curve. Most of the floor specimens failed in the above manner; however, in some instances (Specimens IV, X, and XV), all three joists failed. The load-deflection curve for Specimen V, Figure 2.28, represents values for only one deflection gage since the calibration step for the other deflection gage was lost during the digitizing process.

The values for the load at yield (R_{YIELD}) and the deflection at yield (Y_{YIELD}) were defined to be at the point where the first joist failed, corresponding to the first peak of the load-deflection curve. Maximum load (R_{MAX}) was the highest peak of the load-deflection curve. In many instances, R_{YIELD} and R_{MAX} occurred simultaneously. Maximum deflection (Y_{MAX}) was the total deflection at the point where the load-deflection curve began the unload cycle.

Failure diagrams (Figures 2.39-2.53) were drawn for all test specimens and include facts about each joist of every floor specimen tested. The shaded areas represent the failure zones of the joists.

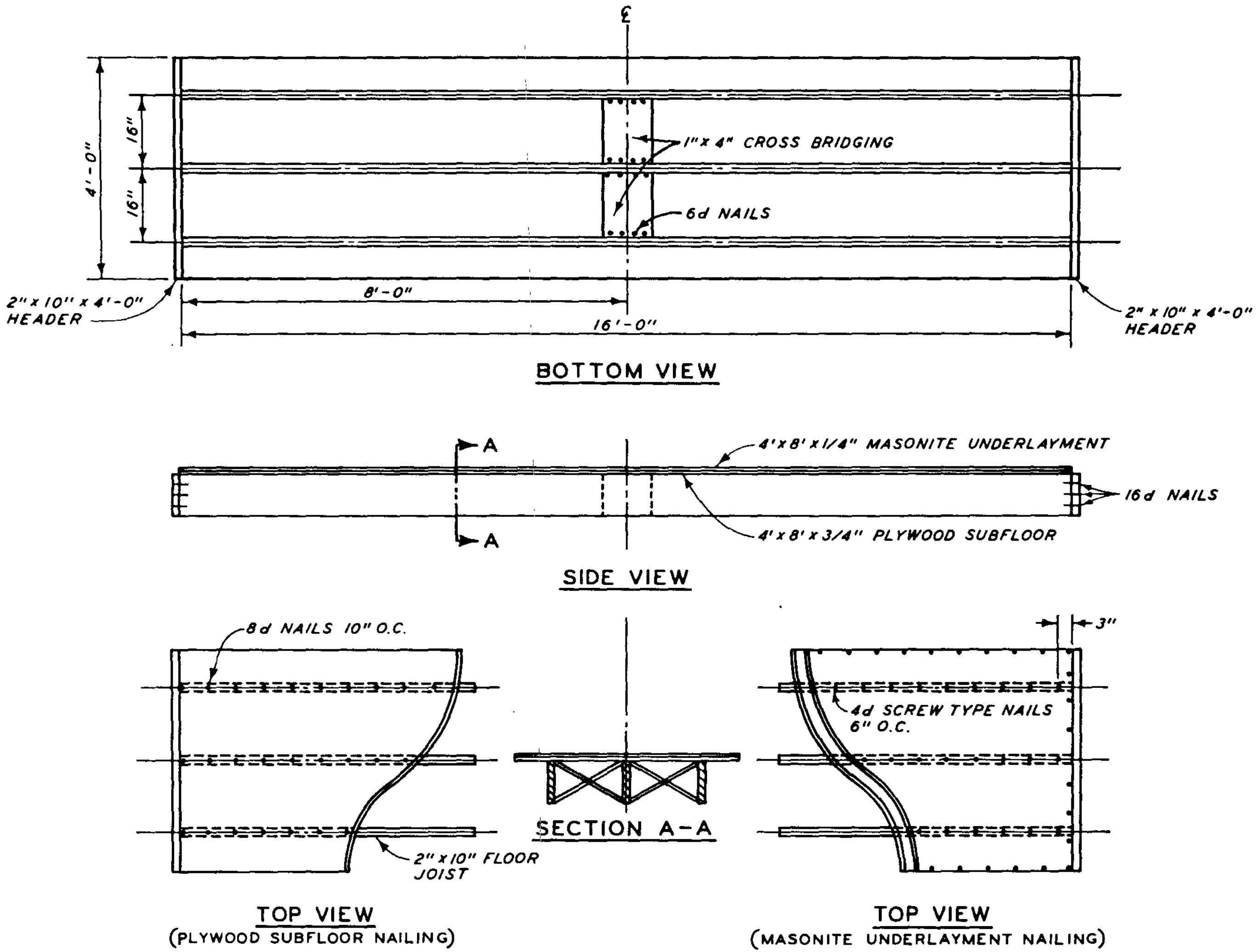


Figure 2.1 Construction drawing for the unreinforced test specimens (I, V, VII, XIV, and XV).

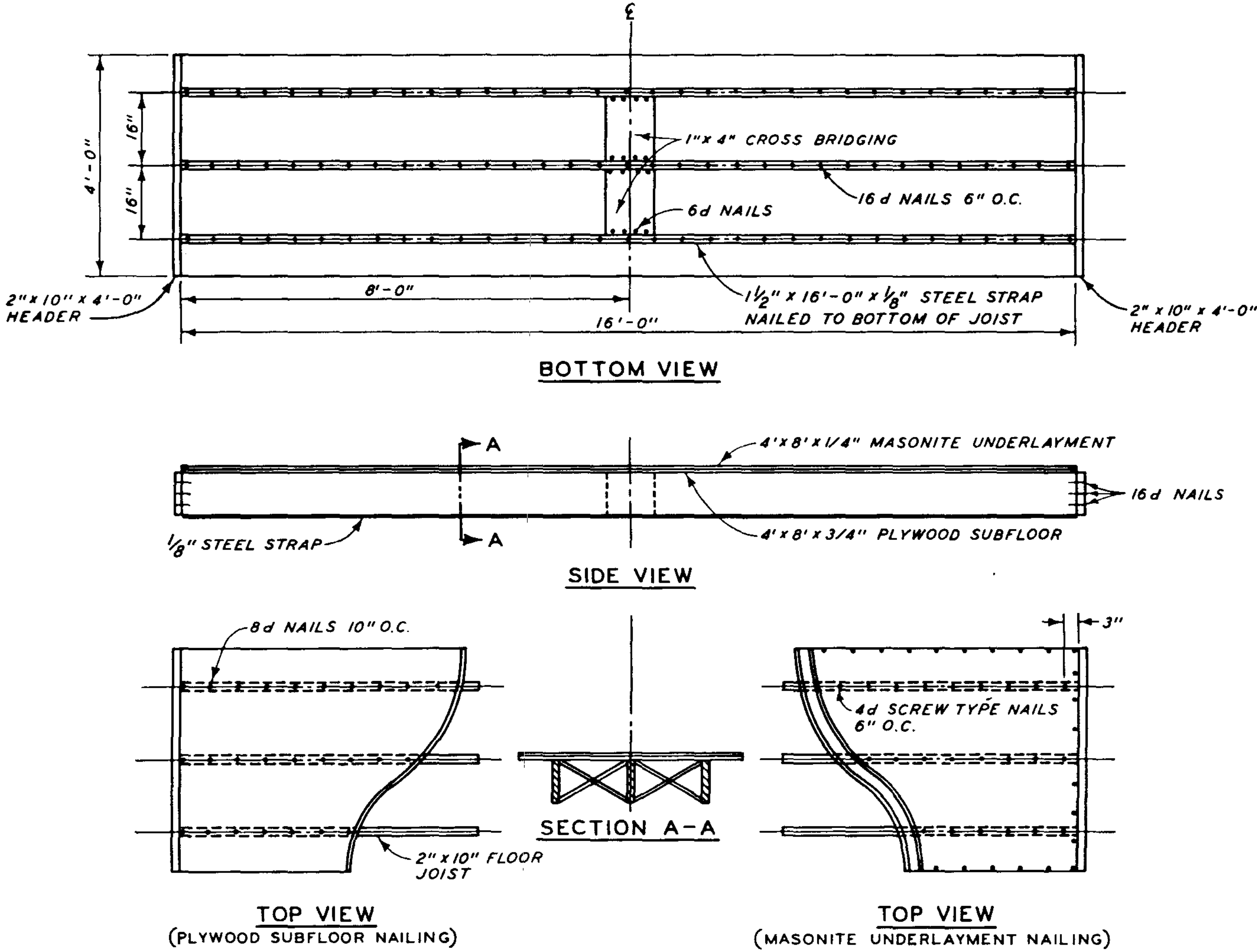


Figure 2.2 Construction drawing for the steel strap reinforced test specimens (II, VI, and IX).

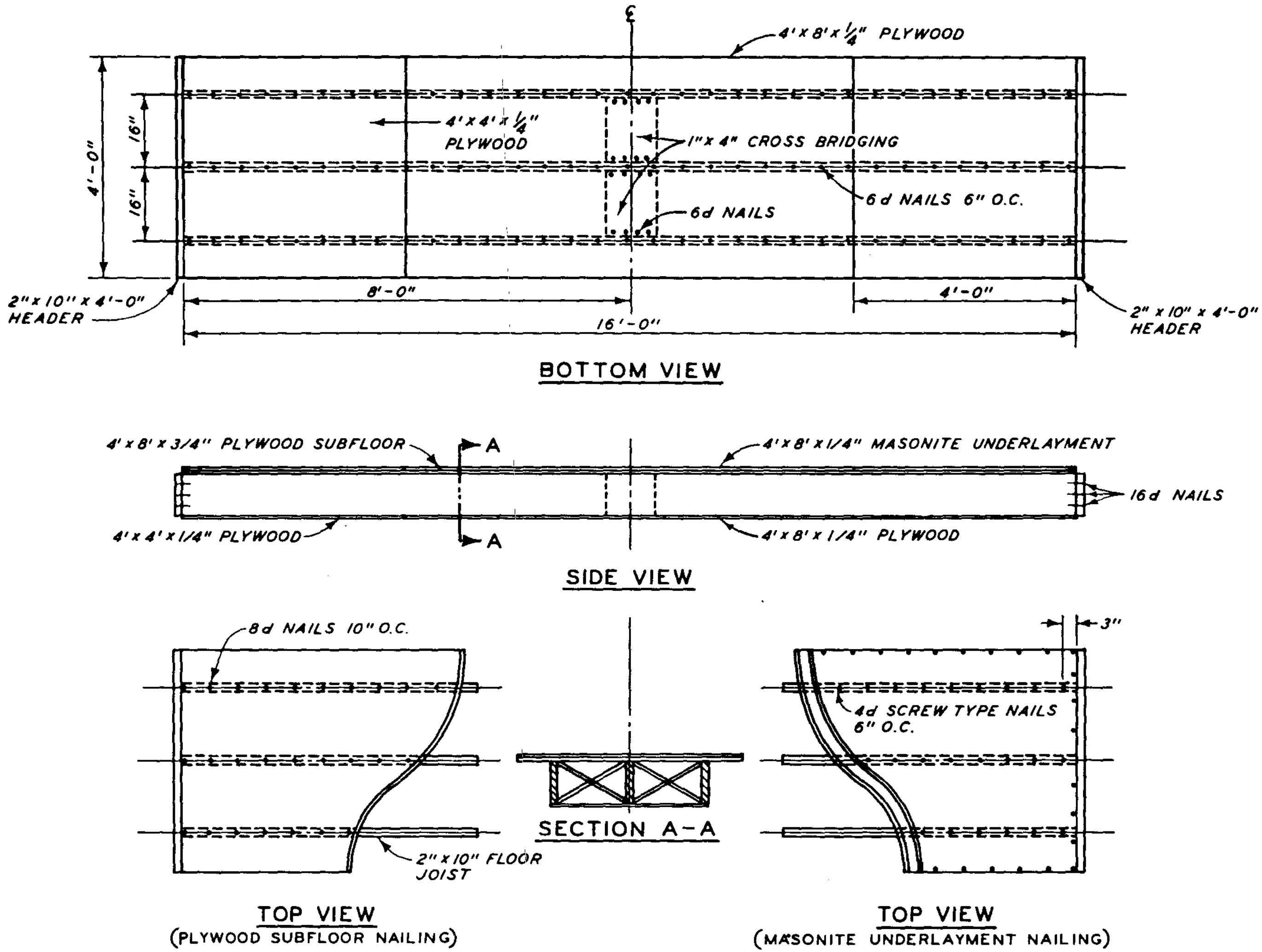


Figure 2.3 Construction drawing for the 1/4-inch plywood reinforced test specimens (III and IV).

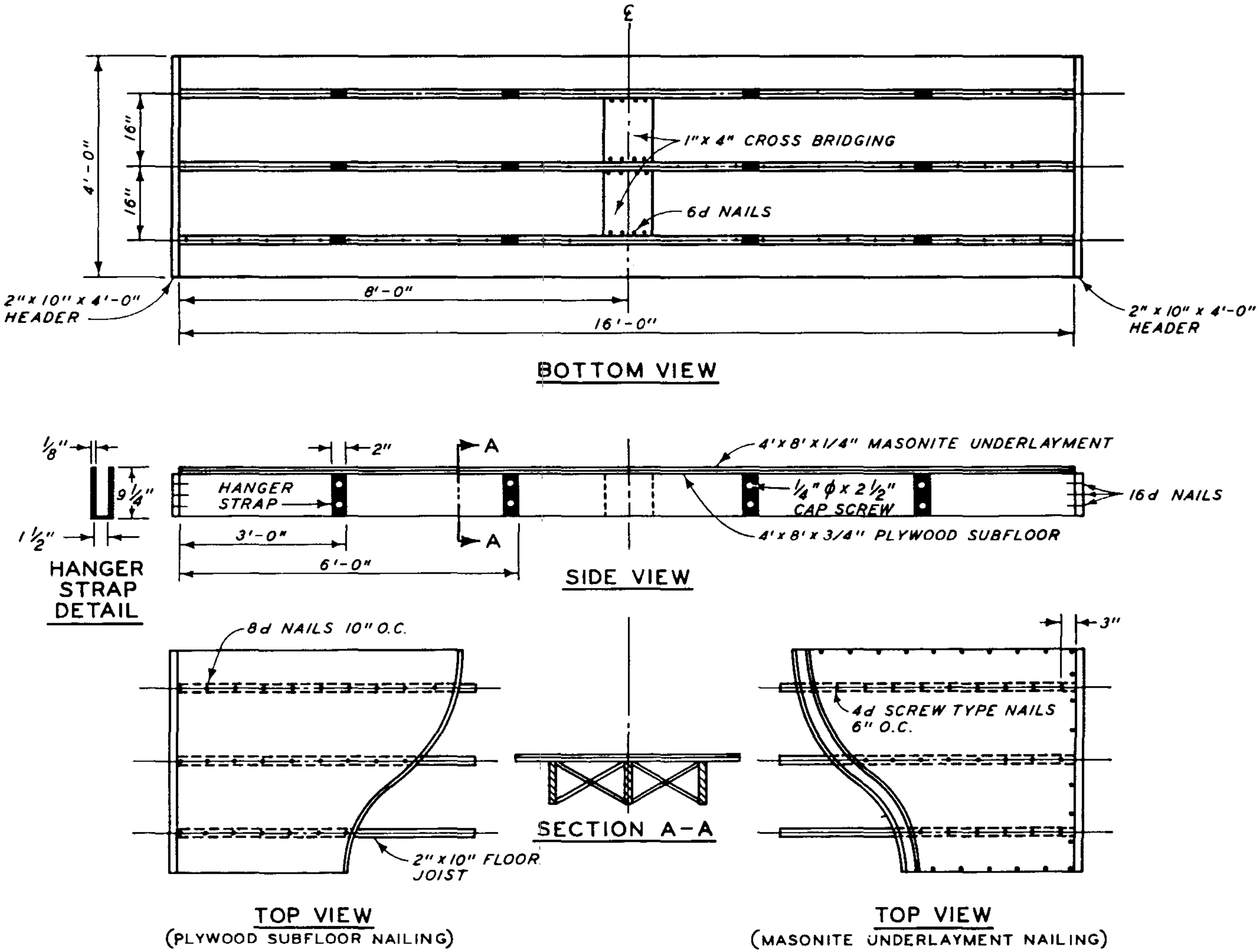


Figure 2.4 Construction drawing for the hanger strap reinforced test specimen (VIII).

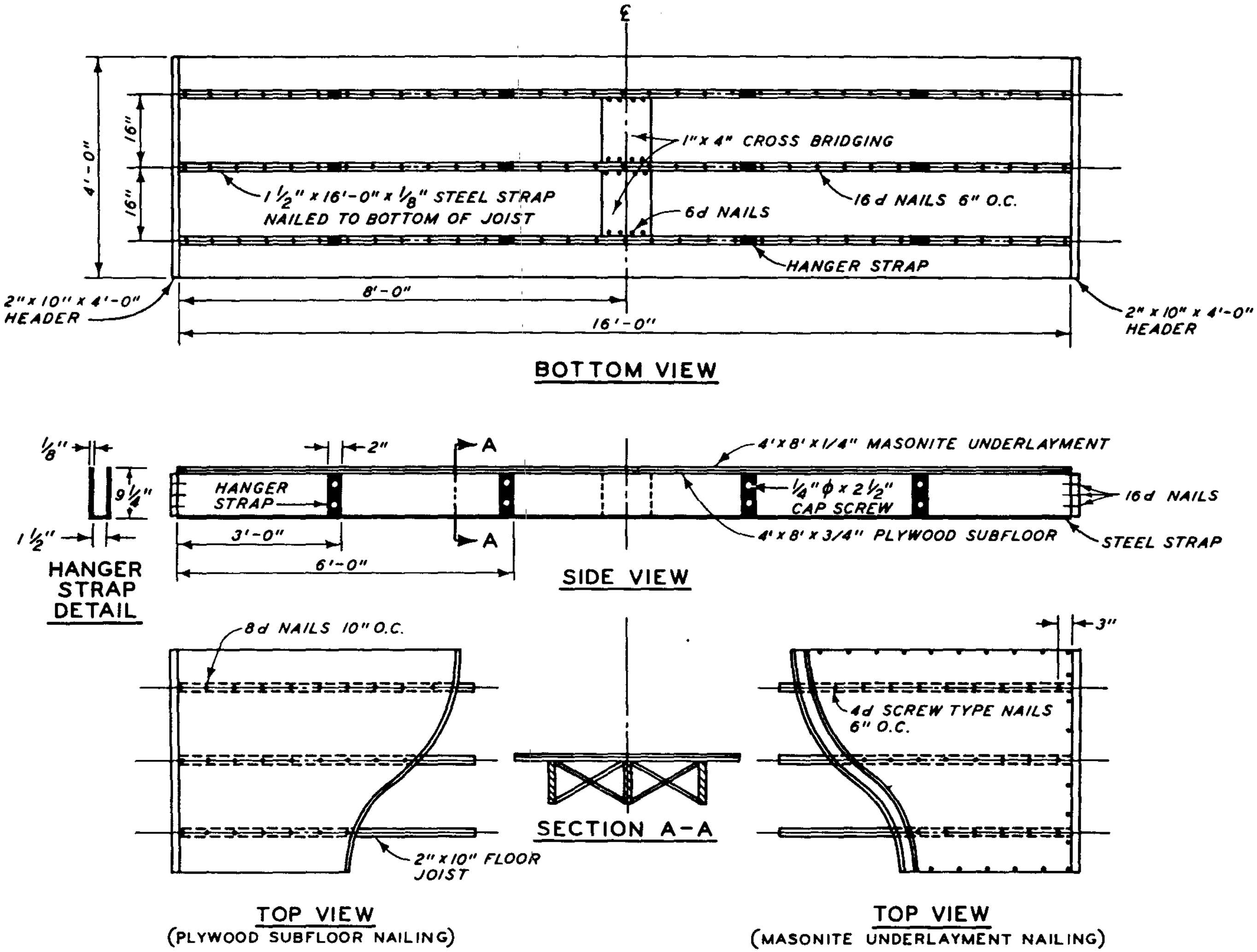


Figure 2.5 Construction drawing for the hanger strap-steel strap reinforced test specimens (X and XI).

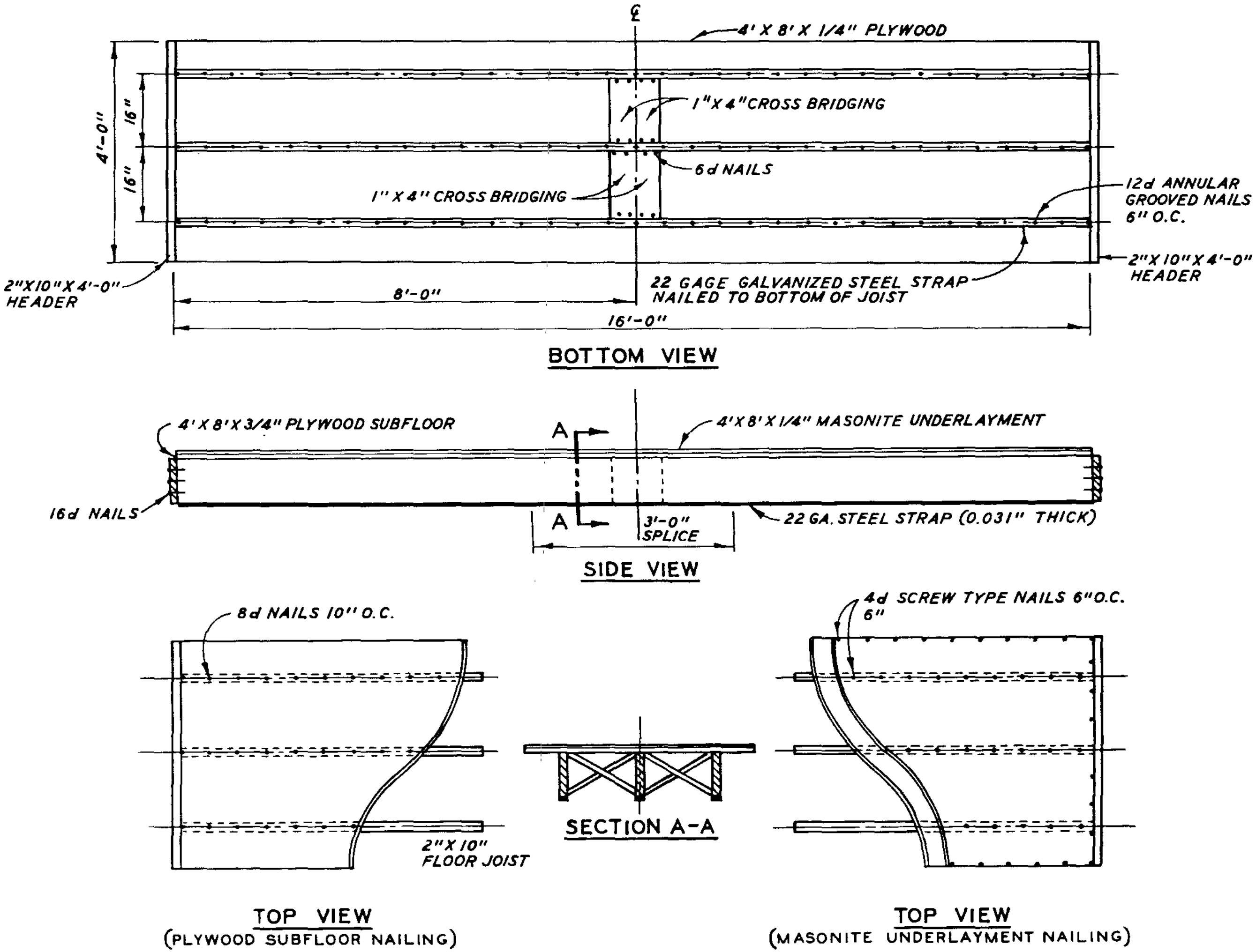
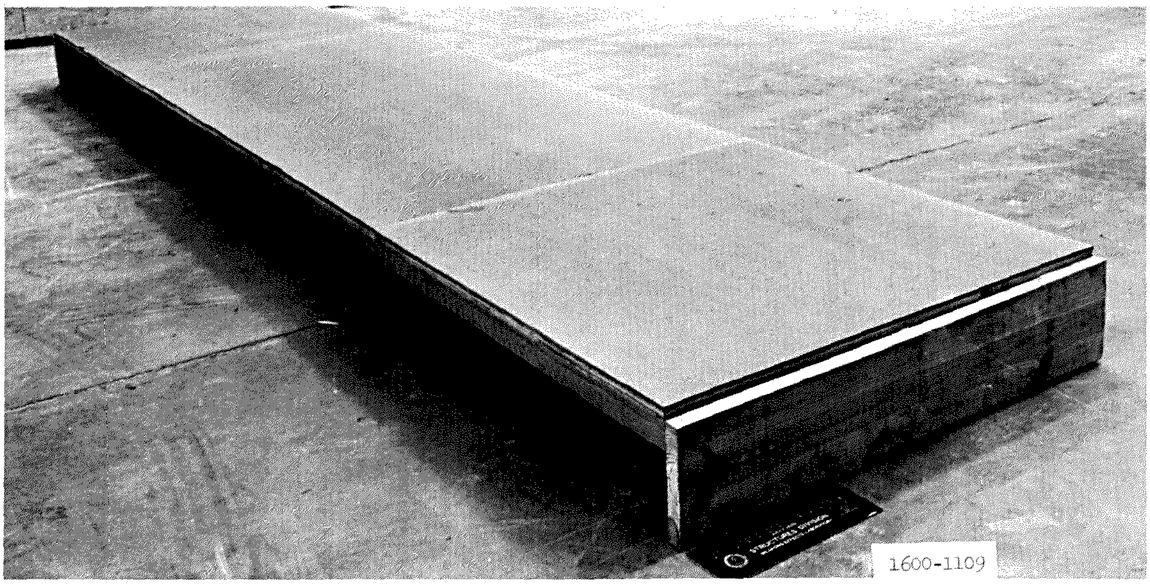
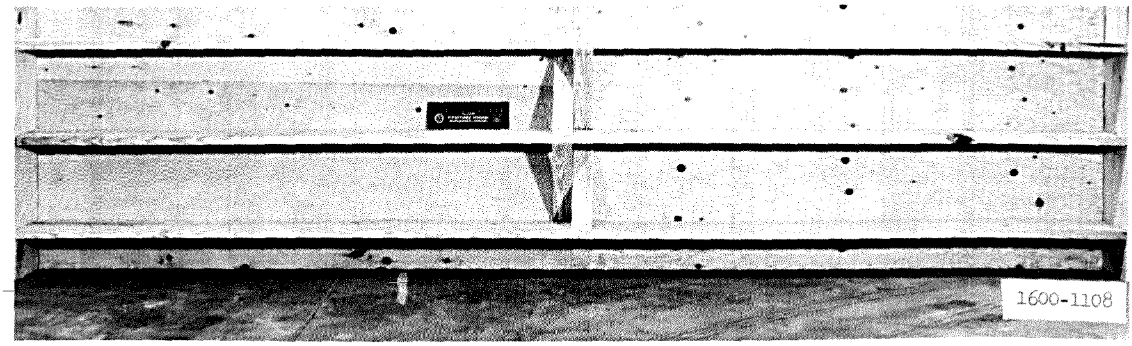


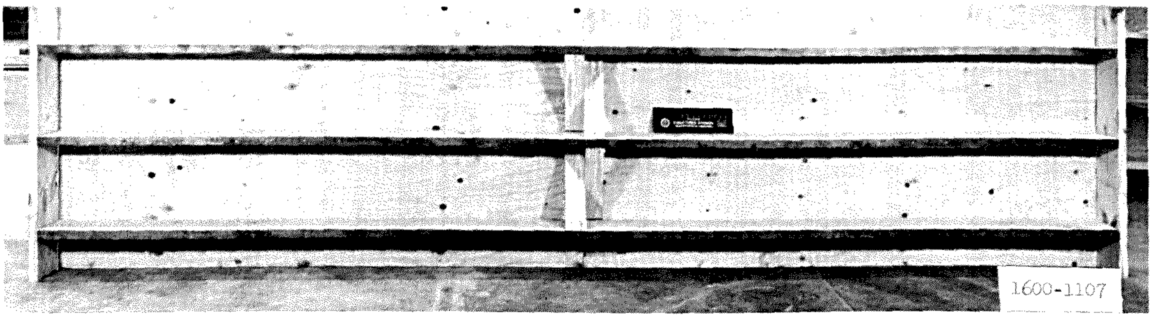
Figure 2.6 Construction drawing for the 22-gage steel strap reinforced test specimens (XII and XIII).



a. Top view of unreinforced test specimen (I).

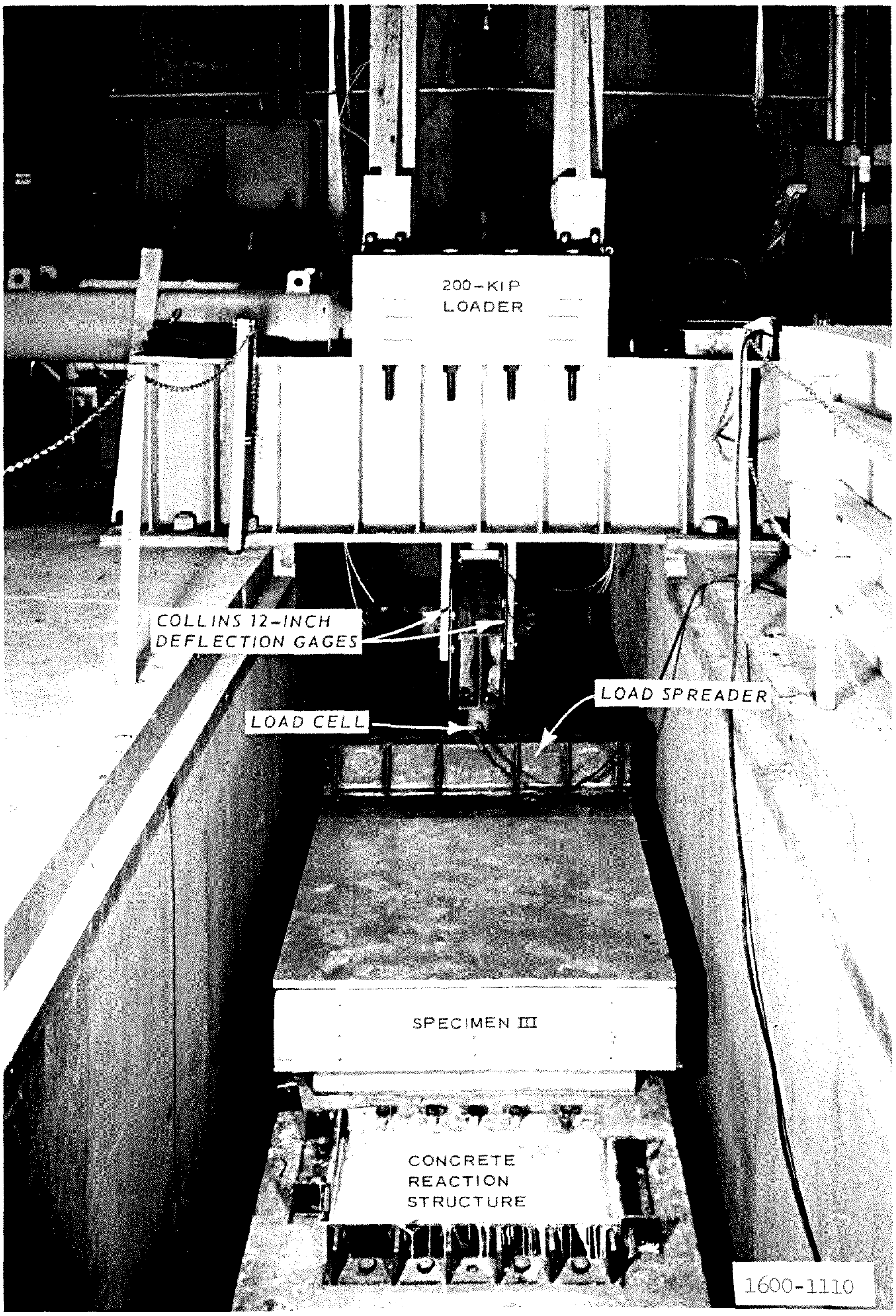


b. Bottom view of unreinforced test specimen (I).



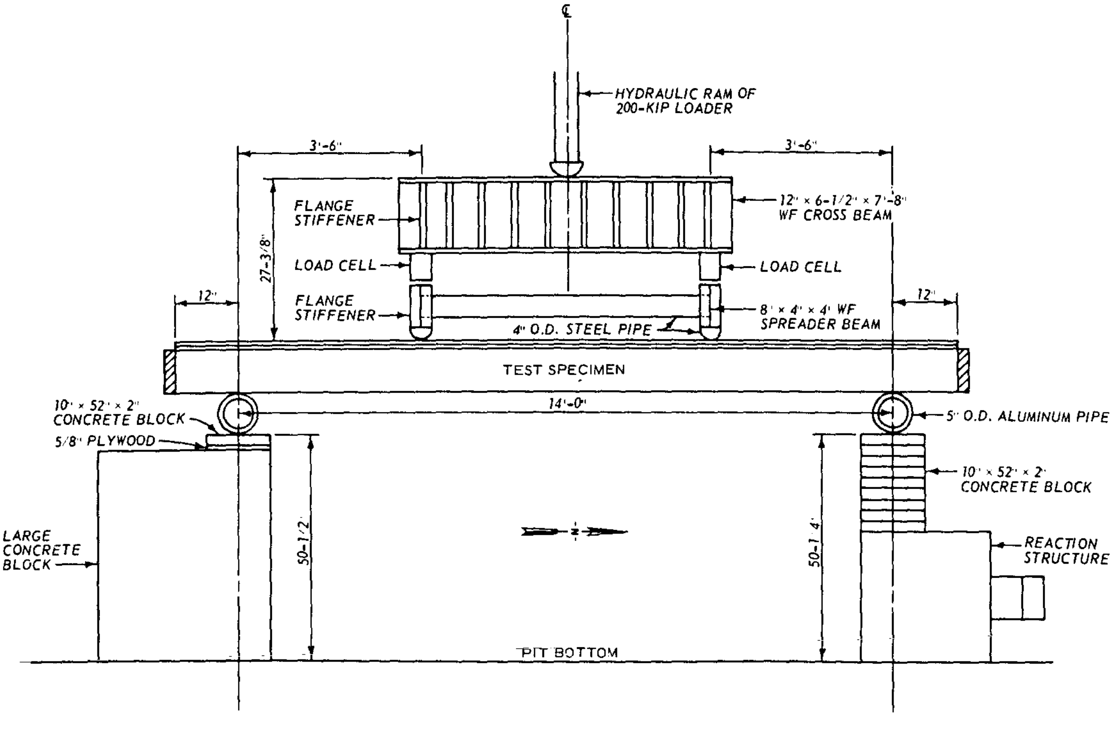
c. Bottom view of steel strap reinforced test specimen.

Figure 2.7 Typical floor test specimens.



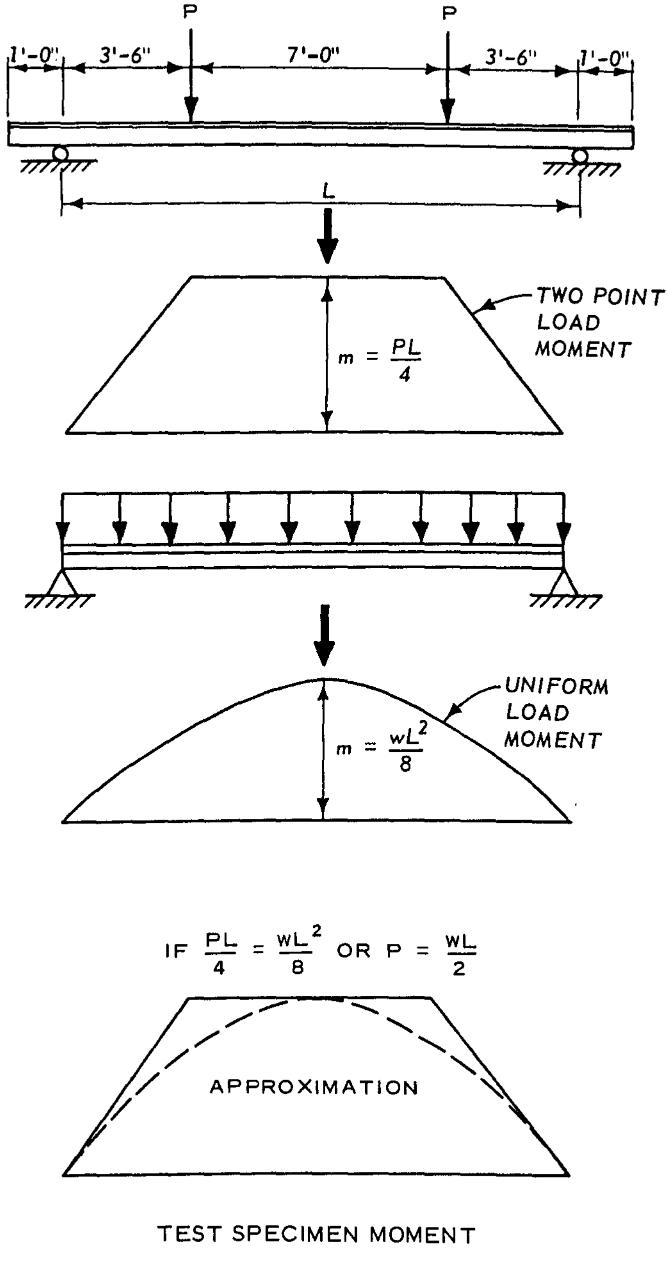
a. End view.

Figure 2.8 Test setup (sheet 1 of 3).



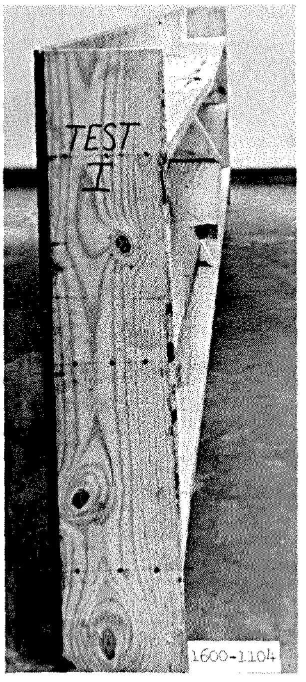
b. Side view.

Figure 2.8 (sheet 2 of 3).

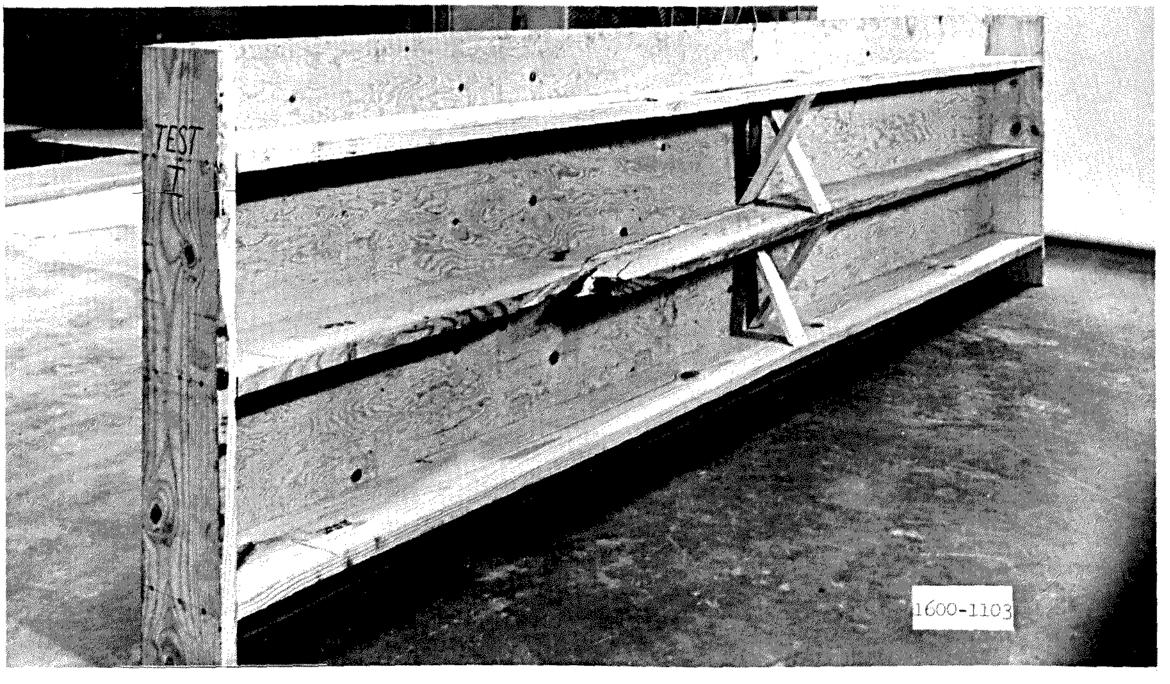


c. Load configuration.

Figure 2.8 (sheet 3 of 3).

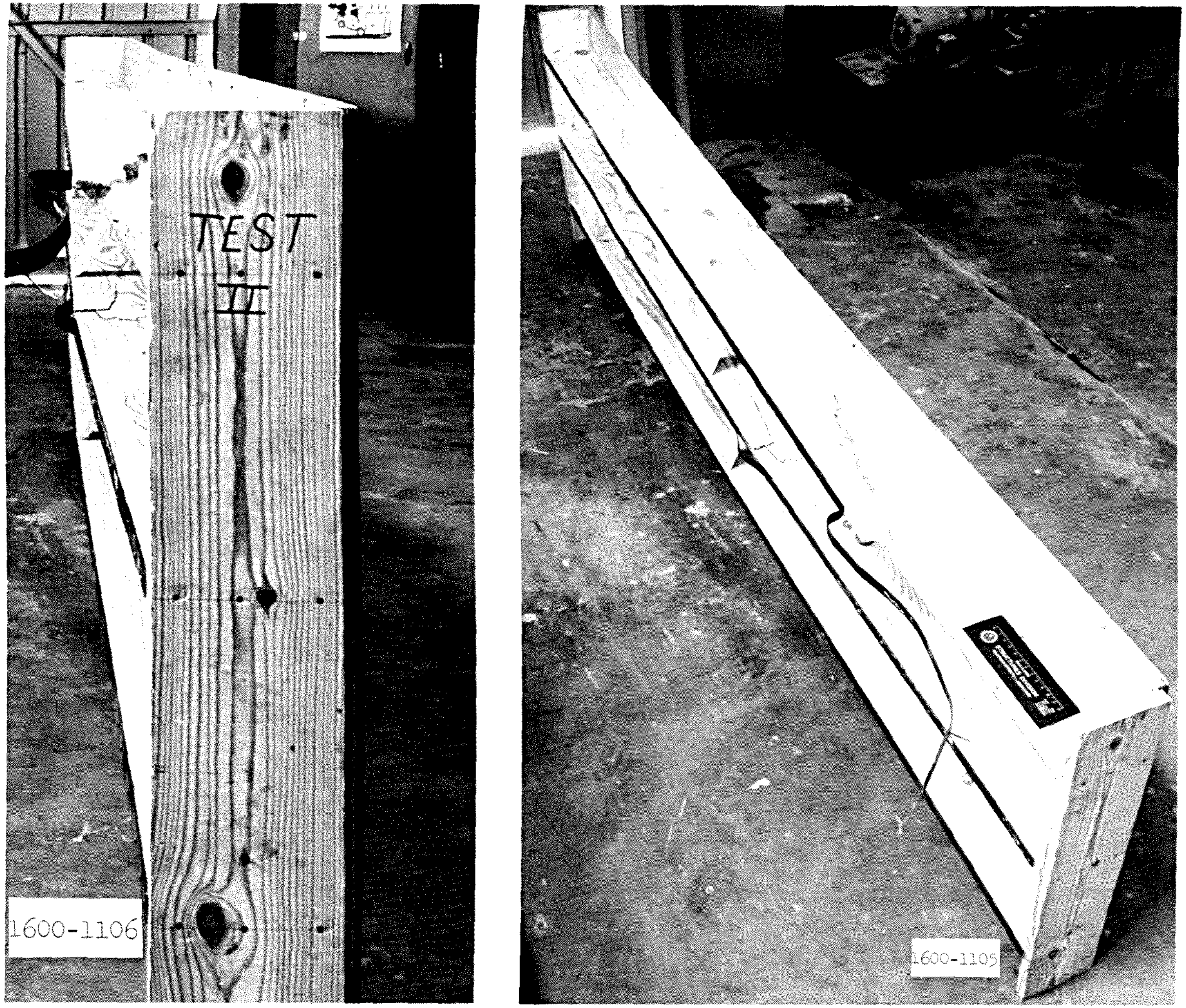


a. End view.



b. Top and middle joist failure.

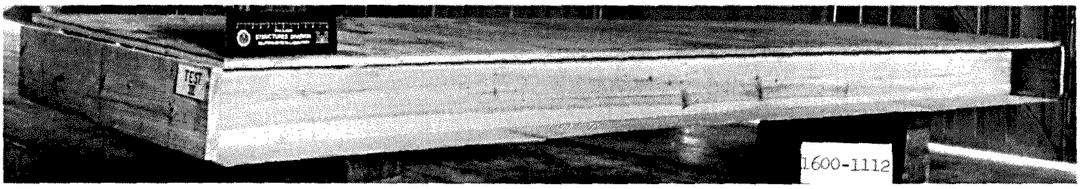
Figure 2.9 Posttest views of Specimen I.



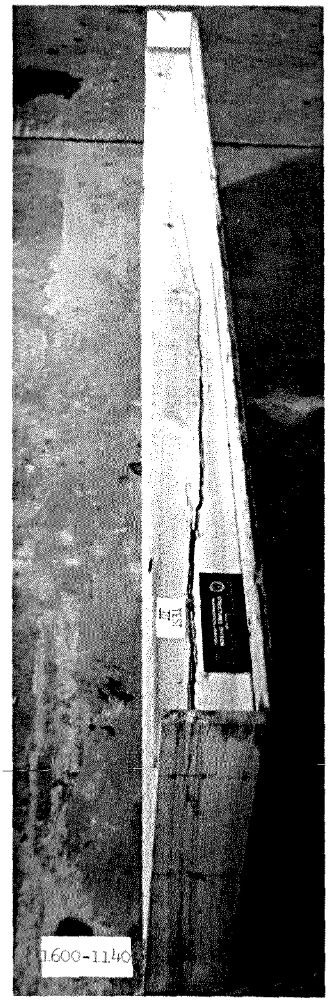
a. End view showing extreme bending of steel strap.

b. Top and middle joist failure.

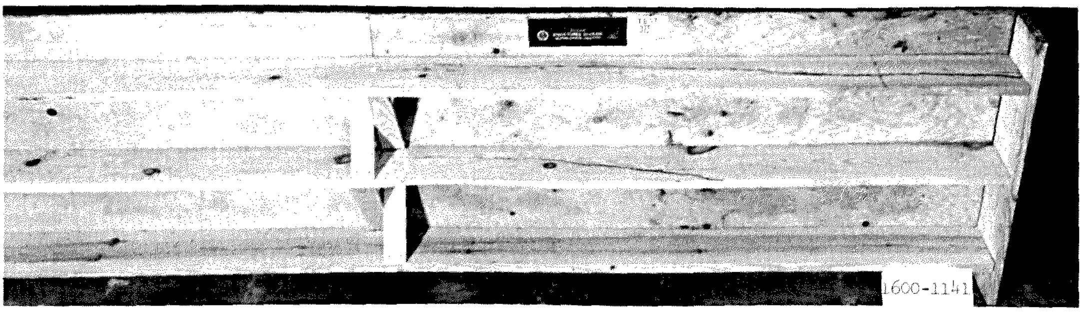
Figure 2.10 Posttest views of Specimen II.



a. Overall view.

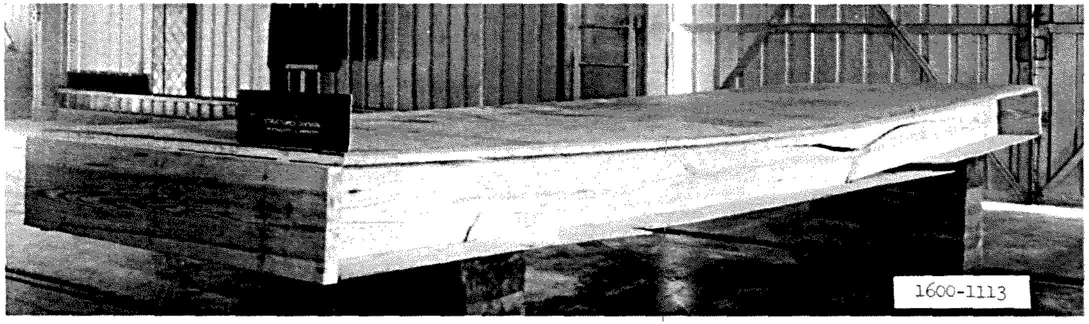


b. Top joist failure (bottom plywood removed).

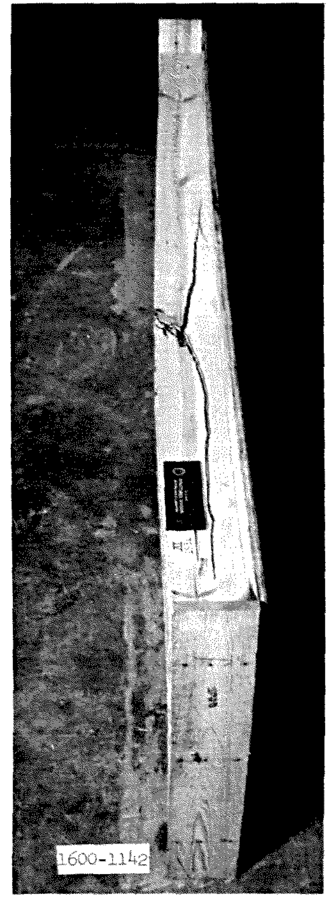


c. Bottom view showing failure of top two joists (bottom plywood removed.

Figure 2.11 Posttest views of Specimen III.



a. Overall view.

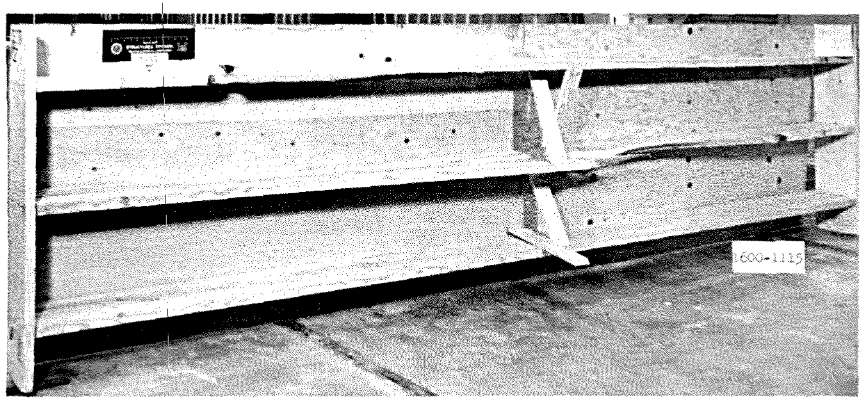


b. End view showing failure of one joist

c. Bottom view showing failure of all three joists (bottom plywood removed).

Figure 2.12 Posttest views of Specimen IV.

a. Joist failure (note plywood nail pullout).

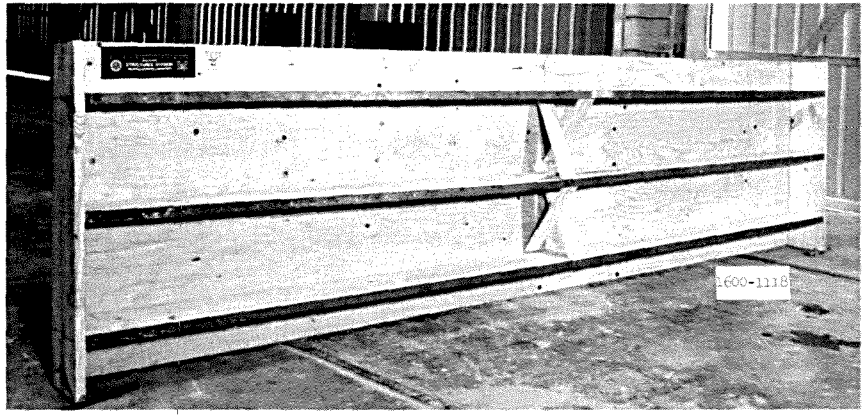


b. Bottom view showing failure of top two joists.

c. Close-up of joist failures.

Figure 2.13 Posttest views of Specimen V.

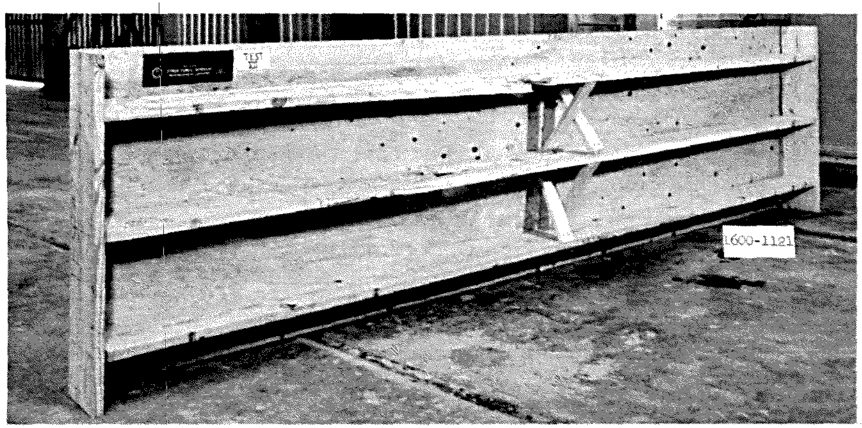
a. Joist failure (note plywood nail pullout).



b. Bottom view.

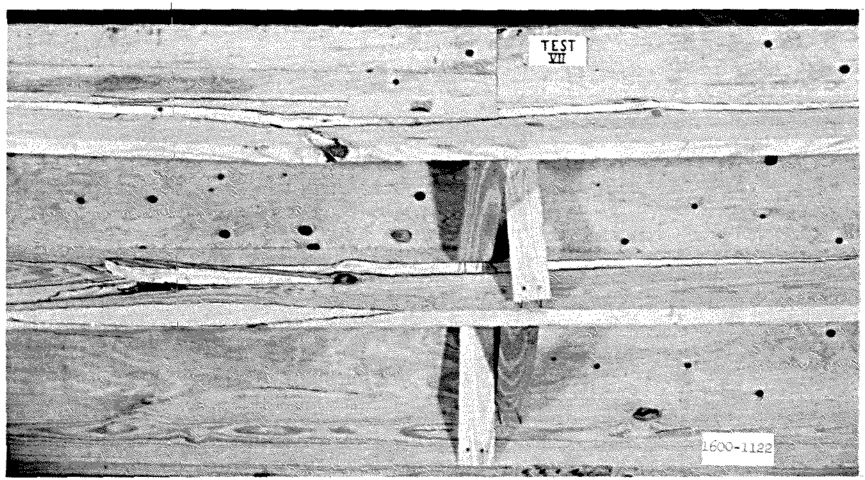
c. Close-up of joist failures

Figure 2.14 Posttest views of Specimen VI.



b. Bottom view.

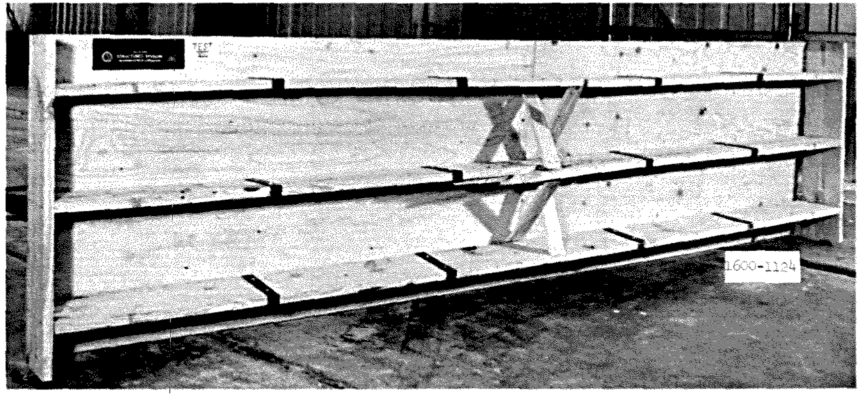
a. Joist failure.



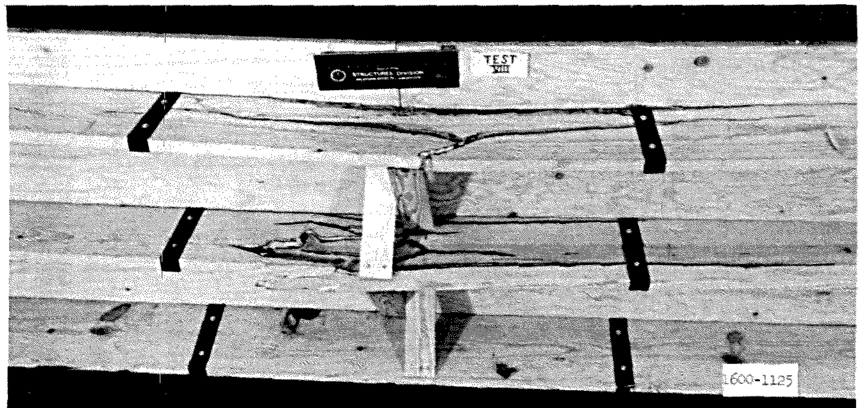
c. Close-up of joist failures.

Figure 2.15 Posttest views of Specimen VII.

a. Joist failure.

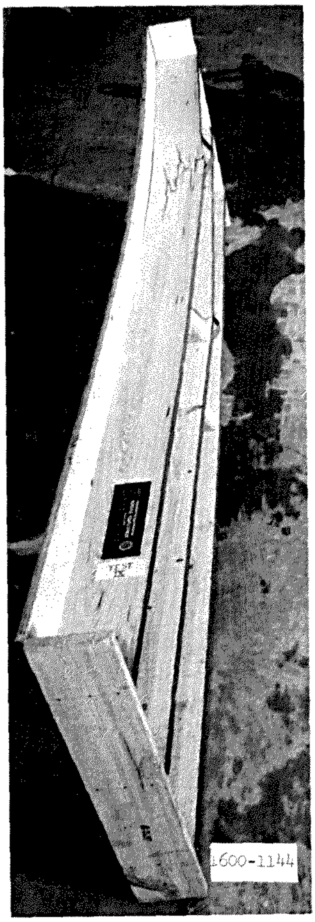


b. Bottom view.

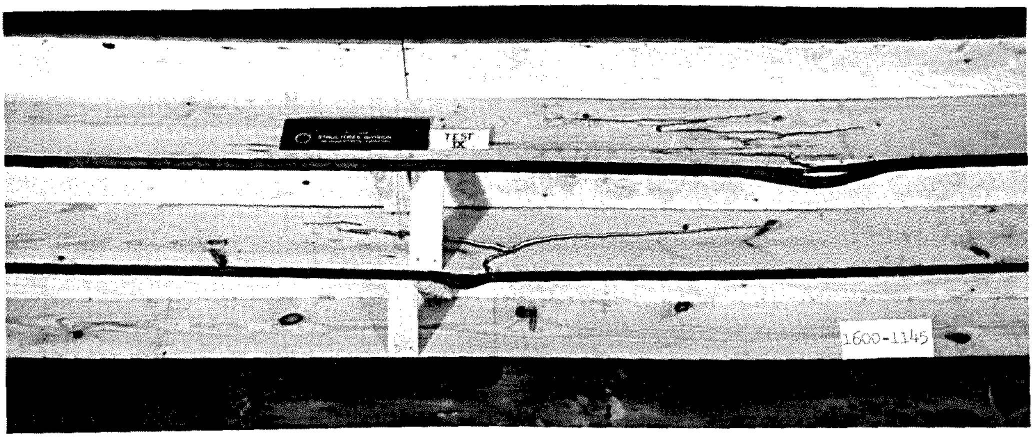


c. Close-up of joist failures.

Figure 2.16 Posttest views of Specimen VIII

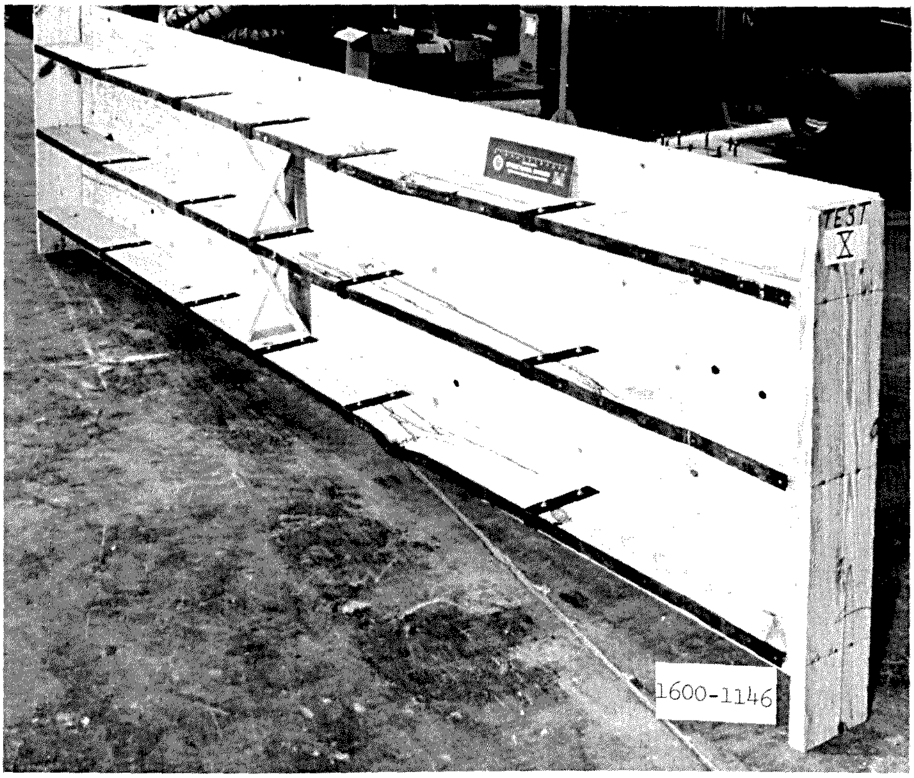


a. Overall view.

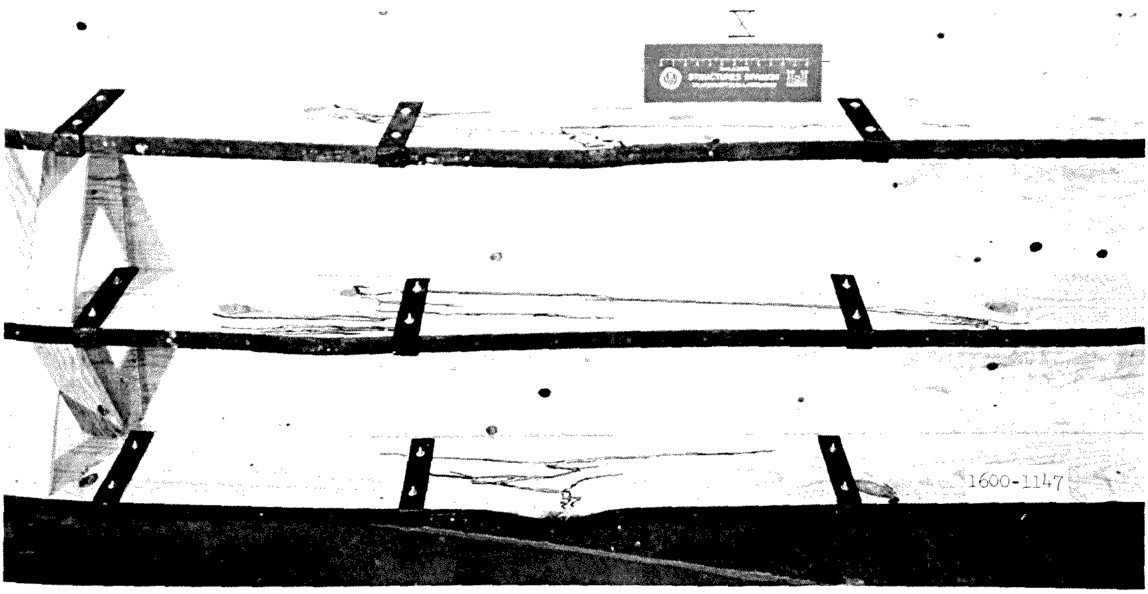


b. Close-up of joist failures.

Figure 2.17 Posttest views of Specimen IX.



a. Overall view (note that all three joists failed).



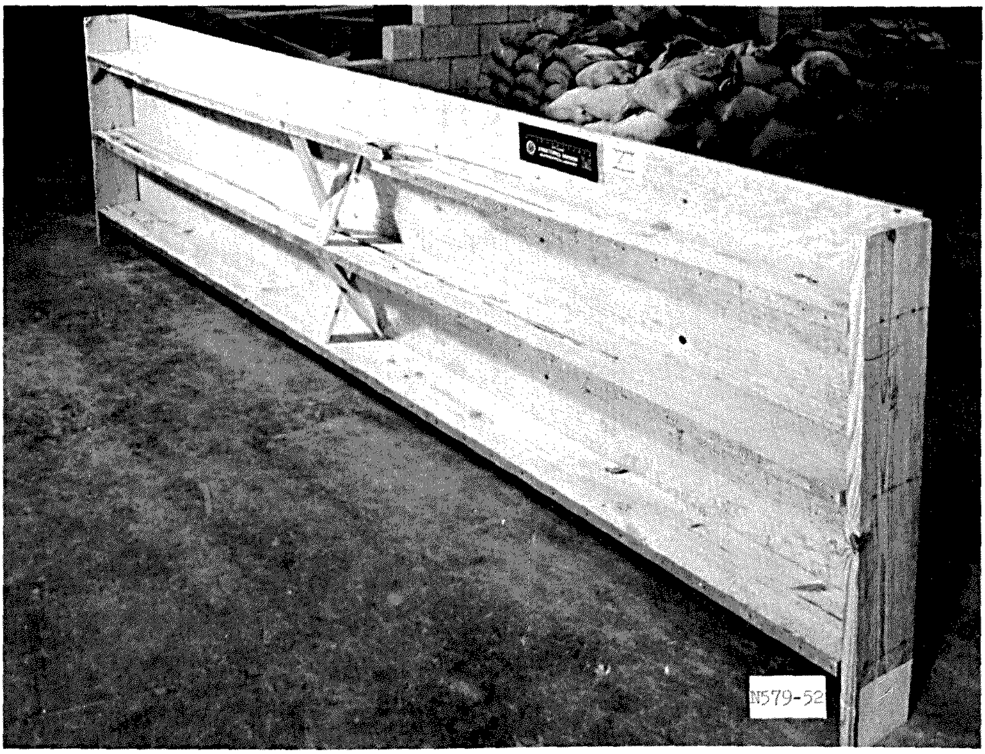
b. Close-up of joist failures.

Figure 2.18 Posttest views of Specimen X.

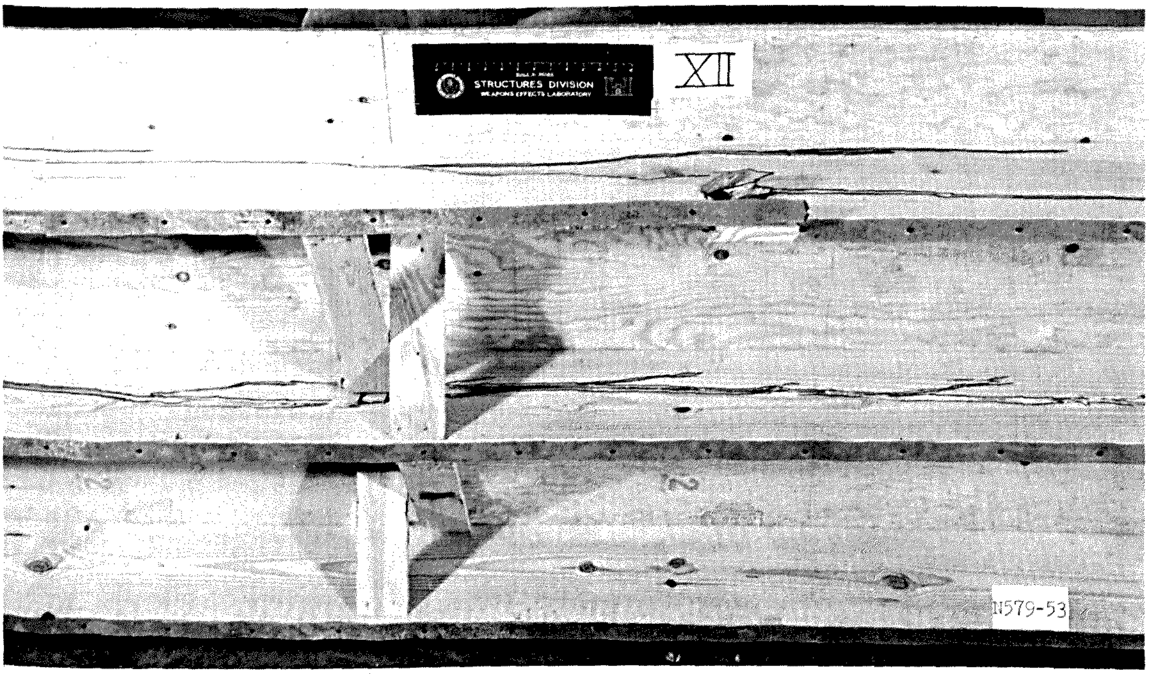
a. Overall view.

b. Close-up of joist failures.

Figure 2.19 Posttest views of Specimen XI.

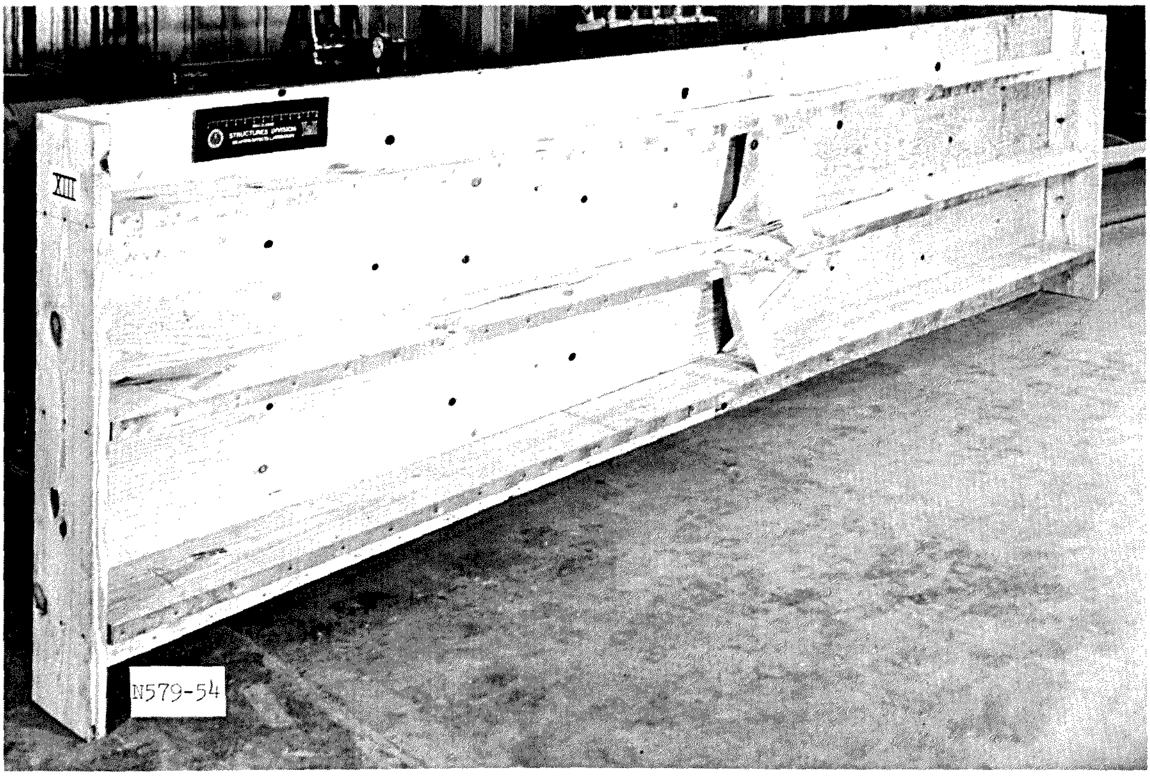


a. Overall view.

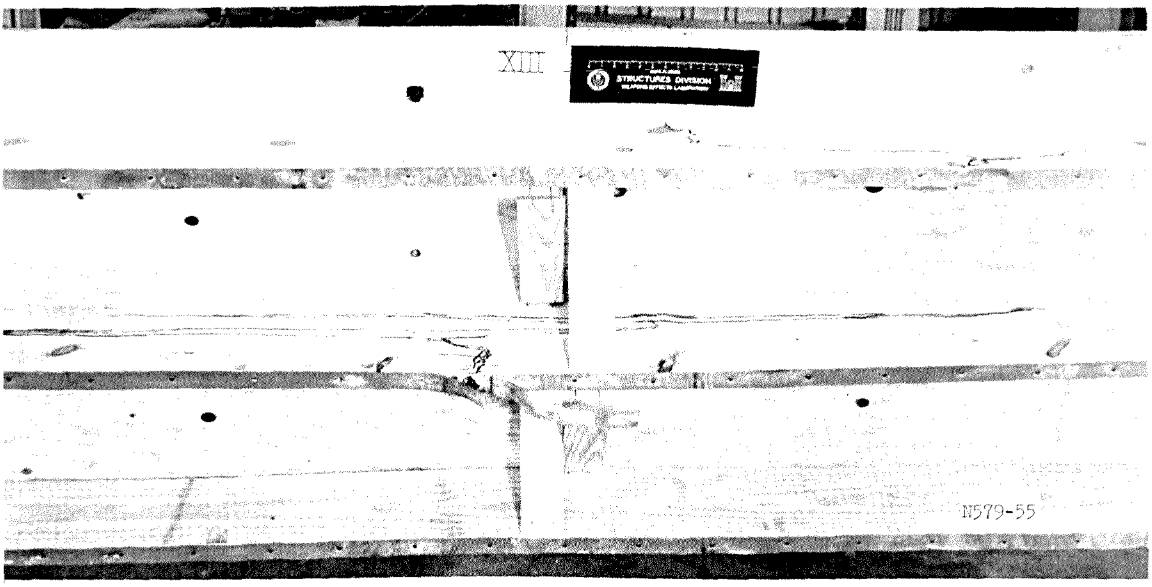


b. Close-up of joist failures.

Figure 2.20 Posttest views of Specimen XII.

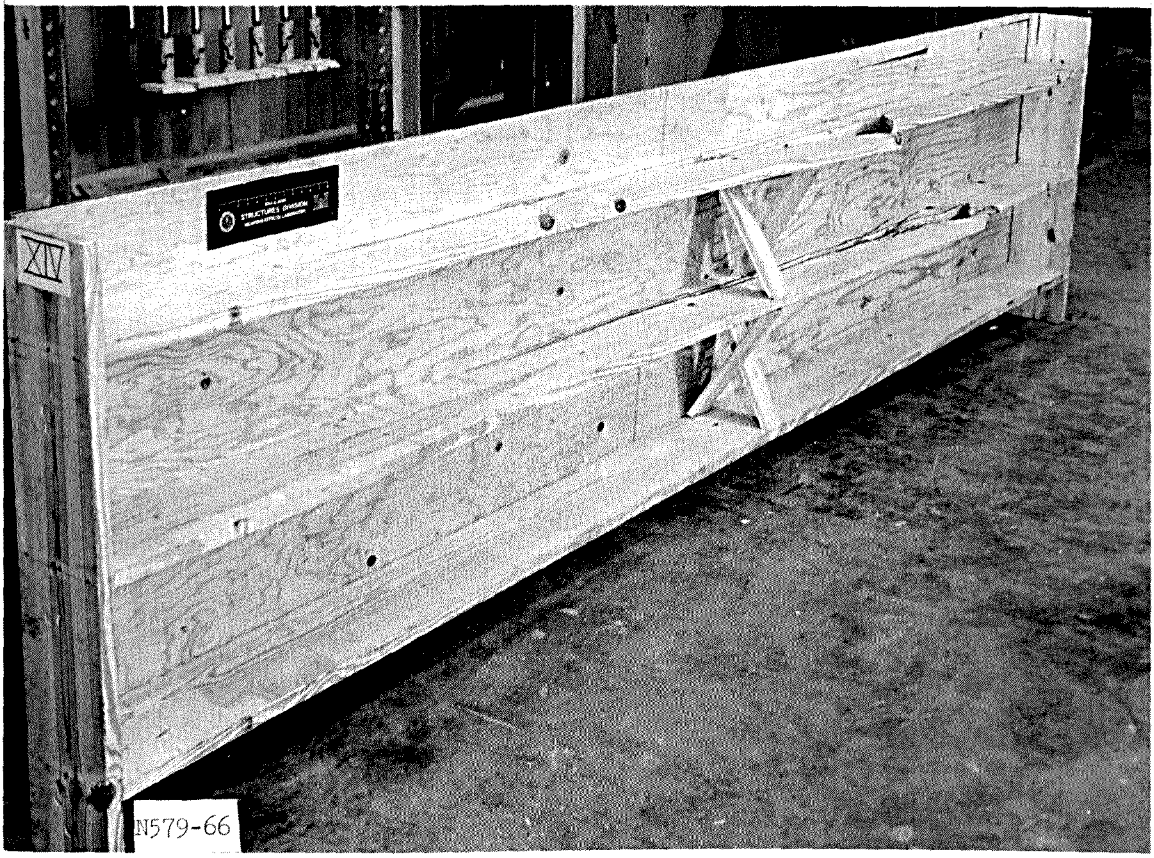


a. Overall view.

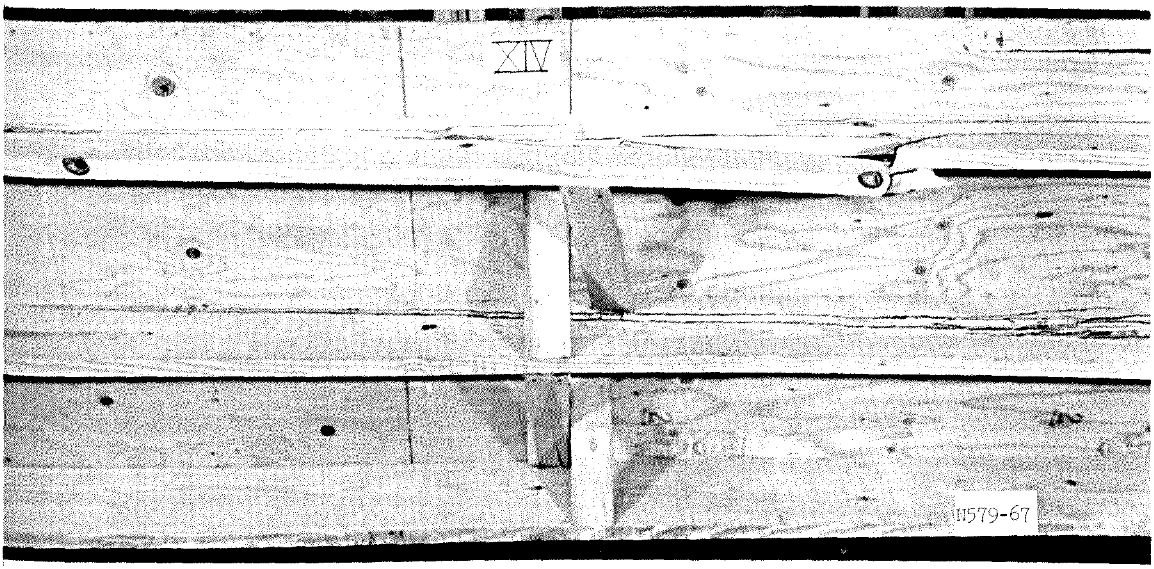


b. Close-up of joist failures.

Figure 2.21 Posttest views of Specimen XIII.

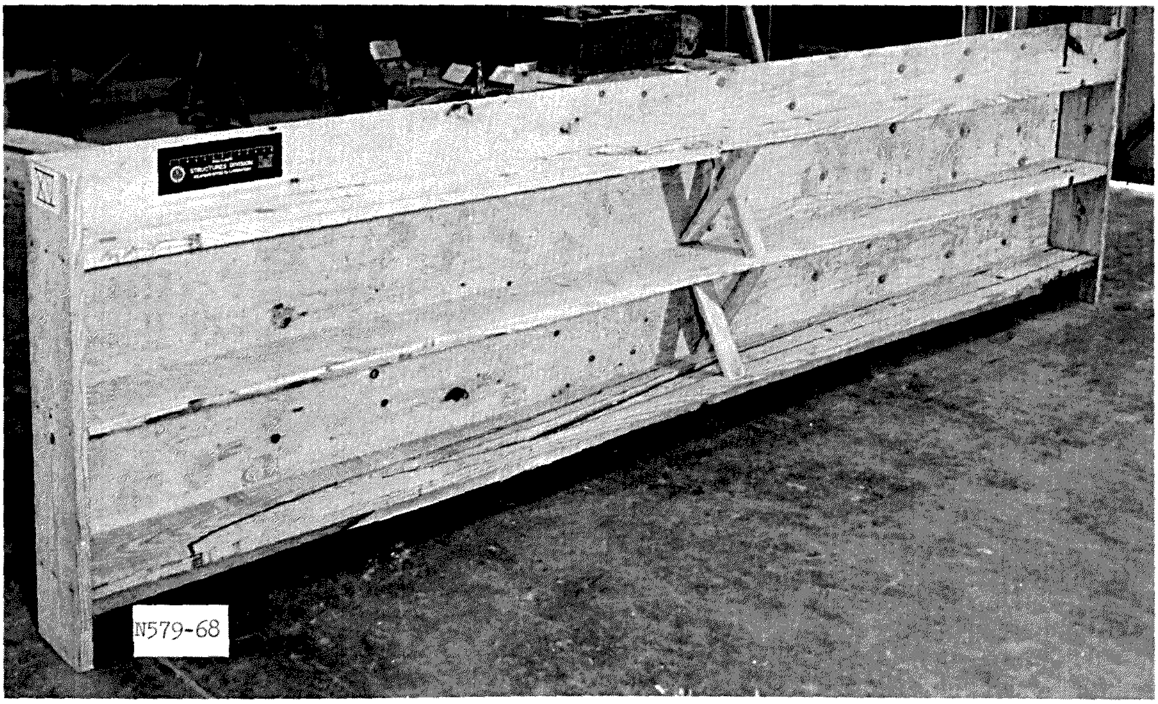


a. Overall view.



b. Close-up of joist failures.

Figure 2.22 Posttest views of Specimen XIV.



a. Overall view.

b. Close-up of joist failures.

Figure 2.23 Posttest views of Specimen XV.

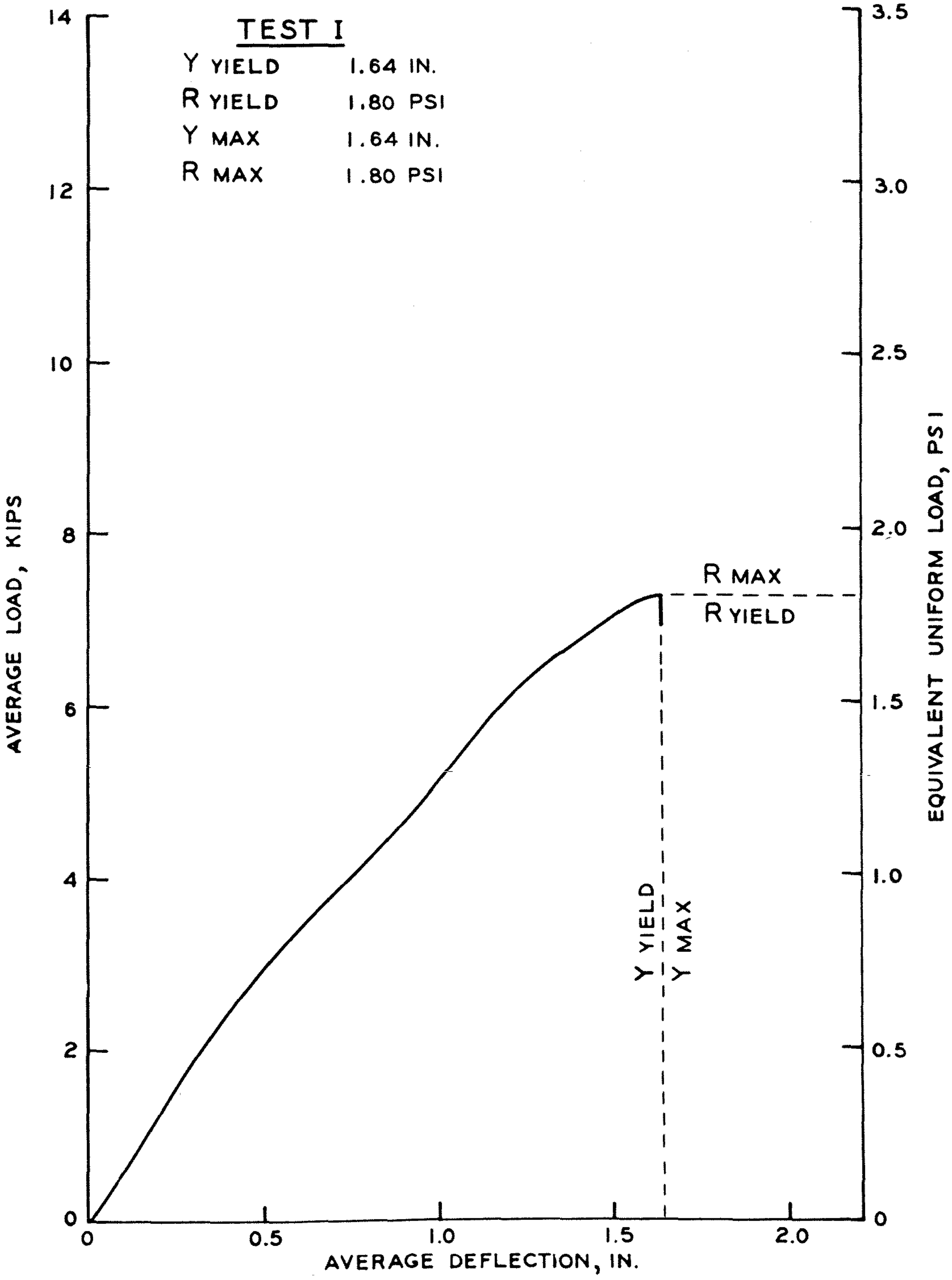


Figure 2.24 Load-deflection curve, Specimen I.

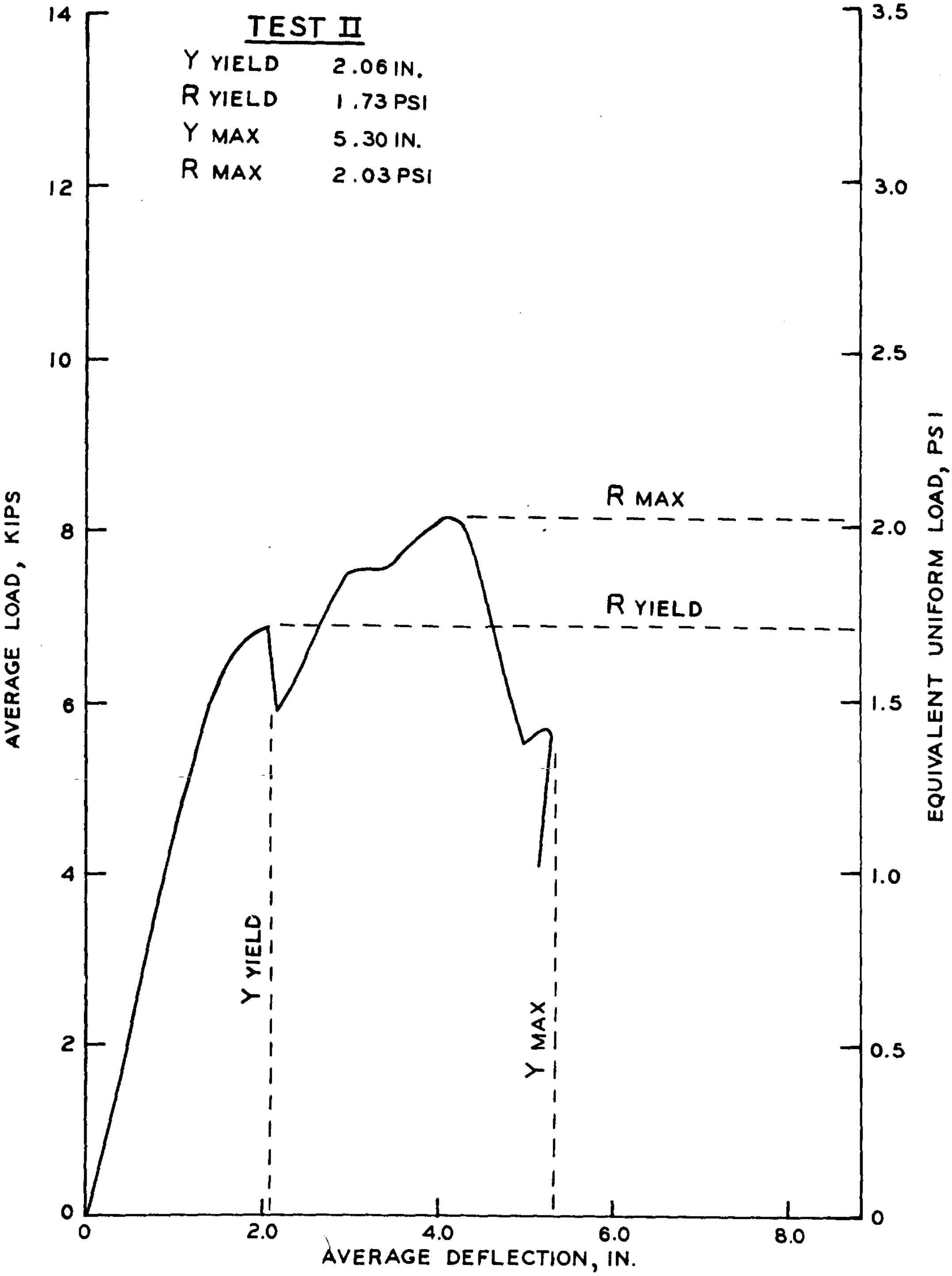


Figure 2.25 Load-deflection curve, Specimen II.

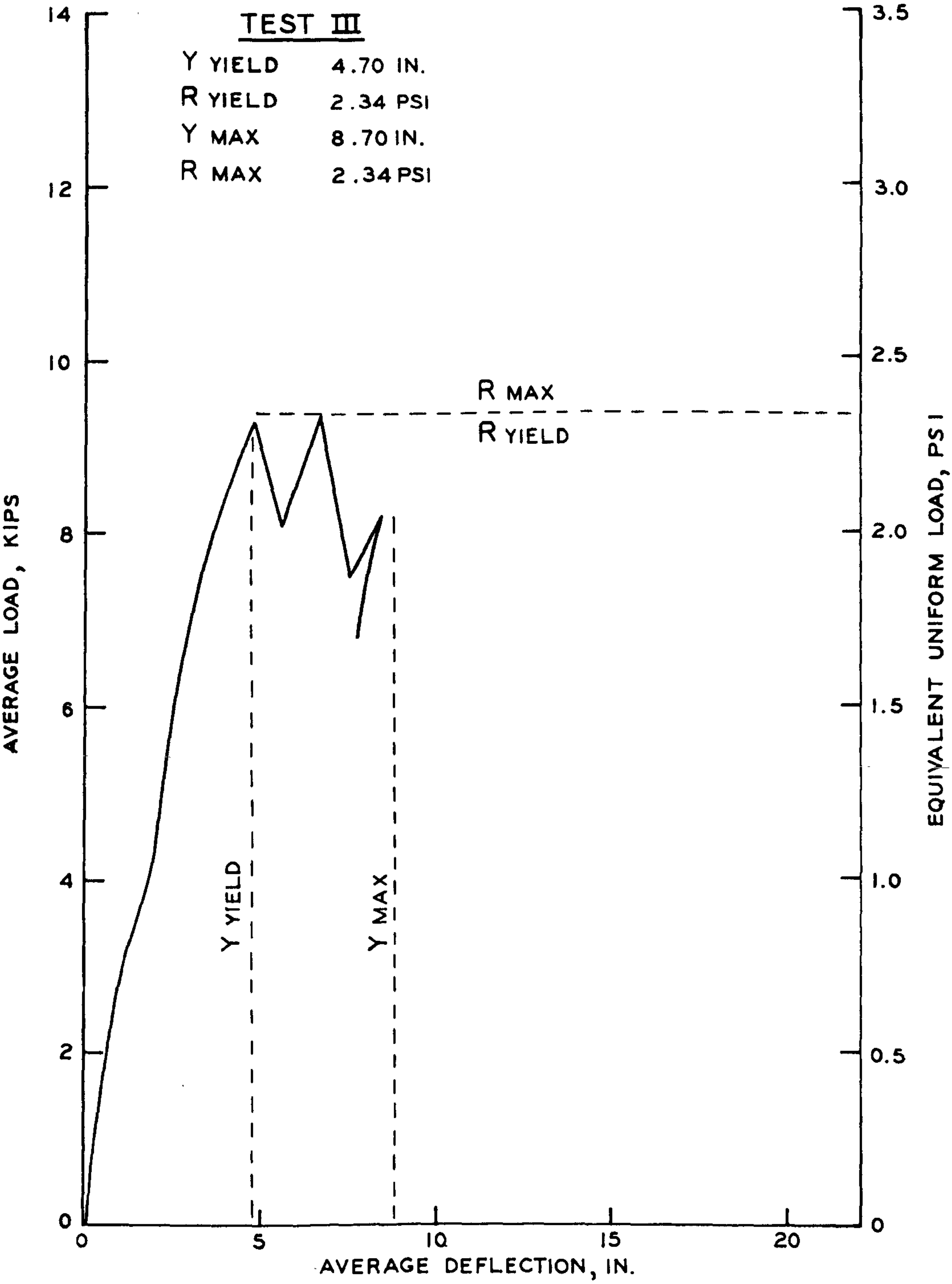


Figure 2.26 Load-deflection curve, Specimen III.

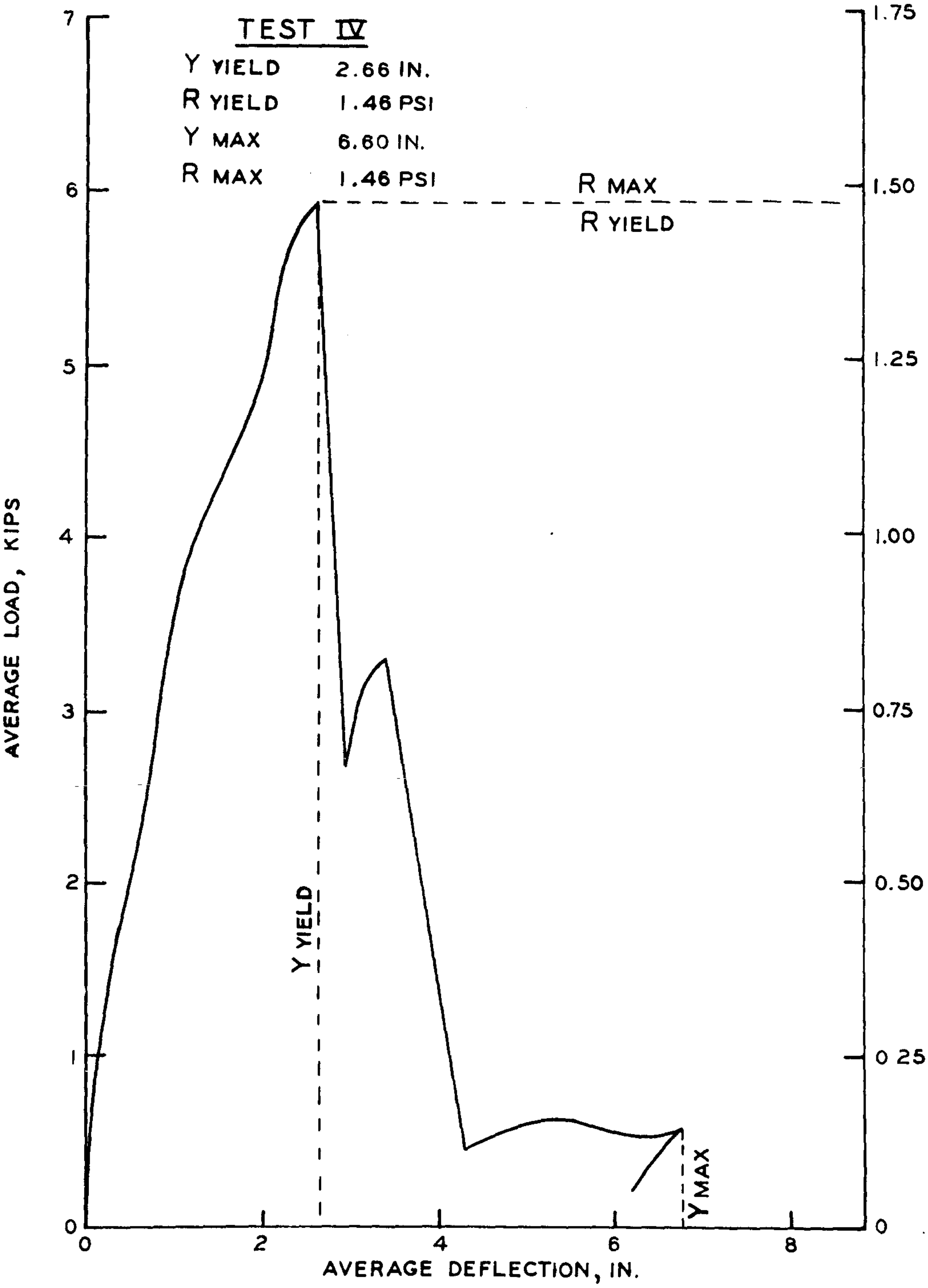


Figure 2.27 Load-deflection curve, Specimen IV.

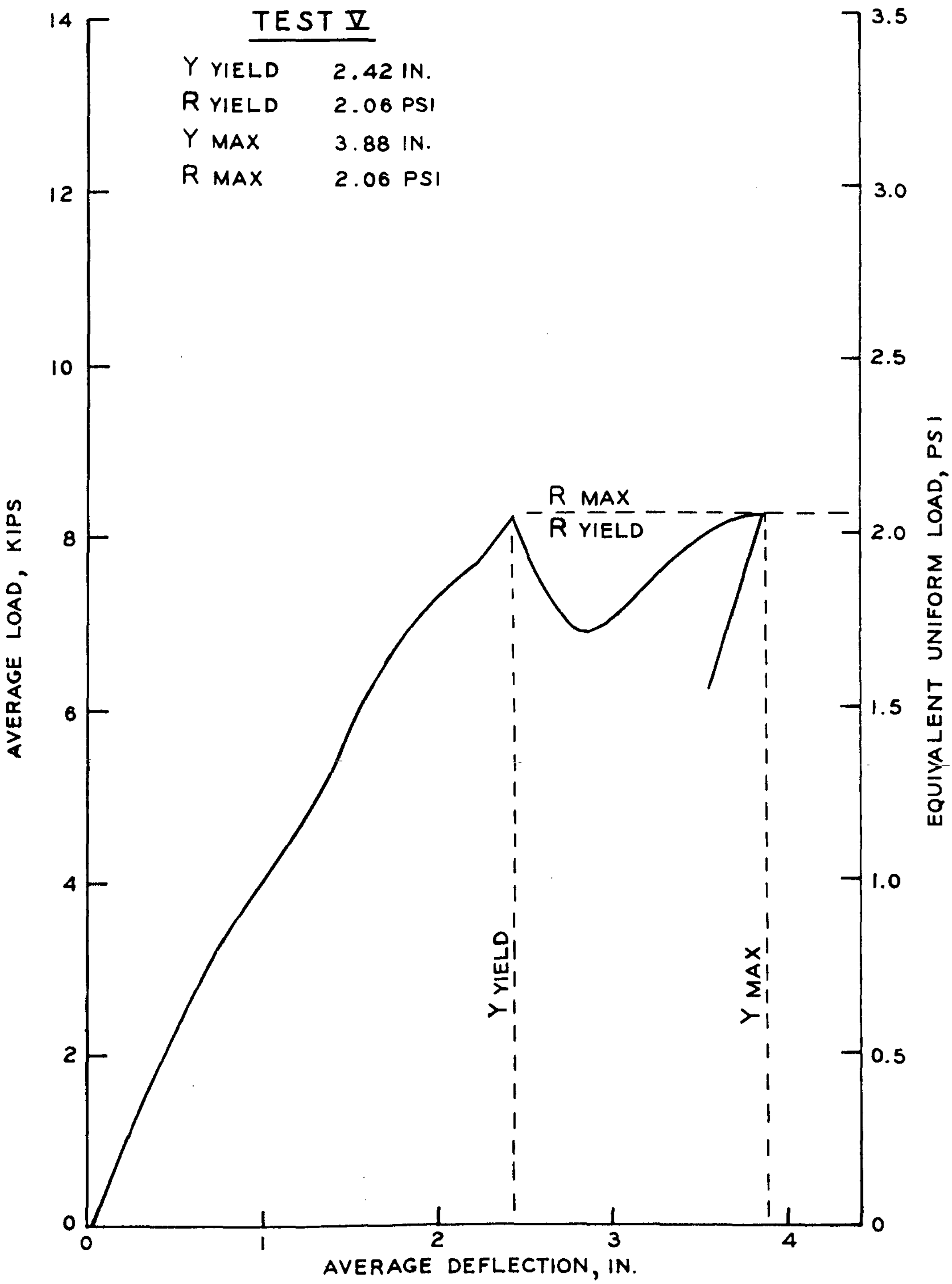


Figure 2.28 Load-deflection curve, Specimen V.

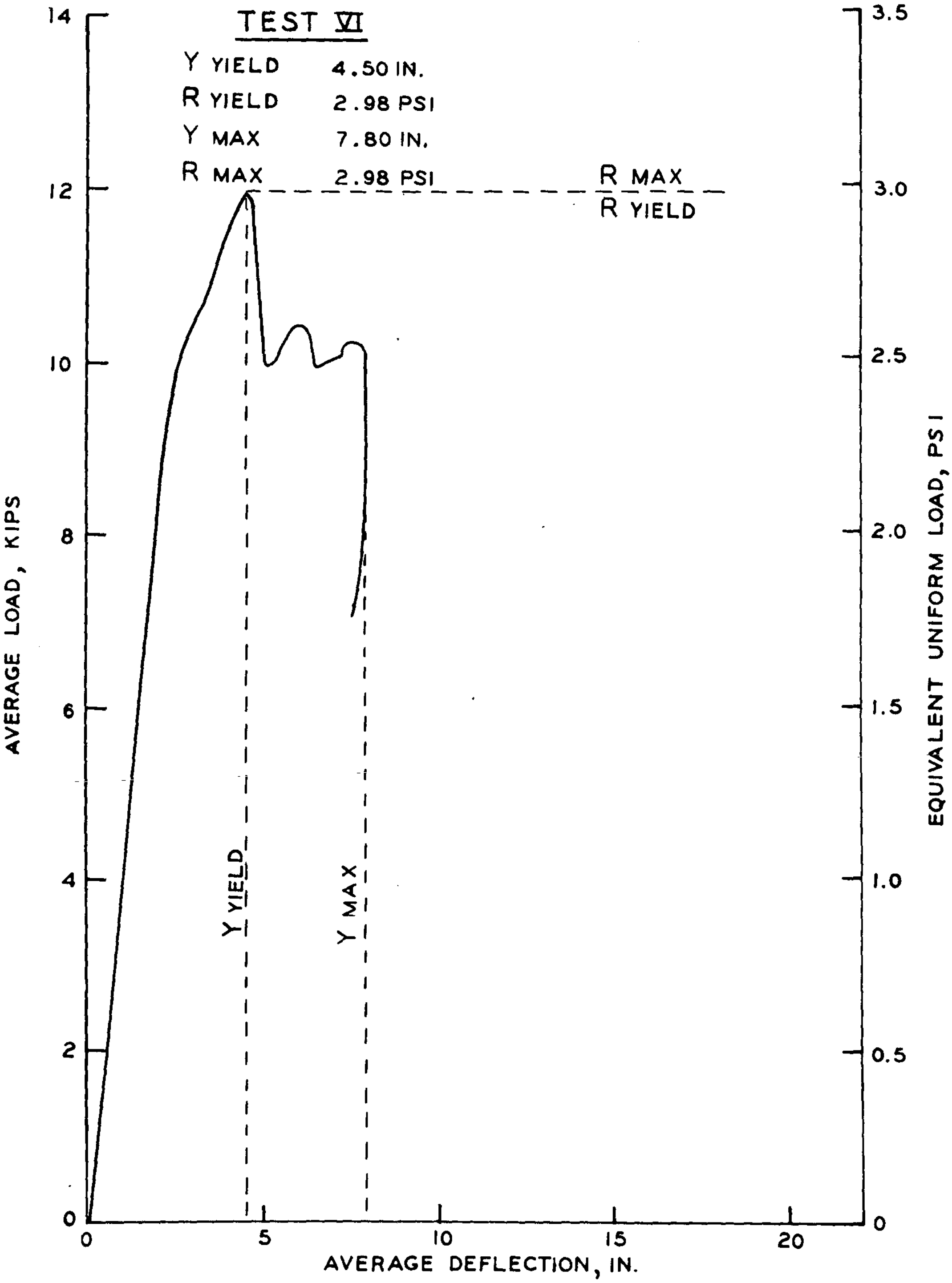


Figure 2.29 Load-deflection curve, Specimen VI.

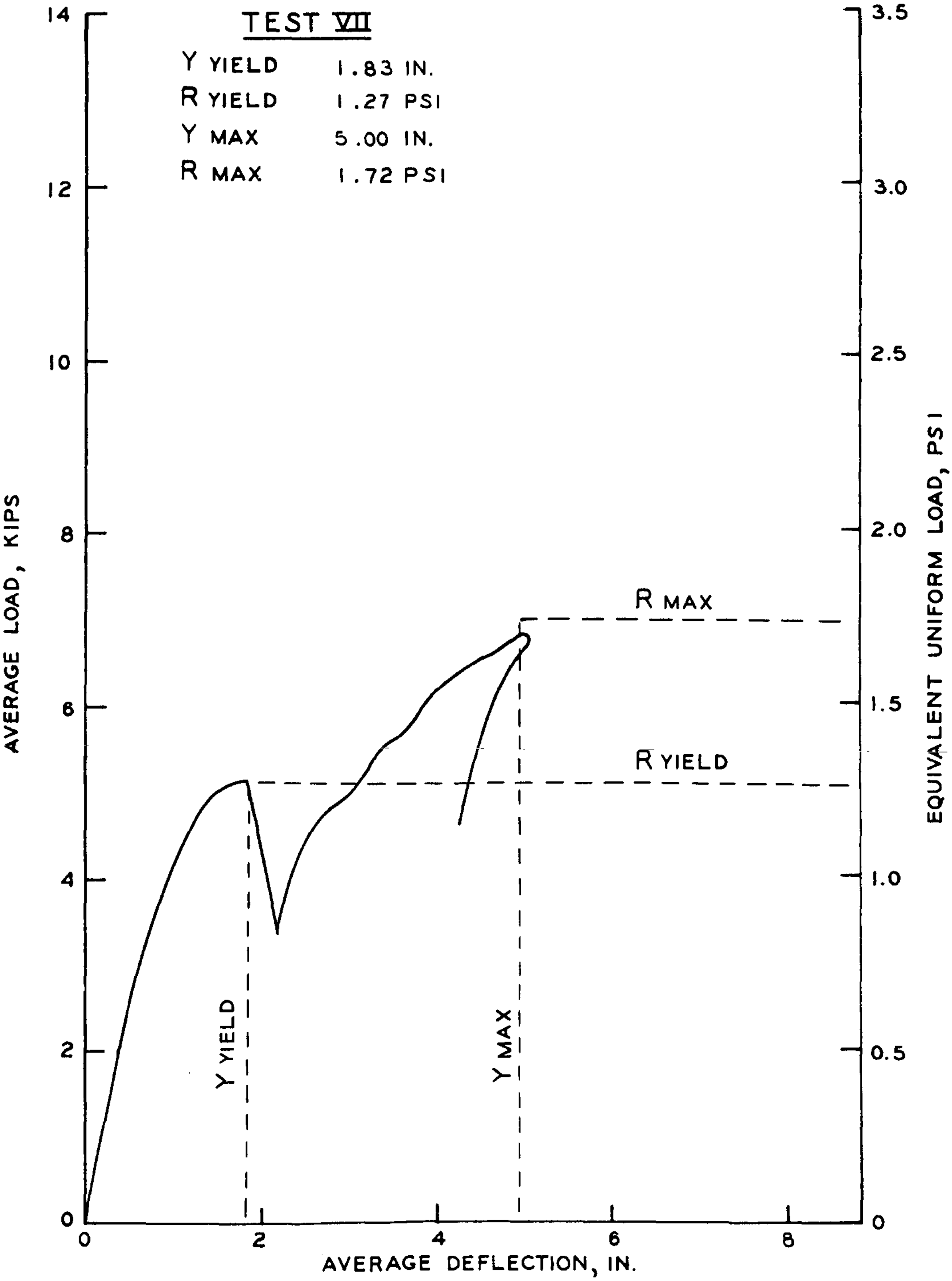


Figure 2.30 Load-deflection curve, Specimen VII.

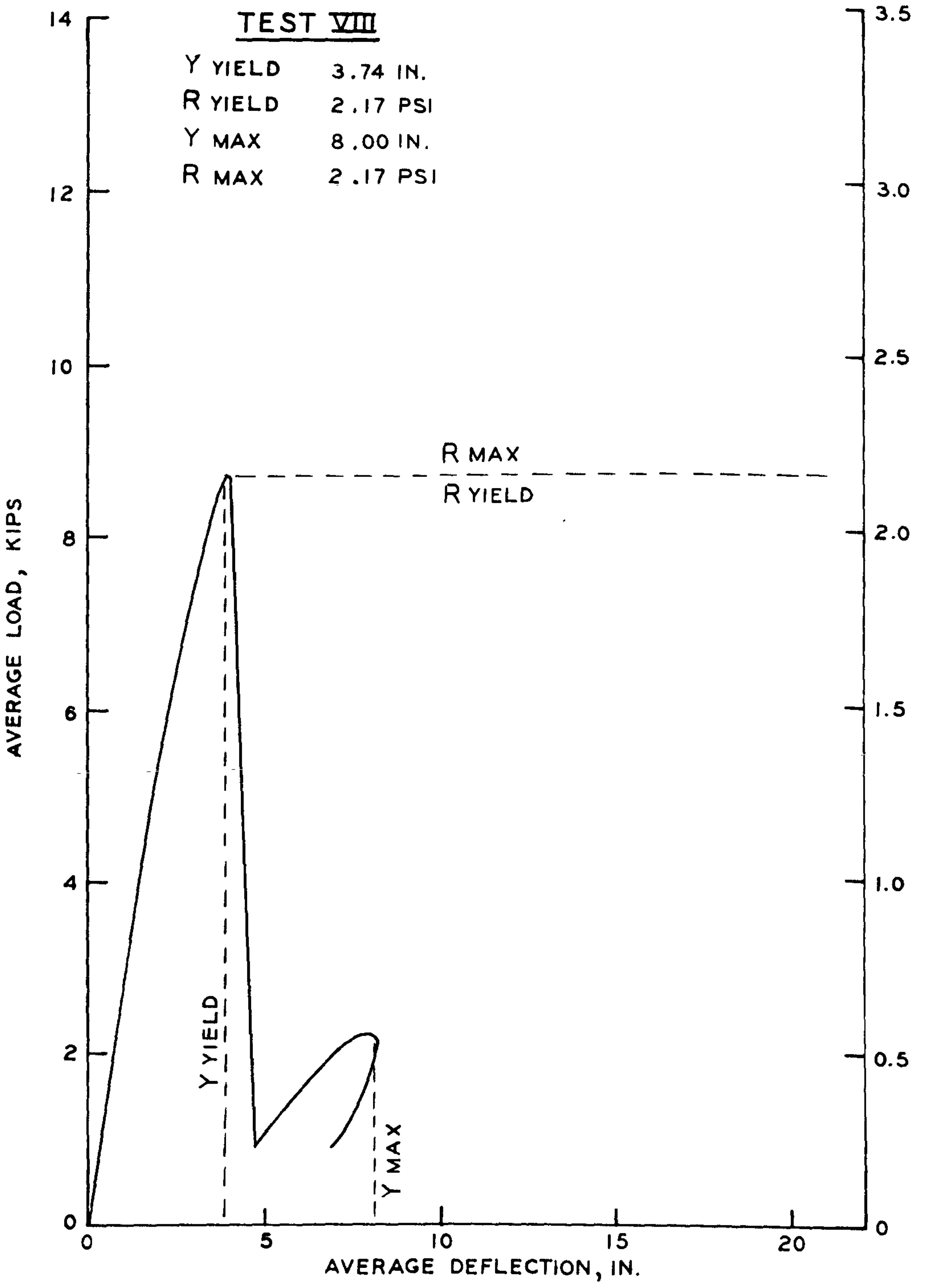


Figure 2.31 Load-deflection curve, Specimen VIII.

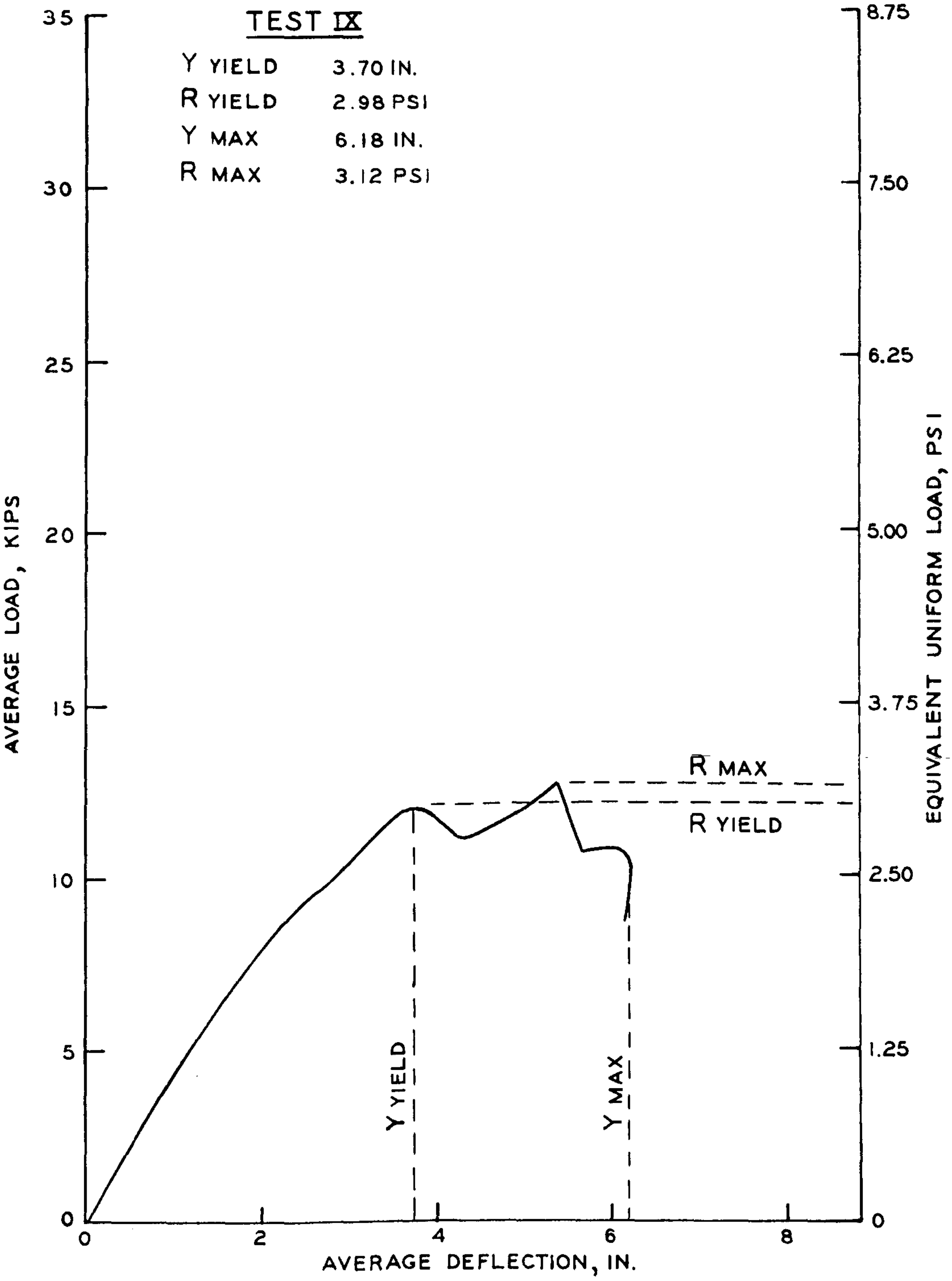


Figure 2.32 Load-deflection curve, Specimen IX.

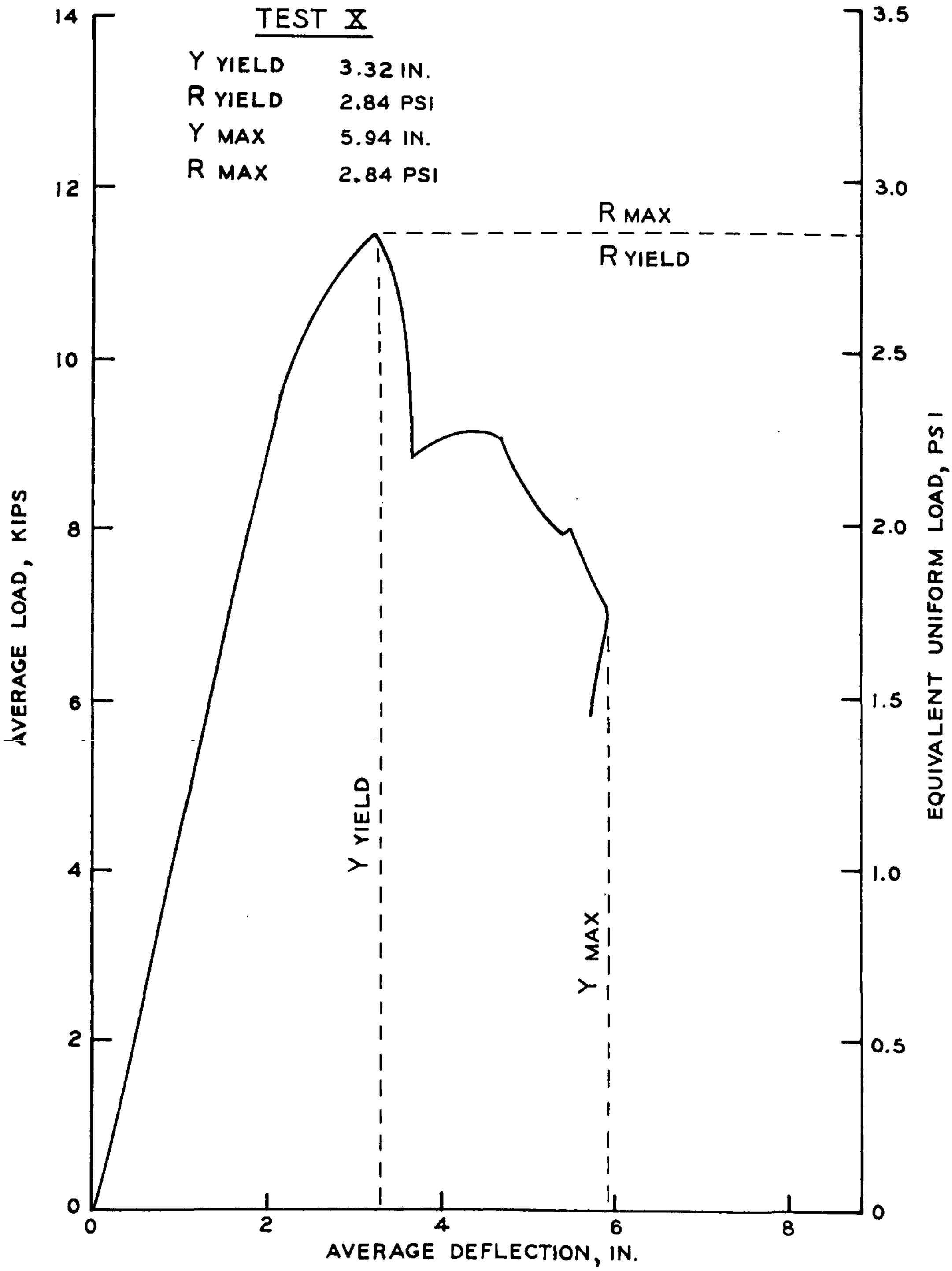


Figure 2.33 Load-deflection curve, Specimen X.

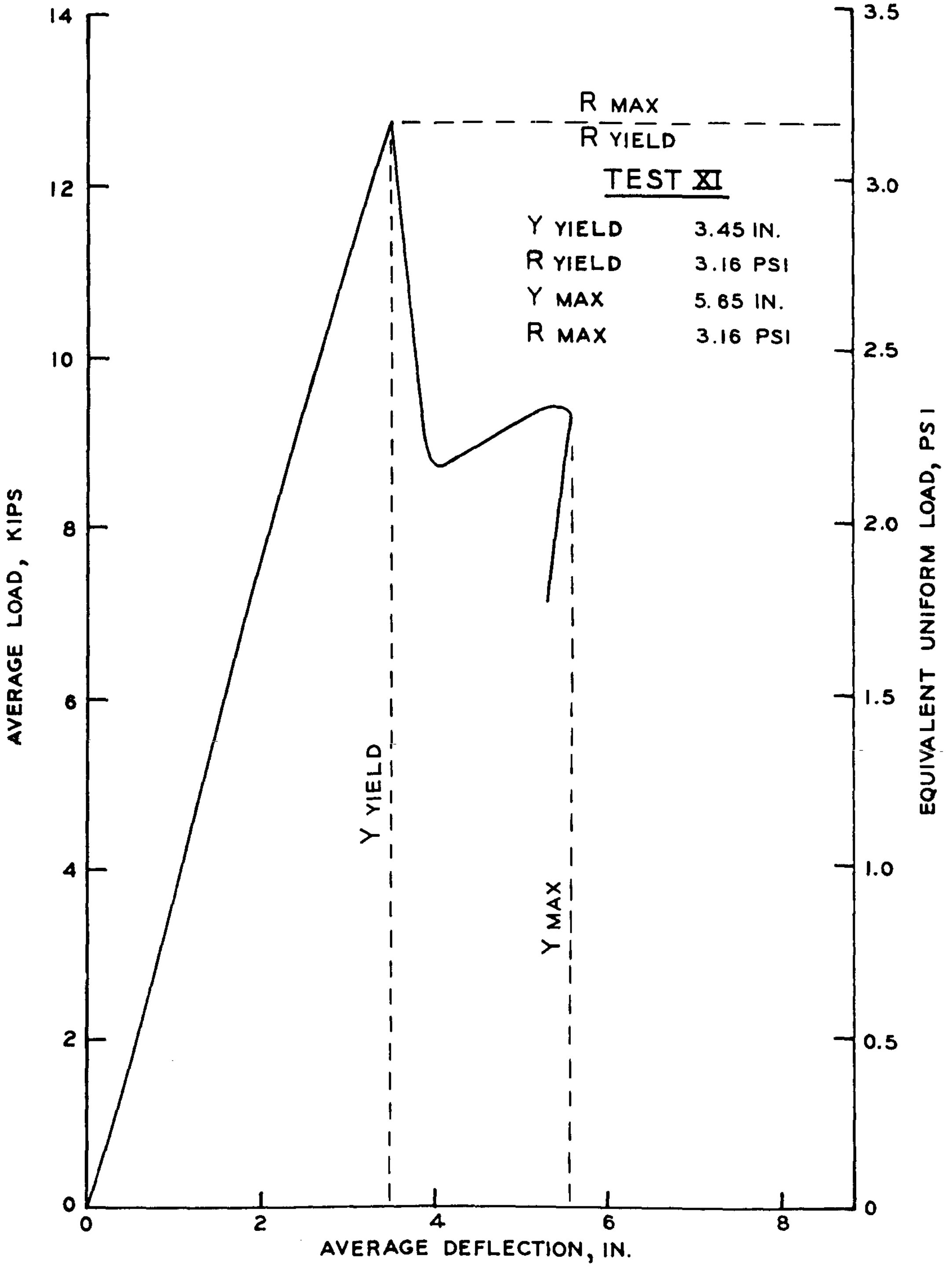


Figure 2.34 Load-deflection curve, Specimen XI.

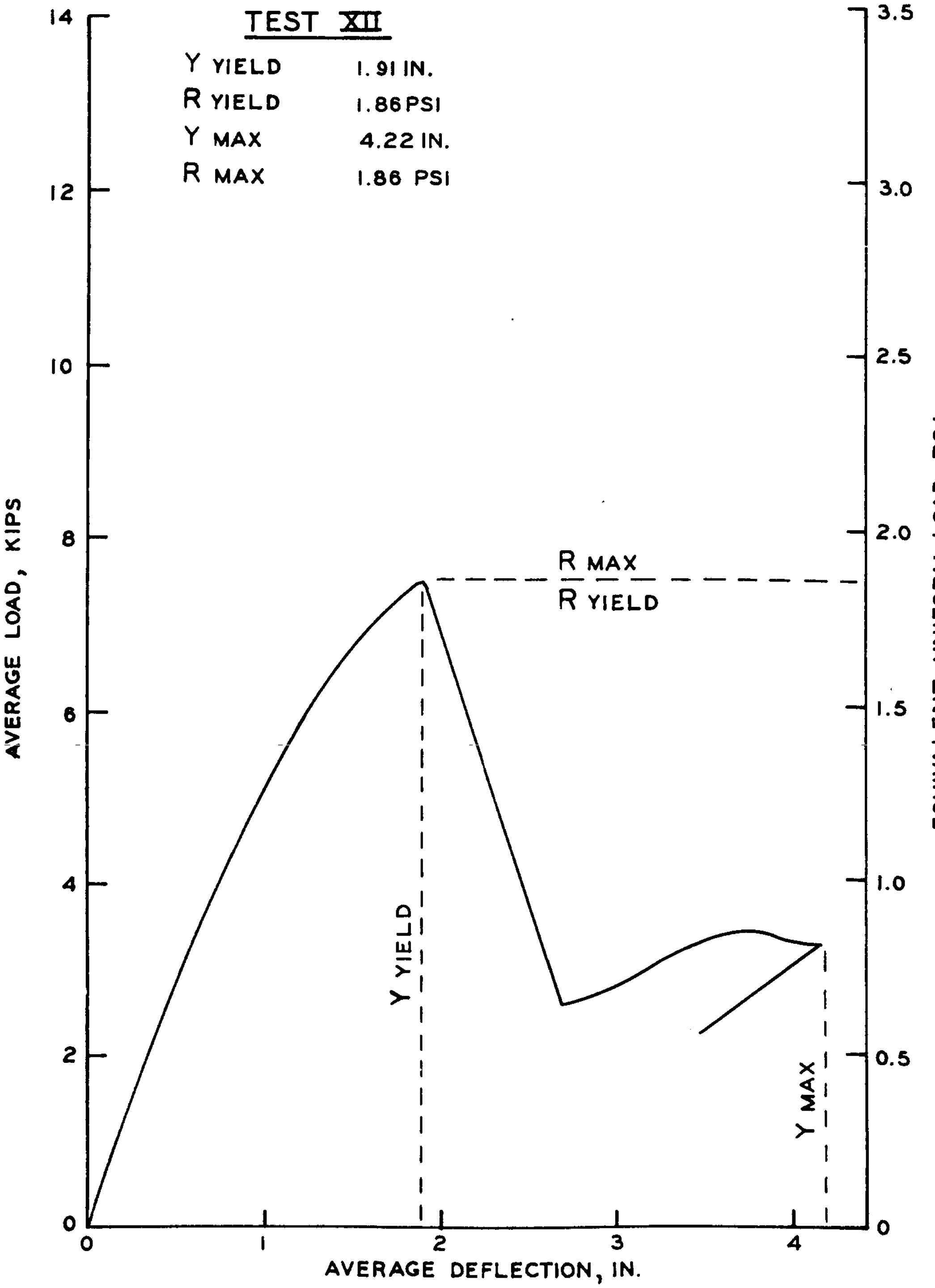


Figure 2.35 Load-deflection curve, Specimen XII.

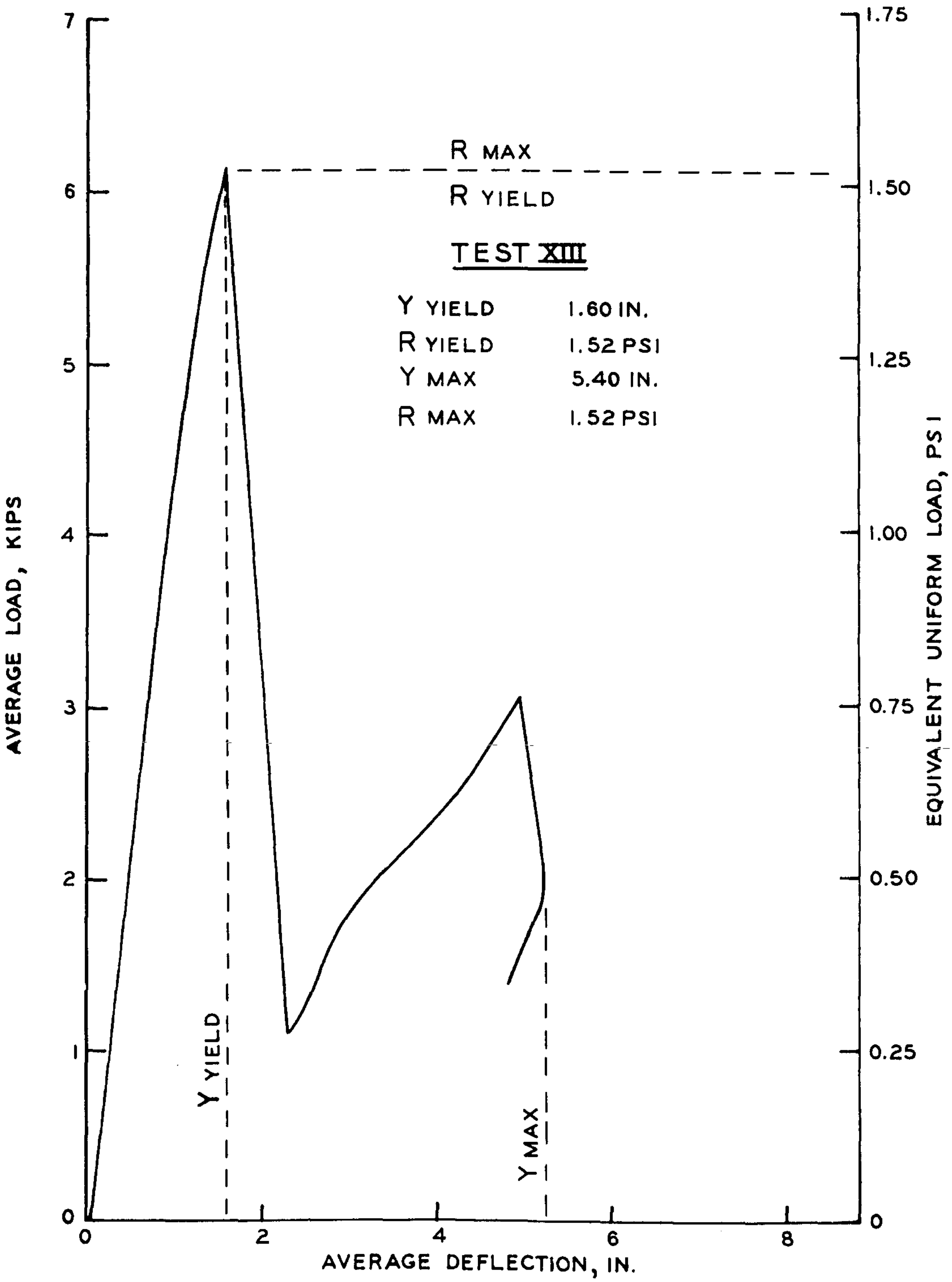


Figure 2.36 Load-deflection curve, Specimen XIII.

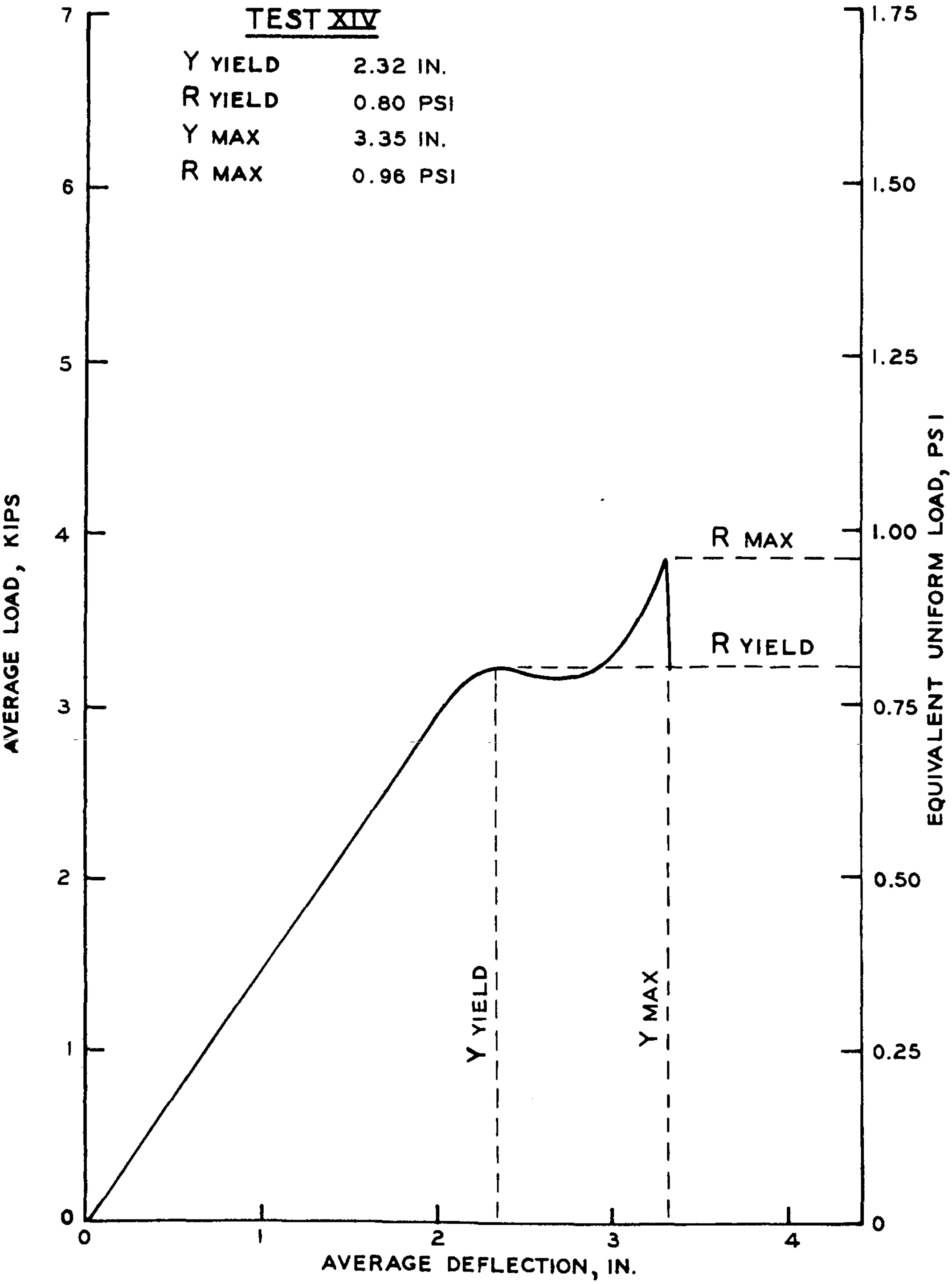


Figure 2.37 Load-deflection curve, Specimen XIV.

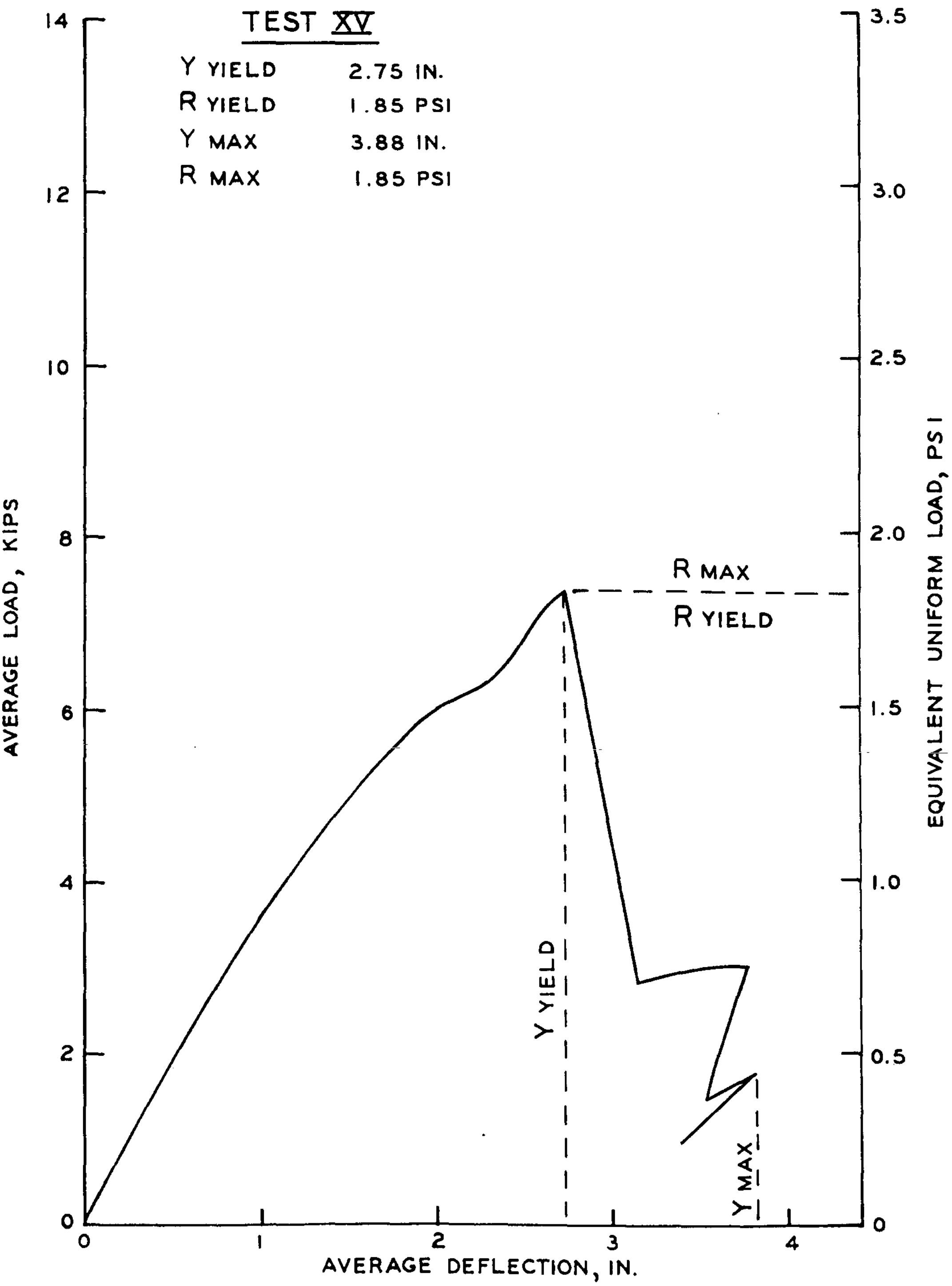


Figure 2.38 Load-deflection curve, Specimen XV.

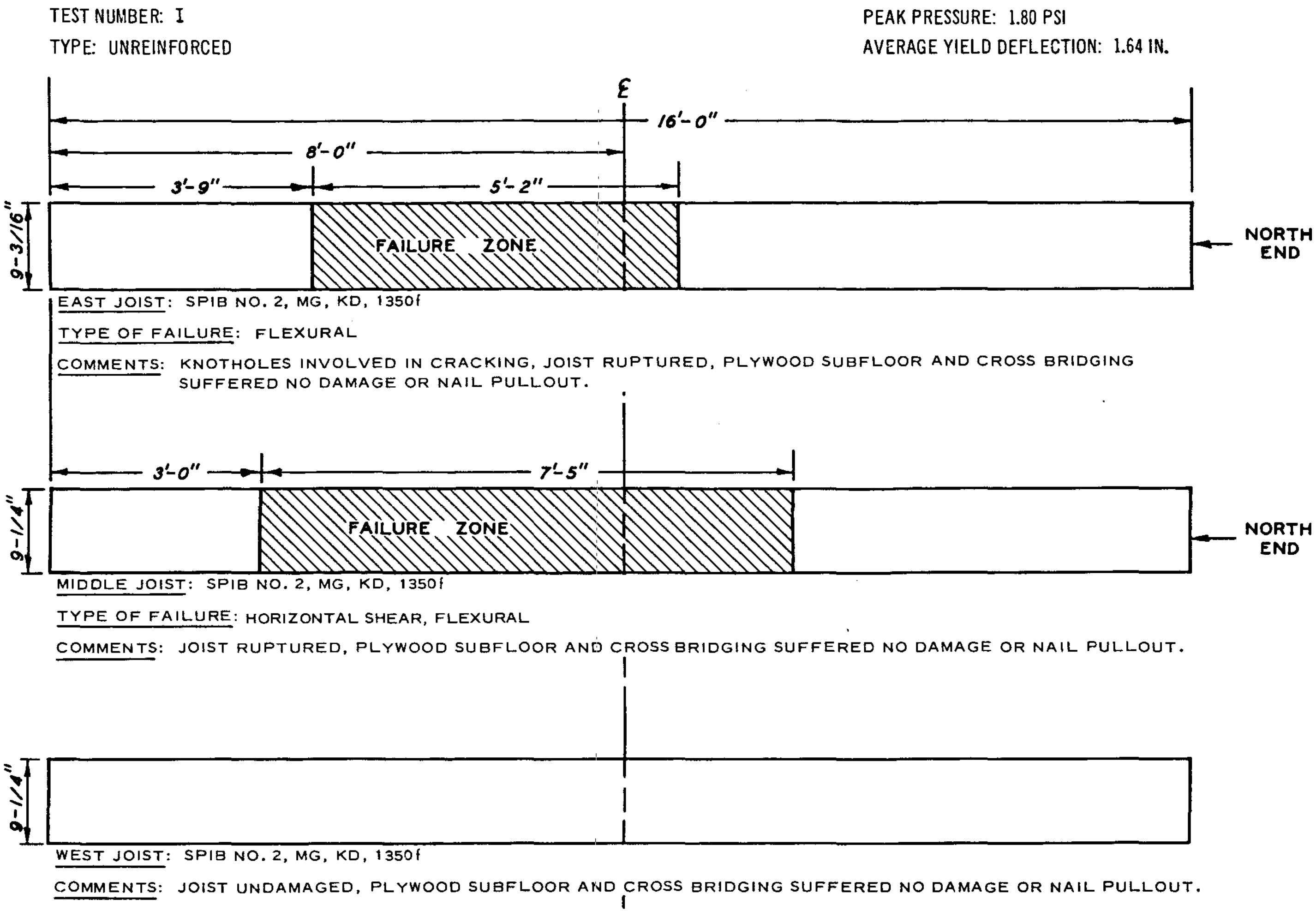


Figure 2.39 Failure diagram, Specimen I.

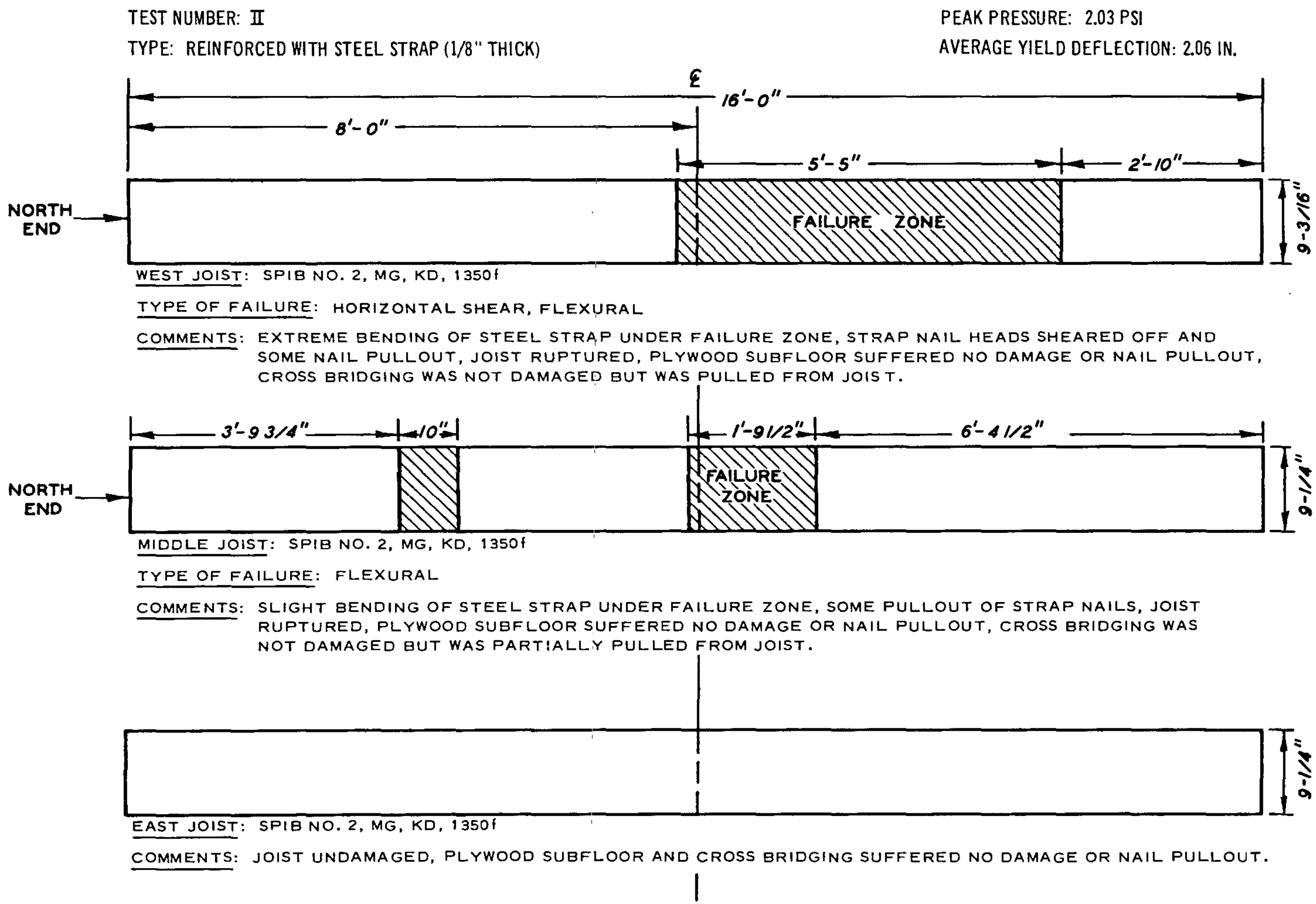


Figure 2.40 Failure diagram, Specimen II.

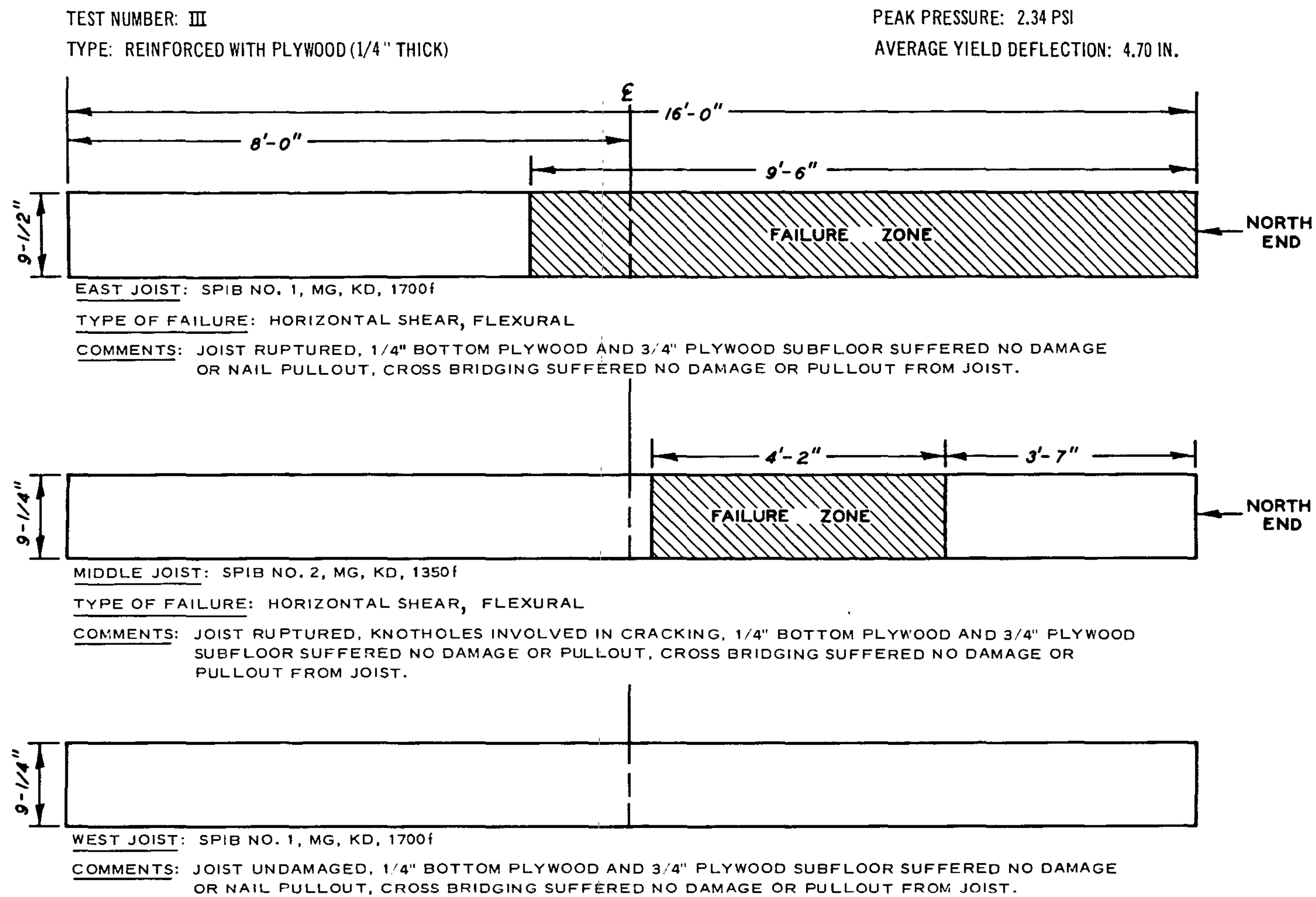


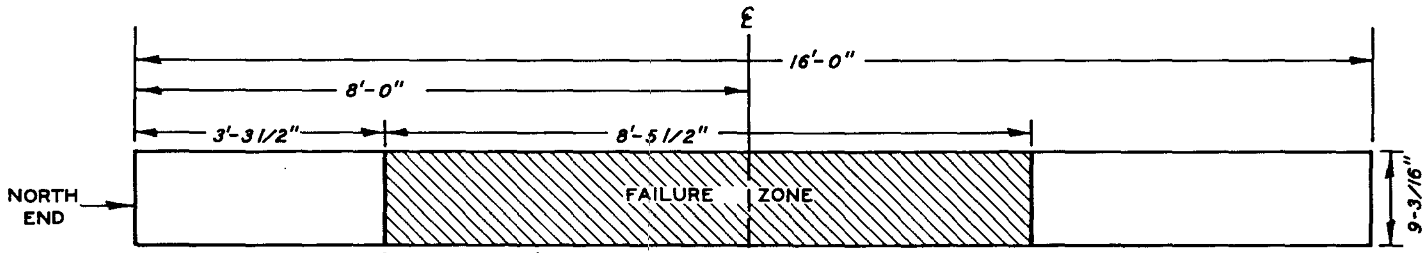
Figure 2.41 Failure diagram, Specimen III.

TEST NUMBER: IV

TYPE: REINFORCED WITH PLYWOOD (1/4" THICK)

PEAK PRESSURE: 1.46 PSI

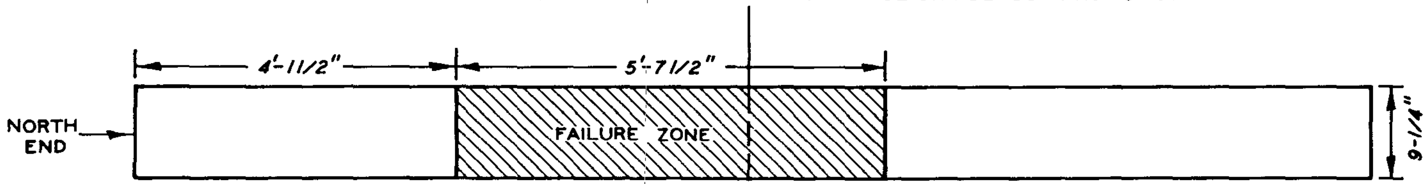
AVERAGE YIELD DEFLECTION: 2.66 IN.



WEST JOIST: SPIB NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

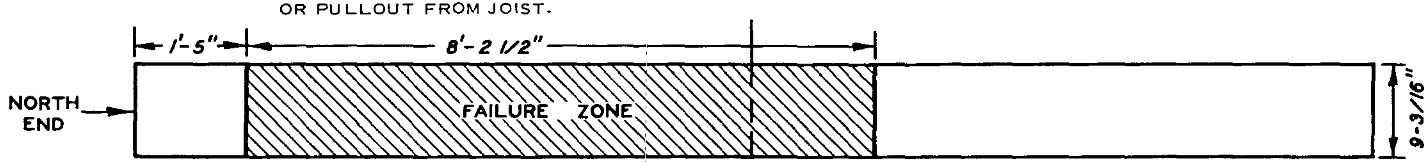
COMMENTS: JOIST RUPTURED, 1/4" BOTTOM PLYWOOD WAS NOT DAMAGED AND SUFFERED NO NAIL PULLOUT, BUT IN SOME INSTANCES, THE PLYWOOD WAS PULLED OFF THE NAIL HEADS. THE 3/4" PLYWOOD SUBFLOOR AND THE CROSS BRIDGING SUFFERED NO DAMAGE OR PULLOUT FROM JOIST.



MIDDLE JOIST: SPIB NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

COMMENTS: JOIST RUPTURED, KNOTHOLES INVOLVED IN CRACKING, 1/4" BOTTOM PLYWOOD SUFFERED NO DAMAGE OR NAIL PULLOUT, BUT IN SOME INSTANCES, THE PLYWOOD WAS PULLED OFF THE NAIL HEADS. THE 3/4" PLYWOOD SUBFLOOR AND THE CROSS BRIDGING SUFFERED NO DAMAGE OR PULLOUT FROM JOIST.



EAST JOIST: SPIB NO. 2, MG, KD, 1350f

TYPE OF FAILURE: HORIZONTAL SHEAR, FLEXURAL

COMMENTS: JOIST RUPTURED, KNOTHOLES INVOLVED IN CRACKING, 1/4" BOTTOM PLYWOOD SUFFERED NO DAMAGE OR NAIL PULLOUT, BUT IN SOME INSTANCES, THE PLYWOOD WAS PULLED OFF THE NAIL HEADS. THE 3/4" PLYWOOD SUBFLOOR AND THE CROSS BRIDGING SUFFERED NO DAMAGE OR PULLOUT FROM JOIST.

Figure 2.42 Failure diagram, Specimen IV.

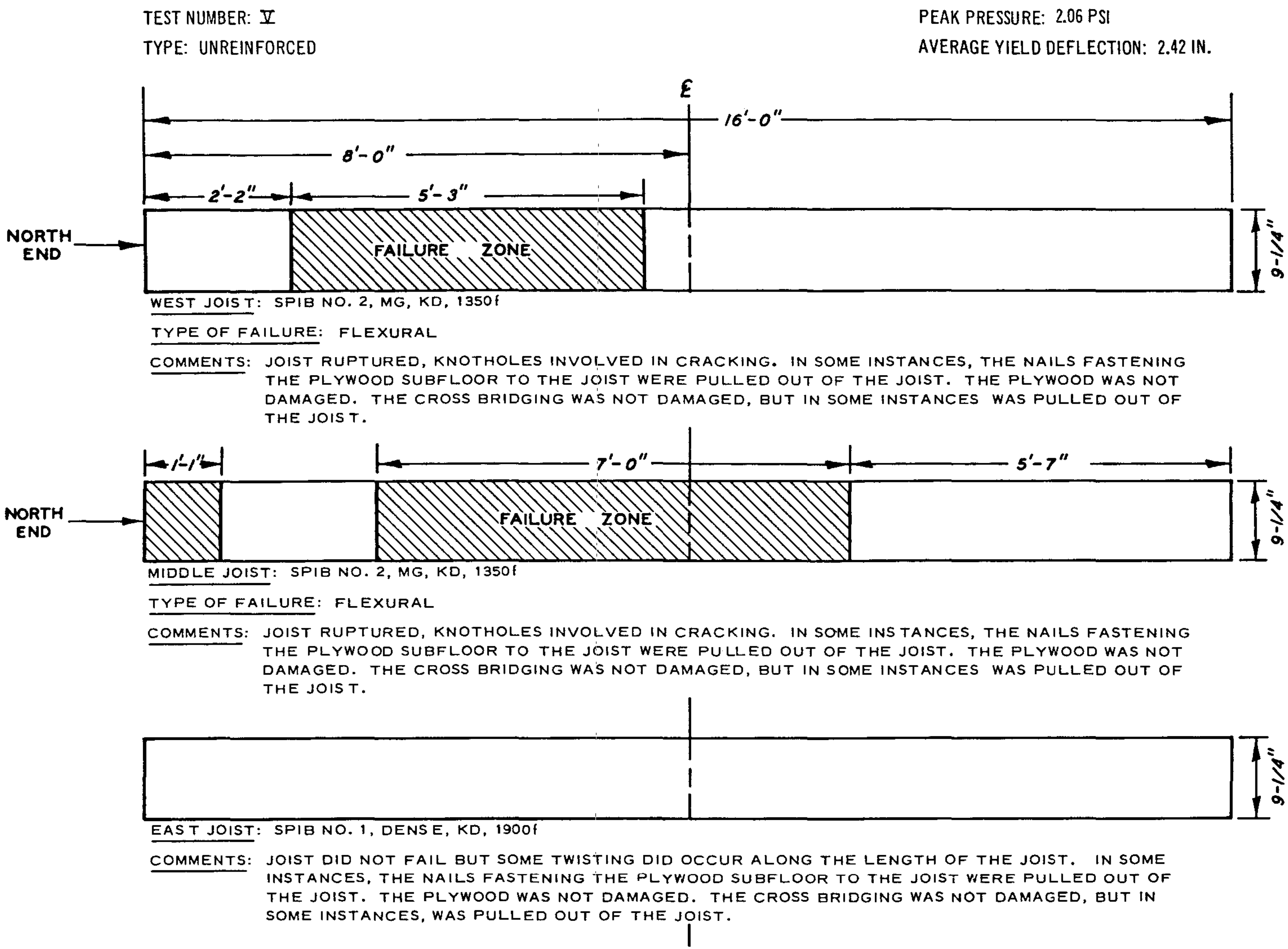


Figure 2.43 Failure diagram, Specimen V.

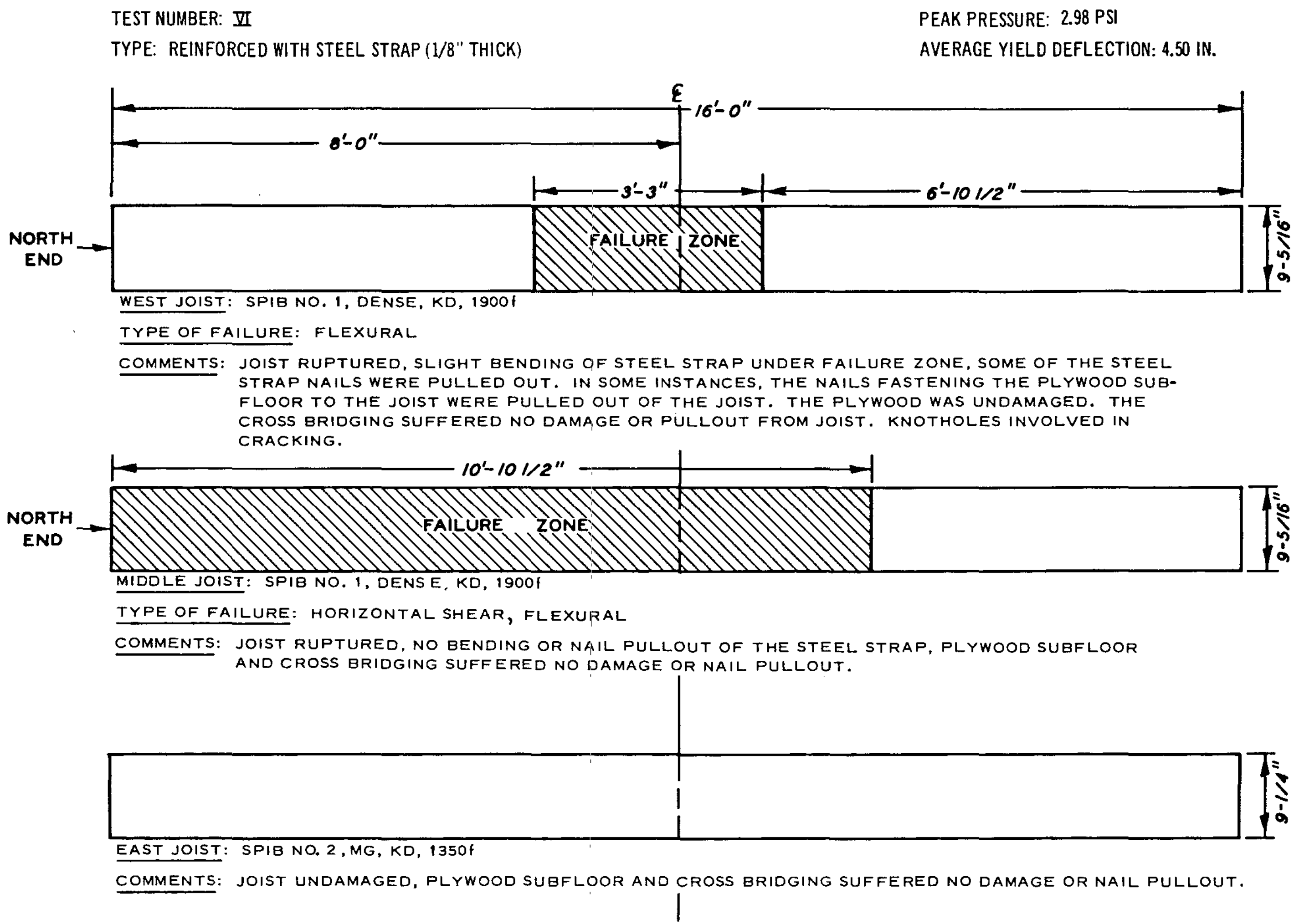


Figure 2.44 Failure diagram, Specimen VI.

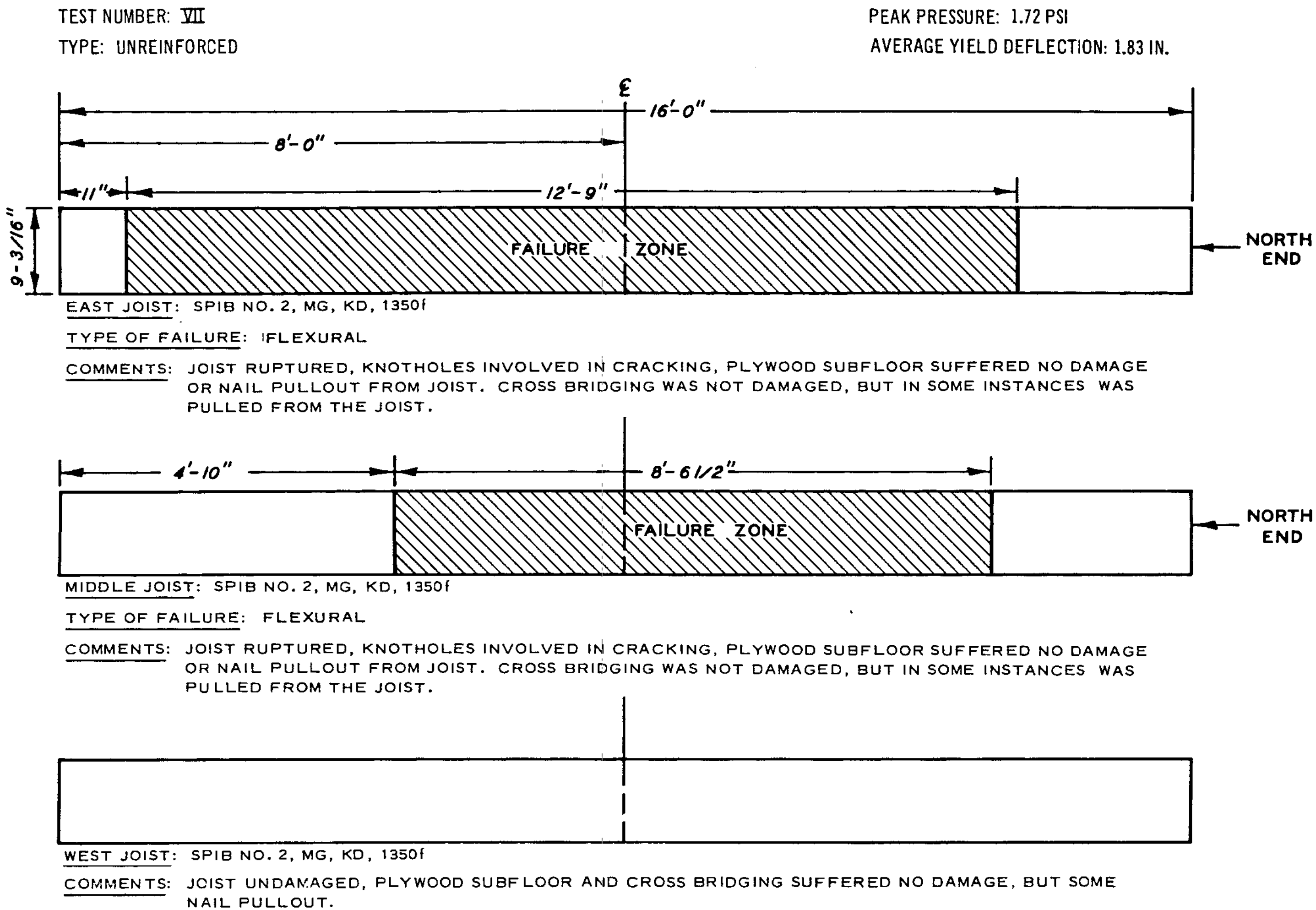


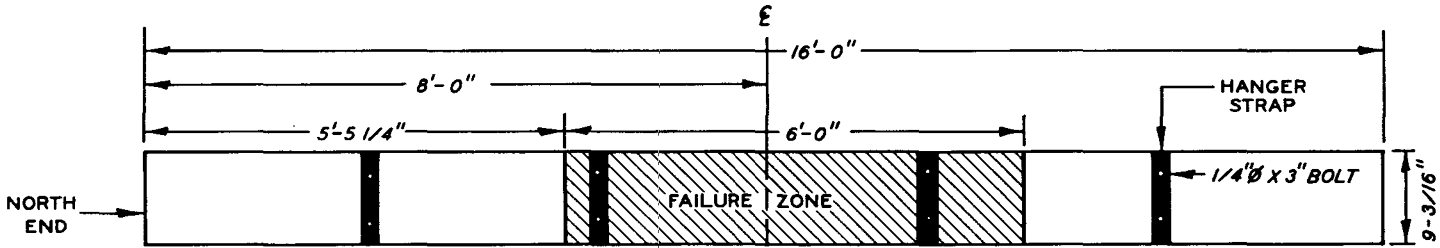
Figure 2.45 Failure diagram, Specimen VII.

TEST NUMBER: VIII

TYPE: REINFORCED WITH HANGER STRAP

PEAK PRESSURE: 2.17 PSI

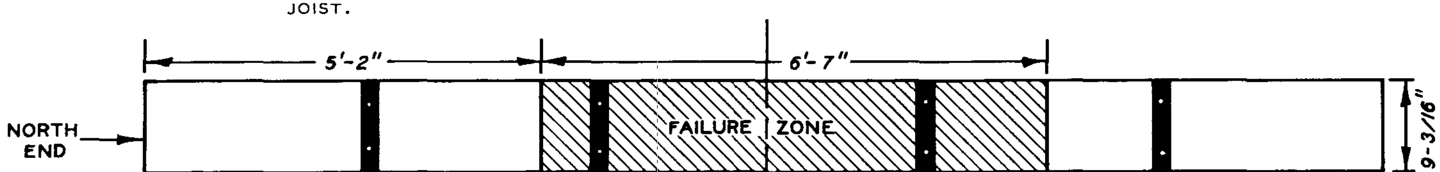
AVERAGE YIELD DEFLECTION: 3.74 IN.



WEST JOIST: SPIB NO. 2, MG, KD, 1350f

TYPE OF FAILURE: HORIZONTAL SHEAR, FLEXURAL

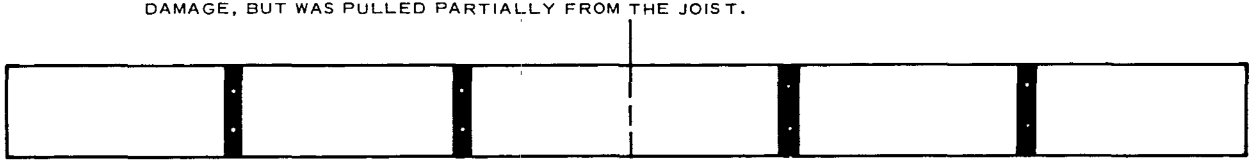
COMMENTS: JOIST RUPTURED, NO DAMAGE TO HANGER STRAP. IN SOME INSTANCES, THE NAILS FASTENING THE PLYWOOD SUBFLOOR TO THE JOIST WERE PARTIALLY PULLED FROM THE JOIST. THE PLYWOOD WAS UNDAMAGED. THE CROSS BRIDGING SUFFERED NO DAMAGE, BUT WAS PULLED PARTIALLY FROM THE JOIST.



MIDDLE JOIST: SPIB NO. 2, MG, KD, 1350f

TYPE OF FAILURE: HORIZONTAL SHEAR, FLEXURAL

COMMENTS: JOIST RUPTURED, NO DAMAGE TO HANGER STRAP, KNOTHOLES WERE INVOLVED IN CRACKING. IN SOME INSTANCES, THE NAILS FASTENING THE PLYWOOD SUBFLOOR TO THE JOIST WERE PARTIALLY PULLED FROM THE JOIST. THE PLYWOOD WAS NOT DAMAGED. THE CROSS BRIDGING SUFFERED NO DAMAGE, BUT WAS PULLED PARTIALLY FROM THE JOIST.



EAST JOIST: SPIB NO. 2, MG, KD, 1350f

COMMENTS: JOIST UNDAMAGED. IN SOME INSTANCES, THE NAILS FASTENING THE PLYWOOD SUBFLOOR TO THE JOIST WERE PARTIALLY PULLED FROM THE JOIST. THE PLYWOOD WAS NOT DAMAGED. THE CROSS BRIDGING SUFFERED NO DAMAGE, BUT WAS PULLED PARTIALLY FROM THE JOIST.

Figure 2.46 Failure diagram, Specimen VIII.

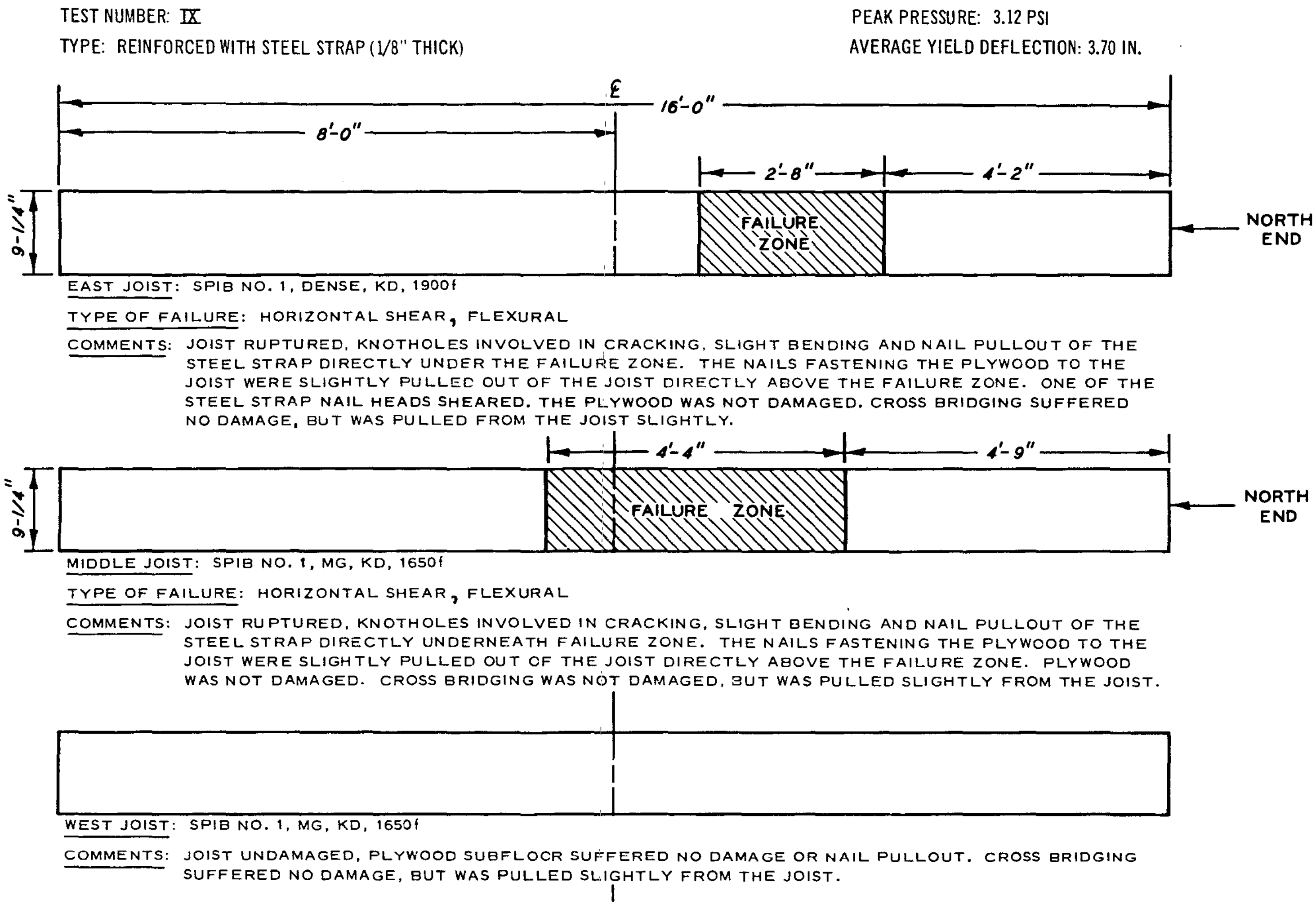


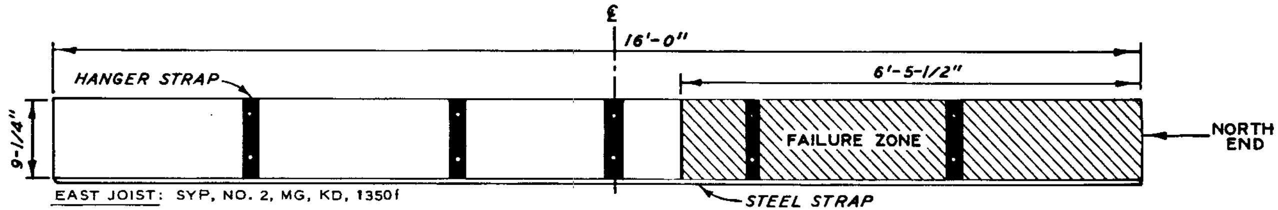
Figure 2.47 Failure diagram, Specimen IX.

TEST NUMBER: X

TYPE: REINFORCED WITH STEEL STRAP AND HANGER STRAP

PEAK PRESSURE: 2.84 PSI

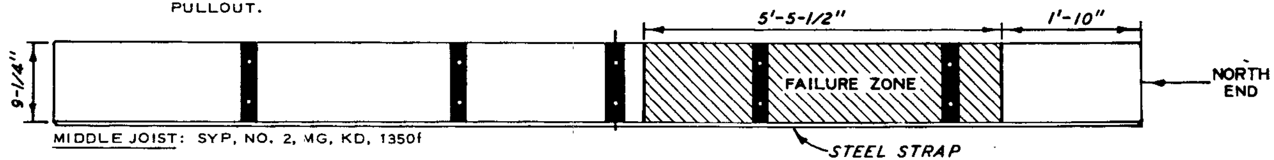
AVERAGE YIELD DEFLECTION: 3.32 IN.



EAST JOIST: SYP, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

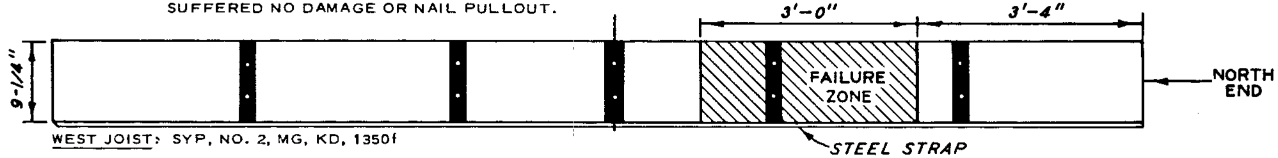
COMMENTS: JOIST RUPTURED,NO DAMAGE TO EITHER HANGER STRAP OR STEEL STRAP, STEEL STRAP DID BEND DIRECTLY UNDER THE FAILURE ZONE AND SOME SLIGHT NAIL PULLOUT OCCURRED. ALSO SOME OF THE STEEL STRAP NAILHEADS SHEARED OFF DIRECTLY UNDERNEATH FAILURE ZONE. KNOTHOLES WERE INVOLVED IN CRACKING BUT NONE OF THE CRACKING INITIATED AT THE BOLT HOLES. IN SOME INSTANCES,THE NAILS FASTENING THE PLYWOOD SUBFLOOR TO THE JOIST WERE PARTIALLY PULLED FROM THE JOIST. THE PLYWOOD WAS UNDAMAGED. CROSS BRIDGING SUFFERED NO DAMAGE OR NAIL PULLOUT.



MIDDLE JOIST: SYP, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: HORIZONTAL SHEAR

COMMENTS: JOIST RUPTURED,NO DAMAGE TO EITHER HANGER STRAP OR STEEL STRAP, SOME OF THE STEEL STRAP NAILS WERE SLIGHTLY PULLED OUT OF THE JOIST DIRECTLY UNDERNEATH FAILURE ZONE. KNOTHOLES WERE INVOLVED IN THE CRACKING BUT NONE OF THE CRACKING INITIATED AT THE BOLT HOLES. IN SOME INSTANCES,THE NAILS FASTENING THE PLYWOOD SUBFLOOR TO THE JOIST WERE PARTIALLY PULLED FROM THE JOIST. THE PLYWOOD WAS UNDAMAGED. CROSS BRIDGING SUFFERED NO DAMAGE OR NAIL PULLOUT.



WEST JOIST: SYP, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

COMMENTS: JOIST RUPTURED,NO DAMAGE TO EITHER HANGER STRAP OR STEEL STRAP, STEEL STRAP DID BEND DIRECTLY UNDERNEATH FAILURE ZONE AND SLIGHT NAIL PULLOUT OCCURRED. KNOTHOLES WERE INVOLVED IN CRACKING BUT NONE OF THE CRACKING INITIATED AT THE BOLT HOLES. PULLOUT OF THE NAILS FASTENING THE PLYWOOD SUBFLOOR TO THE JOIST DID NOT OCCUR, CROSS BRIDGING SUFFERED NO DAMAGE OR NAIL PULLOUT.

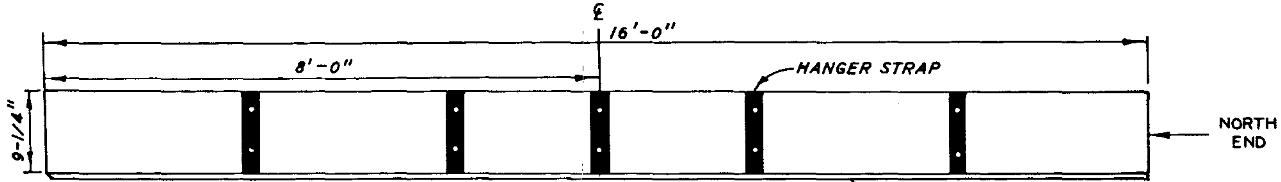
Figure 2.48 Failure diagram, Specimen X.

TEST NUMBER: XI

TYPE: REINFORCED WITH STEEL STRAP AND HANGER STRAP

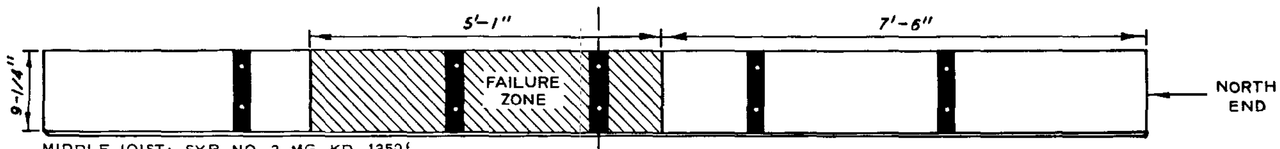
PEAK PRESSURE: 3.16 PSI

AVERAGE YIELD DEFLECTION: 3.45 IN.



EAST JOIST: SYP, NO. 2, MG, KD, 1350f

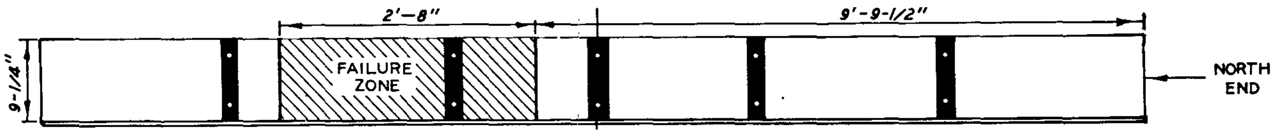
COMMENTS: NO DAMAGE



MIDDLE JOIST: SYP, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

COMMENTS: JOIST RUPTURED, NO DAMAGE TO EITHER HANGER STRAP OR STEEL STRAP, HOWEVER STEEL STRAP DID BEND DIRECTLY UNDER THE FAILURE ZONE AND SLIGHT NAIL PULLOUT OCCURRED. NO NAIL SHEAR OCCURRED. KNOTHOLES WERE INVOLVED IN THE CRACKING, BUT NONE OF THE CRACKS INITIATED AT THE BOLT HOLES. IN SOME INSTANCES, THE NAILS FASTENING THE PLYWOOD SUB-FLOOR TO THE JOIST WERE PARTIALLY PULLED FROM THE JOIST. THE PLYWOOD WAS UNDAMAGED. CROSS BRIDGING SUFFERED NO DAMAGE OR NAIL PULLOUT.



WEST JOIST: SYP, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

COMMENTS: JOIST RUPTURED, NO DAMAGE TO EITHER HANGER STRAP OR STEEL STRAP, HOWEVER STEEL STRAP DID BEND DIRECTLY UNDER THE FAILURE ZONE AND SLIGHT NAIL PULLOUT OCCURRED. NO NAIL SHEAR OCCURRED. THERE WERE NO KNOTHOLES INVOLVED IN THE CRACKING. CRACKING DID NOT INITIATE AT THE BOLT HOLES. IN SOME INSTANCES, THE NAILS FASTENING THE PLYWOOD SUB-FLOOR TO THE JOIST WERE PARTIALLY PULLED FROM THE JOIST. CROSS BRIDGING SUFFERED NO DAMAGE BUT WAS PULLED OUT OF THE JOIST.

Figure 2.49 Failure diagram, Specimen XI.

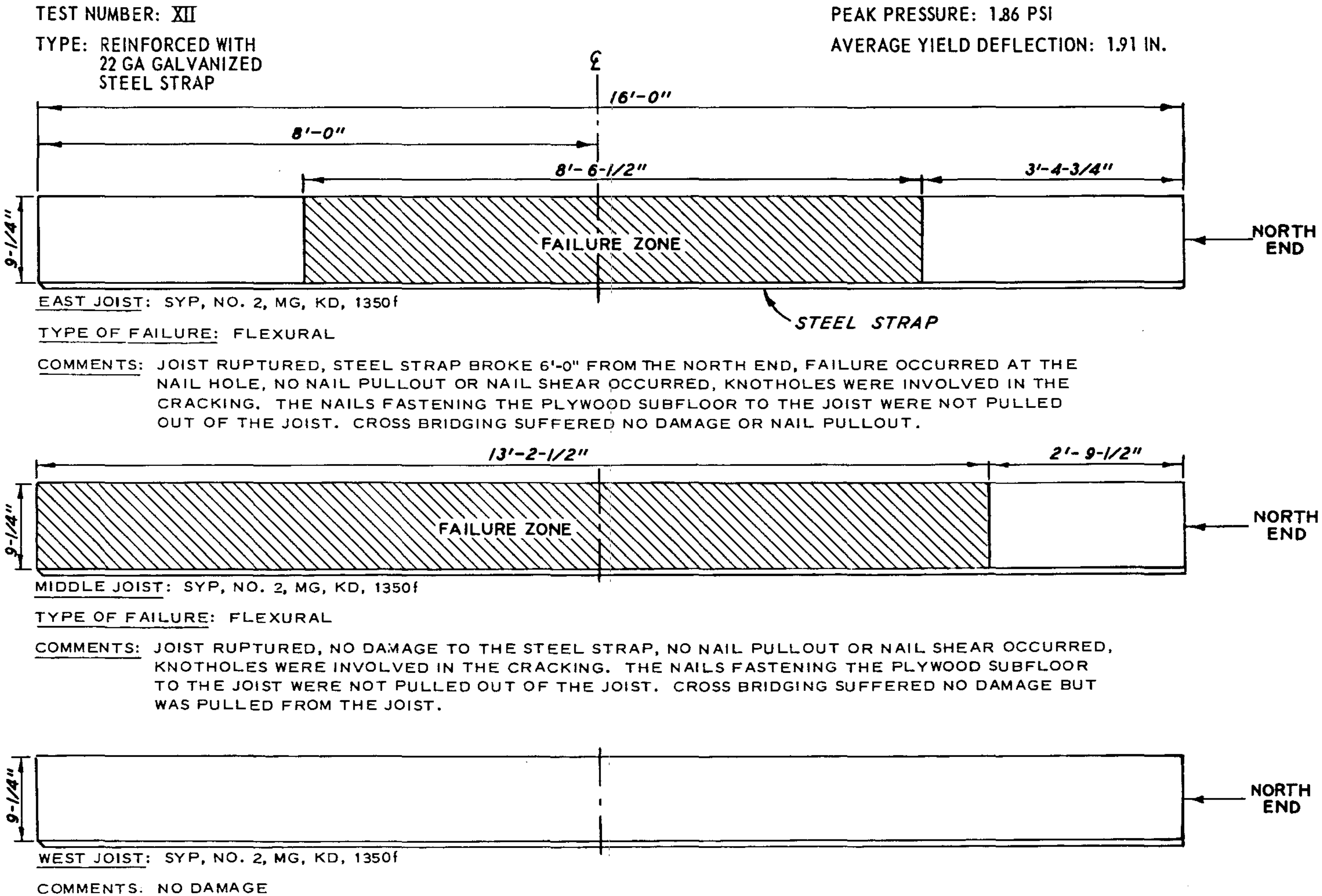


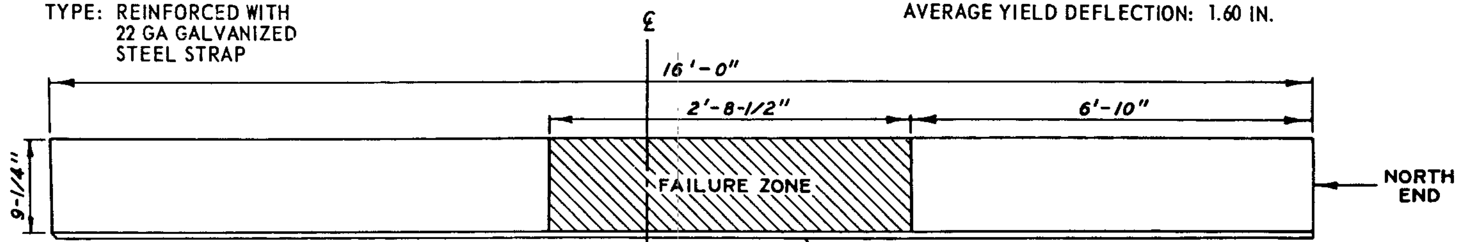
Figure 2.50 Failure diagram, Specimen XII.

TEST NUMBER: XIII

TYPE: REINFORCED WITH
22 GA GALVANIZED
STEEL STRAP

PEAK PRESSURE: 1.52 PSI

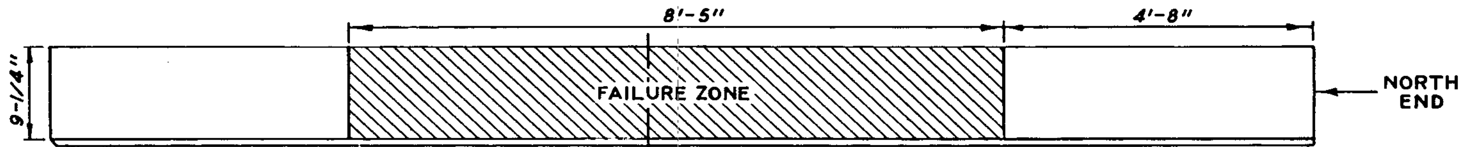
AVERAGE YIELD DEFLECTION: 1.60 IN.



EAST JOIST: SPIB, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

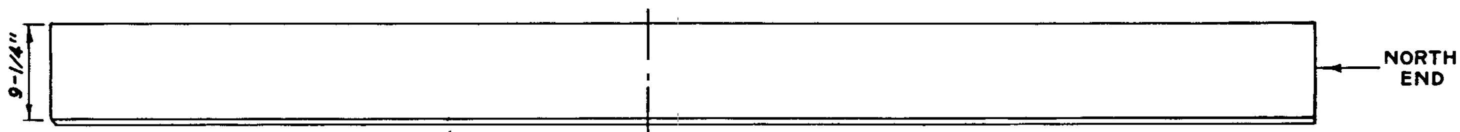
COMMENTS: JOIST RUPTURED, STEEL STRAP BROKE 7'-5" FROM THE NORTH END, FAILURE DID NOT OCCUR AT THE SPLICED PORTION. STRAP FAILED AROUND A NAIL HOLE, NO NAIL PULLOUT OR SHEAR OCCURRED, KNOTHOLES WERE INVOLVED IN THE CRACKING, THE NAILS FASTENING THE PLYWOOD SUBFLOOR TO THE JOIST WERE PULLED OUT OF THE JOIST. CROSS BRIDGING SUFFERED NO DAMAGE BUT WAS SLIGHTLY PULLED FROM THE JOIST.



MIDDLE JOIST: SPIB, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

COMMENTS: JOIST RUPTURED, STEEL STRAP BROKE 9'-0" FROM THE NORTH END, FAILURE OCCURRED AT THE SPLICED PORTION OF THE STRAP AROUND A NAIL HOLE, SLIGHT NAIL PULLOUT OCCURRED WHERE THE STRAP BROKE BUT NO SHEAR OCCURRED, KNOTHOLES WERE INVOLVED IN THE CRACKING. THE NAILS FASTENING THE PLYWOOD SUBFLOOR TO THE JOIST WERE NOT PULLED OUT OF THE JOIST. CROSS BRIDGING WAS NOT DAMAGED BUT WAS SLIGHTLY PULLED FROM THE JOIST.



WEST JOIST: SPIB, NO. 2, MG, KD, 1350f

COMMENTS: NO DAMAGE

Figure 2.51 Failure diagram, Specimen XIII.

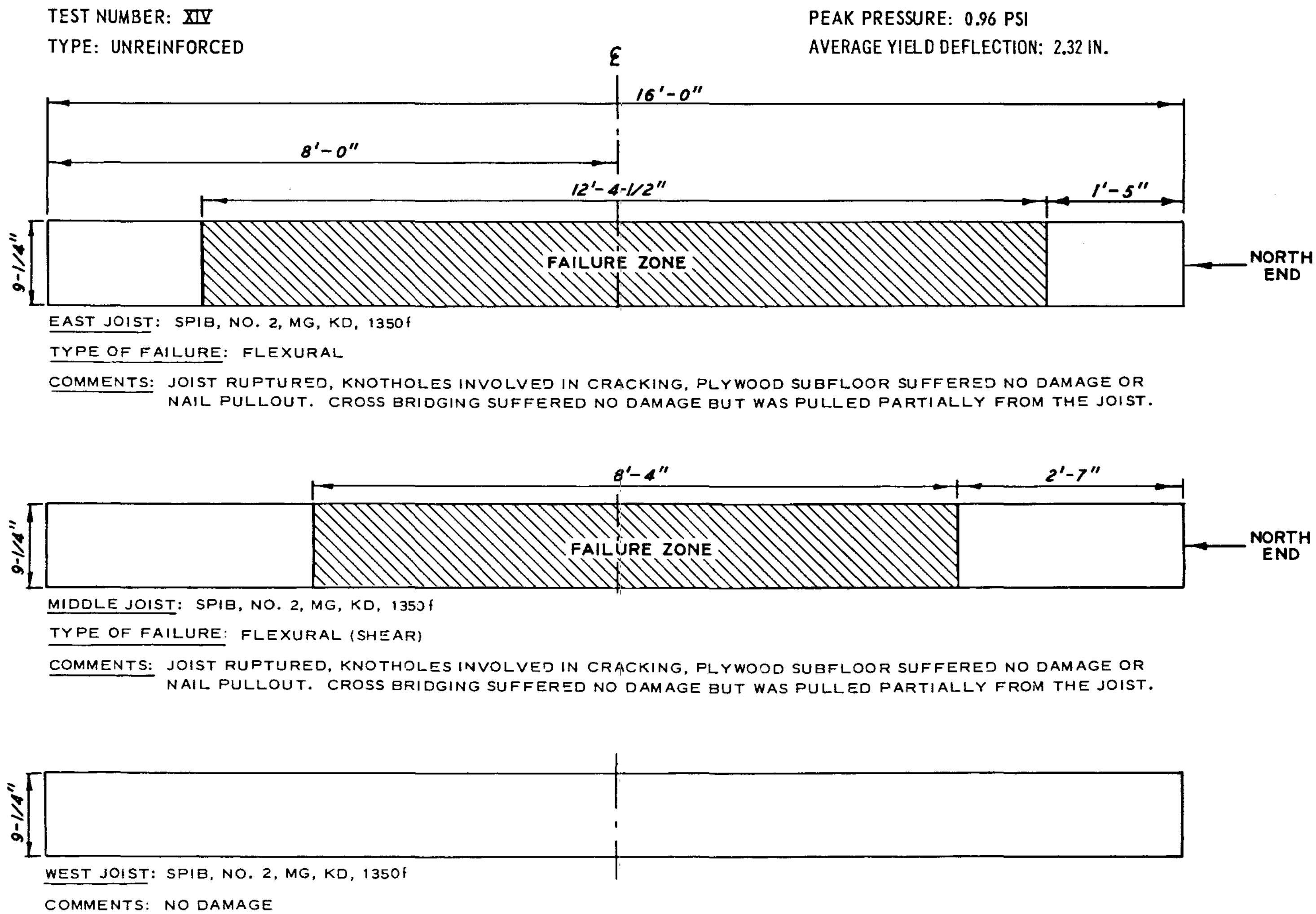
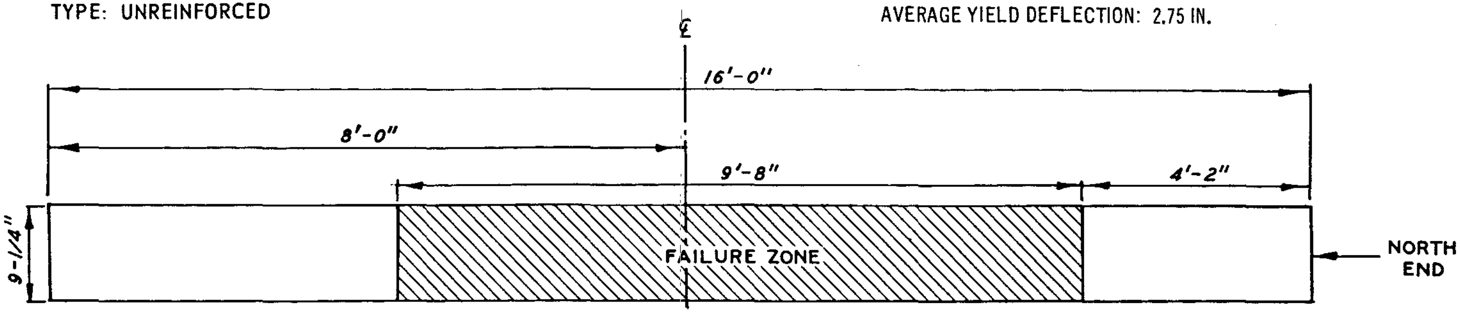


Figure 2.52 Failure diagram, Specimen XIV.

TEST NUMBER: XV
TYPE: UNREINFORCED

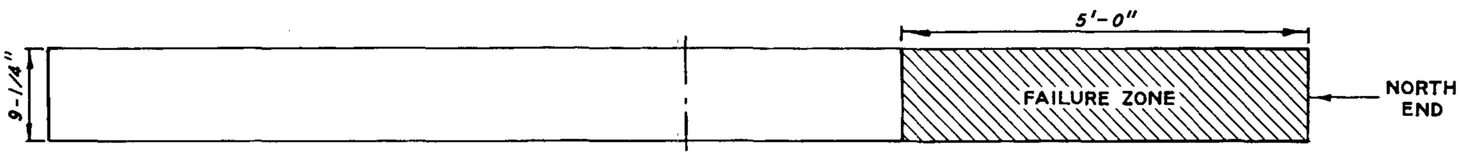
PEAK PRESSURE: 1.85 PSI
AVERAGE YIELD DEFLECTION: 2.75 IN.



EAST JOIST: SPIB, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

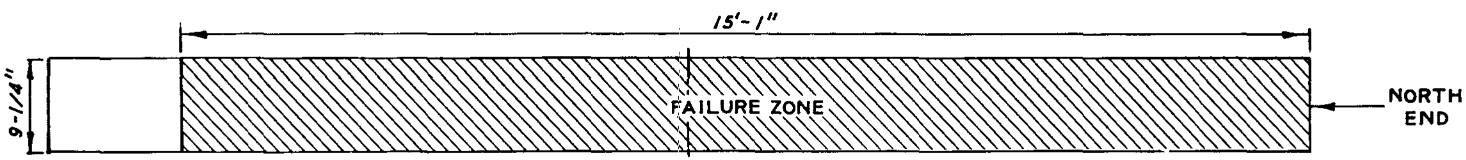
COMMENTS: JOIST RUPTURED, KNOTHOLES INVOLVED IN CRACKING, PLYWOOD SUBFLOOR SUFFERED NO DAMAGE OR NAIL PULLOUT, CROSS BRIDGING WAS NOT DAMAGED NOR PULLED OUT OF THE JOIST.



MIDDLE JOIST: SPIB, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: HORIZONTAL SHEAR

COMMENTS: JOIST DID NOT RUPTURE BUT WAS CRACKED THROUGHOUT FAILURE ZONE, KNOTHOLES INVOLVED IN CRACKING, PLYWOOD SUBFLOOR SUFFERED NO DAMAGE OR NAIL PULLOUT. CROSS BRIDGING SUFFERED NO DAMAGE BUT WAS PARTIALLY PULLED OUT OF THE JOIST.



WEST JOIST: SPIB, NO. 2, MG, KD, 1350f

TYPE OF FAILURE: FLEXURAL

COMMENTS: JOIST RUPTURED, KNOTHOLES INVOLVED IN THE CRACKING, PLYWOOD SUBFLOOR SUFFERED NO DAMAGE OR NAIL PULLOUT. CROSS BRIDGING WAS NOT DAMAGED NOR PULLED FROM THE JOIST.

Figure 2.53 Failure diagram, Specimen XV.

CHAPTER 3

DISCUSSION OF TEST RESULTS

Of particular interest was the determination of whether or not composite action between the plywood decking and floor joists occurred. Consequently, the connection of the plywood subfloor to the joists was of prime importance. Nailing schedules followed those set forth in Reference 1 to reproduce conventional practice. Therefore, data obtained from these floor specimens should yield a realistic relative account of composite action in residential flooring systems.

To determine if composite action between the flooring and the joists occurred, the composite moment of inertia of the floor specimen was calculated and then compared with the actual moment of inertia of the test specimen. The composite moments of inertia, I_c , for the steel hanger-steel strap reinforced test specimen were considered the same as the I_c for an unreinforced specimen since the hanger straps were not a continuous reinforcement. The moment of inertia of the test specimen, I_{test} , was determined from the elastic deflection equation. The deflection equation for point loads acting at quarter points of the span takes the general form of:

$$y = \frac{PL/4}{24EI}\left[3L^2 - 4\left(\frac{L}{4}\right)^2\right] = \frac{11PL^3}{384EI} \qquad (3.1)$$

Therefore:

$$I_{test} = \frac{11PL^3}{384EY} \text{, where } P \text{ is in pounds} \qquad (3.2)$$

Values for the yield deflection and load in Equation 3.2 were taken from the slopes of the load-deflection curves (Figures 2.24-2.38) up to about one-half of the load corresponding to the first joist failure. A modulus of elasticity, E , equal to 1.76×10^6 psi was used in Equation 3.2. This value, taken from Reference 4 for the shortleaf Southern Yellow Pine in the dry condition, was used for all computations throughout this section. I_{test} values and ratios of I_{test} to I_c are tabulated for each test specimen in Table 3.1. From the data in this table it is apparent that little composite action developed between the plywood flooring and the joists.

The moment of inertia for three wooden 2- by 10-inch floor joists, I_{joist}, was also calculated and I_{test} was compared with I_{joist} (Table 3.1). The results present further evidence that composite action did not occur because the ratios of I_{test} to I_{joist} are much closer to unity than are the ratios of I_{test} to I_c. So, in fact, the floor specimen behaved more as three joists than as a composite floor section. The contribution of the plywood flooring to the strength of the floor structure and to the effective moment of inertia of the floor section was small.

The fiber stresses at the proportional limit were calculated for each test specimen using the I_{test} values and pressures from Figures 2.24-2.38. These stresses, tabulated in Table 3.1, seem reasonable when compared with textbook values (Reference 4) for the proportional limit fiber stresses for Southern Yellow Pine (7700 to 9300 psi in a kiln-dried condition). Table 3.2 presents the averages of the data in Table 3.1 arranged according to the type of reinforcement used in the test specimens.

There is considerable scatter present in the test data. In Figure 3.1 the yield deflection is plotted against the yield pressure for all of the test specimens. Each curve represents a specific reinforcement type. The curves overlap, illustrating that in some instances a reinforced specimen failed at a pressure lower than that required for an unreinforced specimen failure.

Some of the scatter in the data is due to the different structural grades of the lumber used. This can be verified by observing the yield pressures tabulated in Table 3.1 and the failure diagrams (Figures 2.39-2.53). According to the failure diagrams, test Specimens III, V, and VI contained one or more joists that were graded No. 1 and Specimen IX contained three No. 1 graded joists. The yield pressures for these test specimens were higher than those of most of the other test specimens, all of which consisted of three No. 2 joists. Wood is a natural product over which man has no control. Breaking strength, modulus of elasticity, etc., generally follow a normal distribution curve, as pictured in Figure 3.2 (Reference 5). The statistical aspects of wood properties and the different structural grades of wood used in four of the test specimens are considered to account for the scatter of the data in Table 3.1.

Four of the five reinforcing methods tested showed some increase in yield load and deflection over the average values for the unreinforced specimens. The average yield load for the two specimens reinforced with the thin galvanized steel straps was about the same as that for the unreinforced specimens. The test moment of inertia (I_{test}) of the reinforced test specimens varied from approximately 30 percent below to approximately 13 percent above the moment of inertia for three joists alone (see Table 3.2). The test moment of inertia is a better indicator of the development of composite action than the values of yield load or deflection.

Since it was shown previously that the subfloor and underlayment did not act compositely with the joists, it is necessary to compare the test moment of inertia to the moment of inertia calculated considering only the joists and the reinforcing. From Table 3.2, the average I_{test} for the three specimens reinforced with the 1/8-inch-thick steel strap (II, VI, and IX) was 324.4 in^4. The calculated moment of inertia for the joists and reinforcing strap was 512.5 in^4 and that for the joists alone was 296.8 in^4. The test moment of inertia was approximately 9 percent higher than the moment of inertia of the three joists alone. Comparing the increase of I_{test} over the moment of inertia of the joists alone (I_{joist}) with the available increase in moment of inertia due to composite action (512.5 - 296.8 = 215.7) shows that only 12 percent of the available composite action was developed.

The plywood reinforced specimens (III and IV) showed an increase of 22 and 66 percent, respectively, over the yield load and deflection of the unreinforced specimens. The test moment of inertia was approximately 30 percent lower than that of the unreinforced specimens. During the test the nails pulled through the 1/4-inch-thick plywood reinforcing.

Had the plywood been glued to the joist instead of nailed, better success with this type of reinforcement might have been realized since the shear strength of the connection would have been greatly enhanced.

Hanger strap reinforced Specimen VIII showed increases of 40 and 70 percent, respectively, over the yield load and deflection of the unreinforced specimens. However, the test moment of inertia was much lower than that for the three joists alone. It was thought that the hanger straps would prevent the horizontal splitting of the joist when the joist began to fail.

Test Specimens X and XI involved combinations of the 1/8-inch-thick steel strap and the hanger straps. These specimens showed a slight increase in strength over the specimens reinforced with the steel straps alone. However, the strength increase was not large enough to justify the additional effort required to install the hanger straps.

Thin galvanized steel straps were used to reinforce test Specimens XII and XIII. The 22-gage strap was chosen because it was the thickest strap through which a nail could be driven without great difficulty. These straps failed at a nail hole during the test. Since it was difficult to view the underside of the test specimens during the test, it is not known whether the straps failed prior to or after the joist failed. To eliminate nail pullout which had occurred during some of the other tests, a grooved nail was used with the thin galvanized steel strap. Some pullout did occur during tests of Specimens XII and XIII but it was slight. The average test moment of inertia for these specimens was 335.9 in^4 and the calculated moment of inertia of the reinforced section neglecting the floor system was 345.5 in^4. This indicates that the section developed 80 percent of the available composite action.

As mentioned previously, the general objective of this study was to evaluate expedient methods for strengthening floor joists. Although only static data on joist strength were obtained, it was desirable to extrapolate the dynamic behavior of the floor specimens from these static data. A computer program developed at WES to approximate the response of deep slabs subjected to blast loading conditions was utilized to make this extrapolation. It solves for the peak pressure of a given weapon yield which causes a predefined amount of damage to the slab. The slab analysis and its development are described in detail in References 6 and 7. This analysis assumed that the maximum response of the slab can be represented by a single-degree-of-freedom elastoplastic system subjected to an exponential pressure pulse resulting from a nuclear detonation.

With minor changes, this program was adapted to predict peak pressures of various weapon yields for Specimens I through IX. Input parameters were obtained from the static test results. Peak static pressures and yield and maximum deflection values were obtained from the load-deflection curves (Figures 2.24-2.38). For purposes of this study, a surface burst geometry was chosen. Weapon yields of 10 kt, 100 kt, 1 Mt, and 10 Mt were assumed to represent a reasonable range in weapon size. Peak pressures, P_{so} , were calculated for each of Specimens I-IX from the computer program using the above weapon yields and then averaged for each reinforcement type and arranged in Table 3.3. These peak pressures will produce the same maximum deflections as the static test, i.e., dynamic failure will be as extensive as static failure because parameters such as stiffness, yield stress, and ductility factors for the dynamic analysis were based on the static test results. The average values of P_{so} are plotted against the various weapon yields in Figure 3.3. The curves in this figure represent a relation between the average peak pressure or kill pressure required to produce failure of the floor structures (defined by the static tests) and weapon yield. According to the curves, there was little difference in the kill pressure for any of the specimen types tested over the range of weapons used.

TABLE 3.1 MOMENTS OF INERTIA AND FIBER STRESSES FOR THE TEST SPECIMENS

Test No.	Static Yield Deflection Y_{YIELD} in.	Static Yield Pressure R_{YIELD} psi	Moment of Inertia of Test Specimen I_{test} in.^{4}	Moment of Inertia of Three 2- by 10-in. Joists I_{joist} in.^{4}	Moment of Inertia of Composite Section I_c in.^{4}	Ratio of I_{test} to I_{joist}	Ratio of I_{test} to I_c	Fiber Stress at Yield f_f psi
I	1.64	1.80	417.2	296.8	887.5	1.41	0.47	5,385
II	2.06	1.73	354.8	296.8	1481.6	1.20	0.24	6,151
III	4.70	2.34	162.5	296.8	1501.6	0.55	0.11	16,290
IV	2.66	1.46	263.1	296.8	1501.6	0.87	0.18	6,278
V	2.42	2.06	308.7	296.8	887.5	1.04	0.35	8,329
VI	4.50	2.98	324.9	296.8	1481.6	1.09	0.22	11,571
VII	1.83	1.27	401.3	296.8	887.5	1.35	0.45	3,950
VIII	3.74	2.17	203.1	296.8	887.5	0.68	0.23	13,334
IX	3.70	2.98	293.6	296.8	1481.6	0.99	0.20	12,805
X	3.32	2.84	342.9	296.8	1481.6	1.17	0.23	10,450
XI	3.45	3.16	308.7	296.8	1481.6	1.04	0.21	12,915
XII	1.91	1.86	363.1	296.8	1011.2	1.22	0.36	6,395
XIII	1.60	1.52	308.7	296.8	1011.2	1.04	0.31	6,145
XIV	2.39	0.80	106.4	296.8	887.5	0.36	0.12	11,260
XV	2.75	1.85	268.4	296.8	887.5	0.90	0.30	8,600

TABLE 3.2 MEAN MOMENTS OF INERTIA AND FIBER STRESSES

Test No.	Type	Mean Static Yield Pressure R_{YIELD} psi	Mean Static Yield Deflection Y_{YIELD} in.	Mean Moment of Inertia of the Test Specimens Mean I_{test} $in.^4$	Ratio of Mean I_{test} to Mean I_{joist}	Ratio of Mean I_{test} to Mean I_c	Mean Fiber Stress at Yield f'_f psi
I, V, VII, XIV, XV	Unreinforced	1.55	2.21	300.4	1.01	0.34	7,505
II, VI, IX	Reinforced with steel strap on joist bottom	2.56	3.42	324.4	1.09	0.22	10,175
III, IV	Reinforced with 1/4-in. plywood on joist bottom	1.90	3.68	212.8	0.71	0.15	11,284
VIII	Reinforced with steel hanger straps	2.17	3.74	203.1	0.68	0.23	13,334
X, XI	Reinforced with hanger straps and steel strap on joist bottom	3.00	3.39	325.8	1.11	0.22	11,683
XII, XIII	Reinforced with 22-gage steel strap on joist bottom	1.69	1.75	335.9	1.13	0.34	6,270

TABLE 3.3 STATIC TEST RESULTS AND PREDICTED PEAK OVERPRESSURES

Test No.	Type	Mean Peak Static Pressure R_{MAX} psi	Mean Static Yield Deflection Y_{YIELD} in.	Mean Static Maximum Deflection Y_{MAX} in.	Weapon Yield megatons	Mean Peak Pressure P_{so} psi
I, V, VII	Unreinforced	1.86	1.96	3.51	0.01	1.43
					0.1	1.37
					1.0	1.33
					10.0	1.30
II, VI, IX	Reinforced with steel strap on joist bottom	2.71	3.42	6.43	0.01	2.27
					0.1	2.13
					1.0	2.07
					10.0	2.03
III, IV	Reinforced with 1/4-in. plywood on joist bottom	1.90	3.68	7.65	0.01	1.65
					0.1	1.55
					1.0	1.50
					10.00	1.45
VIII	Reinforced with steel hanger straps	2.17	3.74	8.00	0.01	1.90
					0.1	1.80
					1.0	1.70
					10.0	1.70

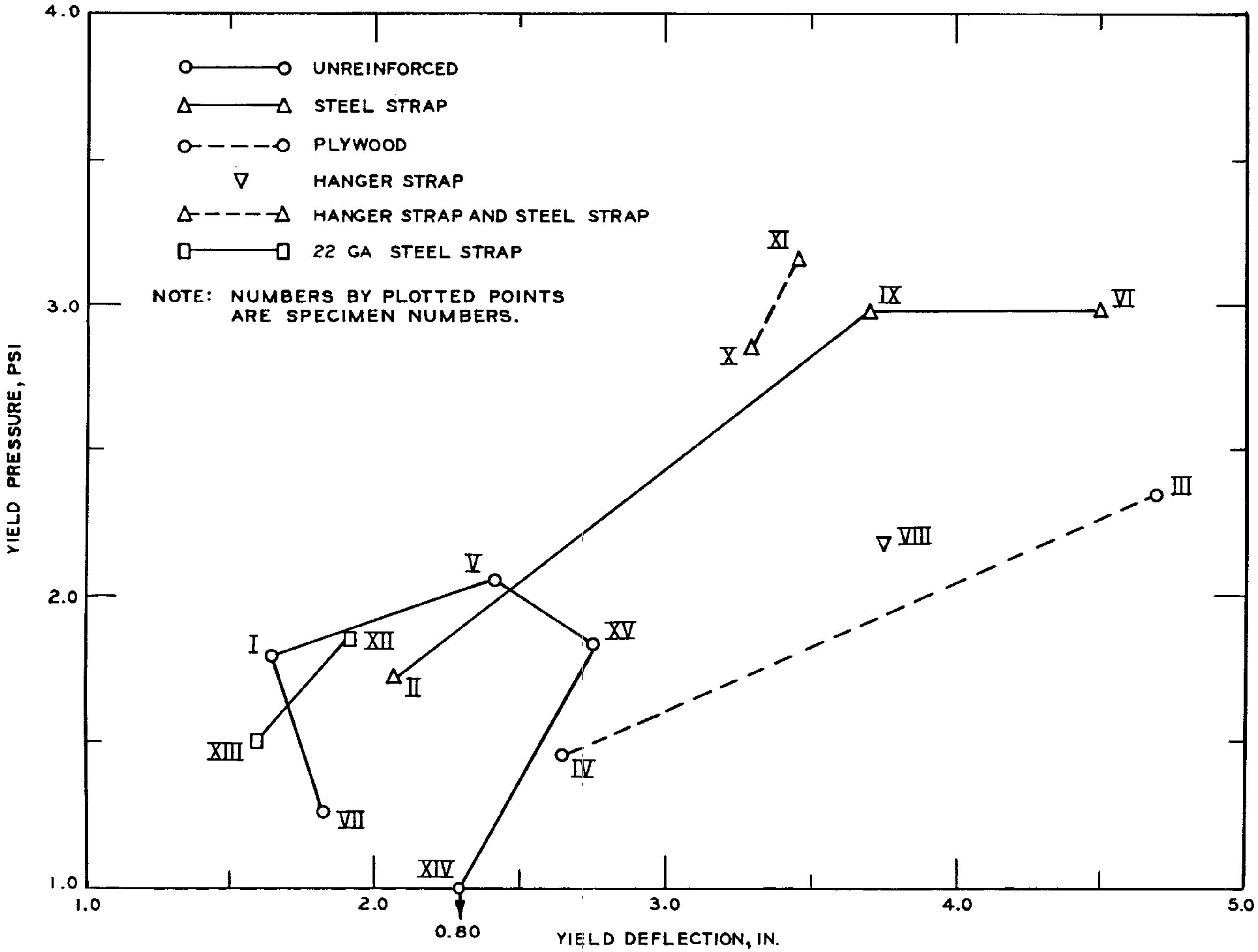


Figure 3.1 Plot of yield pressure and yield deflection from Table 3.1.

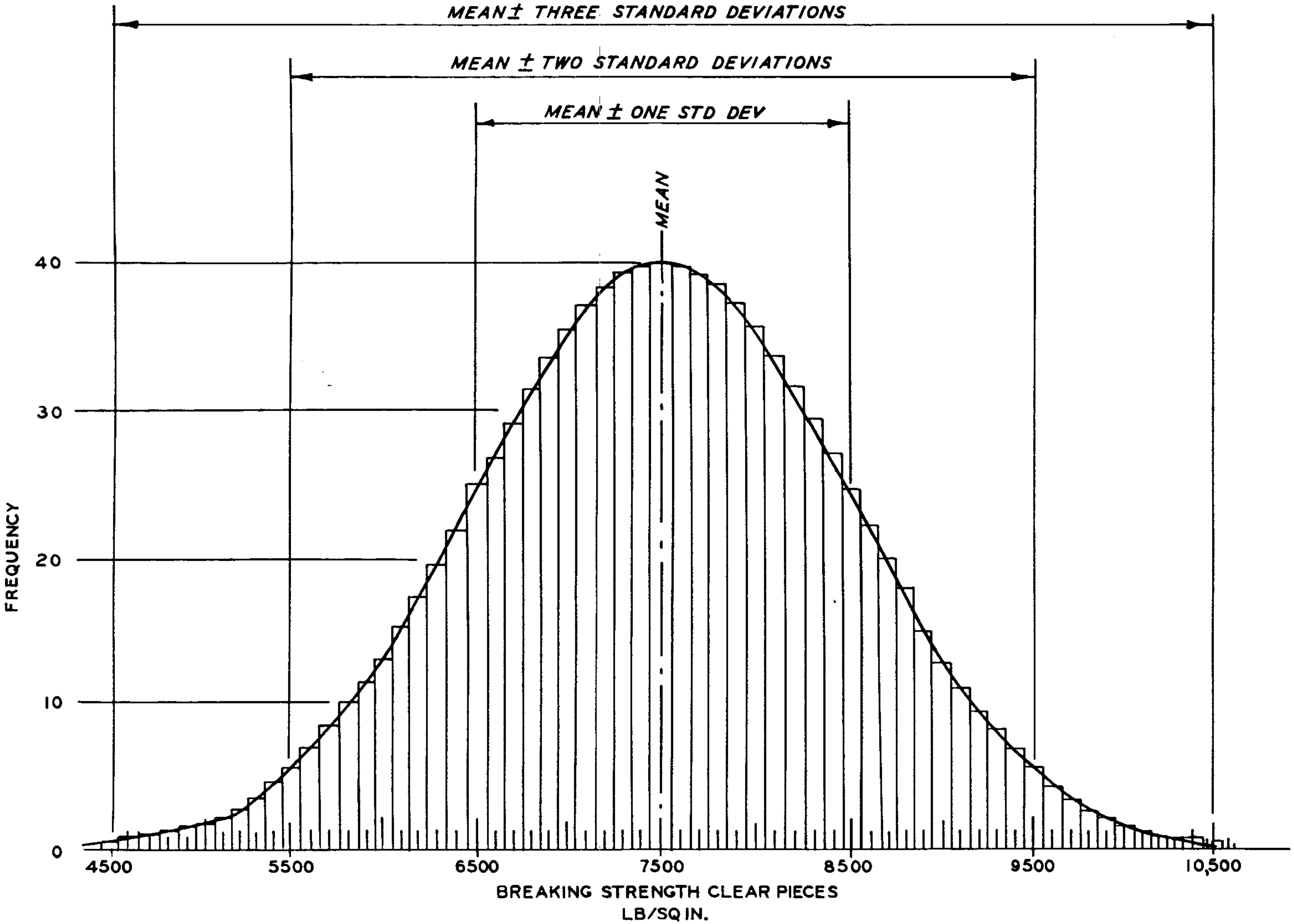


Figure 3.2 A normally distributed population of 1000 tests.

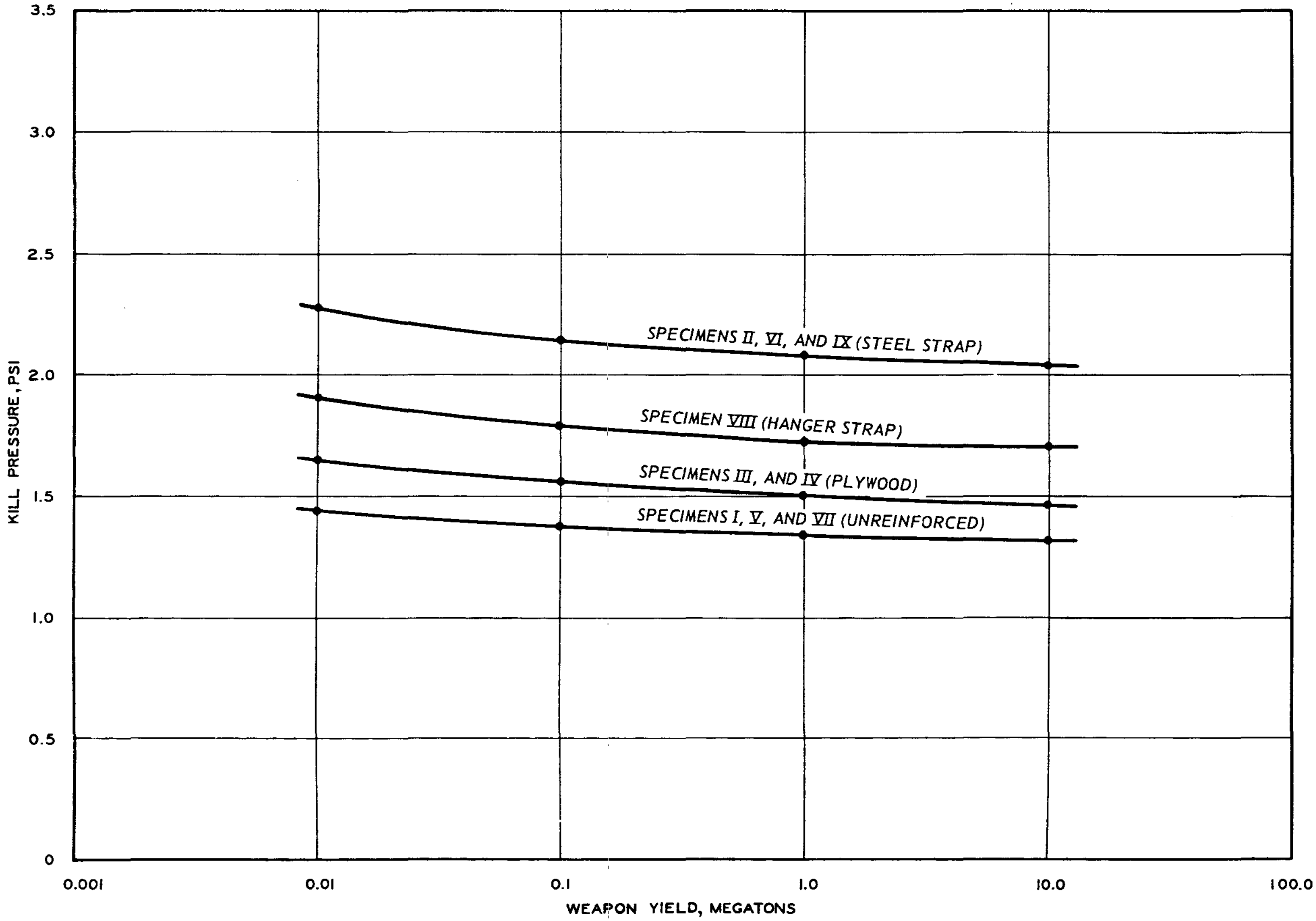


Figure 3.3 Relation between kill pressure and weapon yield for a surface burst.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

It was apparent from the results of the five tests on the unreinforced specimens that little composite action developed between the floor joists and the plywood subflooring. The calculated moment of inertia for three floor joists alone was 296.8 in^4, and the experimentally determined moment of inertia averaged 300.4 in^4 for the five unreinforced specimens.

All of the reinforcing techniques except the method using hanger straps depended on the development of composite action between the floor joist and the reinforcing to provide an increase in strength. No significant composite action developed during the testing of the specimens reinforced with the 1/8-inch-thick steel straps or the 1/4-inch-thick plywood. However, the specimens reinforced with the 22-gage steel strap developed sufficient composite action to cause the strap to fail when the joist failed. The test moment of inertia of the two specimens reinforced with the 22-gage steel straps averaged 335.9 in^4, while the specimens reinforced with the 1/8-inch-thick steel straps had an average test moment of inertia of 324.4 in^4. The additional thickness of steel available with the 1/8-inch-thick strap over the 22-gage strap was not utilized in the development of composite action. With the nailing procedure used to attach the steel straps to the underside of the joist, there was no benefit in using a strap thicker than 22 gage.

In a limited test program of this type, only a limited number of the many possible techniques of joist strengthening could be investigated. Several other methods for increasing the bending strength of floor joists which were suggested but not tested were: (1) nailing plywood plates to the sides of the joist, (2) nailing a 2-by-4 to the underside of the joist, and (3) gluing a 2- by 2-inch strip of wood to the side of the joist and the underside of the subfloor to aid the development of composite action between the subfloor and the joist.

Nails were used in this study instead of glue for simplicity. Some nail pullout did occur; however, some nails held and were sheared off. The use of grooved nails could possibly eliminate nail pullout as was the case with the specimens reinforced with the 22-gage steel straps. Prevention of nail shearing could be helped by increasing the size and spacing of the nails. However, it was felt that the nail spacing and size used in the tested specimens were the maximum an average homeowner would be willing to use.

Reinforcing methods utilizing glued joints would probably provide a higher degree of composite action than that provided by the tested specimens. Determination of these strength increases could be obtained from a test program similar to the one described herein. However, it is suggested that an adequate number of specimens be tested to provide a good statistical base for the test results. The test program could also provide methods of gluing which could be easily used by the average homeowner. One point of interest would be to determine whether nailing or clamping would obtain better joint pressure while the glue cures.

Also of interest would be the determination of support size and spacing to be used with a reinforcing system utilizing added supports to increase floor strength.

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APPENDIX A: NOTATION

E	Modulus of elasticity, 1,760,000 psi
f	Rated working stress of joist lumber, psi
f_f	Fiber stress at proportional limit, psi
f'_f	Average fiber stress at proportional limit, psi
I_c	Moment of inertia of the composite floor section, in^4
I_{joist}	Moment of inertia of three joists, $3(bh^3/12)$, in^4
I_{test}	Moment of inertia of test specimens calculated from the elastic deflection equation, in^4
Kill pressure	Peak pressure, P_{so} , to produce failure defined by the static test results, psi
kt	Kiloton
KD	Kiln-dried
L	Span length, feet
Mt	Megaton
MG	Medium grain
P	Concentrated point load, pounds
P_{so}	Peak pressure required to produce failure defined by the static test results, psi
R_{MAX}	Peak static pressure, psi
R_{YIELD}	Static pressure at yield, psi
SPIB	Southern Pine Inspection Bureau
SYP	Southern Yellow Pine
w	Uniformly distributed load, lb/ft
WF	Wide flange
y	Deflection, inches
Y_{MAX}	Deflection at maximum static pressure, inches
Y_{YIELD}	Deflection at yield static pressure, inches

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