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BEHAVIOR OF TENSION BUTT JOINTS USING BOLTS AND WELDS IN COMBINATION

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April 25, 1986

Mr. Nestor R. Iwankiw
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Dear Mr. Iwankiw:

Enclosed herewith please find two copies of my report on tension joints with bolts and welds in combination that you requested. If you need any additional information, feel free to contact me at (317) 494-2220.

Sincerely yours,

Mark D. Bowman

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Behavior of Tension Butt Joints Using Bolts and Welds in Combination

by

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June 1985

ABSTRACT

Very little experimental research has been conducted on joints fabricated with bolts and welds in combination. Consequently, a series of twelve butt splices made from A36 steel were loaded to failure in tension to examine the behavior of combination connections. The joints were fastened by various combinations of bolts and welds. Results of the two duplicate tests performed for each of the six specimen types were fairly consistent. The strength of connections with welds parallel to the applied load increased notably with the addition of bolts. However, connections with welds transverse to the load showed little increase in strength with the addition of bolts.

1. INTRODUCTION

Combination joints, also known as load-sharing joints, are connections that utilize a combination of high-strength bolts and structural welds. Two different types of combination joints are occasionally used in the fabrication of steel structures: shear splices where the bolts and welds share the load on a common shear plane, and connections where the bolts and welds are used on shear planes that are not common. The former type of connection is occasionally used when repairing or modifying a connection. The welds for these connections are compact and can easily be added to an existing high-strength bolted connection to provide additional strength. The latter connection type occurs commonly in steel construction to simplify the erection of beam-column connections. For example, one leg of the framing angles used for the connection is shop welded to either the column flange or beam web, while the opposite leg is attached in the field with high-strength bolts.

2. OBJECTIVES AND SCOPE OF STUDY

The primary objectives of this study are to experimentally examine the strength and load interaction characteristics of combination joints for a variety of weld and bolt configurations and to evaluate methods that are currently available for predicting the ultimate tensile strength of combination joints. The combination joints examined in this study are butt joints which utilize bolts and welds on a common shear plane.

Six different joint configurations were used to examine a variety of different bolt and weld combinations - see Table 1. Two specimens were prepared for each of the six joint configurations, for a total of twelve tests. The dimensions and connection details for the specimens are shown in Figure 1. The specimens were tested to fracture in the 600,000-lb. (2670 kN) capacity Baldwin Universal testing machine in the Structural Engineering Laboratory at Purdue University.

The fabrication, instrumentation, and testing procedures which were used for each of the twelve test specimens are described in the following sections. A discussion of the test results and the techniques used to predict the ultimate strength is included also.

3. BACKGROUND INFORMATION

3.1 Prior Studies

Previous research on combination tensile butt joints using bolts and welds is very limited. Fisher and Struik (1) report the results of three studies conducted in Germany (2-4). The test results reported for these studies included tension type butt splices with two bolts on each side of the splice.

A portion of the results from the tests conducted by Steinhardt et al. (4) are shown in Figure 2. The load-deformation characteristics of the plain welded connection, bolts only connection, and the combination connections are shown together. The results indicate that the capacity of the combination joint can be reasonably predicted by the sum of the slip load of the plain bolted connection and the strength of the welds (1). It is noted that in larger connections than those tested, misalignment of bolt holes may cause the bolts to come into bearing, thereby increasing the combined connection strength. For design purposes Fisher and Struik (1) recommend that the ultimate load of the combination connection "... can be estimated as the sum of the slip resistance of the bolted parts, and the ultimate load of the plain welded connection."

An experimental study of combination joints was conducted also by Holtz and Kulak (5) in Nova Scotia in 1970. Holtz and Kulak's experimental work consisted of nine tension splices and six moment resistant beam-column connections. Based upon their test results, Holtz and Kulak develop a rational analytical method for predicting the ultimate strength of combined connections.

3.2 Ultimate Strength Model

Holtz and Kulak (5) developed a technique, based on connection deformation, for predicting the ultimate tensile strength of combination joints. Reasonable agreement between the predicted and the observed ultimate strengths was obtained for the various types of combination joints tested.

The nine butt joint specimens used by Holtz and Kulak were divided evenly among three groups of combination joints, as shown in Figure 3. Specimens from the first two groups had longitudinal fillet welds in combination with two 3/4-inch (19.1 mm) diameter bolts, while specimens from the third group had transverse fillet welds combined with one 3/4-inch (19.1 mm) diameter bolt. In the first group, Figure 3(a), the bolts fit tightly into the holes to simulate bearing-type connections. The bolts were installed only to a snug tight condition to minimize friction. In the second group, Figure 3(a), the specimens were fabricated with standard size holes drilled 1/16-inch (1.59 mm) larger than the bolt diameter. The bolts were tightened 1/2 turn past the snug tight condition, as is commonly done in practice, to simulate a friction connection. Specimens from group three, Figure 3(b), had one standard hole, with the bolts tightened 1/2 turn past snug. The sequence of fabrication in this study was the reverse of that commonly used in practice - i.e., the welds were made prior to the installation of the bolts.

Typical load-deformation curves from test specimens in groups 2 and 3 are shown in Figures 4 and 5, respectively. The deformations were measured near the middle of the longitudinal or transverse welds. Note that there is virtually no deformation in the longitudinally welded combination joint until approximately 75 kips (334 kN). However, deformation of the transversely welded combination joint begins upon load application. From these curves, Holtz and Kulak (5) concluded that the frictional force was, "... too unreliable to be considered in the analysis of the connection."

The increase in the slope of the load-deformation curve in Figure 4 (longitudinal weld) at a deformation of 0.05 inch (1.27 mm) indicates that the bolts are beginning to come into bearing. Conversely, since the slope of the curve in Figure 5 (transverse weld) continuously decreases, it can be inferred that the bolts do not go into bearing. The higher strength of the second connection is associated primarily with the superior strength of transverse welds (6). Accordingly, Holtz and Kulak base their analytical method for predicting the ultimate load of combination joints on the deformation characteristics of each fastening element.

It has been shown that the load-deformation response of mechanical fasteners can be expressed by the following relationship (7):

$$R = R_{ult}(1 - e^{-\mu\Delta})^{\lambda} \qquad [1]$$

where R = force developed by a fastener at a given deformation Δ, R_{ult} = ultimate shear force attainable by the fastener, e = base of natural logarithms, and μ, λ = empirical regression coefficients. The total deformation of the fastener includes bending, bearing, and shearing deformations, as well as local bearing deformations of the connected plates.

From tests conducted by Butler and Kulak (6) on 1/4-inch (6.35 mm) E60 fillet welds, it was shown that the strength of a weld depends on the orientation of the weld relative to the axis of the applied load. Curve fitting methods yielded the following expressions for use in Eq. [1].

$$R_{ult} = \frac{10 + \theta}{0.92 + 0.0603\theta} \qquad [2]$$

$$\mu = 75.0e^{0.0114\theta} \qquad [3]$$

$$\lambda = 0.4e^{0.0146\theta} \qquad [4]$$

where θ equals the angle (expressed in degrees) between the load and the longitudinal axis of the weld. R_{ult} in Eq. [2] is the ultimate load in units of kips per lineal inch.

Furthermore, it was found that the ultimate weld deformation in inches, Δ_{max}, could be expressed as (6):

$$\Delta_{max} = 0.225(\theta + 5)^{-0.47} \qquad [5]$$

The tests conducted by Holtz and Kulak (5) indicated that the welds reach ultimate load prior to failure of the bolts. Therefore, to evaluate the ultimate load of a combination joint, the critical weld must first be identified; i.e., the weld with the greatest angle to the applied load. Assuming that all portions of the weld deform the same amount, then Δ for all the sub-critical welds is set equal to the value of Δ_{max} for the critical weld. Substitution of Eqs. [2] through [4] and the value for Δ_{max} into equation [1] will give the expression for the strength of a unit length of weld as a function of θ.

Then, the ultimate strength of the weld group, R_w, is given as

$$R_w = \sum_{i=1}^{m} L_{\theta i} R_{\theta i} \qquad [6]$$

where $L_{\theta i}$

= total length of weld in the direction of θ_i, $R_{\theta i}$ = strength of a unit length of weld in the direction of θ_i, and m = number of different angles between weld axes and load direction.

To account for the contribution of the bolts to the ultimate connection strength, the deformation of the bolts is found by

$$\Delta_b = \Delta_{max} - C \qquad [7]$$

where C = clearance between the bolt and the hole edge.

By substituting values of Δ_b into Eq. [1], and using the appropriate values for R_{ult}, λ, and μ, the strength of each bolt, R_b can be obtained.

Hence, the ultimate capacity of the connection is given by summing the contribution of the bolts and the welds:

$$P_{ult} = nR_b + R_w \qquad [8]$$

where n = the number of bolts. Using the above approach, Holtz and Kulak (5) obtained reasonable estimates of the strength of the specimens tested.

3.3 Specification Requirements

The AISC Specification (8) clearly spells out acceptable uses of combination joints. The specification requirements state in Par. 1.15.10 that:

> "In new work, rivets, A307 bolts, or high-strength bolts used in bearing-type connections shall not be considered as sharing the stress in combination with welds. Welds, if used, shall be provided to carry the entire stress in the connection. High-strength bolts installed in a friction-type connection may be considered as sharing the stress with the welds.
>
> "In making welded alterations to structures, existing rivets and properly tightened high-strength bolts may be utilized for carrying stresses resulting from existing dead loads, and the welding need be adequate only to carry all additional stress."

The Commentary comments on Par. 1.15.10 indicate that it is permissible to use friction-type connections in conjunction with welds in new construction. The rigidity of the connection allows the loads to be transferred across the fraying surfaces. A bearing-type connection is not permitted because the welds may prevent the bolts from going into bearing.

In making alterations to existing structures, use of bearing-type connections is permitted. Presumably, the slip will have occurred and the bolts will be in bearing. Consequently, any additional loads will be taken by the welds placed after the slip has occurred. Obviously, the criterion that the AISC requirements consider in determining the acceptability of bearing-type connections is the opportunity for slip to occur after the weld is placed.

4. EXPERIMENTAL STUDY

4.1 Specimen Fabrication

4.1.1 Plate Preparation

ASTM A36 steel plates were cut to the dimensions of 18" x 6 3/4" (475 mm x 171 mm) and 11" x 5 1/2" (279 mm x 140 mm) from single plates of 1-inch (25.4 mm) and 5/8-inch (15.9 mm) thicknesses, respectively. The plates were cut at the Central Machine Shop with a plasma arc cutter (exception: W0B2-1). Adequate space was left between the specimens so that the tapered edge, which is typically produced on one side by the plasma-arc cutting process, occurred on the material between the specimens. This procedure resulted in a nearly vertical edge along the specimen periphery.

The cutting process also left some slag along what will be referred to as the "bottom" edges. The slag was removed with chisel and hammer, resulting in a clean cut edge with virtually no burrs. At this time all the plates were wire brushed by hand to remove loose dirt and loose mill scale.

4.1.2 Hole Drilling

Sixty-six standard sized holes - 1/16 inch (1.59 mm) larger than the bolts - were drilled in twenty-seven of the forty-eight plates. The holes were drilled from the top side, that is, the side of the plate on which no slag developed as a result of the cutting. This "top" side was then free from any burrs from the cutting and drilling processes. Each plate was drilled separately.

A centering bit was used to start each hole. The 13/16-inch (20.6 mm) holes were made with one pass of the bit, using plenty of cutting oil. The 1 1/16-inch (27 mm) holes in the 1-inch plates were drilled out first with the 13/16-inch bit, and then enlarged with the 1 1/16-inch bit. For the 5/8-inch plates, the 1 1/16-inch holes were drilled in one pass. Most of the cutting oil was wiped off with a rag.

4.1.3 Surface Preparation

A solvent (pure xylene) was applied with a rag to thoroughly remove the oil from the steel. After wiping the surfaces clean with the rag, the steel was wire brushed by hand, and again wiped with a clean rag. All the plates were cleaned prior to assembling the specimens.

Three of the specimens (WLB2-1, WTB2-1, LTB2-1) were originally designated to have several electric resistance strain (ERS) gages in two lines across the 5/8-inch plate. Accordingly, the mill scale on three 5/8-inch plates was removed with a power grinder (exceptions: WOB2-1, LTB2-2).

4.1.4 Specimen Assembly

Prior to assembling each specimen, the width and thickness of each plate and the diameter of each hole were measured with micrometers and recorded. The width and thickness of Plates B, C1, and C2 as shown in Figure 6 were measured three times each to obtain average values (exception: WOB2-1). Additionally, the hole locations were measured, from edge of plate to edge of hole, and recorded.

Each plate of the specimen has a "top" side and a "bottom" side as described above. The contact surface for the Plates C1 and C2 is the "top" side. That is, the "top" side of Plate C1 is in contact with the "top" sides of Plates A and B. The "top" side of Plate C2 is then in contact with the bottom sides of Plates A and B. The purpose for this placement was to maintain consistency.

The 5/8-inch (15.9 mm) plates were positioned and clamped in place to the 1-inch (25.4 mm) B plate with C-clamps (see FIg. 6). Alignment of the holes was done by eye. For specimens with bolt holes, the hole alignment was used as the primary guide for positioning. Specimens with welds only were positioned as shown in Figure 7 using a 6-inch metal scale. On the specimens with welds only, approximately 4 1/2-inches (114 mm) are available for welds, whereas the combination connections have 4 3/4-inches (121 mm) available.

Three-quarter inch diameter A325 bolts were centered, as close as possible, in the holes and tightened to a snug tight condition, as defined in the AISC Specification (8). Washers were placed on the nut end, which was later turned for final tightening. For Specimens WOB2-1, LTB2-1 and LTB2-2, two 1-inch (25.4

mm) diameter A490 bolts were installed on Side A in addition to the welds. Therefore, the A plates were fastened between the C plates, and the 1-inch bolts tightened to a snug condition as well. The bolts were installed with the bolt heads on Plate C1. This side of the specimen is subsequently referred to as the "top of the specimen."

At this point Plates C1 and C2 were bolted to Plate B only (except WOB2-1, LTB2-1, and LTB2-2). This assembly and the corresponding A Plate were both stamped with the specimen identification number. Additionally, alpha-numeric designators were painted onto corresponding connecting plate surfaces to assure correct placement and orientation during the welding of the A Plates to the B Plate assemblies.

4.1.5 Welding

The specimens were welded by one person at the Central Machine Shop. The Shielded Metal Arc Welding (SMAW) process was used to join the C Plates to the "test" side (B Side), while the Tungsten Inert Gas (TIG) process was used on the "anchor" side (A Side) - see Figure 7.

A one-quarter inch (6.4 mm) weld leg size, placed manually using 5/32-in. (4.0 mm) E6010 SMAW stick electrodes, was used on side B to simulate field conditions. One pass was made for each weld, and no end returns were made around the corners. The plates were not preheated. Plates C1 and C2 were joined to Plate B first to prevent the plates from separating on this side when welding Side A (exception: WOB2-1, WOB2-2). For each specimen, the 1/4-inch welds for one side were all made before the specimen was flipped over for placement of the remaining 1/4-inch welds. This procedure was done in an assembly-line fashion, five or six specimens at a time.

Next, the A Plate was placed into position, which required some prying and hammering to fit it between Plates C1 and C2. A 1/4-inch (6.3 mm) gap was left between Plates A and B. Side A was then joined to the C Plates with a 7/16-inch (11.1 mm) TIG weld, after which the specimen was flipped a second time to place the remaining TIG welds. No weld material was permitted to fill the 1/4-inch (6.3 mm) gap between Plates A and B. It should be noted that the weld leg size on Side A is significantly larger than the weld on Side B, so that failure will occur on the test side rather than on the anchor side.

4.1.6 Bolt Tightening

After welding the plates sat for more than a day before the bolts were fully tightened, thereby allowing them to return to room temperature. The 3/4-inch diameter bolts were re-snugged, and then turned one-half turn with a long-handled socket wrench. The bolt closest to Plate A was tightened first. On the specimens with both 3/4-inch diameter A325 bolts and 1-inch diameter A490 bolts, the 1-inch bolts were turned 1/3 turn (or as much as possible) prior to tightening the 3/4-inch bolts.

4.2 Instrumentation

The instrumentation used for the project consisted of five dial gages and sixty-six electrical resistance strain (ERS) gages. Two dial gages were 0.0001-inch (0.00254 mm) precision and three were 0.001-inch (0.0254 mm) precision. The ERS gages were connected through a quarter-bridge circuit within the switch and balance units. The 3-wire leads made from 26-gage wire were approximately twelve feet long (3.5 m). A Vishay/Ellis strain indicator was used to read the strains.

On each specimen two small metal brackets with threaded rods were attached using super-glue at the appropriate locations on the 5/8-inch plate to support the dial gages. The gages were located along the edges of the plate to measure the relative displacement of the plates, as shown in Figure 8. Another metal bracket was attached with super-glue to the 1-inch (25.4 mm) plate in order to contact the plunger. The attachment points of the set of brackets were directly opposite each other as shown in Figure 8. Two gages were attached directly on each specimen, and one 0.001 inch precision gage was used to measure the lower head movement. The anticipated amount of deformation governed the choice of dial gage precision used for the two gages on each particular specimen.

ERS gages were placed on several of the specimens in accordance with the application procedures recommended by Micro Measurements. Two types of gages were used: EA-06-240LZ-120 and EA-

06-250BB-120 (exception: WLB2-1). The larger 250BB gages would not fit between the bolt and the plate edge, requiring the smaller 240LZ gages. The location of all instrumentation is described in Table 2, with reference to Figures 9 and 10.

4.3 Testing Procedures

The specimens were pulled to failure in the 600,000-lbs. (2670 kN) Baldwin Universal testing machine in the Structural Engineering Laboratory at Purdue University. The loads were increased in varying increments depending on the magnitude of the deformation experienced; smaller load increments were used as the deformation increased. At each increment, the load was held constant until all of the dial gage and strain indicator readings were recorded.

Plate A of each specimen was clamped by the top grips of the testing machine first. The grips are wedges of steel with roughened surfaces which hold the plate by a clamping force which increases in proportion to the applied load. The strain gages were balanced at this time, and the dial gages were set. The bottom head (loading head) was raised into position to grip the B Plate. Specimens WLB2-1, LTB2-1, and LTB2-2 were warped slightly, although no deviation from the clamping procedure was required. Specimen WLB2-2 was warped to the point that it had to be released from the top grips, loaded into the bottom grips, and then reclamped into the top grips.

The loading was gradually applied in 10 kip to 30 kip (45.5 kN to 133 kN) intervals, depending on the anticipated specimen strength, until significant changes in deformation were observed. Load increments were then reduced to 5 kips (22 kN) or less until fracture. At each increment of loading the strains were read from the Vishay/Ellis strain indicator and recorded manually. The dial gages were read simultaneously within the elastic range, but were read following the strain gage readings within the plastic range to allow the needle movement to stabilize. The order in which the readings were taken was kept constant throughout the test.

4.4 Test Results

Load was applied to each specimen in the test program until fracture occurred. All of the specimens failed through the connecting bolts and/or welds. The ultimate load of each specimen is given in Table 3. The average ultimate load for each pair of specimens is also tabulated.

The load-deformation curves for each specimen are shown in Figures 11-22. Two curves are shown for each specimen, corresponding to the two dial gages monitored during each test to evaluate deformation of Plate A relative to Plate C. For specimens without transverse welds, the two dial gages were positioned to monitor deformation near the middle of the longitudinal welds. However, for specimens with transverse welds, one gage was placed near the middle of the transverse weld and one near the middle of the splice plate.

A discussion of the test results and failure modes for each type of connection is given in the following sections.

4.4.1 Bolts Alone

Both bolts failed in direct shear on the same side at the end of each test. The largest measured relative plate movement prior to failure was 0.17 inch (4.3 mm). The slip load was approximately 35 kips (156 kN) and 25 kips (111 kN) for Specimens WOB2-1 and WOB2-2, respectively. A sudden audible slip occurred on WOB2-1, whereas the slip on WOB2-2 was gradual. There was significant elongation of both 13/16-inch holes in the 1-inch (25.4 mm) plate, with more occurring at the hole closest to the end of the plate. Much less hole deformation was observed on the 5/8-inch (15.9 mm) plates.

The B Plate was pulled from the failed connection before the remaining bolt pieces were removed. In the process, the bolts pried the 5/8-inch (15.9 mn) plate away from the 1-inch (25.4 mm) plate, causing the 5/8-inch (15.9 mm) plate to be permanently bent outward.

The ultimate fastener load computed from R_{ult} of Eq. [1] is compared to the ultimate test load in Table 4. A value of R_{ult} = 74 kips per bolt was used for the 3/4-in. diameter A325 bolts (9). As would be expected for bolts alone, excellent agreement is obtained between the calculated and actual ultimate bolt shear strengths.

4.4.2 Longitudinal Welds Alone

The longitudinal welds sheared along the throat of the weld for most of the weld length. The failure occurred all at once with one "pop." The greatest measured deformation before failure was 0.033 inch (0.84 mm) for Specimen WLBO-2; deformation readings for Specimen WLBO-1 were not taken in the last 27,000 lbs before fracture.

The ultimate load for each of the welded specimens was predicted using Eq. [2] for the ultimate weld load per unit length multiplied times the measured fillet weld lengths. The expression for the ultimate weld shear strength per unit length was developed for welds with 1/4-in. (6.3 mm) leg sizes (6). Consequently, the value of R_{ult} given in Eq. [2] was modified by the ratio of the actual weld throat dimension to that of a 1/4-in. weld. The actual weld throat can be obtained from the following expression:

$$a_{act} = \frac{a_1 a_2}{\sqrt{a_1^2 + a_2^2}} \qquad [9]$$

where a_1, a_2 = vertical and horizontal weld leg sizes, respectively. Several measurements of the weld leg sizes a_1 and a_2 were taken for each fillet weld, so that average weld leg sizes could be determined for each fillet weld.

The predicted ultimate weld loads for Specimens WLBO-1 and

WLBO-2 are given in Table 4. As can be noted, excellent agreement was observed between the predicted and test ultimate weld loads.

4.4.3 Transverse Welds Alone

The transverse welds failed in shear along the interface between the 1-in. (25.4 mm) plate and the weld for nearly the entire length of weld. The welds sheared all at once, with maximum deformations near failure measured at 0.010 inch and 0.021 inch (0.254 mm and 0.533 mm) for Specimens WTBO-1 and WTBO-2, respectively.

The ultimate weld load was predicted as before, using Eq. [2] and the actual throat dimension. The comparison between the calculated and test ultimate load, as shown in Table 4, indicates that the predicted strength is 6 to 10 percent low. The prediction could be improved if the leg size on the weld-plate interface, instead of the minimum throat dimension, was used to calculate the strength.

4.4.4 Longitudinal Welds With Two Bolts

Both specimens with longitudinal welds and bolts (WLB2-1 and WLB2-2) exhibited similar behavior and modes of failure. For Specimen WLB2-1, the last measured relative plate movement before the load peaked was 0.072 inches (1.8 mm) at a load of 250 kips (1100 kN). After reaching the peak at 261 kips (1200 kN), the load dropped off while the plate continued to deform. At a load of approximately 150 kips (670 kN) the entire connection failed at once. Note that the final failure load is roughly equal to the shear strength of two bolts.

Specimen WLB2-1 was one of the four specimens instrumented to monitor the strain in two lines across the plate width. Figure 23 shows the strain gage locations for the four specimens. All four specimens contained Gages 1-10, while only specimens with weld all-around (LTB2-1 and LTB2-2) contained Gages 13 and 14.

Figure 24 shows the measured strain in Specimen WLB2-1 at Gages 6-10, the gage line between the two bolts, for a number of load levels. A uniform strain distribution was observed for loads less than 100 kips (445 kN). However, as the load increased above 100 kips (445 kN), the strain measured between the bolts (Gage 8) was notably less than the strain elsewhere. Furthermore, it appears that the strain between the bolts decreases as failure is approached at 250 kips (1110 kN). The strain decrease suggests that the bolts go into bearing between 225 kips (1000 kN) and 250 kips (1110 kN). The change in slope of the load-deformation curves (Figure 17) at 240 kips (1070 kN) reinforces this observation.

The strain distribution for Gages 1-5, the gage line between the splice plate edge and the first bolt, did not vary significantly throughout the test. The largest measured strain in Gages 1-5 was 250 micro-inches/inch.

The predicted ultimate load is given in Table 4. The strength method overestimates the strength of the specimens by 12-16 percent. In computing the ultimate load, the critical deformation is the ultimate weld deformation given by Eq. [5]. The bolt strength was computed using Eq. [1], with a fastener deformation equal to the ultimate weld deformation minus the bolt clearance of 1/16-in. (1.6 mm).

Another technique for obtaining the strength of the combination joint is to add the ultimate weld load to the load required to cause slip of the bolts. The average slip load from the bolts alone test is 30 kips. Table 5 shows the comparison between the computed and test ultimate loads when the slip load is added to the ultimate weld load. A more favorable comparison is observed.

4.4.5 Transverse Welds With Two Bolts

Failure of the combination joints with transverse welds and two bolts occurred by shearing of the welds at the interface of the 1-in. (25.4 mm) plate and weld. The weld deformation prior to fracture was approximately 0.020-in. (0.5 mm). The bolts did not fail in either test, due to the sudden unloading of the testing machine when the welds fractured. The specimens were reloaded to determine the bolt strength. The bolts failed in shear at loads of 152.2 kips (670 kN) and 155 kips (690 kN) for specimens WTB2-1 and WTB2-2, respectively.

Specimen WTB2-1 was instrumented with Gages 1-10 as shown in Figure 23. The measured strain along a line through Gages 6-10 is given in Figure 25. A lower strain is again observed between the two bolts (Gage 8), although the strain distribution across the plate prior to failure is significantly more uniform than the distribution of measured strains for Specimen WLB2-1.

The strength of the transverse welds was predicted by multiplying the actual weld lengths times the weld ultimate shear strength, Eq. [2]. Prediction of the load-sharing contribution of the high-strength bolts requires consideration of the plate deformation. The bolts will not go into bearing if the plate deformation that occurs at the bolts is less than the bolt hole clearance. The critical weld deformation given by Eq. [5] is 0.026-in. (0.67 mm), which is less than the 1/16-in. (1.59 mm) bolt hole clearance typically assumed for standard holes. Consequently, the ultimate strength of the connection should not include the bearing strength of the bolts.

It should be noted that some shear force is transmitted by friction between the plates in the region of the high-strength bolts. The magnitude of the frictional shear force is not easily quantified, however, and probably cannot be reliably estimated. Therefore, the shear force resulting from friction was not considered.

The predicted ultimate load of the combination joint is given in Table 4. Excellent comparison is observed between the calculated and observed ultimate load values. The strength method accurately predicts the lack of load attributed to the bolts: the average ratio of computed load to test load, which is based on weld strength only, is 1.01.

4.4.6 All-Around Weld with Two Bolts

Failure of the specimens (LTB2-1 and LTB2-2) with two bolts in addition to longitudinal and transverse welds occurred in two stages: welds breaking first, followed shortly afterward, but not immediately, by shearing of the bolts. In the case of LTB2-2, there was one "pop" at 315 kips (1400 kN), after which the load dropped to 295 kips (1300 kN). The load was then increased to 320 kips (1420 kN), at which time the deformations of the longitudinal weld and transverse weld were 0.0133 inch (0.34 mm) and 0.027 inch (0.69 mm), respectively. Failure occurred at 325 kips (1.450 kN).

Both specimens were instrumented as shown in Figure 23. Additional strain gages (Gages 13 and 14) were placed to monitor the strain parallel to the longitudinal weld. The measured strains are shown in Figures 26-29. As before, the strain between the two bolts (Gage 8) prior to failure is significantly less than the strain elsewhere.

The distribution of measured strain parallel to one of the longitudinal welds (Figures 27 and 29) illustrates that very little strain (or deformation) occurs at the intersection of the longitudinal and transverse welds. Moreover, the strain increases significantly near the middle of the longitudinal weld as the ultimate load is reached.

Displacement data from both tests are shown in Figures 21 and 22. The curve labeled Gage X1 refers to the measured deformation near the middle of the longitudinal weld, while Gage Z2 refers to the deformation in the middle of the transverse weld. The deformation of the transverse weld prior to failure was nearly twice that of the longitudinal weld in both tests. The transverse weld deforms elastically up to a load of roughly 220 kips (980 kN). However, after a small plastic deformation, the load incrases sharply above the 220 kip (980 kN) level, indicating that the transverse weld dial gage is picking up a mobilization of load sharing with the high strength bolts.

The measured deformations and strains indicate that the transverse weld failed first, followed by tearing of the longitudinal weld from the free end back towards the transverse weld. Shearing of the bolts occurred in the final stage, as the remaining ligaments of the longitudinal weld fractured.

A comparison of the predicted and test ultimate loads is given in Table 4. The bolt shear strength is ignored because the critical deformation of the transverse weld at failure is less than the amount needed to close the bolt hole clearance and bring the bolts into bearing. The strength method overestimates the ultimate load, even though the bolt strengths are neglected.

The excessive predicted ultimate weld load is most likely due to an overestimation of the strength of the longitudinal welds. The strength method assumes that all welds are subject to the deformation that corresponds to the critical (transverse) weld. However, for the longitudinal weld it is known that the deformations are less than those of the transverse welds near the middle, and that the strain parallel to the weld decreases to nearly zero near the intersection of the transverse and longitudinal welds. Consequently, the ultimate weld strength per unit length will not be equal to the full value, given by the critical weld deformation, for the entire length of the longitudinal weld.

The strength of the combined jointed was also computed for reduced longitudinal weld strengths. A number of average longitudinal weld deformation values, less than the critical value for the transverse weld, were examined. A comparison of the computed and actual weld loads is shown in Table 6. Excellent agreement with the test results is obtained when the longitudinal weld deformation is assumed equal to roughly one-third the critical transverse weld deformation.

Additional test results are needed to further evaluate the strength models of combination joints. The interaction of bolts and welds is complex, and at present subject only to empirical design rules.

5. SUMMARY AND CONCLUSIONS

The deformation characteristics and ultimate static tensile strength of butt joints using bolts and welds in combination has been examined. The experimental program consisted of two specimens for each of six different joint types. The different joint types included: bolts alone, longitudinal welds alone, transverse welds alone, longitudinal welds with two bolts, transverse welds with two bolts, and longitudinal and transverse welds with two bolts. The following observations and conclusions can be drawn on the basis of the limited experimental program described herein.

1. Specimens with bolts alone failed suddenly with shearing of the bolts on one side. The strength model by Crawford and Kulak (9) gave ultimate loads in excellent agreement with the experimental results.

2. Specimens with longitudinal welds alone and those with transverse welds alone both failed suddenly. The longitudinal welds sheared along the weld throat, while the transverse welds failed at interface between the 1-in. (25 mm) plate and the weld. The predicted ultimate weld loads, computed using the relationships given by Butler and Kulak (6), compared favorably with the test results.

3. Specimens with two bolts and longitudinal welds failed with tearing of the weld prior to shearing of the bolts. Adequate deformation occurred so that the bolts went into bearing before failure. The strength method overestimated the ultimate load by 12 to 16 percent. A more conservative and favorable estimate of the ultimate load is obtained by summing the weld strength and the load required to cause bolt slippage.

4. Specimens with two bolts and transverse welds failed by shearing of the weld only. Virtually no difference was observed between the failure load of specimens with transverse welds and those of specimens with transverse welds and two bolts. Assuming the bolts do not participate in carrying load, excellent correlation is obtained between the test results and the load predicted using the strength model.

5. Specimens with two bolts and both transverse and longitudinal welds failed initially at the transverse welds, followed by tearing of the longitudinal weld and shearing of the bolts. The strength method overestimated the ultimate loads by 8 to 14 percent. A more favorable comparison was obtained when the longitudinal weld strength per unit length corresponds to a deformation level equal to one-third of the critical transverse weld deformation at failure.

6. Test results indicate that transverse welds reach their failure load well before the bolts have an opportunity to go into bearing. Moreover, the frictional load developed by the high-strength bolts does not appear to be reliable when a transverse weld is present. Consequently, it is recommended that either transverse welds not be used in combination with bolts or the strength of the high-strength bolts be ignored when transverse welds are used.

Finally, it should be noted that the above observations are based on a very limited number of experimental tests. Further study is needed to develop reliable strength relationships for joints with combined welds and bolts. Many additional tests are needed to evaluate the influence of transverse welds when used in combination with bolts, to determine the effect of a large number of bolts used in combination with welds, and to examine the fatigue behavior of combination joints.

6. ACKNOWLEDGMENTS

The investigation discussed herein was supported in part by the School of Civil Engineering at Purdue University. The research has been conducted by Kenneth H. Jarosch, graduate student in Civil Engineering, under the direction of M. D. Bowman, Assistant Professor of Structural Engineering.

The steel for one specimen and all of the high-strength bolts were provided by International Steel Corporation. The advice and support provided by Mr. John F. W. Koch is gratefully acknowledged. Appreciation is extended also to Mr. William A. Cook who assisted in testing of the specimens.

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TABLE 1. Specimen Descriptions

Specimen No.	Weld Type*	No. Bolts
WOB2-1	———	2
WOB2-2	———	2
WLBO-1	L	0
WLBO-2	L	0
WTBO-1	T	0
WTBO-2	T	0
WLB2-1	L	2
WLB2-2	L	2
WTB2-1	T	2
WTB2-2	T	2
LTB2-1	L,T	2
LTB2-2	L,T	2

Note: *L = longitudinal weld
T = transverse weld

TABLE 2. Strain Gage and Dial Gage Locations

Specimen Number	ERS Gages Location*	Quantity	Type	Dial Gages Location**	Precision
WOB2-1	H, E1,E2	1 each	250BB	X1,X2	0.001"
	I	1 each	240LZ		
WOB2-2	E1, E2	1 each	240LZ	X1, X2	0.001"
WLBO-1	E1, E2	1 each	240LZ	Y1, Y2	0.0001"
WLBO-2	E1, E2	1 each	240LZ	Y1, Y2	0.0001"
WTBO-1	E1, E2	1 each	240LZ	Y2	0.001"
				Z1	0.0001"
WTBO-2	E1, E2	1 each	240LZ	Y2	0.001"
				Z1	0.0001"
WLB2-1	line 1	5	240LZ	X1, X2	0.0001"
	line 2	5	250BB		
WLB2-2	--	--	--	X1	0.0001"
				X2	0.001"
WTB2-1	line 1	5	240LZ	X2	0.001"
	line 2	5	250BB	Z2	0.0001"
WTB2-2	--	--	--	X2	0.001"
				Z2	0.0001"
LTB2-1	line 1	5	240LZ		
	line 2	5	250BB	X1	0.0001"
	F, G	1 each	250BB	Z2	0.0001"
	E1, E2	1 each	240LZ		
LTB2-2	line 1	5	240LZ		
	line 2	5	250BB	X1	0.0001"
	F, G	1 each	250BB	Z2	0.0001"
	E1, E2	1 each	240LZ		

Note: 1 in = 25.4 mm
* Refer to Figure 9
** Refer to Figure 10

TABLE 3. Ultimate Loads for Test Specimens

Specimen No.	Weld* Type	No. of Bolts	Failure Load kips (kN)	Average Load kips (kN)
WOB2-1	--	2	152.5 (678)	152.8 (679)
WOB2-2	--	2	153.0 (681)	
WLBO-1	L	0	177.5 (790)	184.1 (819)
WLBO-2	L	0	190.8 (849)	
WTBO-1	T	0	142.0 (632)	166.8 (742)
WTBO-2	T	0	191.5 (852)	
WLB2-1	L	2	261.0 (1161)	253.5 (1128)
WLB2-2	L	2	246.0 (1094)	
WTB2-1	T	2	175.0 (778)	178.8 (795)
WTB2-2	T	2	182.5 (812)	
LTB2-1	L, T	2	350.5 (1559)	337.8 (1502)
LTB2-2	L, T	2	325.0 (1446)	

Note: *L = longitudinal weld
T = transverse weld

TABLE 4. Comparison of Computed and Observed Ultimate Loads

Specimen No.	Test Load (kips)	Computed Load (kips) Weld	Bolt	Total	Ratio of Computed Load to Test Load
WOB2-1	152.5	0	148.0	148.0	0.971
WOB2-2	153.0	0	148.0	148.0	0.967
WLBO-1	177.5	170.5	0	170.5	0.961
WLBO-2	190.8	181.7	0	181.7	0.952
WTBO-1	142.0	133.3	0	133.3	0.939
WTBO-2	191.5	171.7	0	171.7	0.897
WLB2-1	261.0	208.1	83.1	291.2	1.116
WLB2-2	246.0	203.0	83.1	286.1	1.163
WTB2-1	175.0	181.9	0	181.9	1.039
WTB2-2	182.5	180.5	0	180.5	0.989
LTB2-1	350.5	378.7	0	378.7	1.080
LTB2-2	325.0	370.0	0	370.0	1.138

Note: 1 kip = 4.448 kN

TABLE 5. Ulitmate Load for Combination
Joint Based Upon Weld Strength Plus Slip Load

Specimen	Test Load (kips)	Calculated Weld Load (kips)	Slip Load (kips)	Calculated Total Load (kips)	Ratio of Calculated Total Load to Test Load
WLB2-1	261.0	208.1	30.0	238.1	0.912
WLB2-2	246.0	203.0	30.0	233.0	0.947

Note: 1 kip = 4.448 kN

TABLE 6. Combination Joint Strength for Specimens With All-Around Welds

δ_L/δ_T (Percent)	R_{ult} (kip/in)	P_1 (kip)	$\frac{P_1}{P_{test}}$	P_2 (kip)	$\frac{P_2}{P_{test}}$
100	10.25	378.7	1.080	370.0	1.138
50	9.03	354.6	1.012	347.3	1.069
40	8.55	345.0	0.984	338.3	1.041
35	8.25	339.0	0.967	332.7	1.024
30	7.89	332.0	0.947	326.1	1.003

Notes: 1 kip = 4.448 kN
P_1 = Calculated load for Specimen LTB2-1
P_2 = Calculated load for Specimen LTB2-2
δ_L = Average longitudinal weld deformation
δ_H = Average transverse weld deformation

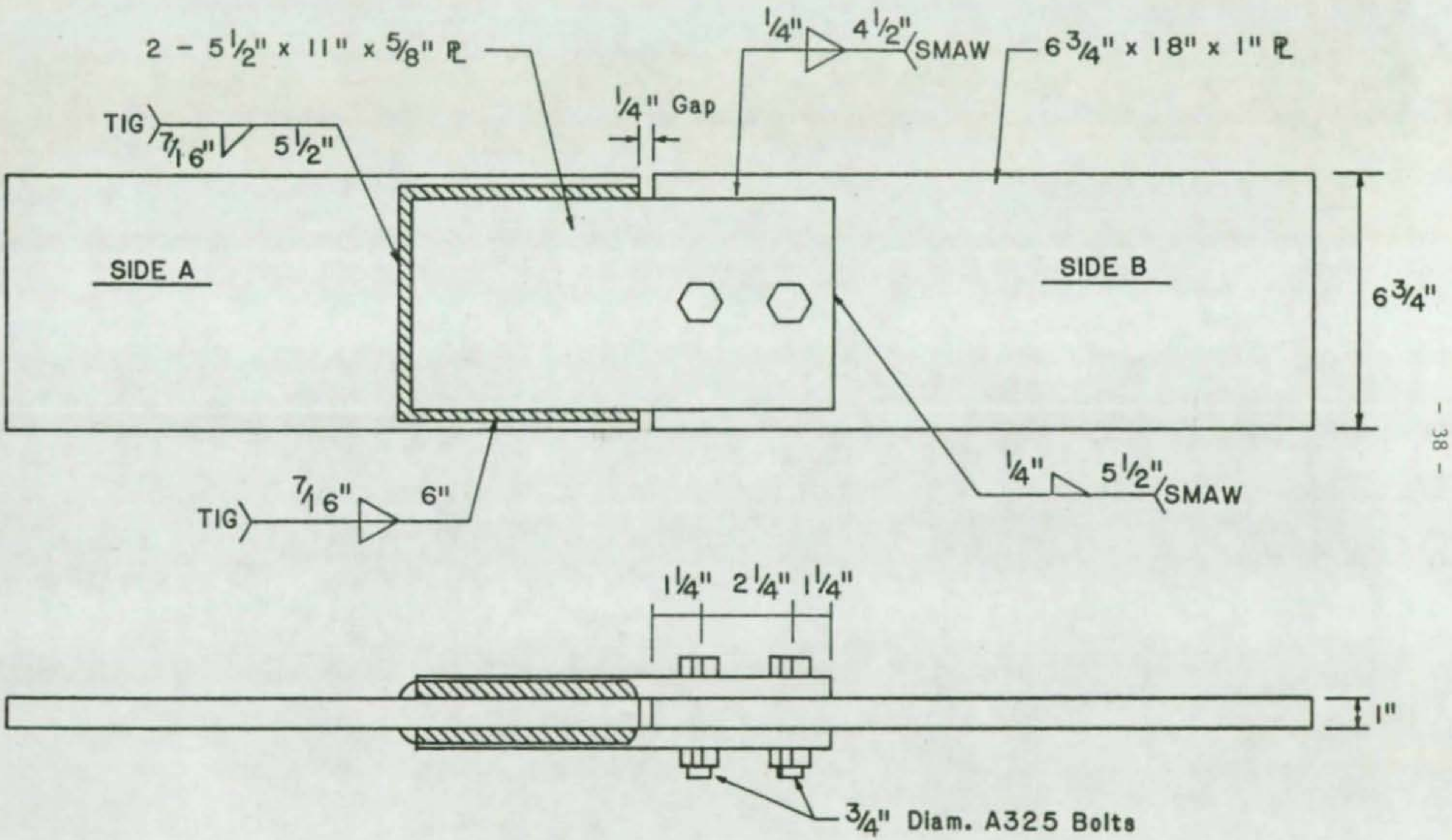


Figure 1. Dimensions of Welded and Bolted Combination Butt Joint Specimens.

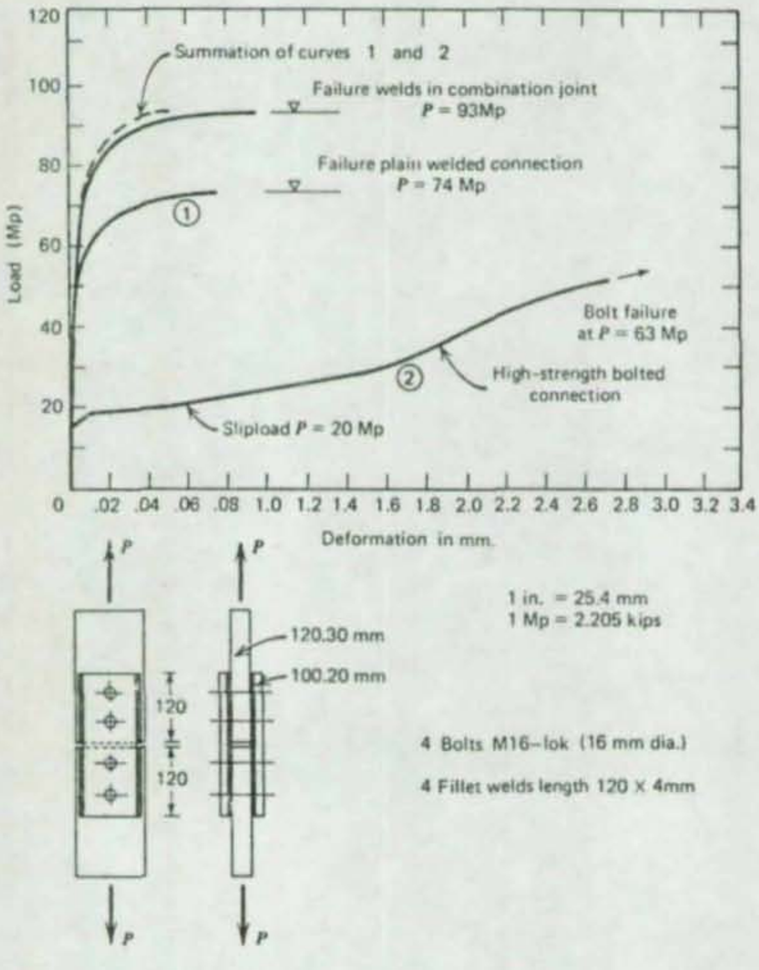
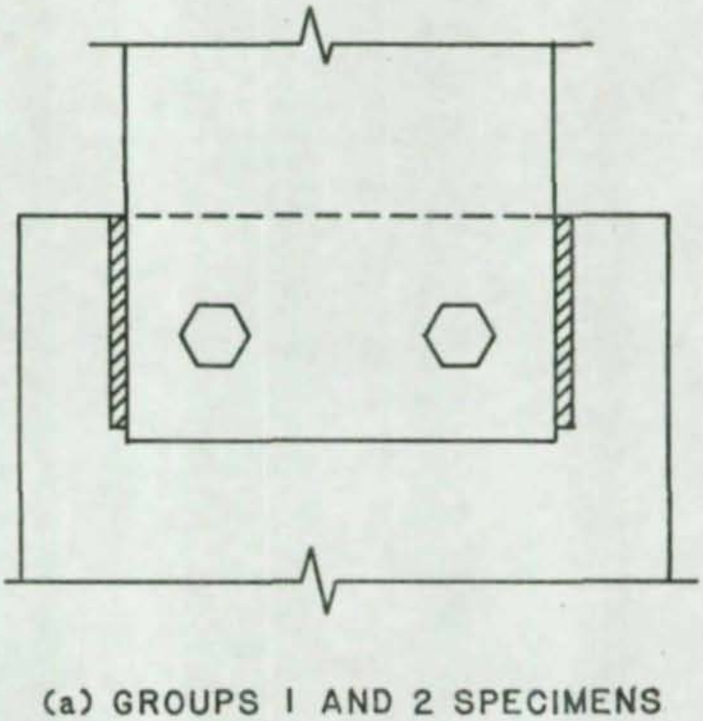


Figure 2. Test Results of Combined Welded-Bolted Joints (1).



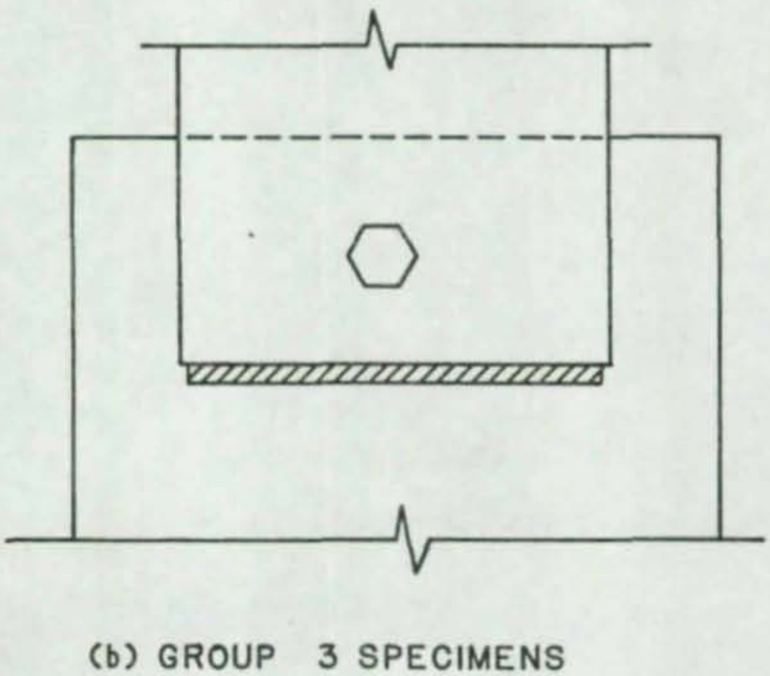


Figure 3. Test Specimen Configurations Examined by Holtz and Kulak (5).

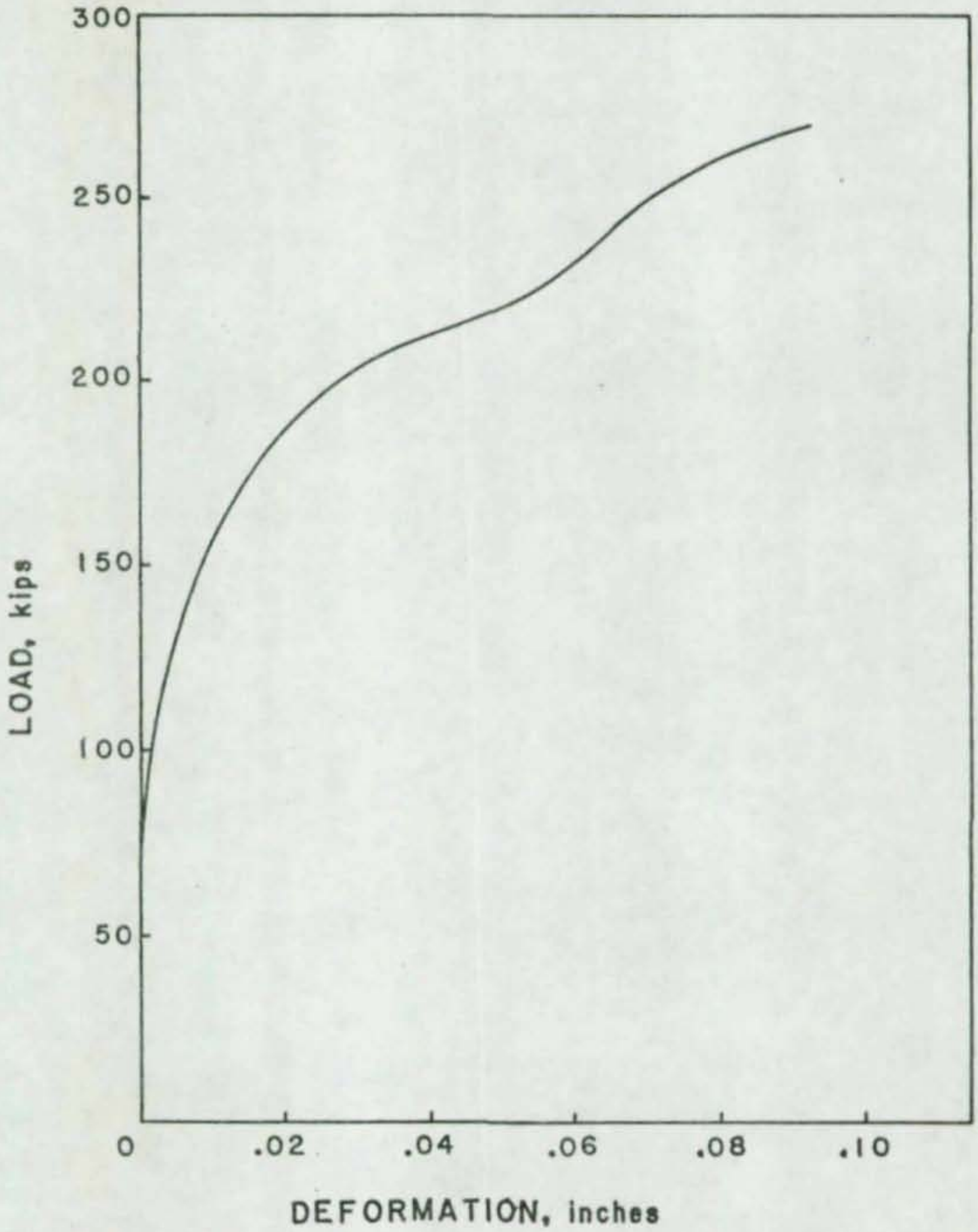


Figure 4. Load-Deformation Curve for Tension Splice with Longitudinal Welds (5).

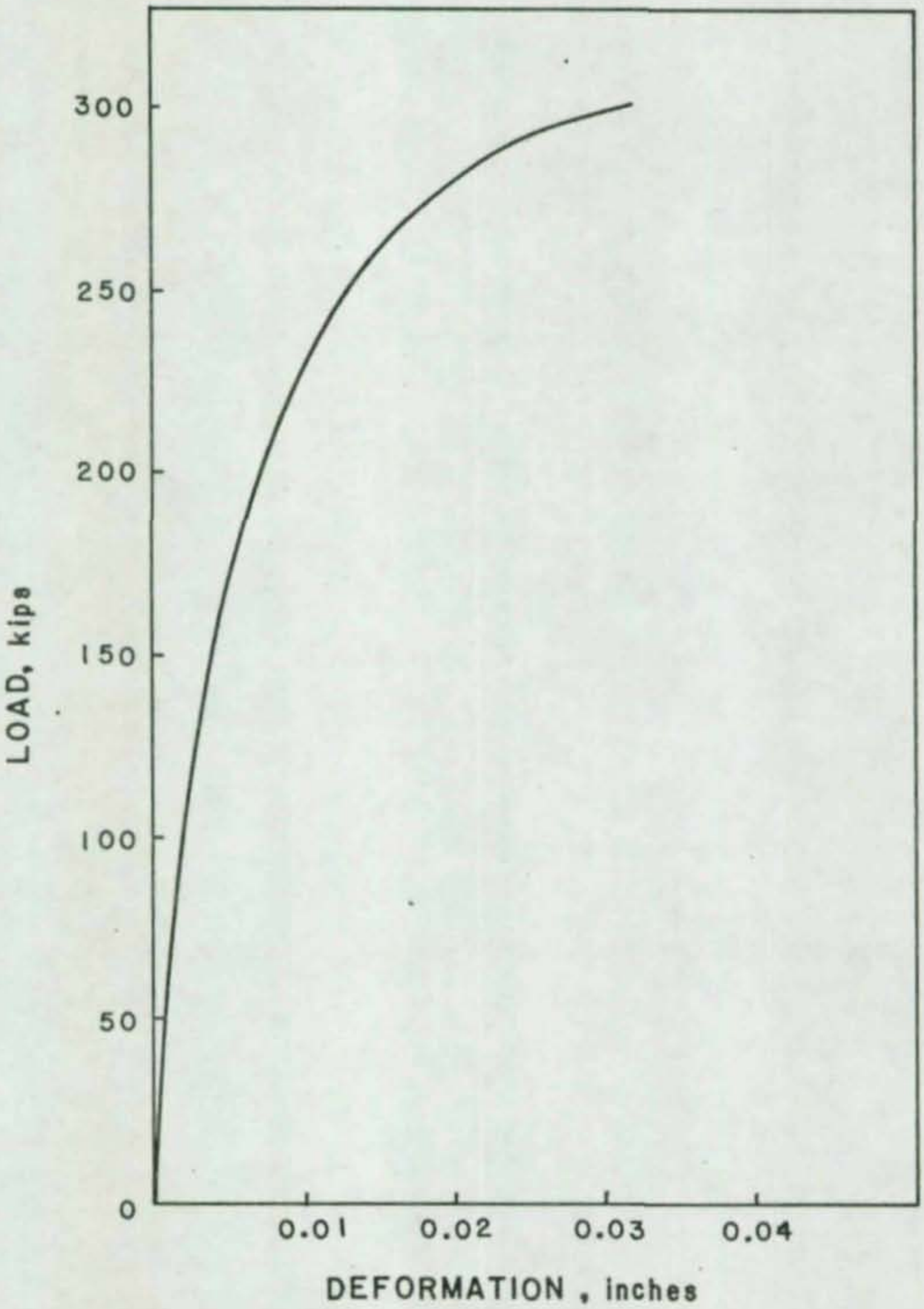


Figure 5. Load-Deformation Curve for Tension Splice with Transverse Welds (5).

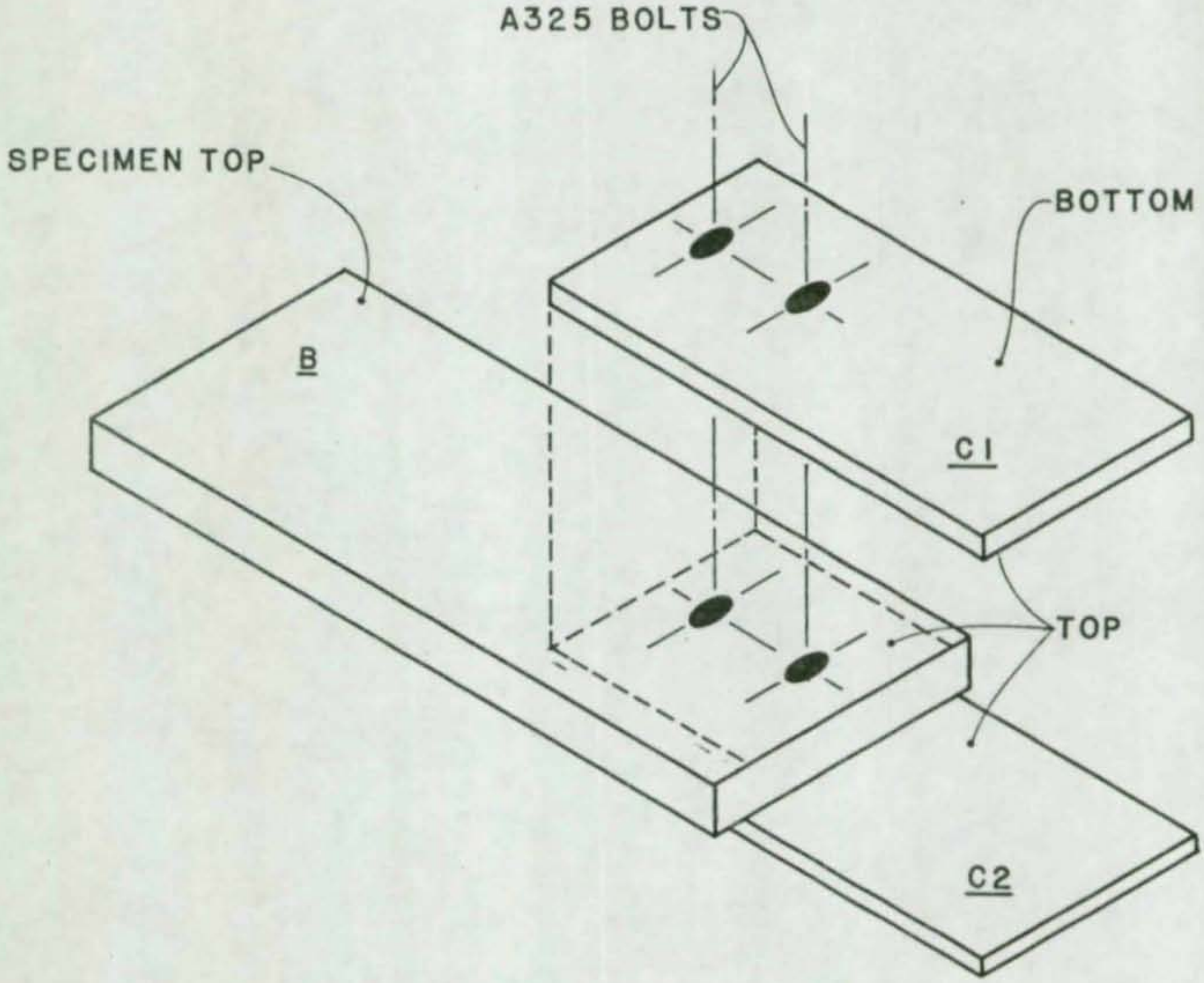


Figure 6. Assembly of Bolted Splice.

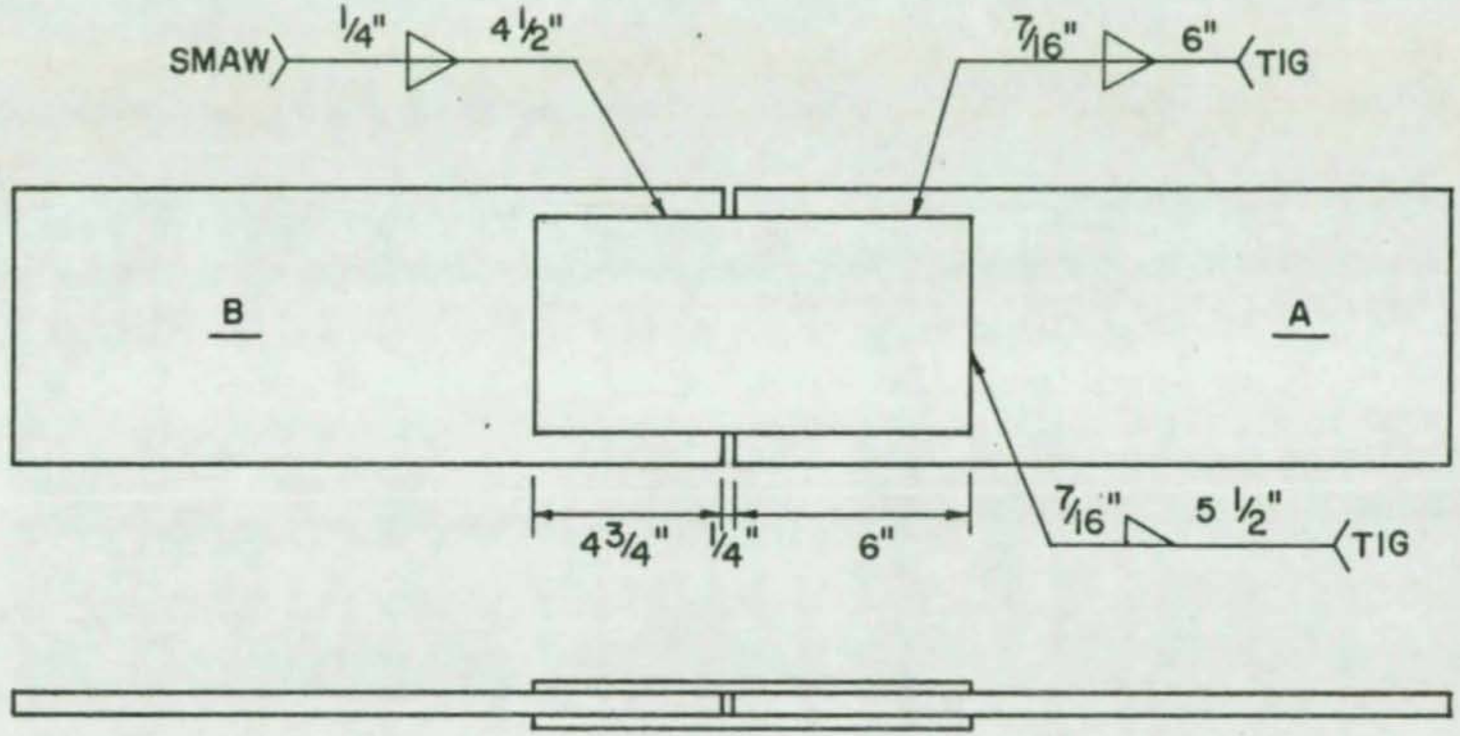


Figure 7. Assembly of Welded Splice.

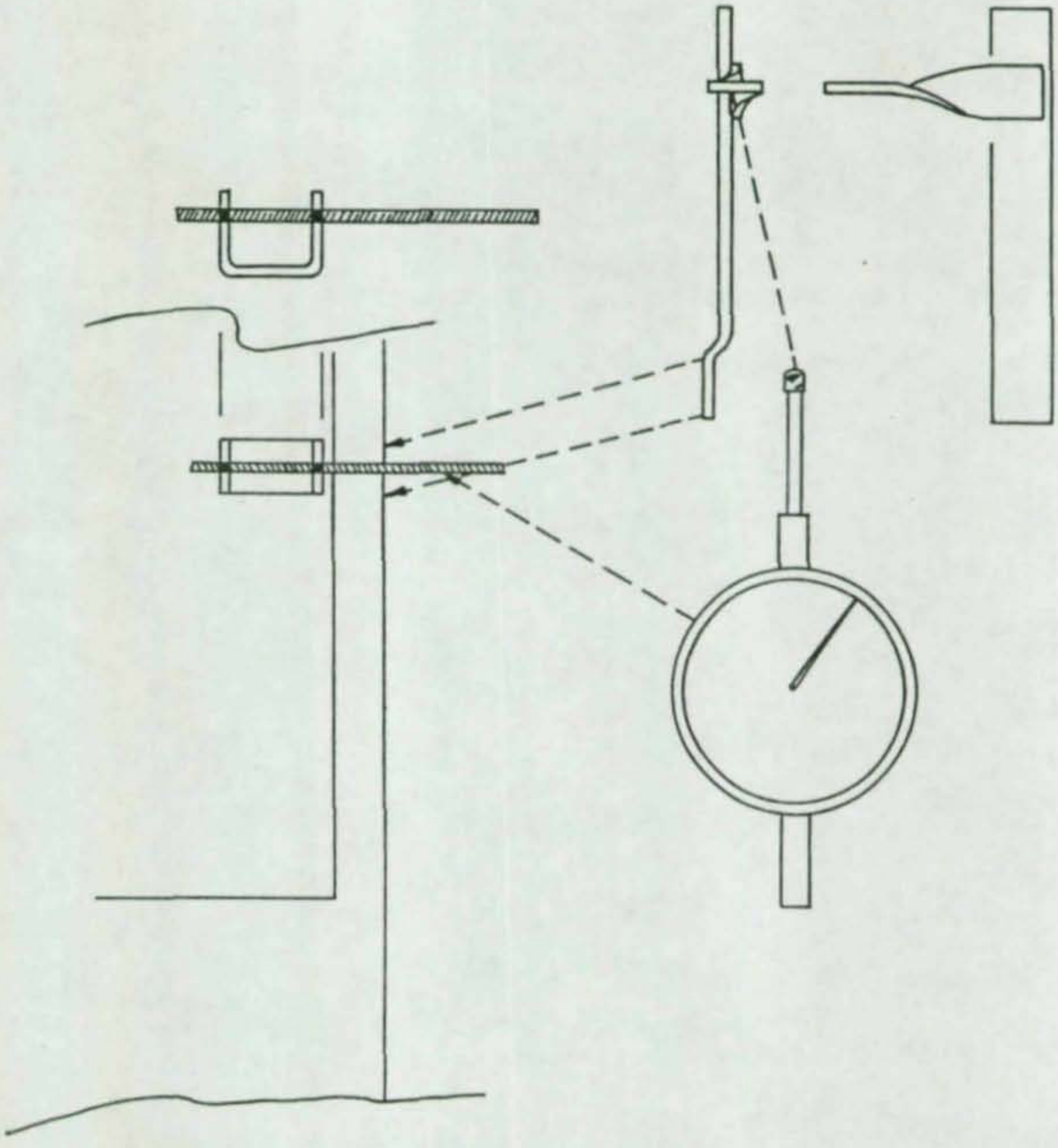


Figure 8. Dial Gage Attachment.

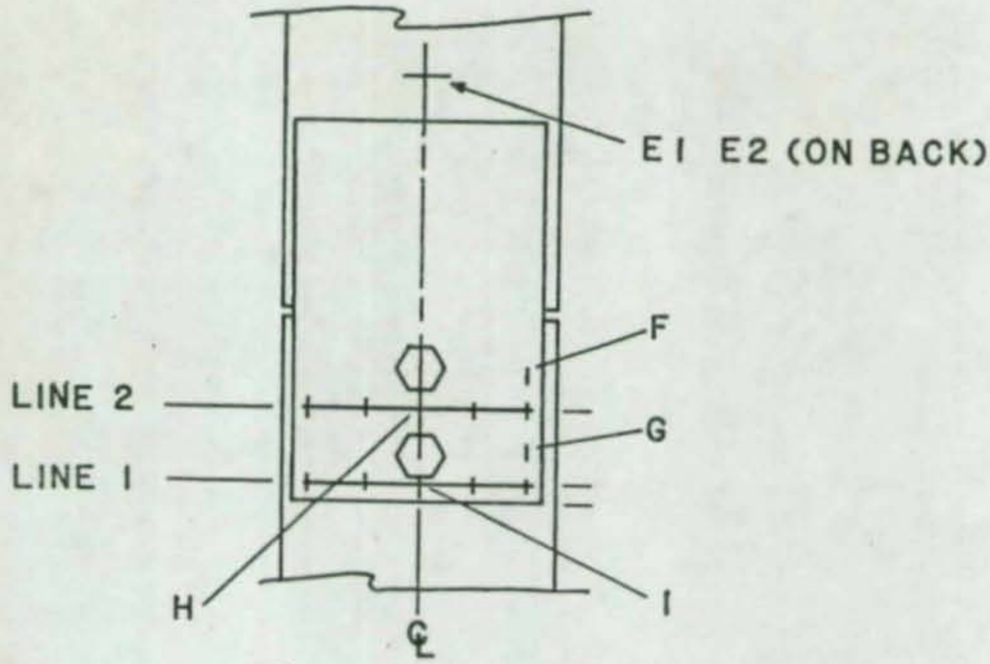


Figure 9. ERS Gage Locations.

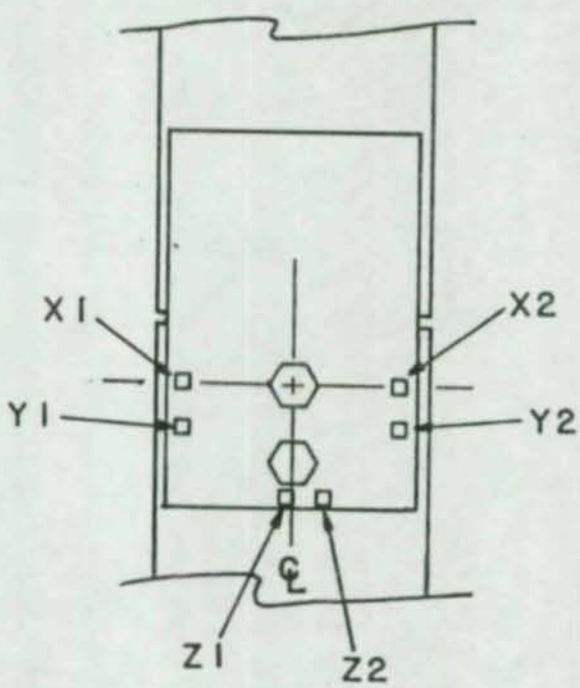


Figure 10. Dial Gage Locations.

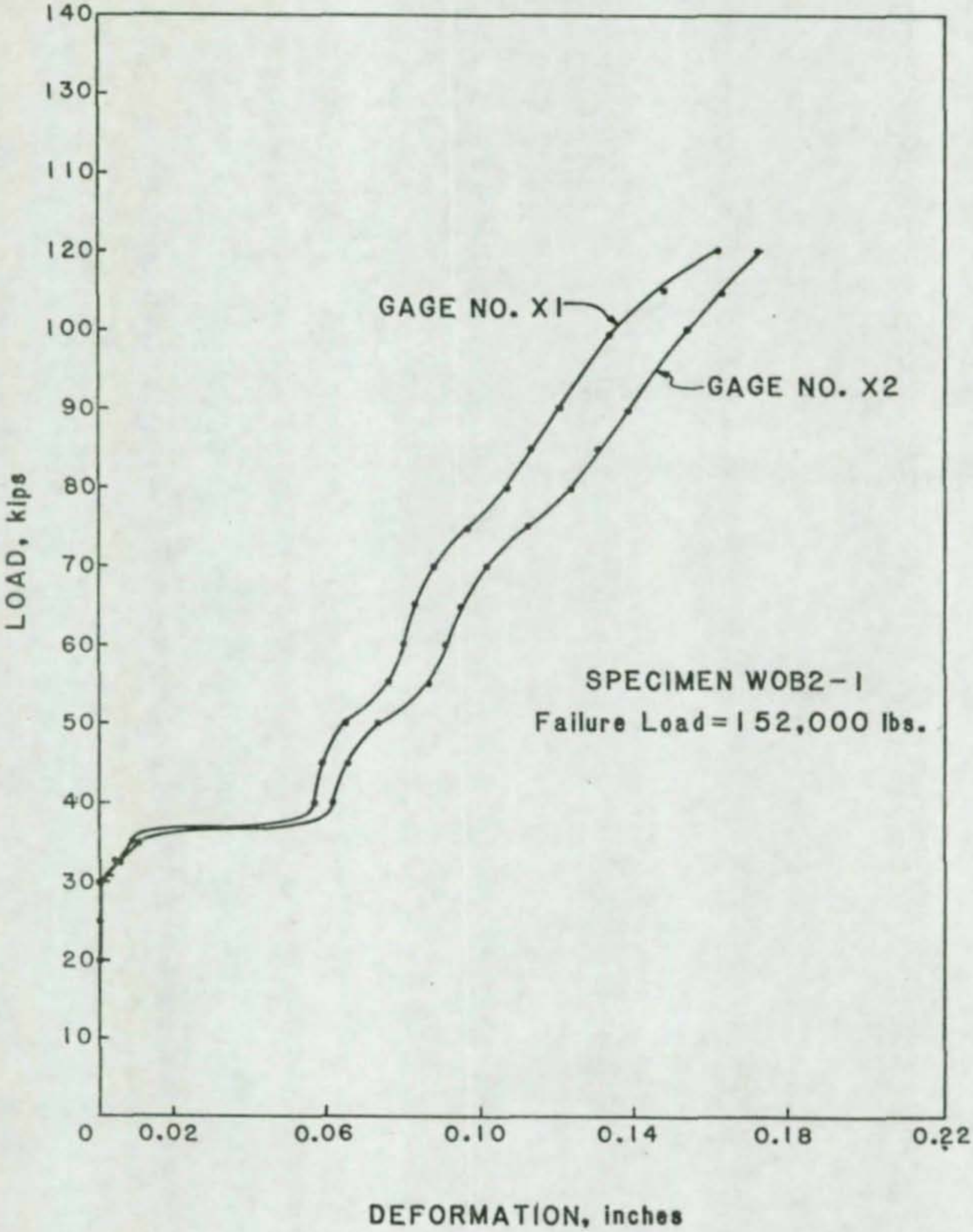


Figure 11. Load-Deformation Curve for Specimen WOB2-1

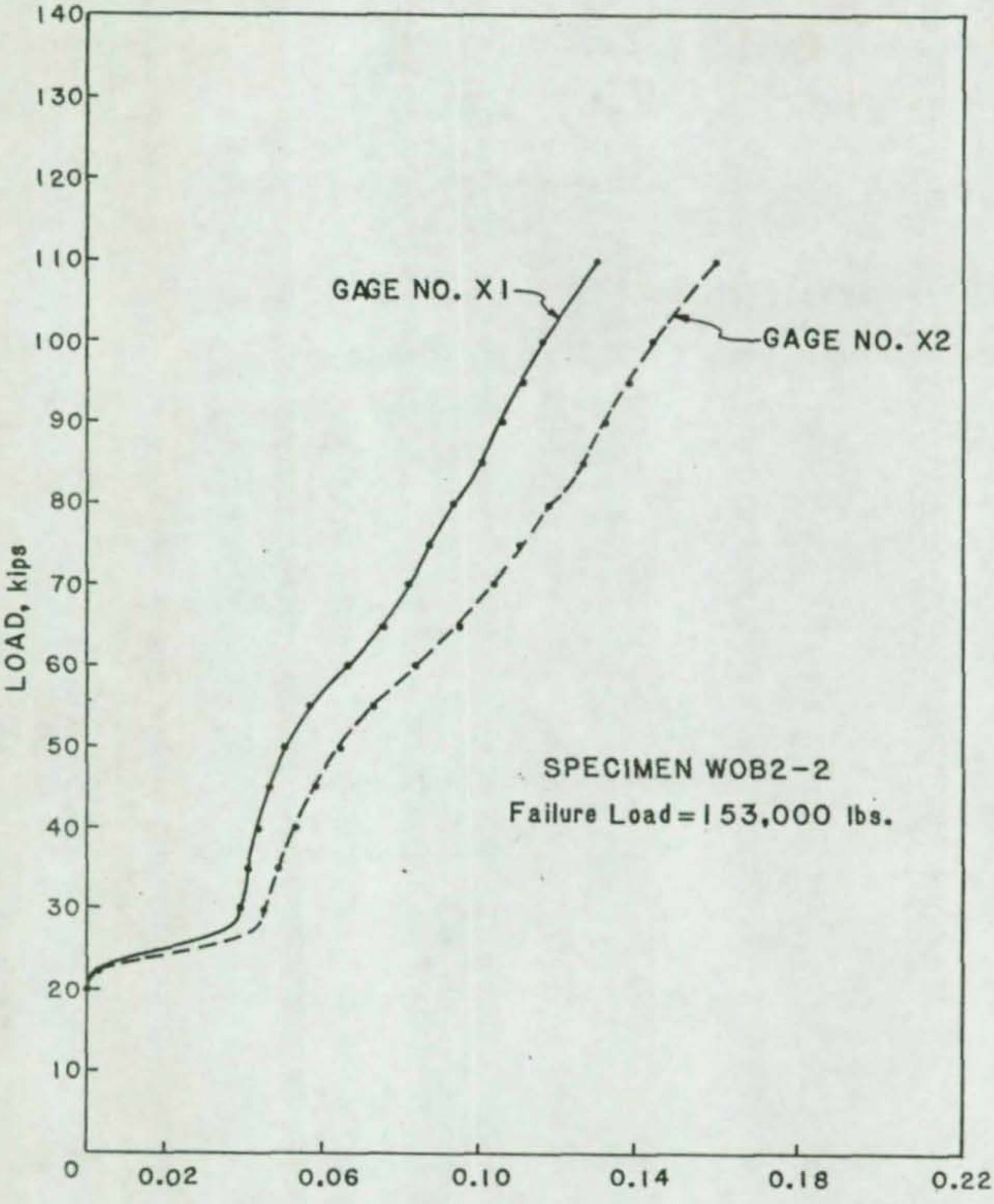


Figure 12. Load-Deformation Curve for Specimen WOB2-2.

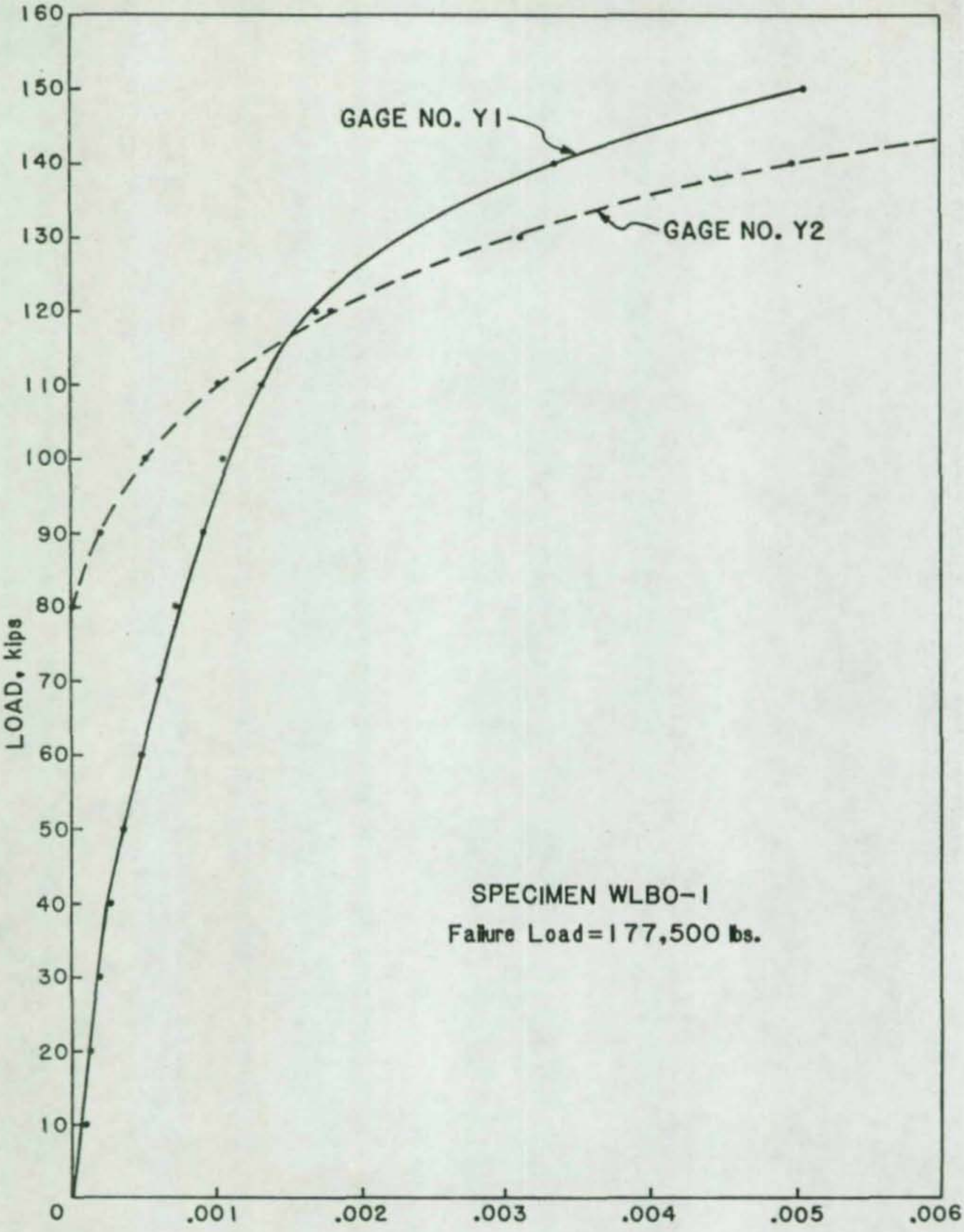


Figure 13. Load-Deformation Curve for Specimen WLBO-1.

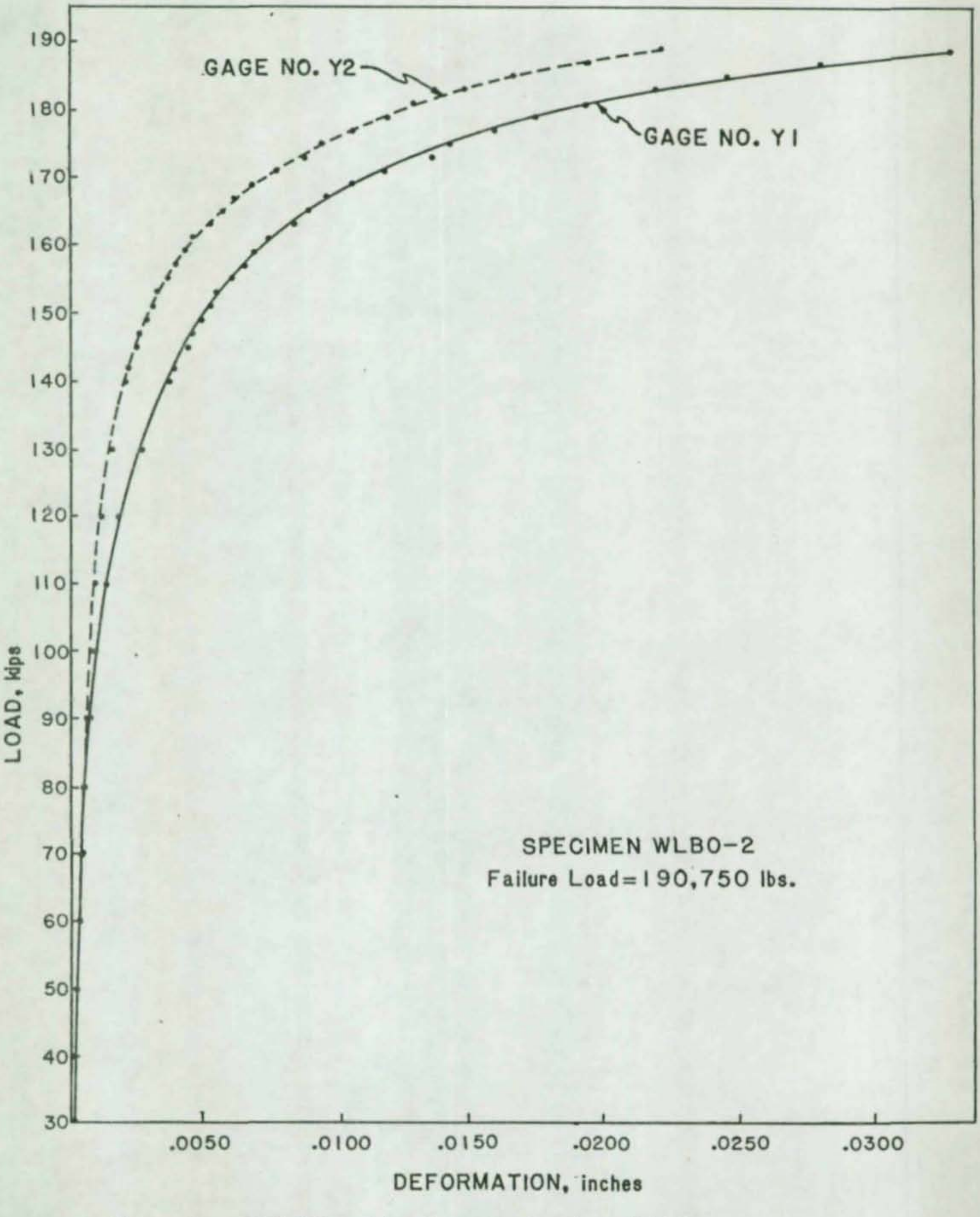


Figure 14. Load-Deformation Curve for Specimen WLBO-2.

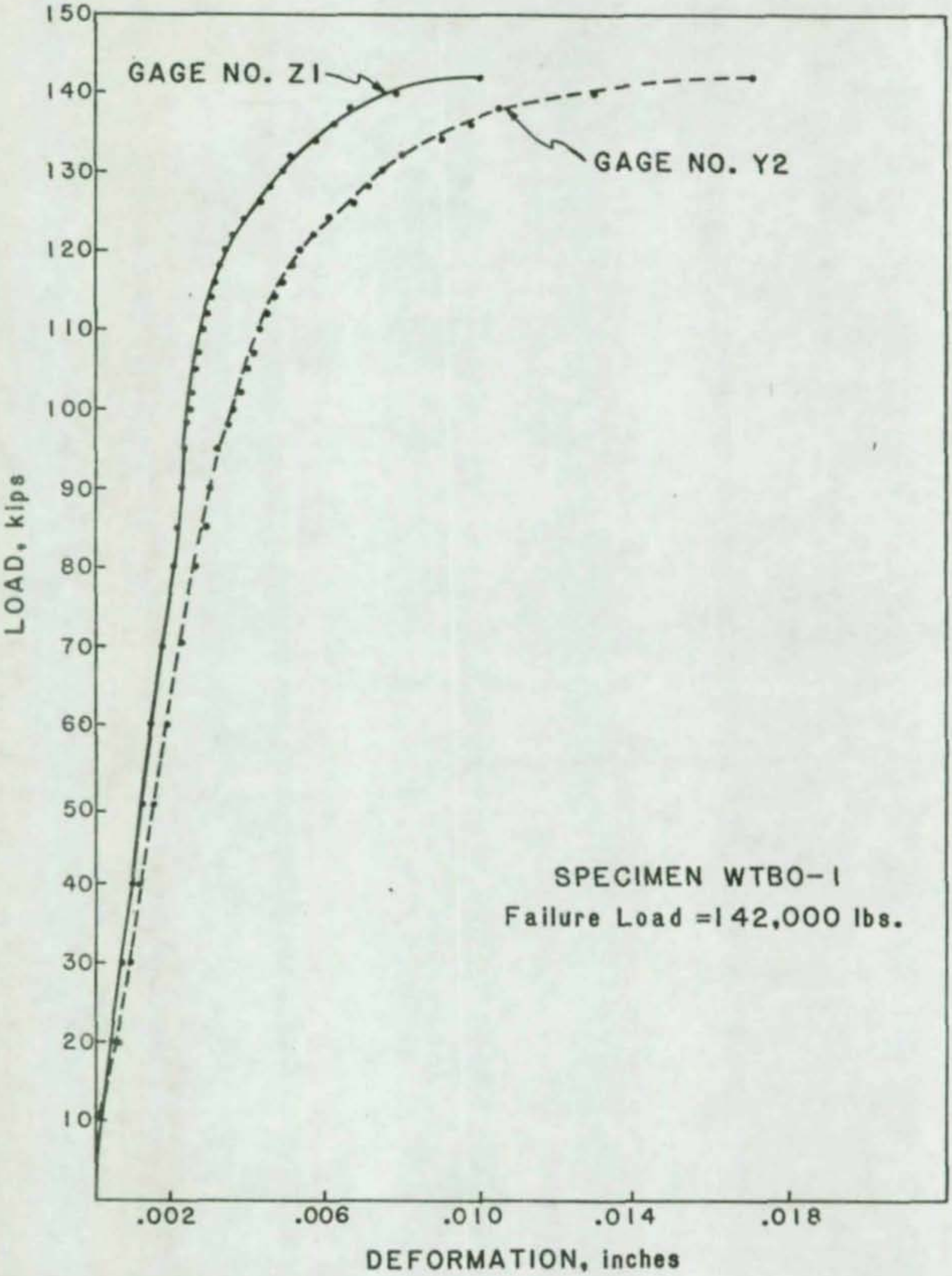


Figure 15. Load-Deformation Curve for Specimen WTBO-1

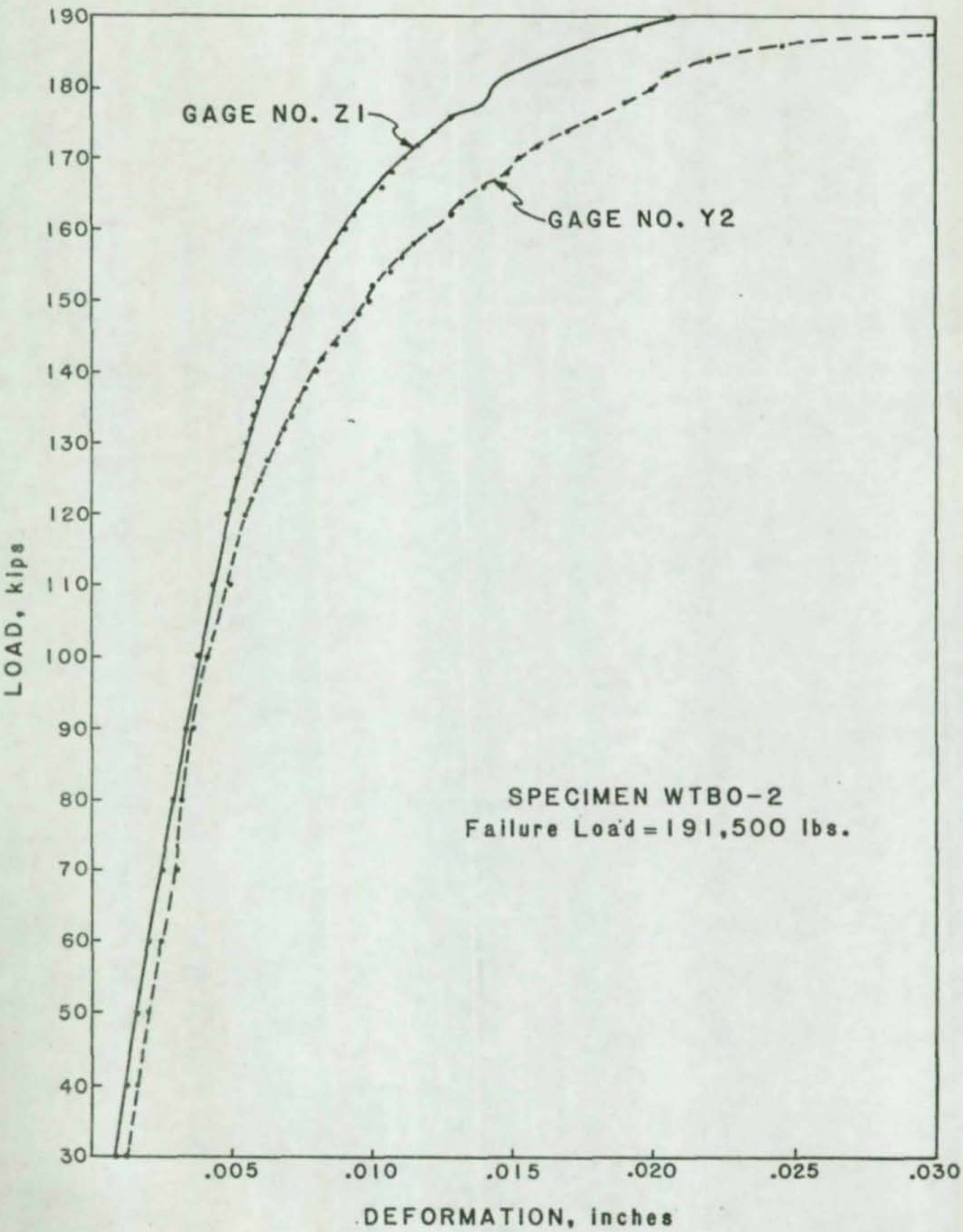


Figure 16. Load-Deformation Curve for Specimen WTBO-2.

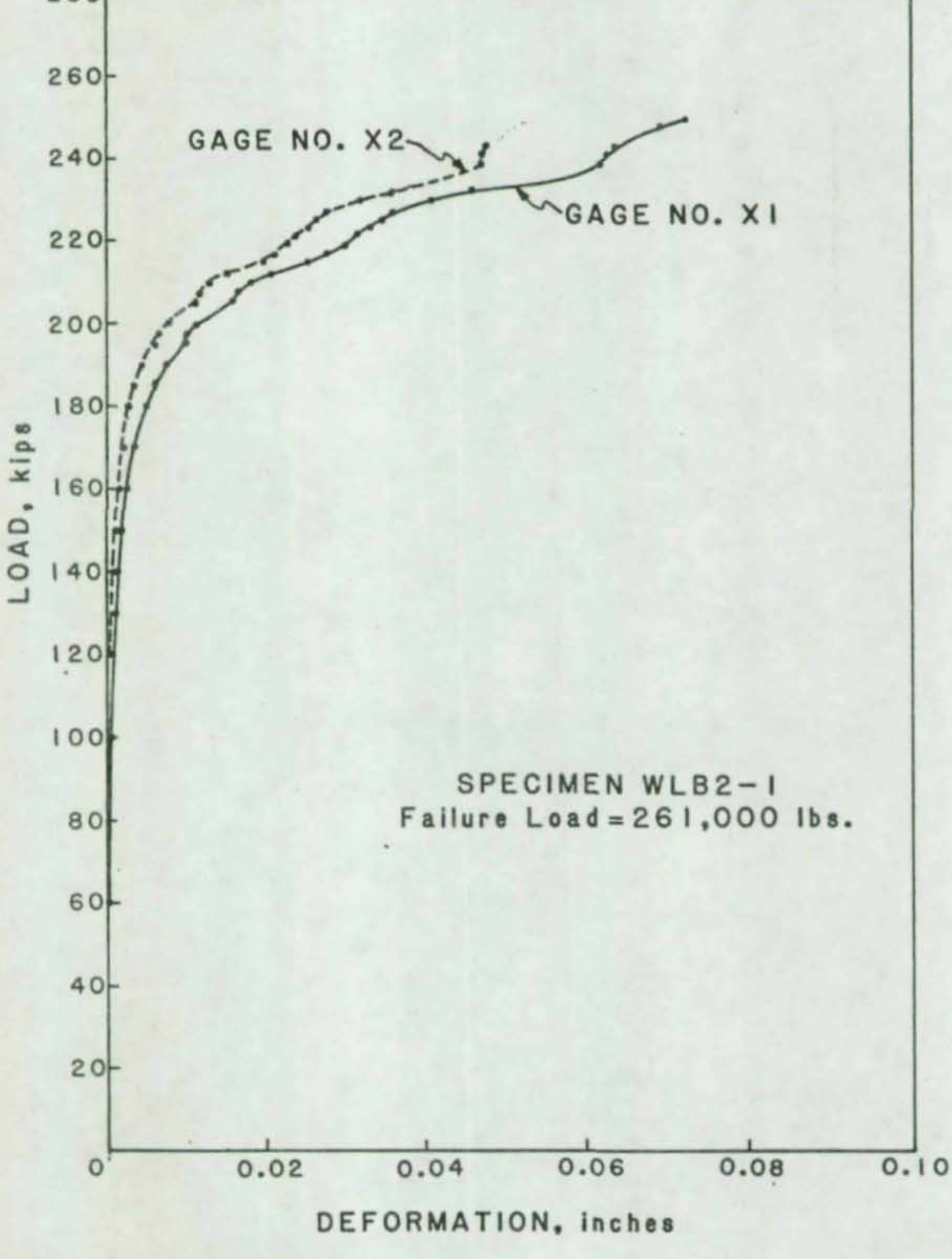


Figure 17. Load-Deformation Curve for Specimen WLB2-1.

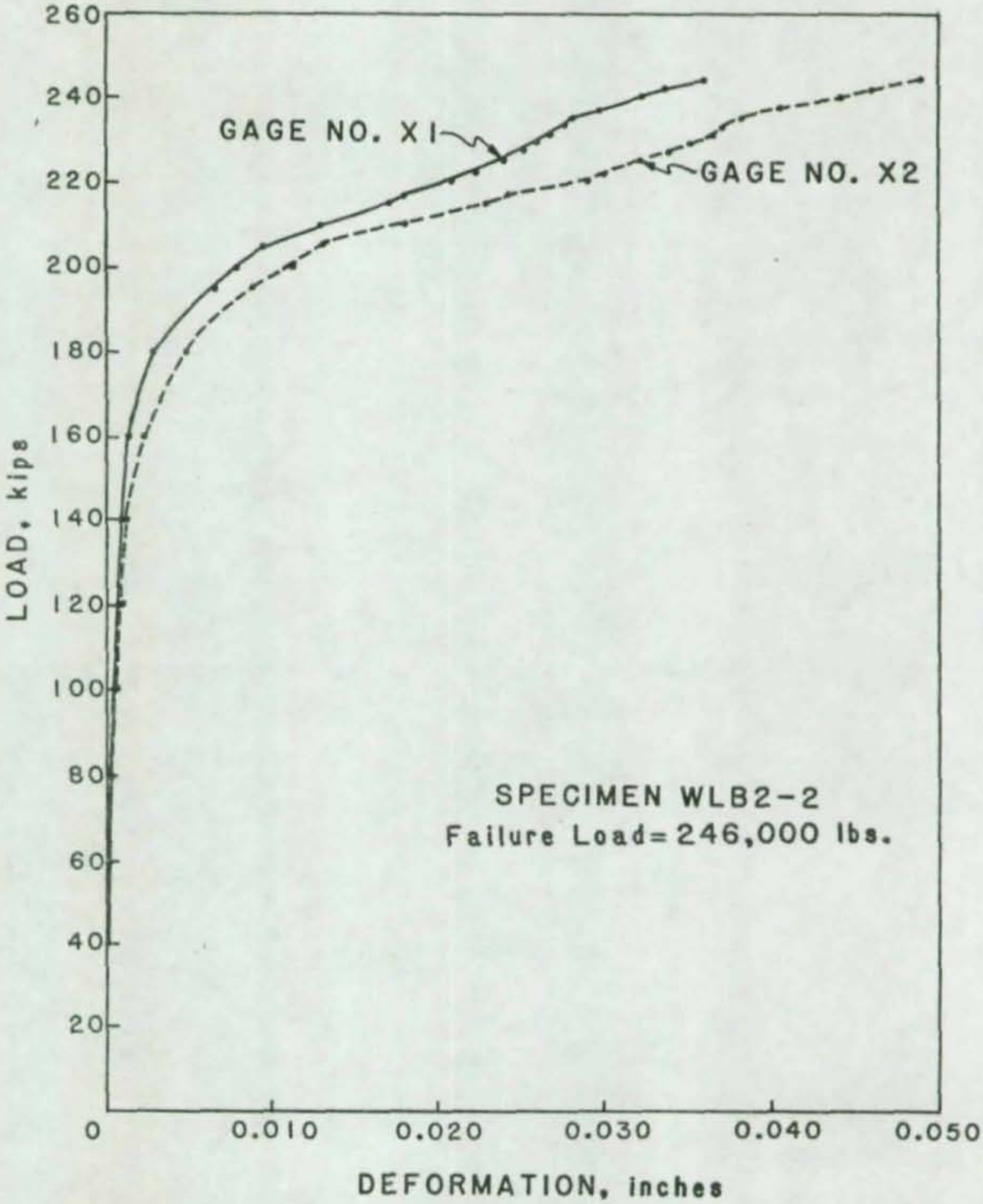


Figure 18. Load-Deformation Curve for Specimen WLB2-2.

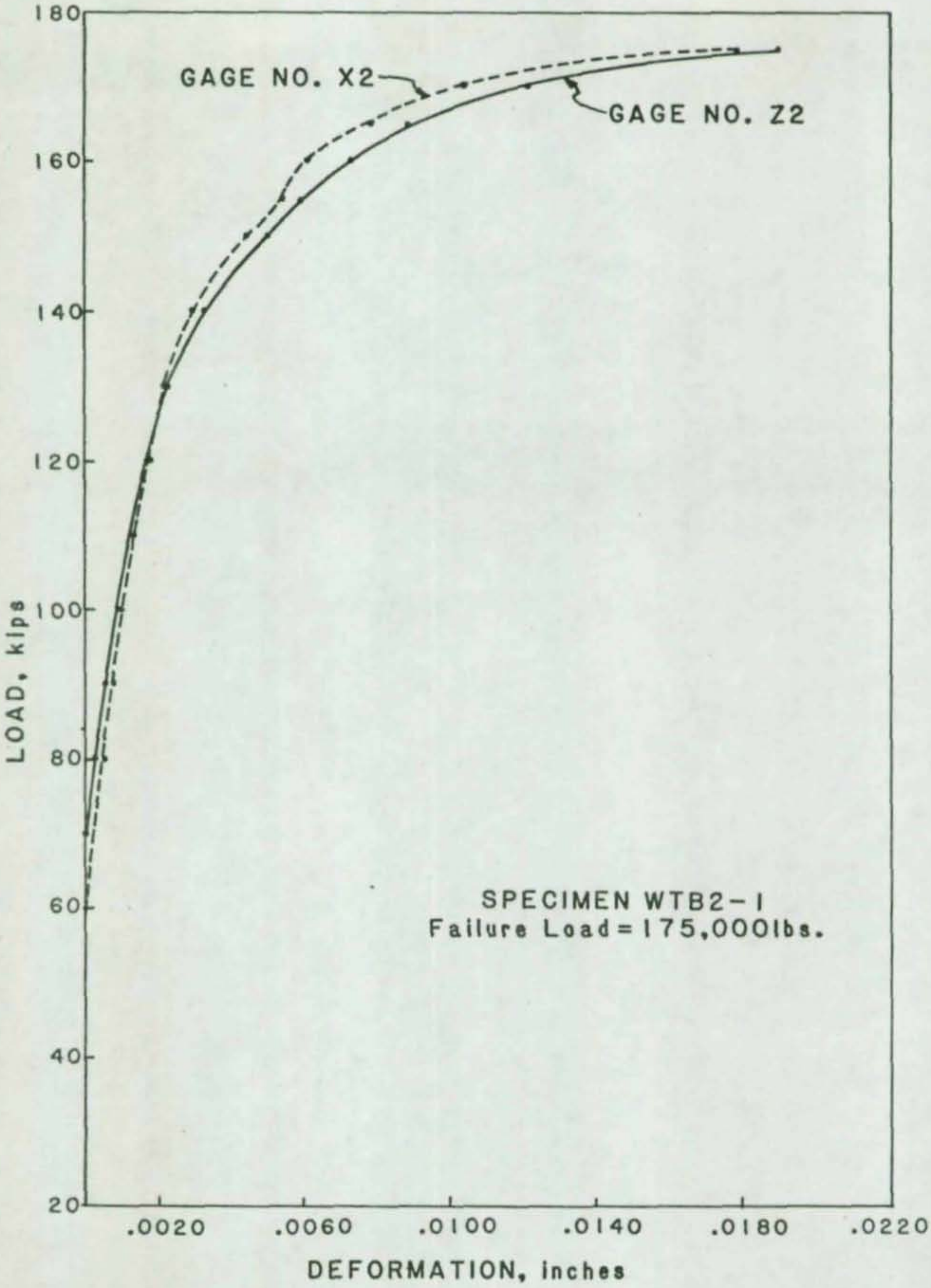


Figure 19. Load-Deformation Curve for Specimen WTB2-1.

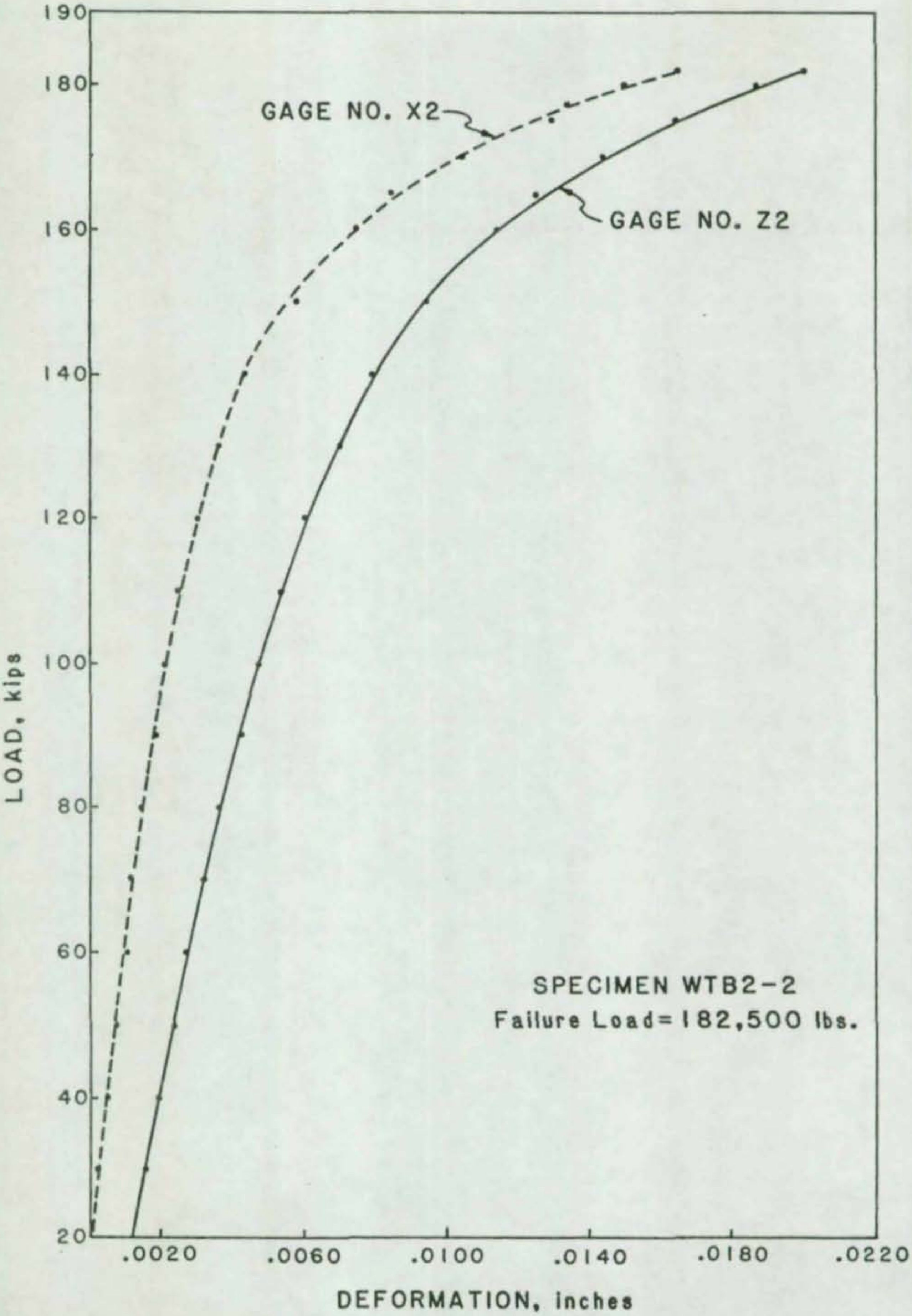


Figure 20. Load-Deformation Curve for Specimen WTB2-2.

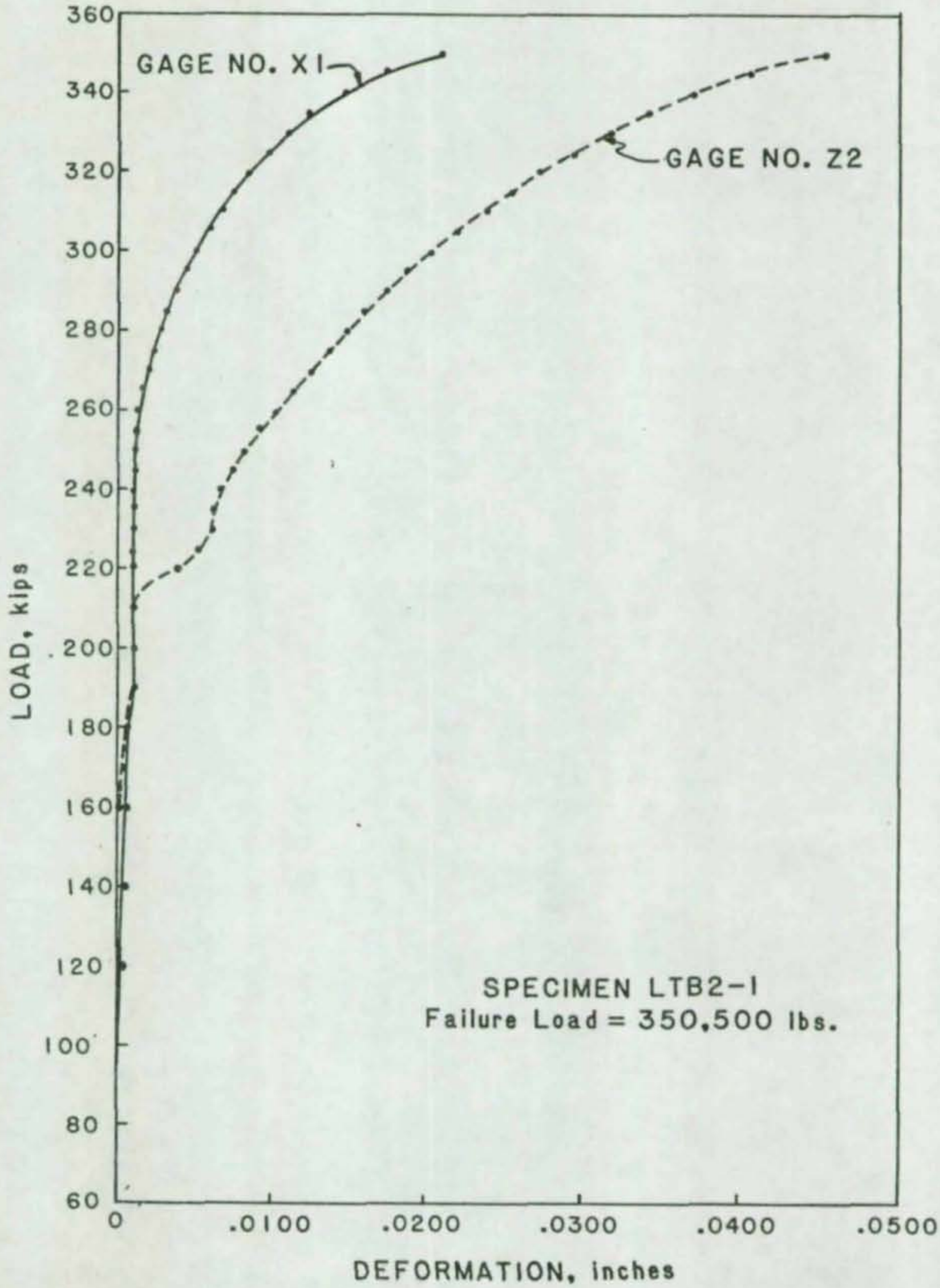


Figure 21. Load-Deformation Curve for Specimen LTB2-1.

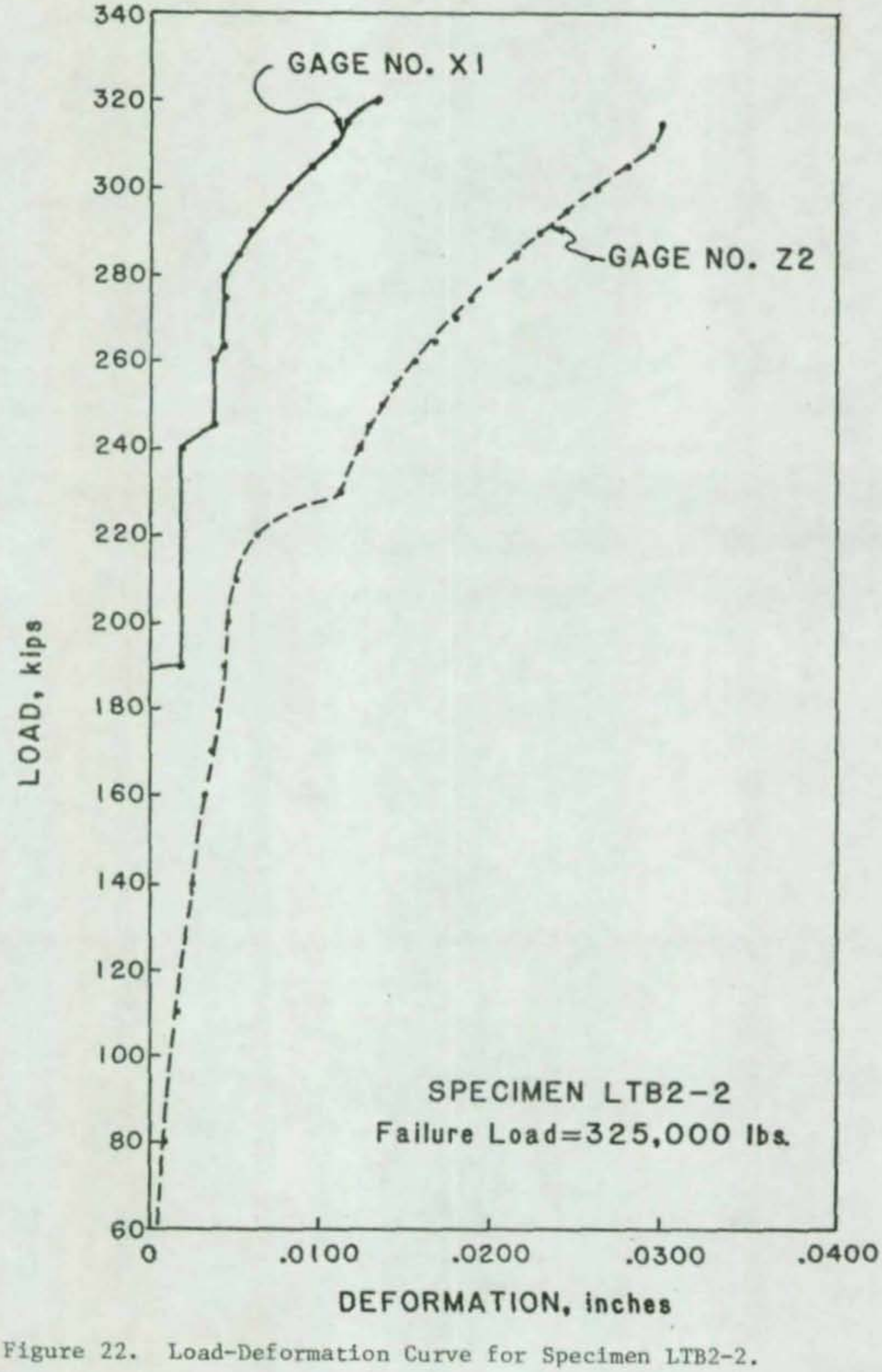


Figure 22. Load-Deformation Curve for Specimen LTB2-2.

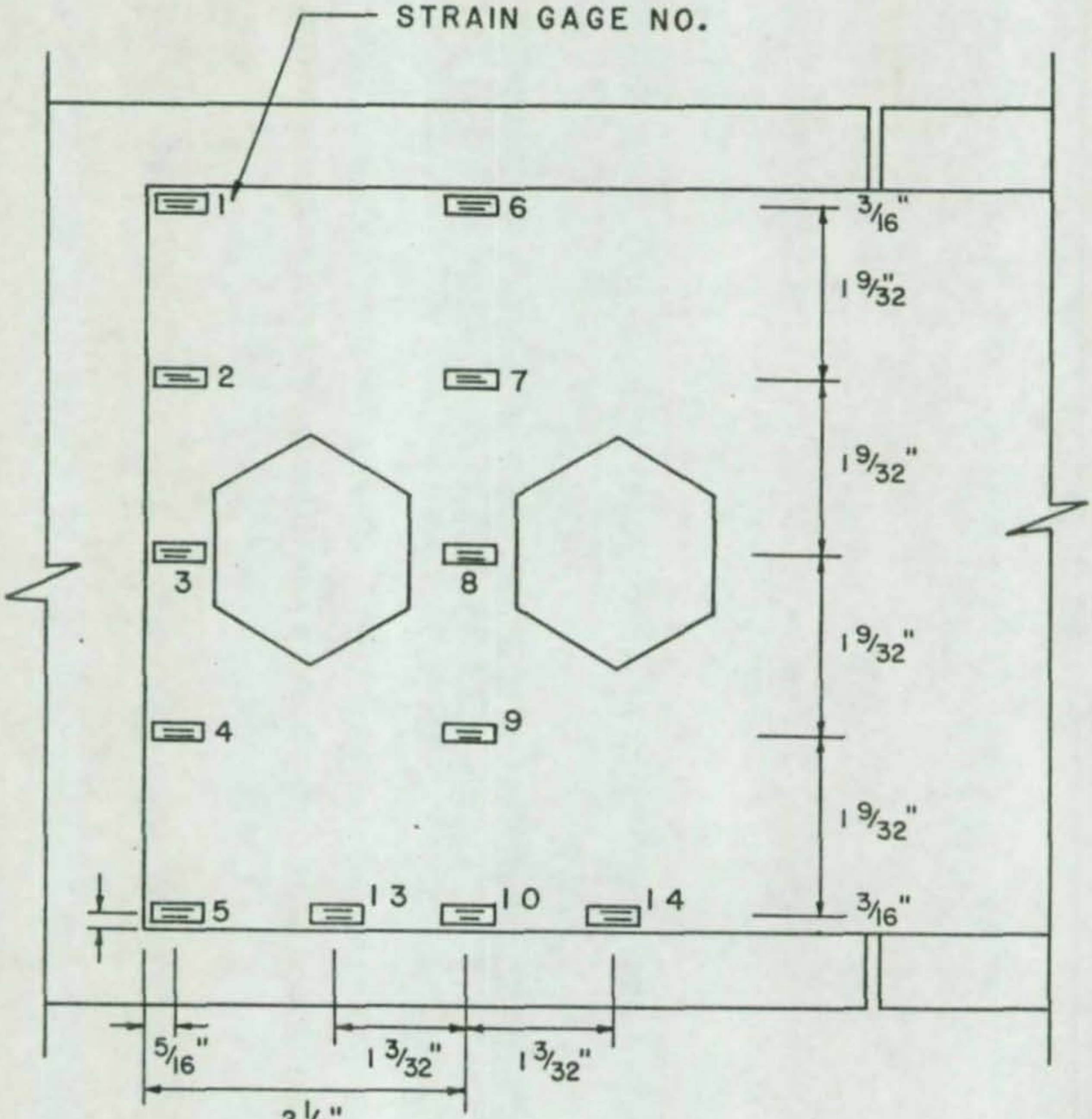


Figure 23. Strain Gage Locations.

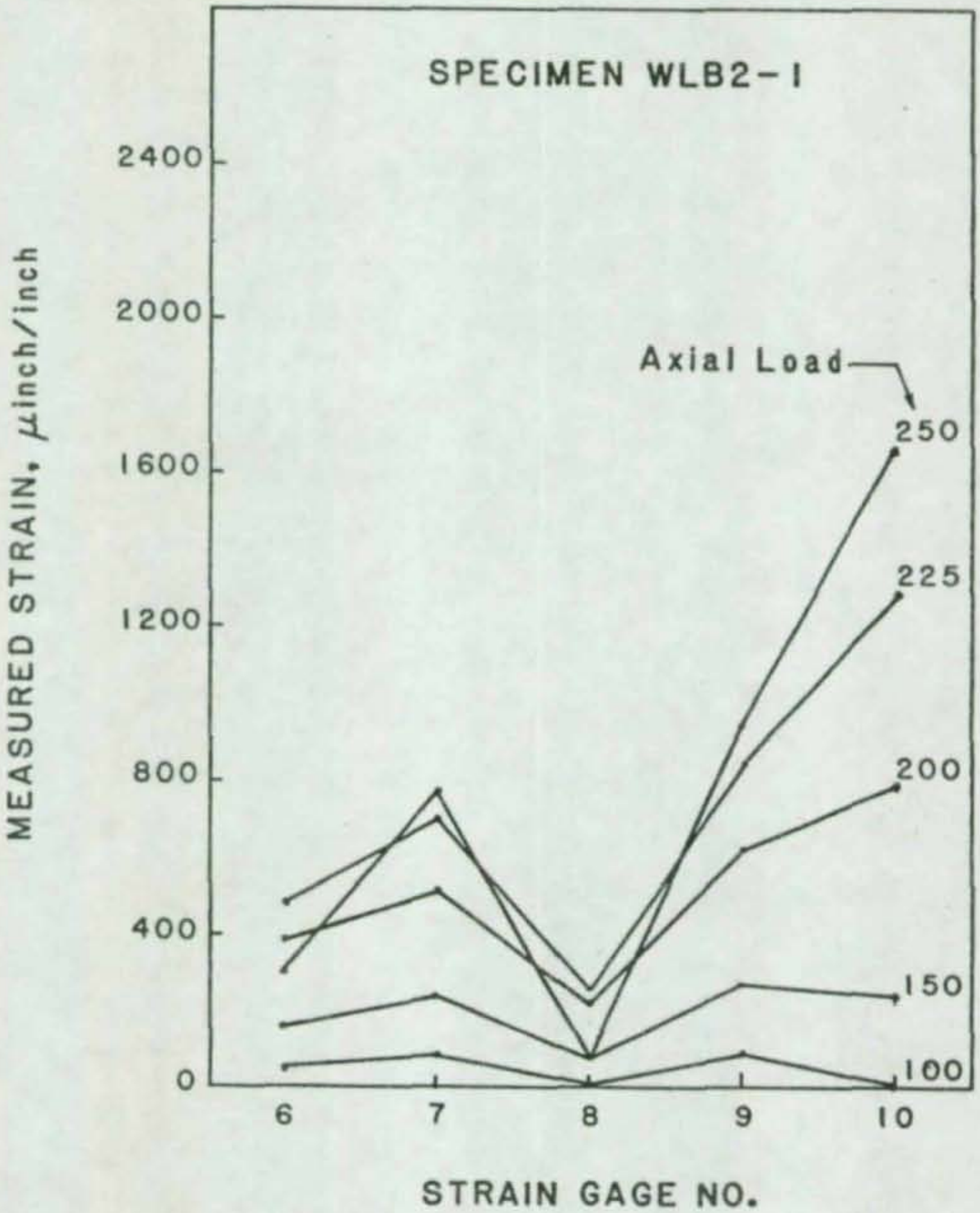


Figure 24. Strains Measured in Gages 6-10 for Specimen WLB2-1.

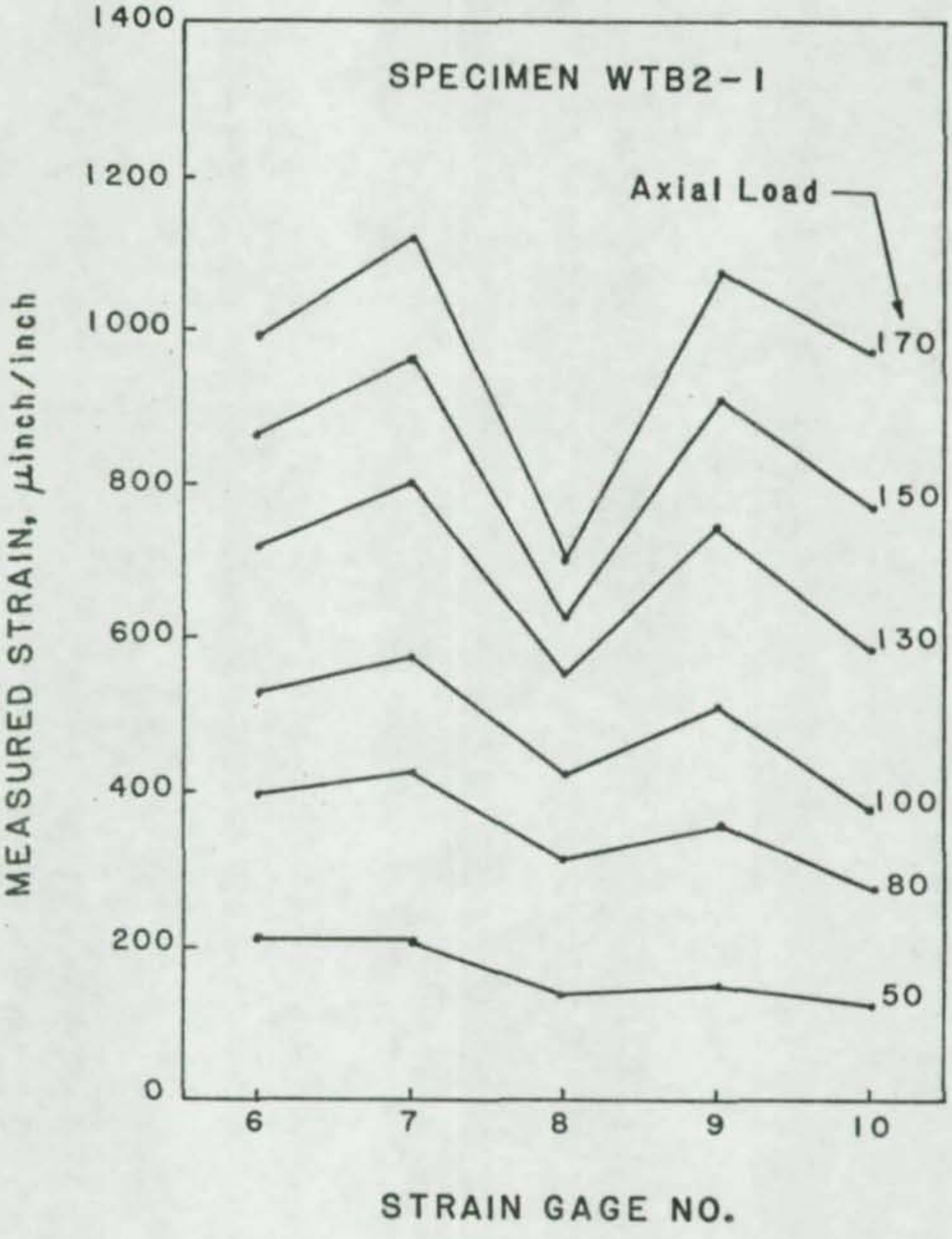


Figure 25. Strains Measured in Gages 6-10 for Specimen WTB2-1.

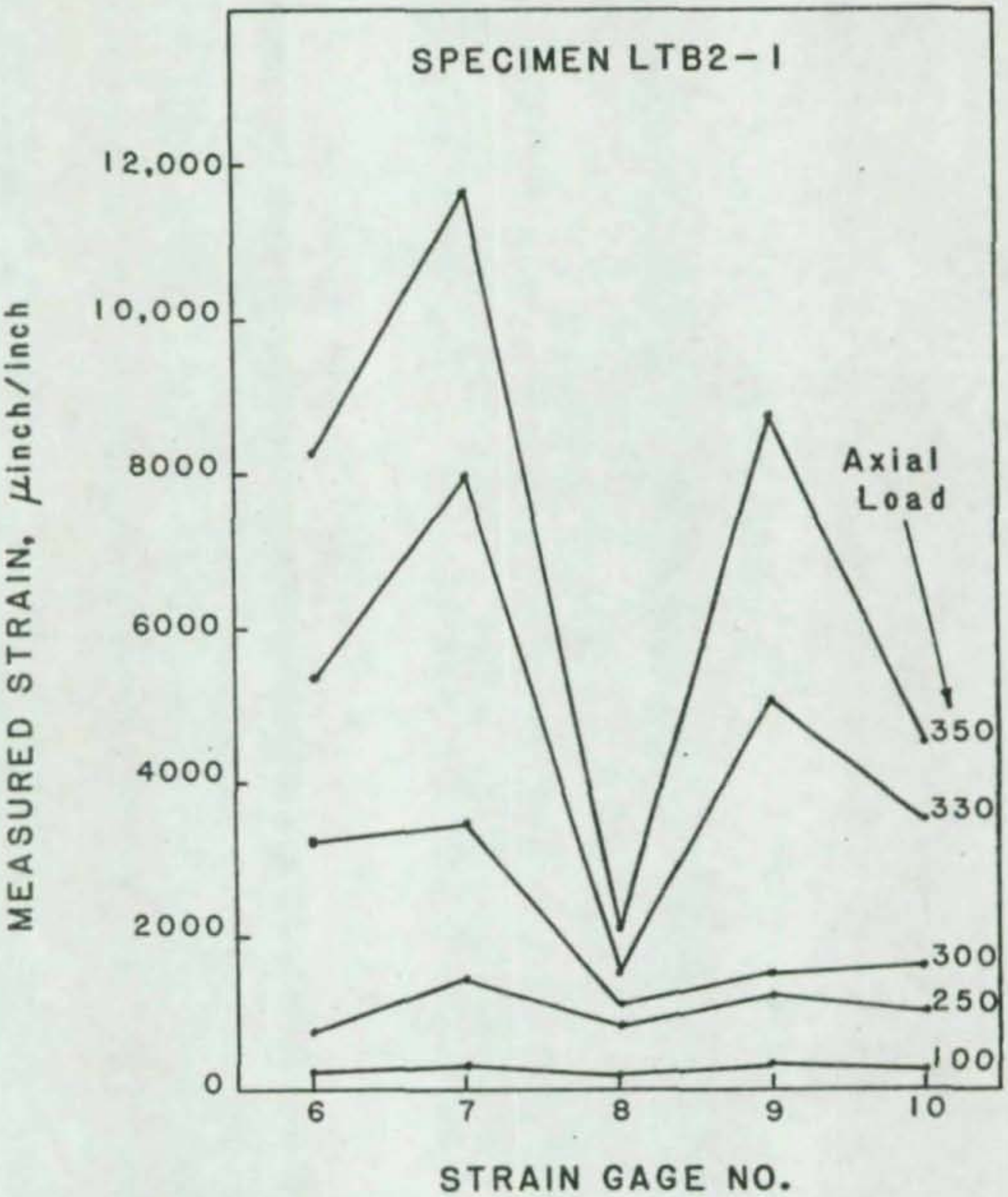


Figure 26. Strains Measured in Gages 6-10 for Specimen LTB2-1.

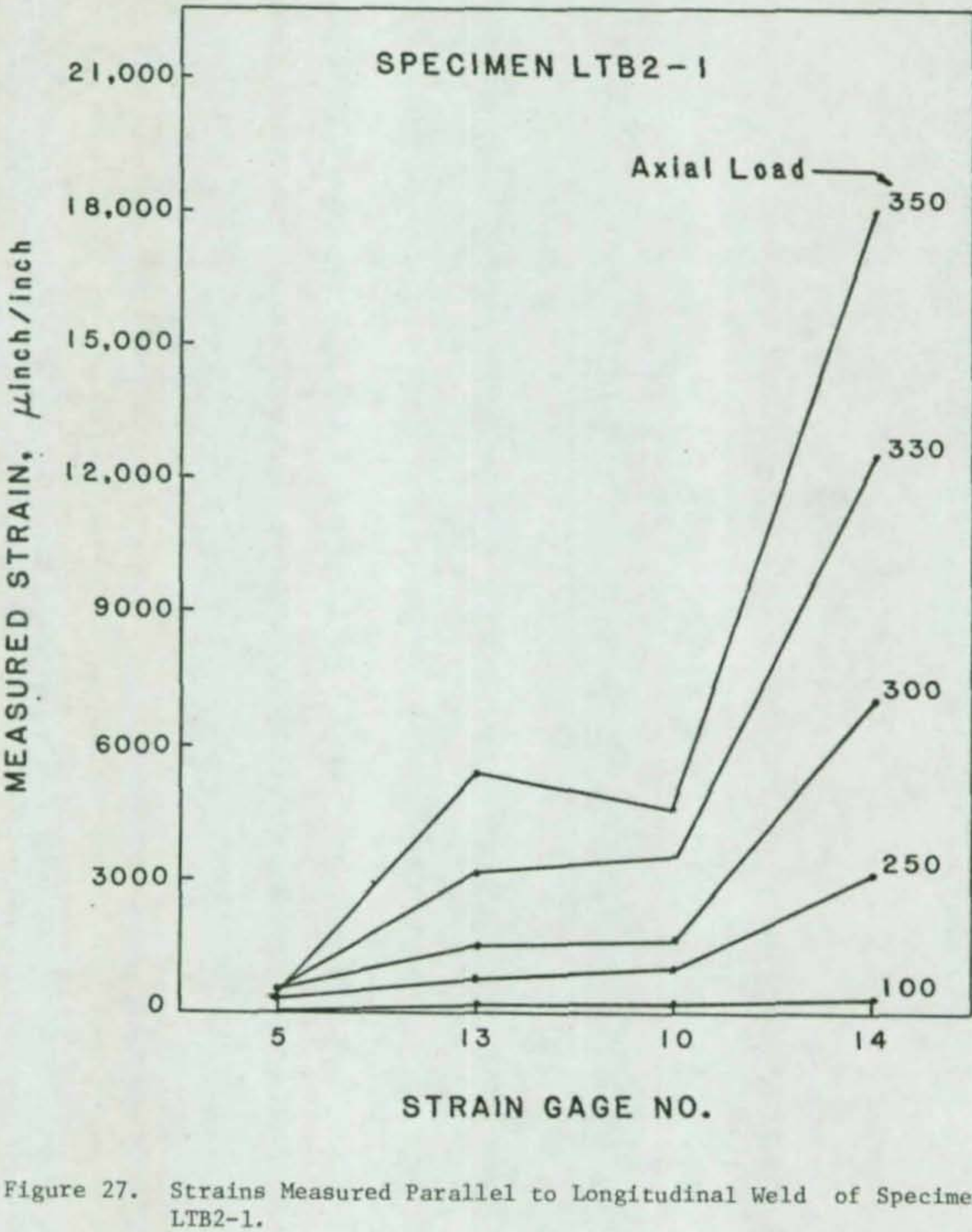


Figure 27. Strains Measured Parallel to Longitudinal Weld of Specimen LTB2-1.

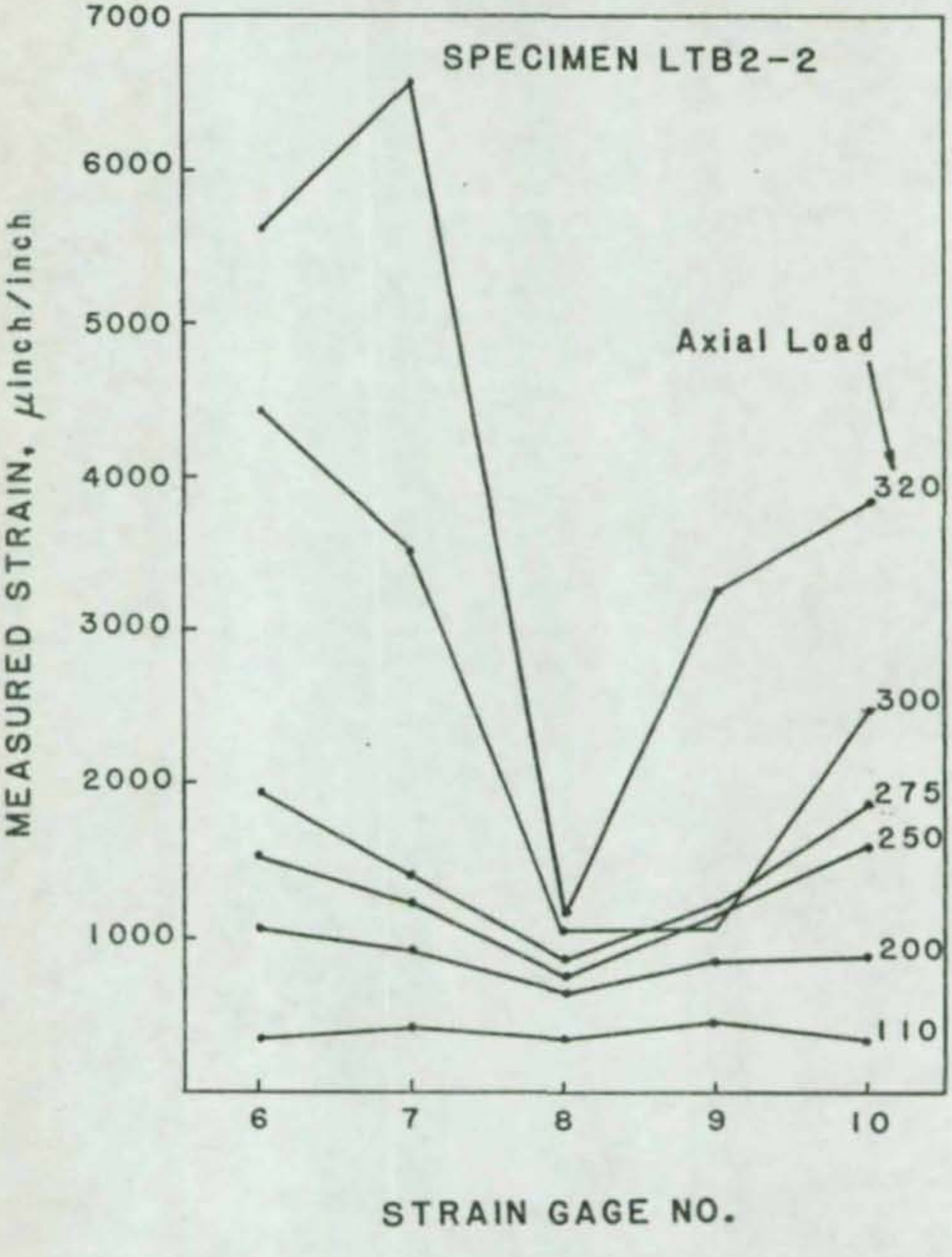


Figure 28. Strains Measured in Gages 6-10 for Specimen LTB2-2.

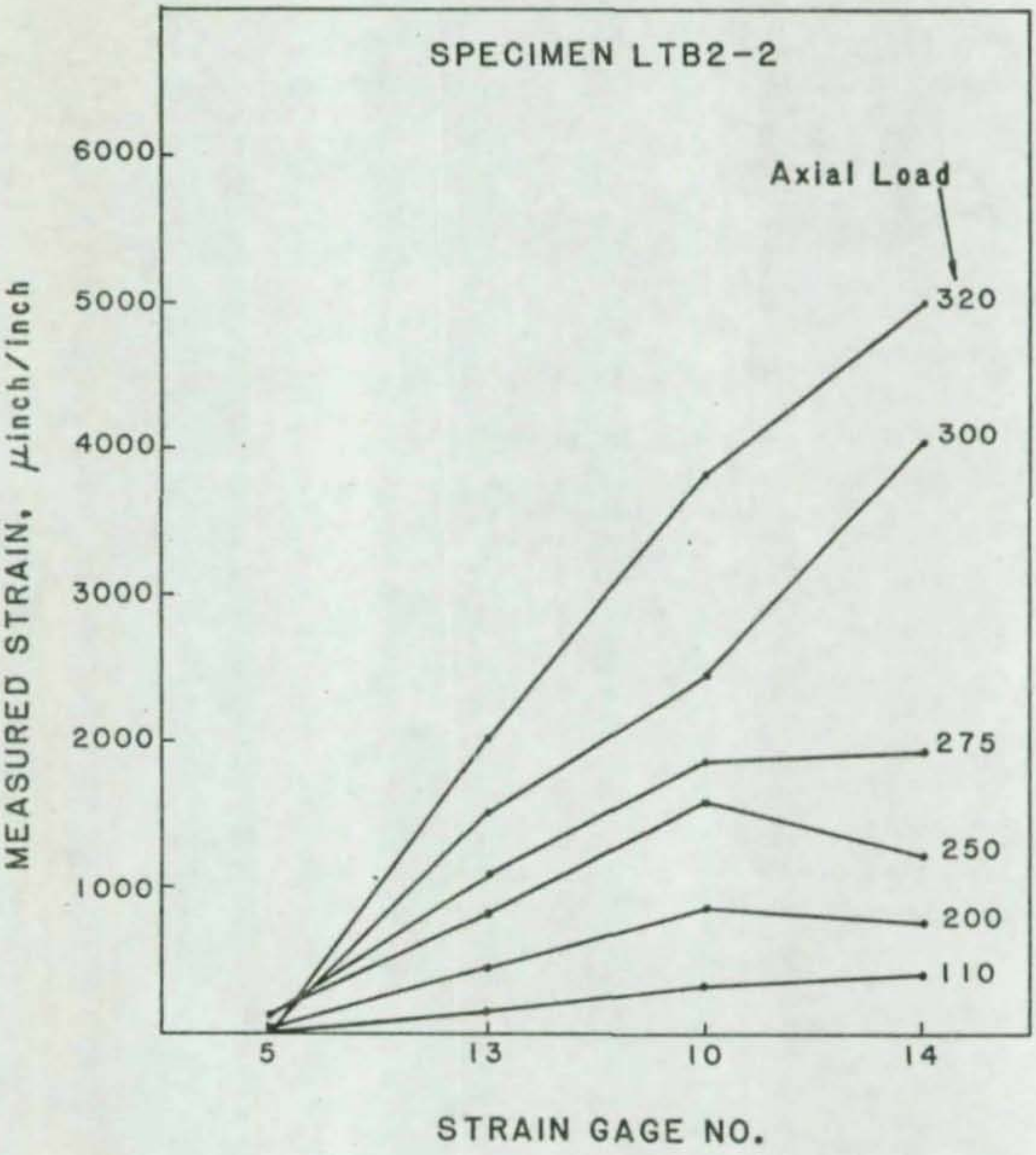


Figure 29. Strains Measured Parallel to Longitudinal Weld of Specimen LTB2-2.

APPENDIX A -- Procedural Deviations

WOB2-1

The steel plates for Specimen WOB2-1 were donated by International Steel Corporation, and were cut frm scrap A36 steel. The plates had clean mill scale on one side, and mill scale with some corrosion on the other side. The contact surfaces were of similar type, that is, clean mill scale to clean mill scale, and rusty mill scale to rusty mill scale.

One ERS gage was placed behind each 3/4-inch bolt. The surface was prepared after the specimen was completely assembled. Only files and sand paper, instead of the power grinder, were used to prepare the surface.

The plate and hole dimensions were measured with a metal scale divided into sixty-fourths of an inch. Plate thickness was measured using a micrometer.

The sequence of fabrication was not the same as for the other specimens. Plates C1 and C2 were fastened to Plate A with 1-inch A490 bolts. This assembly was then welded at the Central Machine Shop using the TIG process. Plate B was fastened later with 3/4-inch A325 bolts. Upon placing the TIG weld, Plates C1 and C2 spread apart slightly, requiring the 3/4-inch bolts to bend them into contact with Plate B. Because of this effect, the sequence of fabrication was changed for the remaining specimens.

WOB2-2

The general procedure indicates side B was welded first, but for this specimen no welds were required on side B.

WLBO-1, WLBO-2, WTBO-2

During the welding, the supply of 5/32-inch (4.0 mm) E6010 electrodes was depleted. As a substitute, 1/8-inch (3.2 mm) E6010 electrodes were used. This shortage occurred after specimen WTBO-1 was completed. One side of each specimen, WLBO-1, WLBO-2, and WTBO-2 had already been welded with 5/32-inch electrodes, so the other side had to be completed using the 1/8-inch electrodes.

WLB2-1

Instead of the specified EA-06-240LZ-120 ERS gages, EA-13-240LZ-120 ERS gages were mistakenly placed on the specimen. The primary difference in the gages is related to the thermal coefficient of expansion, and is critical only under conditions of varying temperature. Accordingly, the temperature was monitored during this test, and was found to vary by only 0.1 degree F (0.06 degree C), which is negligible.

LTB2-1

During the welding process, a portion of one of the 1/4-inch longitudinal welds was found to be defective. It was ground out and replaced. The original weld was made with 5/32-inch E6010 electrodes but, because of a shortage of this electrode size, the repair was made using 1/8-inch E60 electrodes.

LTB2-2

After fabrication of the specimens, it was decided to place ERS gages on this specimen. Therefore, a power grinder could be used only on a limited area of the plate surface. Behind the bolts, the mill scale was removed with files and sand paper.

APPENDIX B -- Load-Deformation Data

TABLE B.1 Specimen WOB2-1

Load (kips)	Deformation Gage X1 (in)	Deformation Gage X2 (in)
0	0	0
10	0	0
20	0	0
25	0.001	0
30	.001	0
32.5	.0055	.006
35	.0090	.0105
40	.0567	.0620
45	.0590	.0650
50	.0650	.0732
52	--	--
55	.0750	.0862
60	.0800	.0910
65	.0830	.0950
70	.0880	.1015
75	.0966	.1118
80	.1070	.1235
85	.1132	.1305
90	.1210	.1390
95	--	--
100	.1345	.1535
105	.1480	.1630
110	.1520	.1720
120*	--	--

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 152.5 kips
*Dial gages removed

TABLE B.2 Specimen WOB2-2

Load (kips)	Deformation Gage X1 (in)	Deformation Gage X2 (in)
0	0	0
10	.0005	0
20	.0008	.0001
30	.0391	.0450
35	.0411	.0486
40	.0436	.0520
45	.0465	.0580
50	.0501	.0640
55	.0565	.0724
60	.0655	.0832
65	.0755	.0945
70	.0814	.1031
75	.0870	.1095
80	.0931	.1172
85	.1000	.1255
90	.1050	.1312
95	.1095	.1370
100	.1150	.1431
110	.1290	.1590
120*	--	--

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 153.0 kips
*Dial gages removed

TABLE B.3 Specimen WLBO-1

Load (kips)	Deformation Gage Y1 (in)	Deformation Gage Y2 (in)
0	0	0
10	.00008	0
20	.00011	0
30	.00019	0
40	.00026	0
50	.00036	0
60	.00047	0
70	.00061	0
80	.00072	0
90	.00091	.00020
100	.00105	.00051
110	.00132	.00101
120	.00170	.00179
130	.00231	.00312
140	.00335	.00495
150	.00505	.00805
160*	--	--

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 177.5 kips
*Dial gages removed

TABLE B.4 Specimen WLBO-2

Load (kips)	Deformation Gage Y1 (in)	Deformation Gage Y2 (in)
0	0	0
10	.00001	0
20	.00005	.00001
30	.00010	.00008
40	.00017	.00015
50	.00023	.00024
60	.00032	.00032
70	.00049	.00042
80	.00062	.00052
90	.00081	.00068
100	.00103	.00081
110	.00140	.00096
120	.00185	.00121
130	.00270	.00159
140	.00371	.00212
142	.00390	.00222
145	.00445	.00255
147	.00465	.00268
149	.00495	.00290
151	.00530	.00310
153	.00565	.00330
155	.00610	.00370
157	.00660	.00400
159	.00705	.00435
161	.00755	.00465
163	.00850	.00530
165	.00905	.00575
167	.00970	.00620
169	.01070	.00690
171	.01190	.00780
173	.01370	.00885
175	.01430	.00950
177	.01600	.01075
179	.01750	.01200
181	.01940	.01305
183	.02200	.01490

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 190.75 kips

TABLE B.5 Specimen WTBO-1

Load (kips)	Deformation Gage Z1 (in)	Gage Y2 (in)
0	0	0
10	.00010	0
20	.00040	.0006
30	.00069	.0009
40	.00095	.0011
50	.00120	.0015
60	.00146	.0019
70	.00175	.0022
80	.00200	.0026
85	.00210	.0029
90	.00223	.0030
95	.00235	.0032
98	.00240	.0035
100	.00248	.0036
102	.00251	.0038
105	.00261	.0040
107	.00268	.0041
110	.00281	.0043
112	.00290	.0045
114	.00300	.0047
116	.00312	.0049
118	.00324	.0051
120	.00339	.0053
122	.00362	.0057
124	.00393	.0061
126	.00423	.0067
128	.00458	.0071
130	.00488	.0075
132	.00511	.0080
134	.00575	.0090
136	.00623	.0098
138	.00663	.0105
140	.0079	.0130
142	.0101	.0170

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 142.0 kips

TABLE B.6 Specimen WTBO-2

Load (kips)	Deformation Gage Z1 (in)	Deformation Gage Y2 (in)
0	0	0
10	.00018	.0005
20	.00045	.0010
30	.00081	.0012
40	.00120	.0016
50	.00158	.0020
60	.00199	.0024
70	.00243	.0030
80	.00288	.0031
90	.00330	.0036
100	.00374	.0041
110	.00427	.0049
120	.00482	.0055
125	.00511	.0060
130	.00549	.0066
134	.00575	.0071
138	.00608	.0076
140	.00628	.0080
142	.00648	.0082
144	.00670	.0087
146	.00697	.0090
148	.00720	.0095
150	.00744	.0099
152	.00762	.0100
154	.00801	.0107
156	.00835	.0111
158	.00865	.0115
160	.00902	.0121
162	.00940	.0128
164	.00975	.0132
166	.01035	.0140
168	.01075	.0148
170	.01110	.0152
172	.01160	.0160
174	.01215	.0170
176	.01275	.0180
178	.01400	.0190
180	.01420	.0200
182	.01485	.0205
184	.01600	.0220
186	.01710	.0245
188	.01950	--
190	.0207	.046

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 191.5 kips

TABLE B.7 Specimen WLB2-1

Load (kips)	Deformation Gage X1 (in)	Deformation Gage X2 (in)
0	0	0
10	.00001	0
20	.00002	.00001
30	.00007	.00001
40	.00011	.00001
50	.00017	.00001
60	.00020	.00002
70	.00028	.00004
80	.00035	.00009
100	.00049	.00029
120	.00083	.00058
130	.00101	.00073
140	.00130	.00091
150	.00175	.00115
160	.00239	.00148
170	.00335	.00199
175	.00400	.00220
180	.00485	.00270
185	.00605	.00340
190	.00750	.00450
195	.00970	.00625
197	.01000	.00640
200	.01130	.00745
205	.01600	.01110
207	.01650	.01140
210	.01840	.01305
212	.0207	.01510
215	.02610	.0198
217	.02790	.0212
219	.02990	.02270
221	.03145	.02400
223	.03330	.02535
225	.03460	.02650
227	.03625	.02785
230	.041	.032
232	.0460	.0360
239	.06170	.0472
241	.0624	.0474
243	.06350	.04770
245	.0660	.051
248	.0693	.0505
250	.07242	.0545

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 261.0 kips

TABLE B.8 Specimen WLB2-2

Load (kips)	Deformation Gage X1 (in)	Deformation Gage X2 (in)
15	0	0
20	0	0
40	.00005	0
60	.00012	.0001
80	.00022	.0003
100	.00036	.0005
120	.00057	.0008
140	.00088	.0012
160	.00135	.0022
180	.00270	.0047
195	.00600	.0088
197	.00650	.0091
200	.00783	.0112
205	.00940	.0130
210	.01280	.0180
215	.01700	.0230
217	.01805	.0242
220	.02180	.0290
222	.02237	.0299
225	.02390	.0320
227	.02500	.0337
229	.02580	.0350
231	.02695	.0365
233	.02740	.0372
235	.02812	.0382
237	.02960	.0405
240	.03210	.0442
242	.03350	.0460
244	.03580	.0490
246	--	--

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 246.0 kips

TABLE B.9 Specimen WTB2-1

Load (kips)	Deformation Gage Z2 (in)	Deformation Gage X2 (in)
0	0	0
10	-.00005	0
20	-.00015	0
30	-.00015	0
35	-.00015	0
40	-.00015	0
45	-.00015	0
50	-.00015	0
60	-.00012	0
70	-.0001	.0001
80	.00025	.0005
90	.00058	.0008
100	.00088	.0010
110	.00128	.0014
120	.00172	.0018
130	.00232	.0022
140	.00330	.0030
150	.00510	.0045
155	.00600	.0055
160	.00735	.0062
165	.00900	.0080
170	.01220	.0105
175	.019	.018

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 175.0 kips

TABLE B.10 Specimen WTB2-2

Load (kips)	Deformation Gage Z2 (in)	Deformation Gage X2 (in)
0	0	0
10	.00100	0
20	.00110	0
30	.00155	.0002
40	.00190	.0005
50	.00229	.0007
60	.00266	.0010
70	.00315	.0011
80	.00360	.0014
90	.00420	.0018
100	.00470	.0021
110	.00535	.0025
120	.00600	.0030
130	.00700	.0036
140	.00780	.0043
150	.00950	.0058
160	.01150	.0075
165	.01250	.0085
170	.01440	.0105
175	.01650	.0130
177	.01715	.0134
180	.01870	.0150
182	.02000	.0165

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 182.5 kips

TABLE B.11 Specimen LTB2-1

Load (kips)	Deformation: Gage X1 (in)	Deformation: Gage X2 (in)
0	0	0
10	0	-.00061
40	.00010	-.00061
70	.00020	-.00060
100	.00031	-.00059
120	.00039	-.00046
140	.00048	-.00017
160	.00058	.00021
170	.00064	.00043
180	.00072	.00068
190	.00081	.00095
200	.00090	.00099
210	.00097	.00105
220	.00102	.00395
225	.00102	.00521
230	.00105	.00610
235	.00110	.00624
240	.00111	.00675
245	.00112	.00749
250	.00119	.00842
255	.00127	.00929
260	.00142	.01035
265	.00160	.01148
270	.00208	.01258
275	.00243	.01372
280	.00276	.01485
285	.00325	.01595
290	.00388	.01748
295	.00448	.01885
300	.00518	.02027
305	.00605	.02220
310	.00681	.02395
315	.00753	.02560
320	.00850	.02737
325	.00983	.02969
330	.01117	.03200
335	.01251	.03425
340	.01490	.03720
345	.01746	.04095
350	.02130	.04595

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 350.5 kips

TABLE B.12 Specimen LTB2-2

Load (kips)	Deformation Gage X1 (in)	Deformation Gage X2 (in)
0	0	0
10	0	0
50	0	.00025
80	0	.00098
110	0	.00168
140	0	.00255
160	0	.00321
170	0	.00357
180	0	.00399
190	.00185	.00428
200	.00185	.00499
220	.00185	.00615
230	.00185	.01118
240	.00185	.01205
245	.00395	.01272
250	.00375	.01345
255	.00375	.01438
260	.00375	.01545
265	.00420	.01661
270	.00420	.01780
275	.00420	.01877
280	.00426	.01980
285	.00510	.02129
290	.00585	.02280
295	.00680	.02429
300	.00809	.02615
305	.00930	.02775
310	.01075	.02930
315	.01145	.02990
320	.01325	.02701

Note: 1 kip = 4.448 kN, 1 in = 25.4 mm
Failure at 325.0 kips