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Low Cycle Fatigue

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RESEARCH

RESIDUAL STRESS REDISTRIBUTION IN WELDED BEAMS SUBJECTED TO CYCLIC BENDING

(PART II)

by
Salvador Lozano
Paul Marek
Ben T. Yen

Fritz Engineering Laboratory Report No. 358.17

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This work was conducted as part of a study of low-cycle fatigue, sponsored by the Office of Naval Research, Department of Defense, under contract N 00014-68-A-514; NR 064-509. Reproduction in whole or part is permitted for any purpose of the United States Government.

Department of Civil Engineering

Fritz Engineering Laboratory
Lehigh University
Bethlehem, Pennsylvania

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ABSTRACT

This study presents some results of an investigation of residual stress distribution and redistribution in welded beams subjected to bending moments which generate flexural stresses in the elastic and inelastic ranges.

The experiments include testing of two beams of different steel grades and measuring strains before loading, under load and after unloading. Repeated bending moments were applied and their effects on strain distribution observed. For low applied moments, the redistribution of residual stresses occurred only in local areas and at the first loading cycle. When applied moments produced nominal stresses near or above the yield point of the beam material, gradual change of residual stress took place from one load to the next but stabilized after a few cycles.

The computer analyses included programs for the evaluation and prediction of the residual stress distribution after any applied load as well as for the prediction of the state of stresses under load.

1. INTRODUCTION

This study is the second part of an investigation of residual stress distribution and redistribution in welded beams subjected to cyclic loading. The first part(1) was mainly oriented to the beams subjected to low cyclic loads but very high number of cycles. In the third part(2) the results from this study and from the first part of the investigation will be correlated to the results of controlled strain tests on tensile specimens considering hysteresis properties of the material. The investigation will be completed by analytical study focused on the redistribution of residual stresses due to cyclic load and the so called shake down.

Residual stresses in a welded structural member are the stresses which exist when the member is subjected to no external load. They result from plastic deformations across parts of the member cross section and are caused by thermal differentials during the process of fabrication or by loading.

Residual stresses may be a very significant factor in the static and fatigue strength of structural members. The magnitude and distribution of residual stresses are known to affect fatigue, stress corrosion, brittle fracture, buckling behavior and load carrying capacity of members,(3) and are the object of numerous studies.(4,5,6,7,8)

In welded beams, the magnitude of tensile residual stresses along the weld is often close to the yield point of the weld material. Under load, rearrangement of stress pattern in a beam will take place when the maximum applied stress plus the residual stress exceeds the yield stress of the material.(9,10,11) If the applied load is removed, residual stresses will be different from those before loading.

The purpose of this study was to investigate the residual stress distribution and redistribution in welded beams subjected to repeatedly applied bending at several magnitudes. The results of this investigation will be used in a study of Low Cycle Fatigue and crack propagation, and shall be useful also for other studies such as the behavior of beams subjected to earthquake loading as well as for plastic design.

Both experimental investigations and computer analyses were made. The computer analyses were done by a program of incremental loads. The experimental part was performed on two beams subjected to high magnitude of moment for a few cycles. Residual stress redistribution as well as the change in the state of stresses in the inelastic range were investigated.

2. METHODS OF ANALYSIS

2.1 Basic Assumptions

For the analysis of residual stress redistribution in this study, it is assumed that the initial distribution of residual stresses before application of loads is known, and that the stress-strain relationship of the beam material has been obtained.

Three procedures of analysis are described below, each for a different amount of available information of the strains.

2.2 Consideration of Stress History

Besides the basic assumptions, it is also assumed that the strain history is recorded at every point in a beam throughout the complete spectrum of loading.

The stress history of any point in this beam is traced from its strain history by adding the applied strains to the initial magnitude of residual strain on the stress-strain diagram. Examples are given in Figs. 1 and

2, which depict respectively an element in residual tension subjected to applied tensile strain and an element in residual compression subsequently loaded in compression. The numbers indicate the sequence of strain measurement, (1) being the starting points corresponding to the initial residual stresses.

By this procedure, the stress distribution in a beam at any load would be the actual distribution since the complete strain pattern is recorded experimentally. A computer program checks the equilibrium at all loads while converting strains into stresses.

2.3 Consideration of Strains

Recording of complete strain history at all points of a beam is tedious in experimental studies, and is impossible for any actual beams in use. More attainable is the measurement of strains under load at one or more points.

Used with Navier's hypothesis, measured strains at a point enables the estimation of bending strains over a cross section by linear proportioning (Fig. 3). Conversion from strains to stresses can then be carried out as described in Section 2.2. If equilibrium of bending moment and axial force is not satisfied, adjustment of estimated bending strain is made and the procedure repeated.

A computer program of iterational process and incremental loads has been developed for the analysis of stresses and residual stresses by this procedure (Appendix 1). So far as the hypothesis of linear bending strain distribution holds, the results of this method should be very close to those from direct measurements of Section 2.2.

2.4 Prediction of Stress Distribution

If no information at all is available with regard to strains in a beam, assumptions in addition to those basic ones have to be made for stress analysis. For common cases of beams, it could be assumed that the neutral axis at very low loads coincides with the centroidal axis, and that Navier's hypothesis applies. Furthermore, for this study, the stress-strain relationship is assumed to be elastic-perfectly plastic.

When loads or bending moments are applied to a beam, linear variation of bending stresses results and the neutral axis remains in place unless bending exceeds the elastic limit. In that case, the stress distribution follows the stress-strain diagram and the neutral axis shifts position in order to maintain equilibrium. Subsequent unloading would cause residual stresses as shown in Fig. 4. If initial residual stresses exist, the elastic limit usually is drastically reduced, and redistribution of residual stresses takes place after application and then reduction of low loads.

A computer program for the prediction of stress distribution has been developed (Appendix 2). In this program, the cross section of a beam is divided into elements which have initial residual stresses. When the sum of residual and applied stresses reaches the elastic limit in an element, its area would be assumed zero for additional increment of bending moment. The neutral axis is next located by equilibrium. These steps are continued till the magnitude of desired moment is reached. The resultant stress distribution would be that correspondent to the applied moment. Similarly, residual stress pattern will be obtained by decrease of moments in the same manner.

For the study of beam behavior under low-cycle fatigue, earthquake loading or any elasto-plastic loading conditions, this procedure provides a method of stress prediction. The accuracy of results depends on the accuracy of the assumptions as well as the magnitude of incremental load.

The application of this as well as the procedures for the Consideration of Stress and Strain History (Sections 2.2 and 2.3 respectively) are presented in Chapter 4.

3. EXPERIMENTAL INVESTIGATION

3.1 Specimen Properties, Set Up and Instruments

For residual stress measuremens, two specimens of 11" lengths were taken from two welded beams, the cross section of which is shown in Fig. 5. The component parts of the beams were first tack welded together and then connected by the automatic submerged arc process resulting in 3/16" fillet welds. For the beam of ASTM A36 steel, Lincoln L60 electrodes were used whereas L61 electrodes were applied to the A514 beam. The measured cross-sectional dimensions and the mechanical properties of the steels are listed in Table 1.

The specimens were subjected to various loading conditions through loading of the beams. The applied bending stresses of the individual specimens and their locations in the beams are summarized in Table 2.

In loading the beams, the simply-supported condition was employed. Figure 6 is a photograph of the test setup for a beam under high bending moment in a 300 kips Baldwin hydraulic type universal testing machine. Lateral bracing was used to reduce lateral movement of the beam and stiffeners at the load points and the supports helped in preventing distorsion of the cross-sectional shapes. For this particular beam in the photograph, the specimen for stress evaluation is at the centerline where electrical resistance strain gages can be seen.

Electrical strain gages on beams provided means of monitoring the testing and of checking strain measurements by the Whittemore gage, which was the main instrument for the experimental study. Gage holes 10" apart were drilled on the surface of the 11" specimens for the Whittemore gage. The same holes were used for recording the strain history and for the standard method of sectioning in residual stress evaluation.(12,13)

3.2 Description of Tests

In essence, testing involved measurements of strains in specimens before loading, under load and after completion of loading. "Initial" residual stresses in a specimen were measured by the standard method of sectioning (Fig. 7) without prior application of load on the specimens, and "final" residual stresses after loading. Measurements under load gave the magnitude and distribution of strains at the load. The testing of beam No. PWC-001 (Table 2) illustrates the general procedure.

A small segment of the beam (location b) was first removed as a specimen for the determination of initial residual stresses. The remainder of the beam was then put under load. The history of loading is indicated in Fig. 8 which shows the load intensity versus the number of load applications on the beam. Strain measurements took place at sixteen stations of different load levels. Station (1) corresponded to the initial condition, (2) when setup was completed, (3) under load, and (4) after unloading. The magnitude of applied loads at different levels and the correspondent moments and bending stresses are given in Table 3. Between stations (4) and (5), a small number of cycles of loading and unloading were applied and the change of strains observed at a few points in the specimen. When the stabilization of strain was achieved at unloading, measurements at station (5) could begin. Testing then continued at the next load level. After completion of unloading at station (14), the beam was removed from the testing position, the stiffeners were removed and measurements were performed again (15) for the final state of strain. Sectioning for residual stress determination took place at station (16).

Testing of beam PWA-001 was carried out similarly. The loading history is shown as Fig. 9.

Specimens which were subjected to relatively low loads$^{(14)}$ sustained large number of cycles (Table 2) before the measurements of strains. Only the "final" state of residual stresses was obtained by sectioning.

3.3 Results

Only results are summarized in this section. Discussions are given in Chapter 4.

3.3.1 Initial Residual Stresses

The initial residual stress distribution for the as-welded specimen PWC-001 (A514) is shown in Fig. 10. The residual stresses at the flange tips, developed mainly from flame cutting, were about one half of the yield point of the flange plates. The tensile residual stresses were observed to approach the yield strength in the vicinity of flange to web connections. Uniform and relatively low compressive stresses existed in the web and flanges.

Figure 11 shows the residual stress distribution in the as-welded shape PWA-001 (A36). Again, the tensile residual stresses at the flange tips were about half of the yield point, which was 35.3 ksi (Table 1). The maximum tensile stresses near the flange to web connections were comparable to the yield strength of the weld, whereas the average stresses were 38 and 23 ksi respectively for the top and bottom flanges. The compressive residual stresses in both flanges varied with a maximum value of 16 ksi.

3.3.2 Strains Under Load

Strains under moderate to high loads changed the initial residual strain patterns to a great extent and are presented here.

The strain patterns corresponding to the loading and unloading process throughout the testing of specimen PWC-001 (A514) are summarized for the top flange, web and the bottom flange in Figs. 12, 13 and 14, respectively. The lines 3, 6, 9 and 12 represent total strains of residual plus bending stress under load at the respective stations (Fig. 8), and the lines 4, 7, 10 and 13 indicate strains after unloading, that is, residual strains.

Figures 15, 16 and 17 show the strain patterns in the top flange, web and the bottom flange of the beam PWA-001 (A36). The strains under load are recorded at stations 3, 6, 9 and 11 (Fig. 9). The corresponding unloading strains at stations 4, 7, 10 and 12 have the same pattern as those under load.

It is obvious from Fig. 15 that the strains were not uniform across the width of the beam flange. The variation was linear, clearly indicating a lateral deflection of the flange (to the left). This was observed during testing of the beam. Discussion will be made in Section 4.3.

3.3.3 Residual Stresses After Application of High Loads

The "final" residual stress pattern of the specimen PWC-001 (A514), which was subjected to a maximum bending moment of 1.04 times the yielding moment, was obtained by sectioning. The results are shown in Fig. 18.

The compressive residual stress in the top flange was almost uniform with an average of about 10 ksi. The tensile residual stresses at the tips of the top flange were around 50 ksi and 80 ksi at the welds. In comparing the stress pattern of this top flange with the initial conditions in Fig. 10, it can be seen that only small changes of magnitude took place. However, both the pattern and magnitudes in the bottom flange were drastically different. There were practically no residual stresses after application of high loads, except at the flange tips. The residual stresses in the web conformed to those in the flanges, being higher at the top, lower below and varied linearly in between.

Figure 19 shows the final residual stress pattern of the specimen PWA-001 (A36) after a maximum bending moment of 1.1 times the yield limit. Some residual tension remained near the welds and at flange tips with a magnitude of about 25 ksi. In large parts of the flanges, most of the compressive residual stresses were wiped out by loading. The compressive residual stress distribution in the web changed pattern from that before loading (Fig. 11), and was generally reduced near the flanges.

3.3.4 Residual Strain History of a Point

Sometimes it is important to trace the strain history or residual strain history of some crucial points of a structure as it undergoes a series of loading. Examples for a couple of points have been presented in Figs. 1 and 2, where the histories of stresses, strains and residual stresses can all be obtained. The history of change of residual strains at the point of Fig. 1 is shown as Fig. 20 for further illustration.

From the load station numbers in this figure, it can be followed that, for every load level, practically all the change in residual strain took place in the first cycle of loading and unloading. Only when the applied moment was above the yield limit (after station 11) was there a gradual change of residual strain from one load to the next. Even then, stabilization came about in a few cycles. Similar behavior was observed for specimen PWA-001 at a higher load of 1.1 times the yield moment.

4. DISCUSSION

4.1 Initial Residual Stresses

Residual stresses in welded beams were obtained in this study, both before and after loading, by the method of sectioning.(13) The conditions of equilibrium were automatically satisfied when employing this method. For an indication of the accuracy of the measurements made, all results were subjected to the equilibrium check of bending moment and axial force. In no case was the error more than 30 kip-in or 5 kips.

The comparison of initial residual stresses in various shapes is a tedious and time consuming undertaking,(15) and is not the concern of this work. Nevertheless, it is interesting to note the difference of patterns and magnitudes between the A514 (PWC-001, Fig. 10) and the A36 (PWA-001, Fig. 11) specimens. Both had the same geometry and both were welded by the automatic submerged arc procedure. Yet the difference in base metal, weld electrode and heat input caused dissimilarity. A bigger portion of the A36 cross section was in residual tension than that of the A514 shape, whereas the magnitude of tensile residual stresses was higher in the latter.

4.2 Redistribution of Residual Stresses After Low Loads

In the first part of the investigation,(1) applied loads or stresses on specimens were considered to be low when stress magnitudes were in the nominal working range for structural members. Thus 20 to 30 ksi (Table 3, Ref. 1) regarded as low stresses. In fatigue consideration, these stresses correspond to repeated load application of one hundred thousand times or more.

Experimental results(1) indicate that only limited redistribution of residual stresses took place after application of low loads. For example, Figs. 21 and 22 show the residual stresses of A514 and A36 specimens before and after repeated application of -10 to +20 ksi.(1) The residual stress distribution for the beam PWC-131 was obtained from Reference 1. In both cases, a change of stress magnitude was detected, with a maximum of about 20 and 15 ksi for A514 and A36 respectively, in the flange to web welded connection. However, since the specimens of each material did not originate from the same beam and the similarity of initial residual stress is only assumed, it is not definite what magnitudes of stress change were the results of stress redistribution due to loading. The important phenomenon probably is that the magnitude of residual stress was usually close to the yield stress at the weld thus local inelastic behavior occurred, and redistribution followed.

Computer analysis by the procedure of Section 2.4 confirmed qualitatively the experimental finding. By using stress-strain relation and initial residual stress pattern from experiments, it was found that only local redistribution of residual stress took place at the welds of A514 shapes, and at larger portions of the A36 specimens.

4.3 Strains and Stresses Under Load

The strains in beams under load are presented in Figs. 12 through 17. It is significant to discuss the change of strain distributions at different loads.

Prior to the application of any load, the residual stresses at a section of a beam were in equilibrium.(16) As loads were applied, the neutral axis of bending remains at or near the center of gravity of the section until yielding occurred at certain points. For welded beams with flame-cut flanges, first yielding took place at the welds and then at the tips of the tension (bottom) flange. For equilibrium, this caused shifting of the neutral axis towards the top flange, as was the case of the A36 specimen (loads 3 and 6, Figs. 9 and 16). This resulted in higher strains in the tension flange than in the compression flange. Further loading introduced yielding in the compression flange and a downward shifting of the neutral axis (loads 6, 9, and 11, Fig. 16).

The shifting of neutral axis was not evident for the A514 specimen (Fig. 13, loads 3, 6, 9, and 12). Yet it is obvious from Figs. 12 and 14 that the strains under load were higher in the bottom flange. After unloading, the neutral axis suffered quite a change as can be observed in Fig. 13. A comparison on strain increments in the top and bottom flanges of the A514 beam (Fig. 23) depicts the relatively higher straining at the bottom flange and later on at the top as applied moment was increased.

Stresses in the component parts of the A514 and the A36 specimens were converted from the measured strains by the procedure of Section 2.2, and are presented in Figs.

24 through 29. For the computer program of conversion, each specimen cross section was divided into 212 elements, the initial residual stress distributions of Figs. 10 and 11 were modified to doubly symmetric patterns, and a bilinear stress-strain relationship (elastic-perfectly plastic) was assumed, with the yield stresses listed in Table 1. The stress-strain history of two individual elements have been given as examples in Figs. 1 and 2. The maximum discrepancy in equilibrium check for the specimens under load was 5 kips in axial force and 5% in bending moment.

That the tension (bottom) flange reached the yield stress prior to the compression flange can be clearly seen in Figs. 24 and 26 for the A514 shape and in Figs. 27 and 29 for A36. At the last load, practically the whole tension flange of the A36 specimen was yielded. In the web, because of initial residual stresses, the points of zero stress did not coincide with those of zero strain (Figs. 13 and 25, and 16 and 28).

Analysis of stresses by the process of Section 2.3 provided results very close to those presented above. Prediction of stress distributions by the procedure of Section 2.4, on the other hand, gave stress magnitudes which did not agree very well when the applied moments were above yielding. The maximum deviation was 5 ksi in the top flange of the PWC-001 (A514) specimen. However, if adjustment of results are made to account for the influence of lateral deflections of the compression flange (Fig. 12 for A514 and Fig. 15 for A36) and the effects of strain stabilization above the elastic limit (Figs. 20 and 36), the maximum deviation between the predicted and those presented is only 1 ksi, or 1% of σ_y.

The attention on the lateral deflection of a beam is incidental to this study. It is interesting to know that such deflections not only caused unequal strains in the compression flange and the tension flanges when they were under load (Figs. 12, 15 and 17), but they also influenced the residual strain and stress distribution after the loads had been removed. This will be presented in the next Section.

4.4 Residual Stresses After Unloading

Residual stresses after unloading are obtained in the same manner as for stresses under load. Results are presented in Figs. 30 through 35 for the two specimens tested under various levels of high loads. When examined with reference to the stresses under load and the loading history, it becomes clear how the magnitude of residual stresses decreased step by step as applied loads increased. Each distribution of residual stresses was the basis of the strain and stress evaluation in the next application of load.

For the A36 specimen (PWA-001), the lateral deflection of the top flange took place at the very first load and increased magnitude at higher loads (Fig. 15). The corresponding residual stresses after each unloading reflected this, as is indicated by the linearly varying stress magnitude across the flange in Fig. 33. For comparison, the initial residual stress distribution prior to loading is also included in the figure.

The residual stress distribution after the last unloading should agree with those obtained by sectioning (Section 3.3.3). This is obvious when Figs. 30, 31 and 32 are compared with Fig. 18 for the A514 specimen and Figs. 33 to 35 with Fig. 19 for A36. That the residual stresses could be predicted by the procedure of 2.4 and that the results could be confirmed by experiments lends a strong support to the applicability of the method of analysis.

4.5 Stabilization of Strains

It was pointed out earlier with the aid of Fig. 20 that residual strains stabilized after a few cycles of application of high loads. This phenomenon was registered at all points of a specimen under study, and its effect in redistributing the residual stresses is illustrated by Fig. 36.

To examine further this stabilization or "shake down" phenomenon,(17) the strain history of a point in specimen PWA-001 is presented in Fig. 37. It is clear from this figure that the gradual change of strain occurred both under load and after unloading, and that more cycles were required for stabilization at higher loads. The amount of changes in stresses and strains in the cross section of this specimen can be visualized by comparing the magnitudes of stations 9 and 11 or 10 and 12 in all related figures of this report.

It is believed that the underlying cause of "shake down" is the Bauschinger effect of stress-strain relationship (or the effect of non-linear cyclic stress-strain relationship). To explain fully the behavior of the two beam specimens thus, requires the evaluation of the mechanical properties of the beam material. The exact strain history of a point must be applied to an element for the stress history of that point. Then one of the methods of analysis of Chapter 2 can be applied, using the exact stress-strain diagrams. New computer programs must be developed. All these are being considered in the next step of this study.(2)

At this time, it can be said that, probably, except for fatigue with very low cycle or for strong earthquake loading on structural members, the stresses and strains in a beam corresponding to a given load stabilize after a moderate number of cycles, and these stresses or strains are nominally used in fatigue considerations.

5. SUMMARY AND CONCLUSIONS

The investigation described in this study is concerned with the distribution and redistribution of residual stresses in welded beams subjected to repeated bending. Low and high magnitudes of bending moments were applied in order to investigate residual stresses in both the elastic and inelastic ranges. Using the method of sectioning, residual stresses were measured in two as-fabricated specimens.

A theoretical analysis was carried out by means of three different procedures with computer programs to evaluate the residual stress redistribution in beams as well as the state of stresses under any applied load. The outcome from the theoretical analysis was compared with the measured stress patterns of the tested beams. The following is a summary of the results and conclusions:

1. High tensile residual stresses existed in the vicinity of the flange-to-web welds. For the specimens examined, the magnitudes were close to the yield stress in the

A514 shape, and higher than the yield stress of the base metal in A36 shape. The tensile residual stresses at the flange tips were close to half of the yield stress for both A36 and A514 steels.

2. Redistribution of residual stresses in a beam took place when the maximum applied stress plus the residual stress exceeded the yield stress of the material. For nominal magnitudes of bending moment, most of the changes occurred in the vicinity of the weld.

3. Under high magnitudes of moments, the neutral axis of a cross section may deviate from its centroidal axis because of stress redistribution by yielding. Strain distributions were generally linear. The change of strains for an increment of load could be higher in either the top or the bottom flange, depending upon the stress pattern and the location of neutral axis before the load increment. Stresses in a flange became more uniform as more yielding took place.

4. The magnitude and distribution of residual stresses after high loads depended on the intensity and pattern of the load. Generally, the higher the load, the smaller the

residual stresses and the more uniform in distribution. After an application of the yielding moment, only low residual stresses remained except at the welds and flange tips. However, significant difference between the final residual stress distribution in the top flange and the bottom flange was observed and theoretically confirmed.

5. Three procedures of analysis were used, each for a different amount of experimental data. The basic assumption was that the stress-strain relationship and the initial residual stresses were known. The first method converted recorded strains into stresses, the second evaluated stress distribution when strains at a point were recorded, and the third predicted strains and stresses under load and after unloading. All three provided results which agreed well with experimental stresses. The maximum difference was 5% in bending moment.

6. For relatively low moments, redistribution of residual stresses occurred at the completion of the first cycle. For high moments near or above the yield moment, gradual change of strain was observed both under load or after

loading. The number of cycles necessary for the stabilization of strains and stresses, or shake down, increased with load magnitude.

7. A technique of analysis is needed for the incorporation of the effects of shake-down and lateral deflections of the flanges so as to predict more accurately stresses under load and residual stresses after cyclic loading.

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TABLE 1 MECHANICAL AND GEOMETRICAL PROPERTIES

Beam No.		PWC-001	PWA-001
Steel Grade		A514	A36
Mech. Prop.	σ_{ys} (ksi)	110.3	35.3
	σ_u (ksi)	119.6	61.1
	Elong % in 8"	12.70	30.75
Top Flange	Width	6.78	6.66
	Thickness	0.384	0.375
Web	Thickness	0.297	0.250
Bottom Flange	Width	6.78	6.67
	Thickness	0.384	0.375

TABLE 2 SPECIMEN CONDITIONS

Beam No.	Steel		Specimen Location	Applied Stress (ksi)	Number of Cycles	Virgin State
	Grade	σ_{ys} (ksi)				
PWC-001	A514	110.3	a	110.3	104	
			b			0
PWA-001	A36	35.3	a	35.3	70	
			b			0

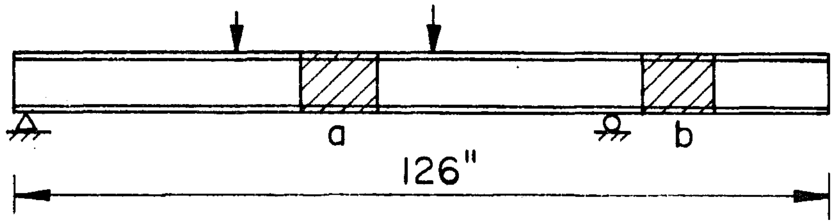

TABLE 3 LOADING ON BEAMS

	Beam No.	PWC-001	PWA-001
	Steel Grade	A514	A36
	Yield Point (ksi)	110.3	35.3
	P_y (kips)	282	83.5
	M_y (kip-in)	4655	1378
Load Level I	Stress (ksi)	49	28
	Load (kips)	125	66
	Moment (kip-in)	2062.5	1089
2	Stress	72.5	35.3
	Load	185	83.5
	Moment	3052	1378
3	Stress	96	35.3
	Load	245	91.5
	Moment	4042	1510.0
4	Stress	110.3	
	Load	290	
	Moment	4785	

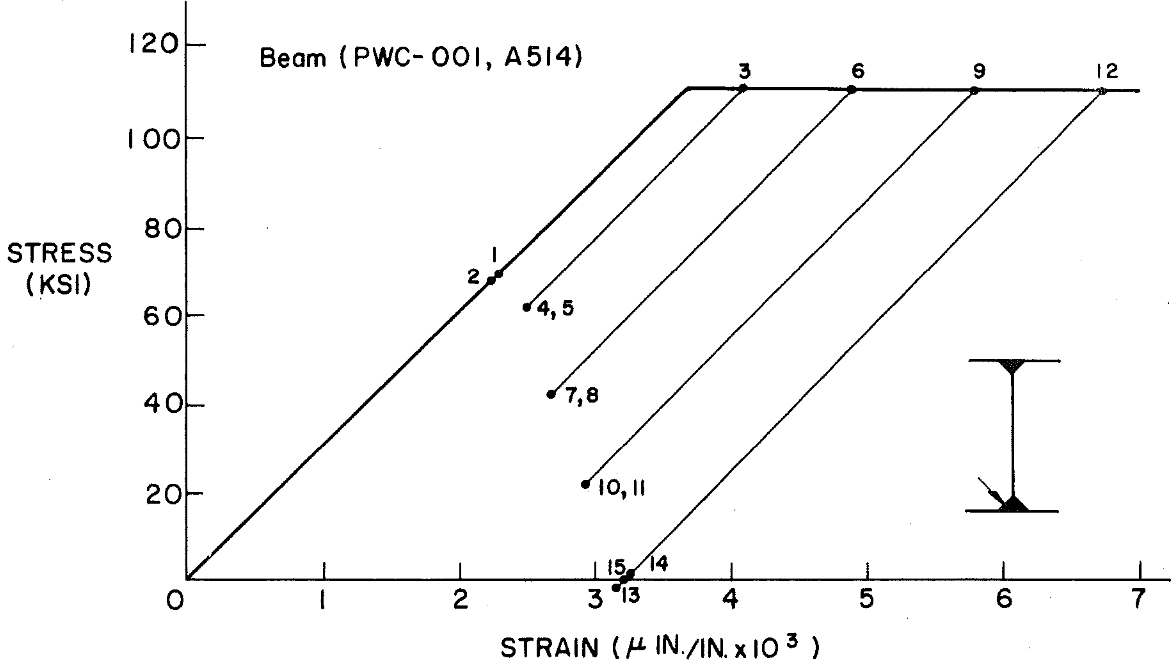

Fig. 1 Stress-Strain History of a Point (Tension)

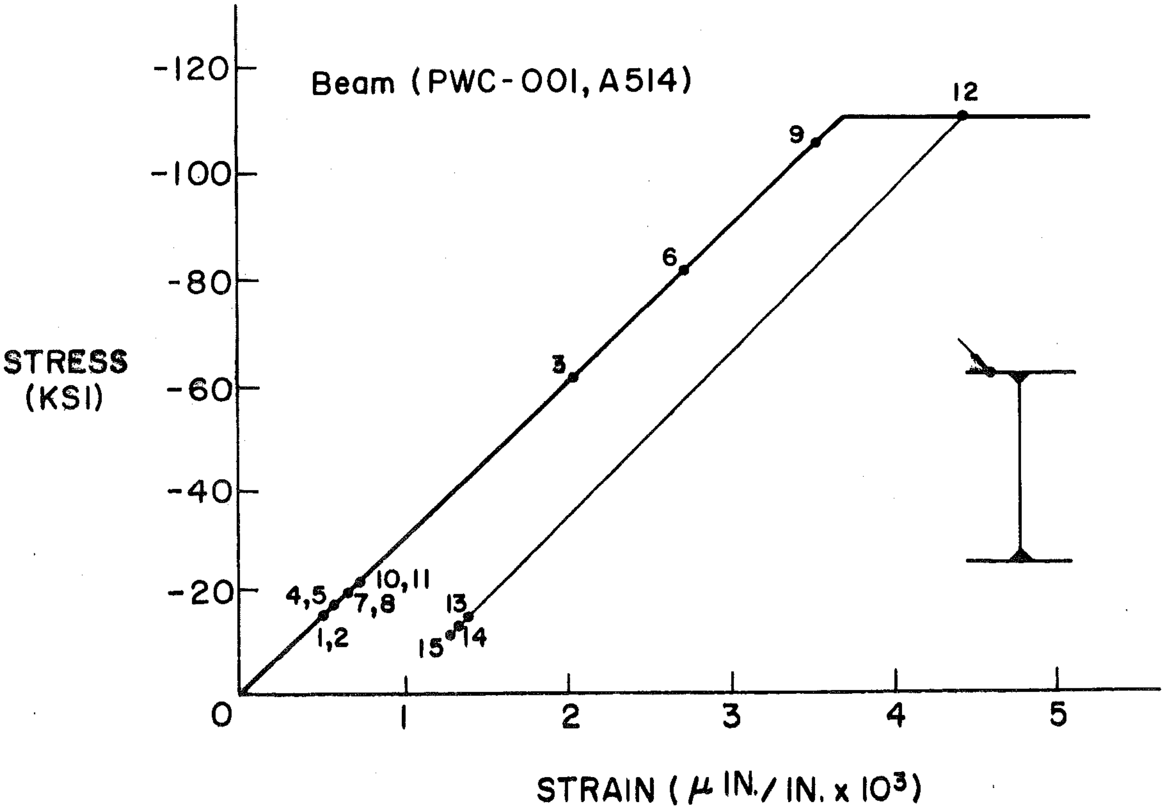

Fig. 2 Stress-Strain History of a Point (Compression)

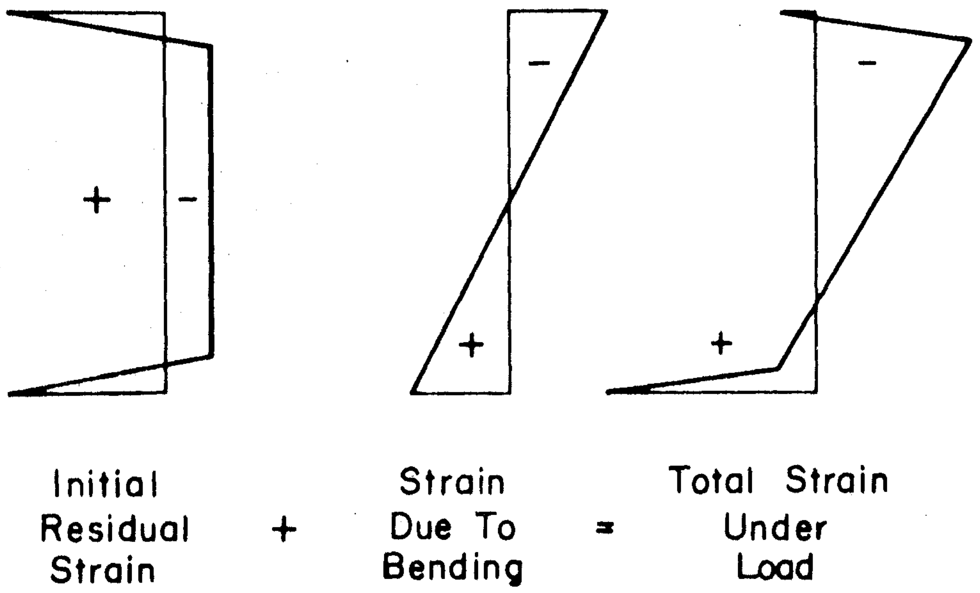

Fig. 3 Strains Under Load

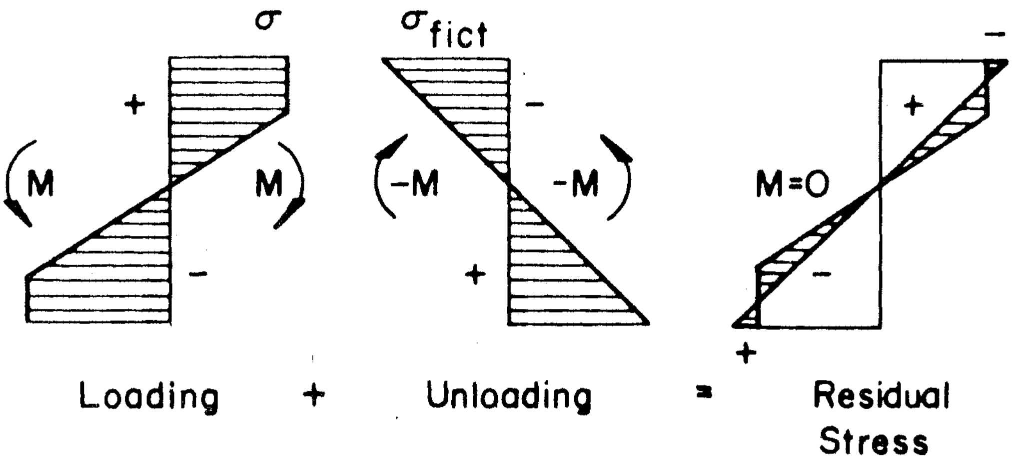

Fig. 4 Residual Stresses After Unloading

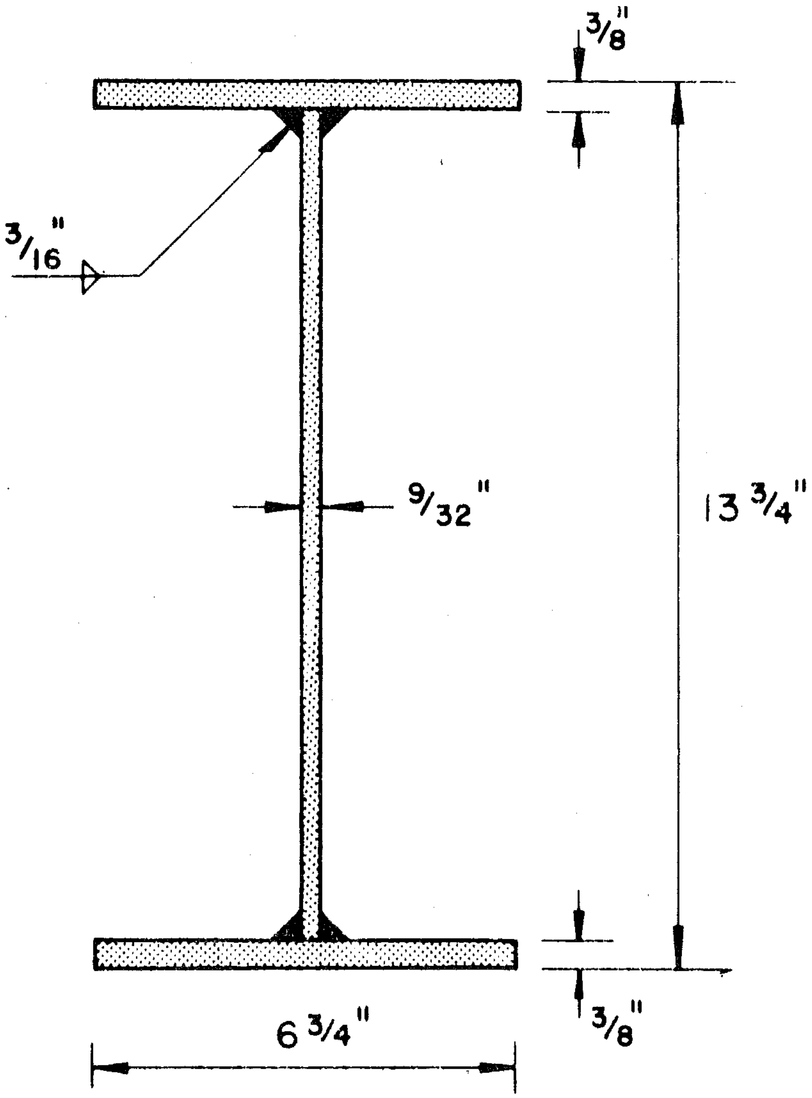

Fig. 5 Cross Section of Beams

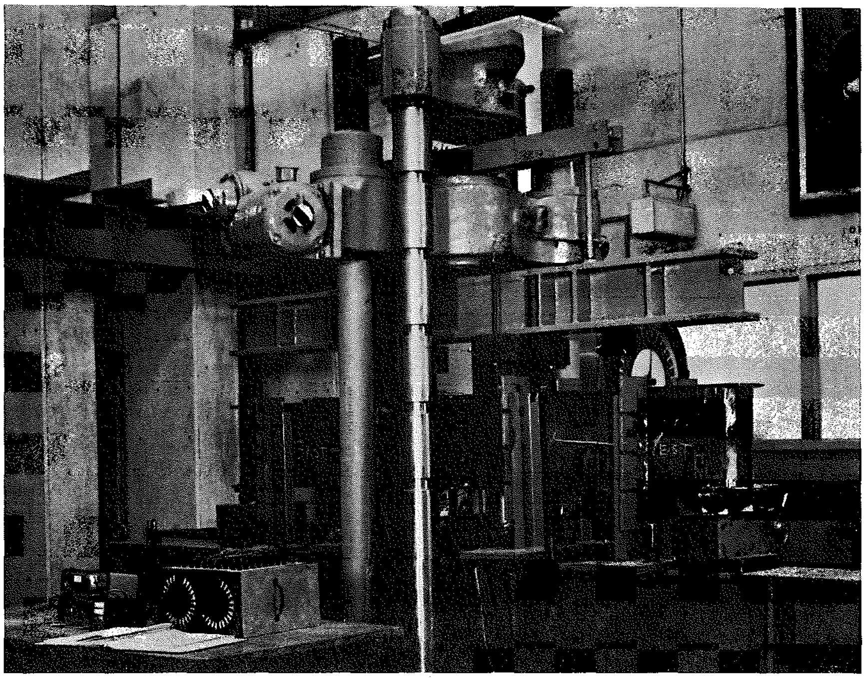

Fig. 6 Test Set-Up (High Moments)

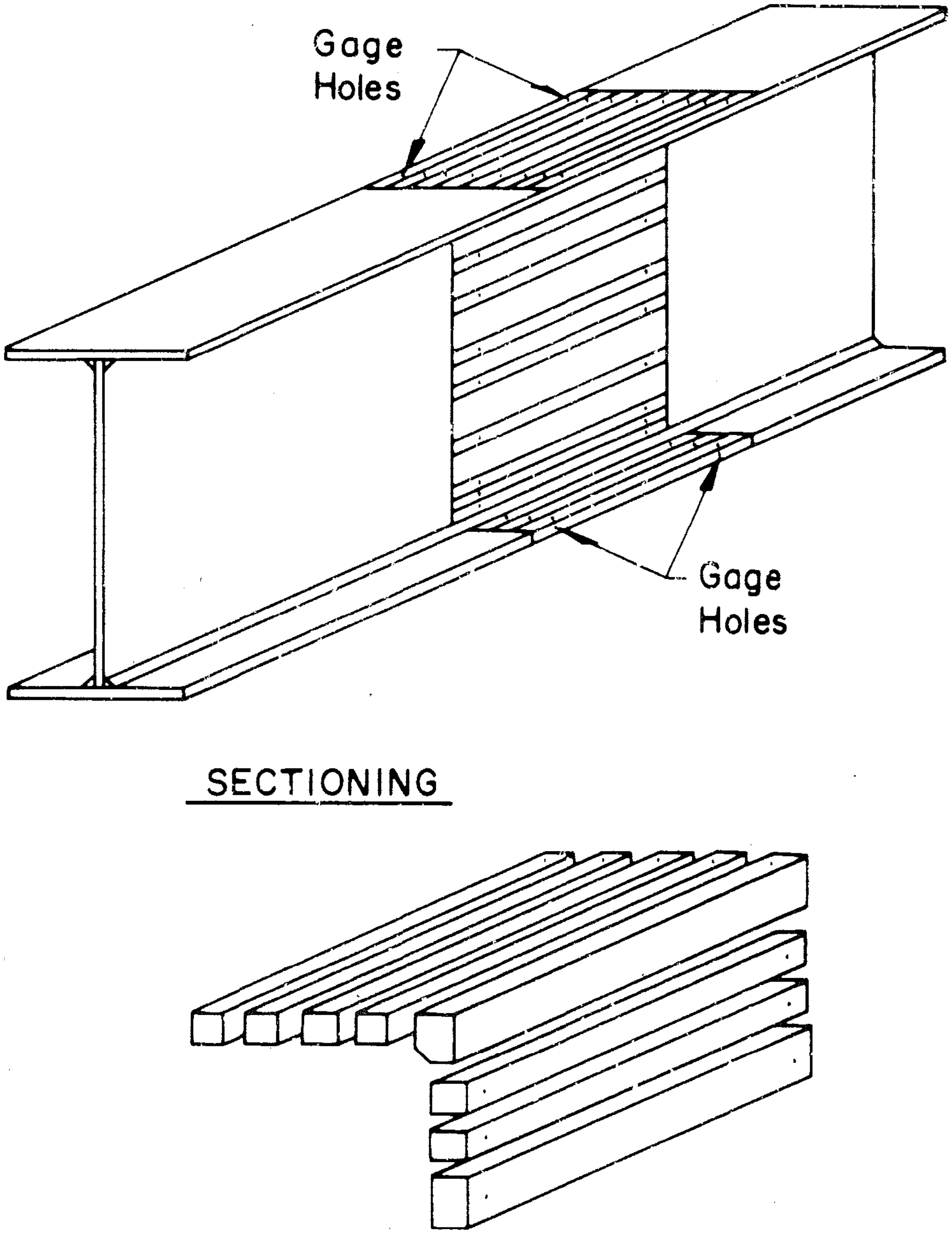

Fig. 7 Method of Sectioning

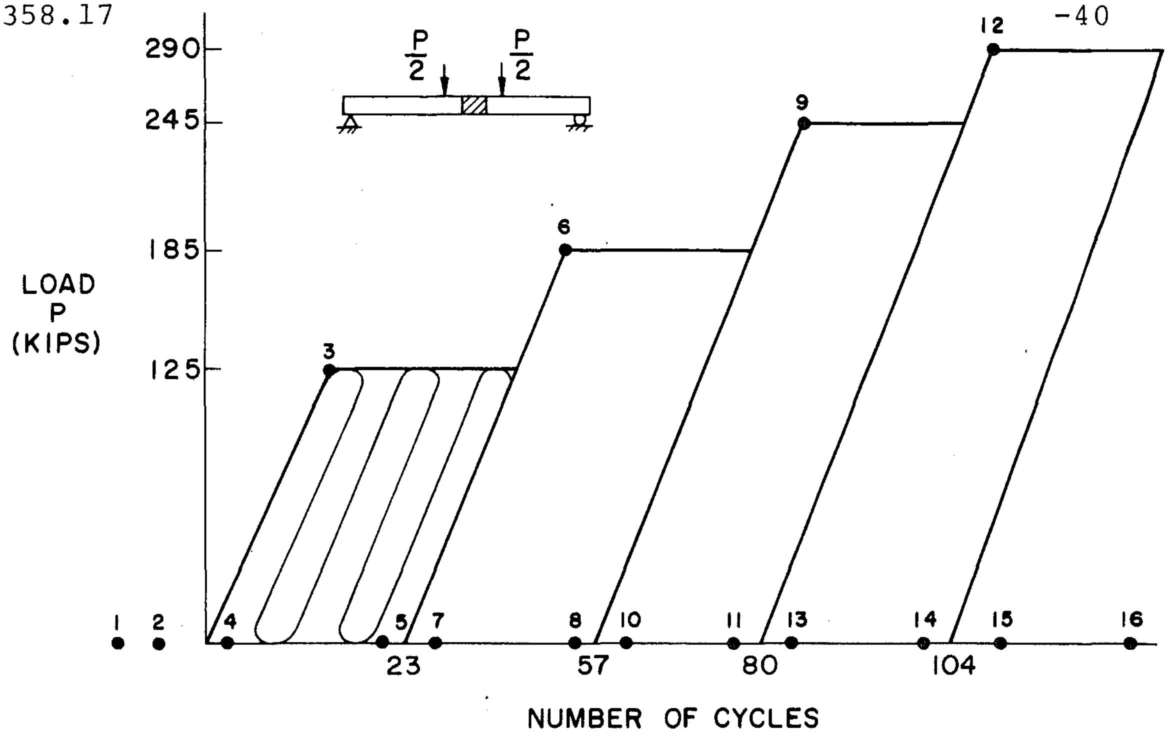

Fig. 8 History of Loading (PWC-001, A514)

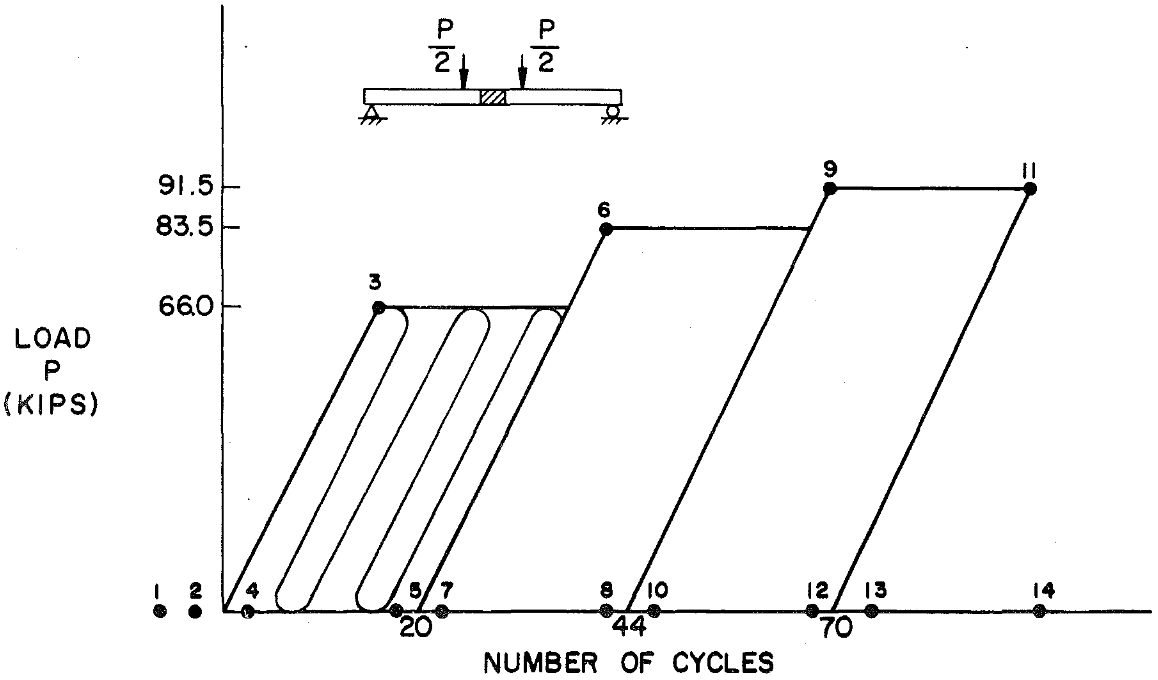

Fig. 9 History of Loading (PWA-001, A36)

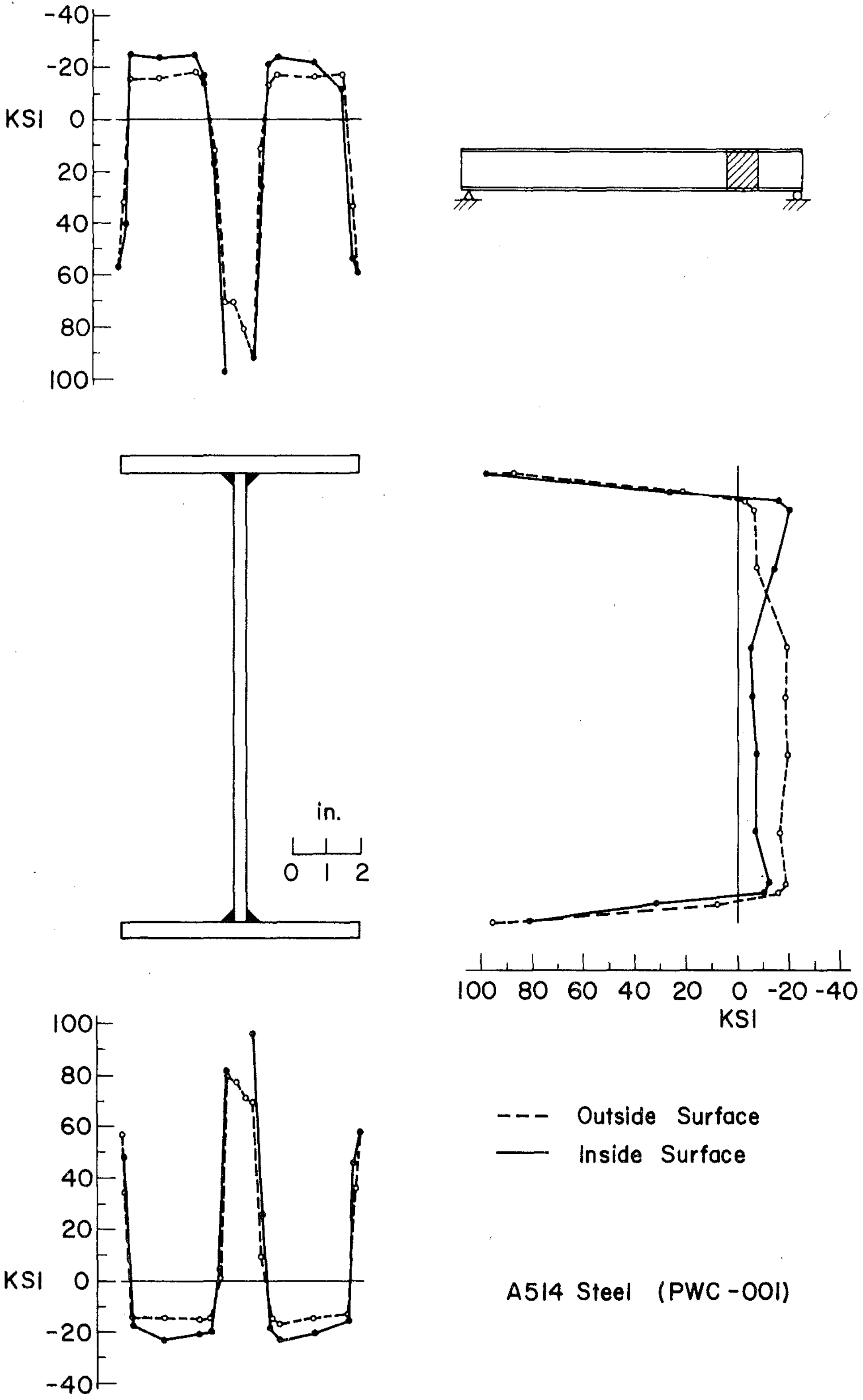

Fig. 10 Residual Stresses in As-Welded Shape PWC-001, A514

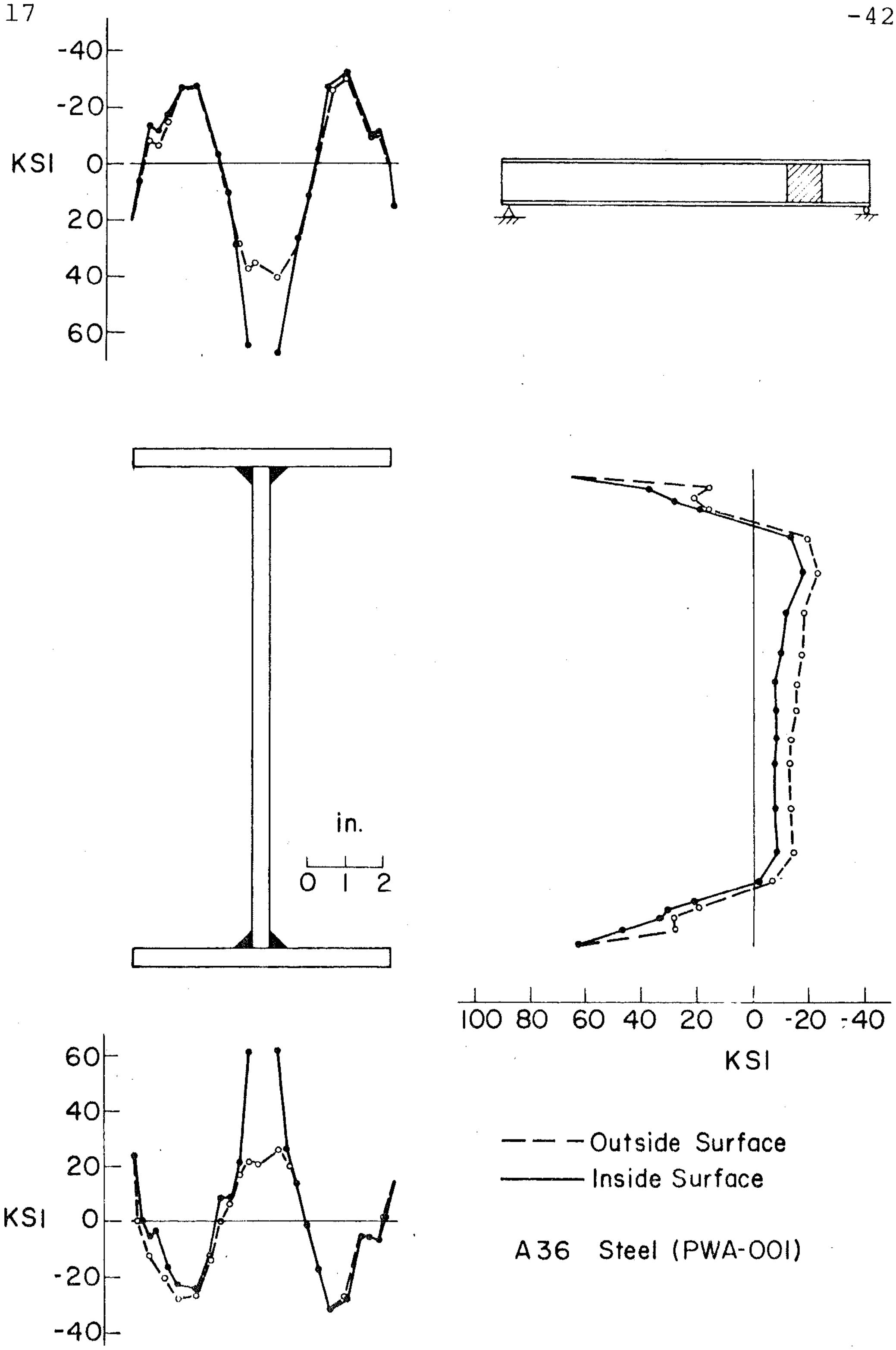

Fig. 11 Residual Stresses in As-Welded Shape PWA-001, A36

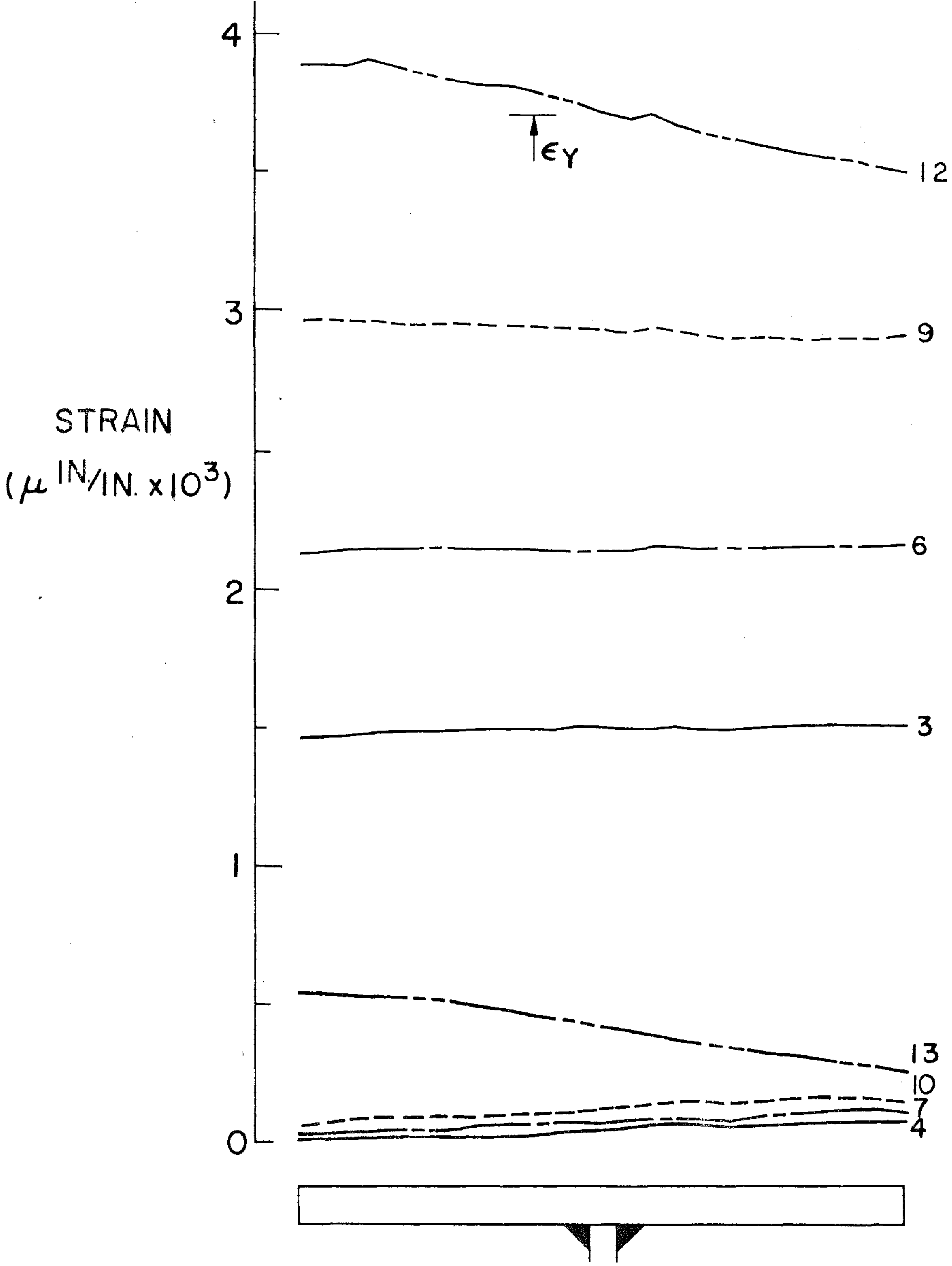

Fig. 12 Strains in Top Flange, PWC-001, A514. (Loading and Unloading)

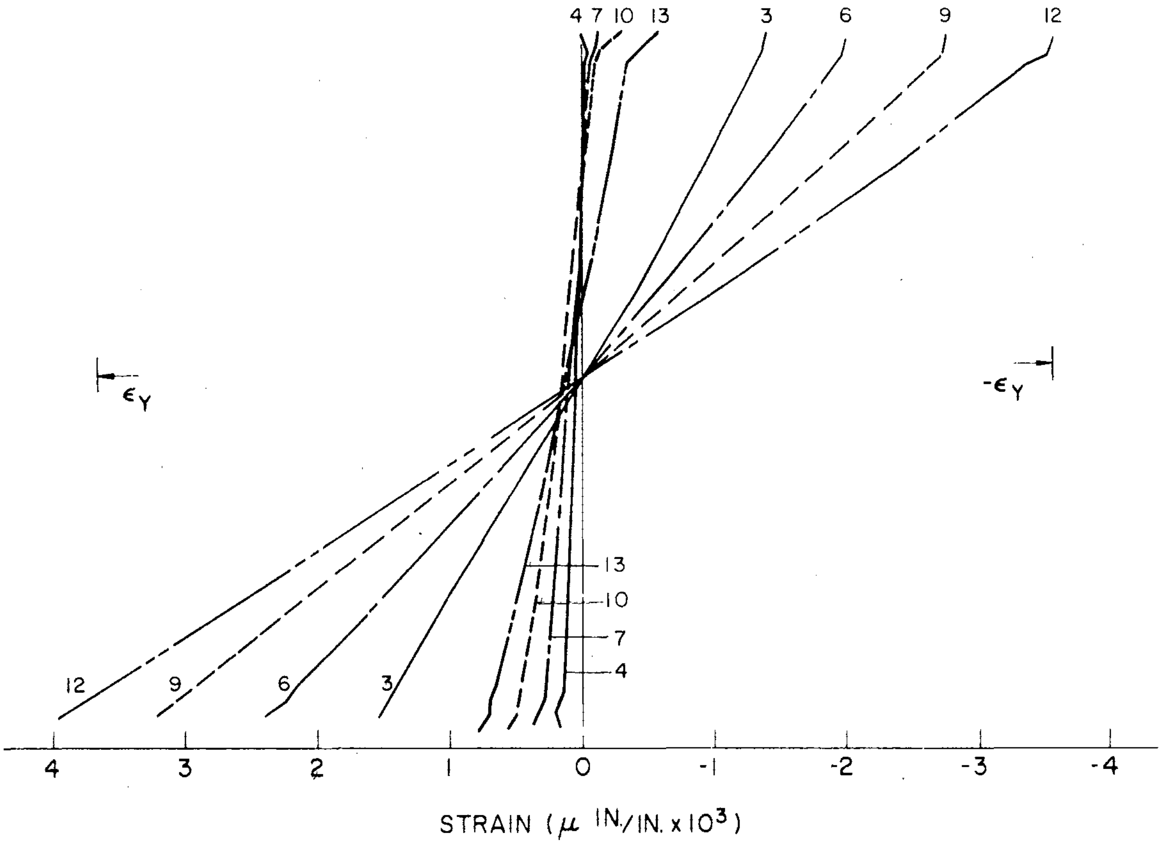

Fig. 13 Strains in Web, PWC-001, A514.
(Loading and Unloading)

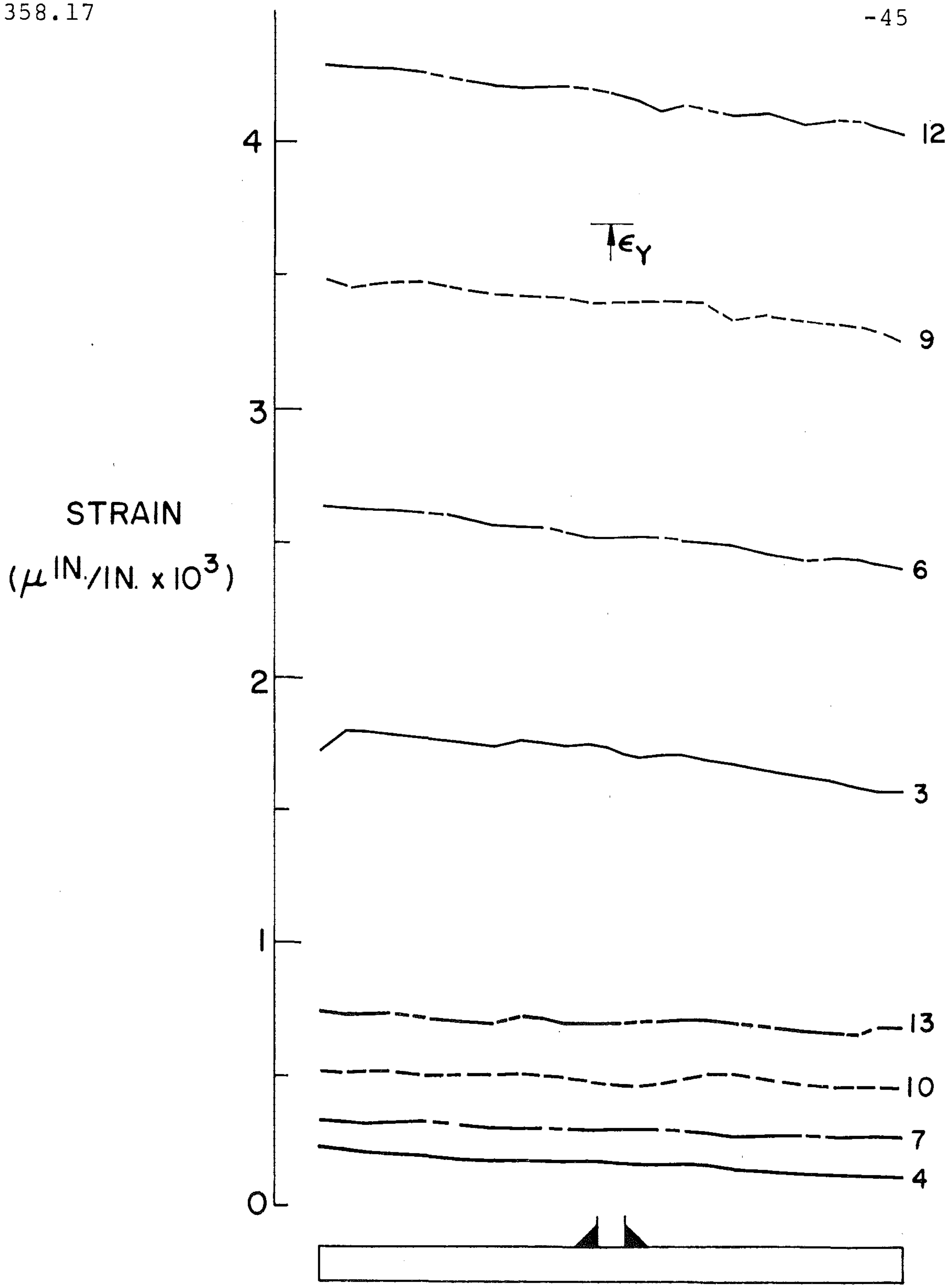

Fig. 14 Strains in Bottom Flange, PWC-001, A514.
(Loading and Unloading)

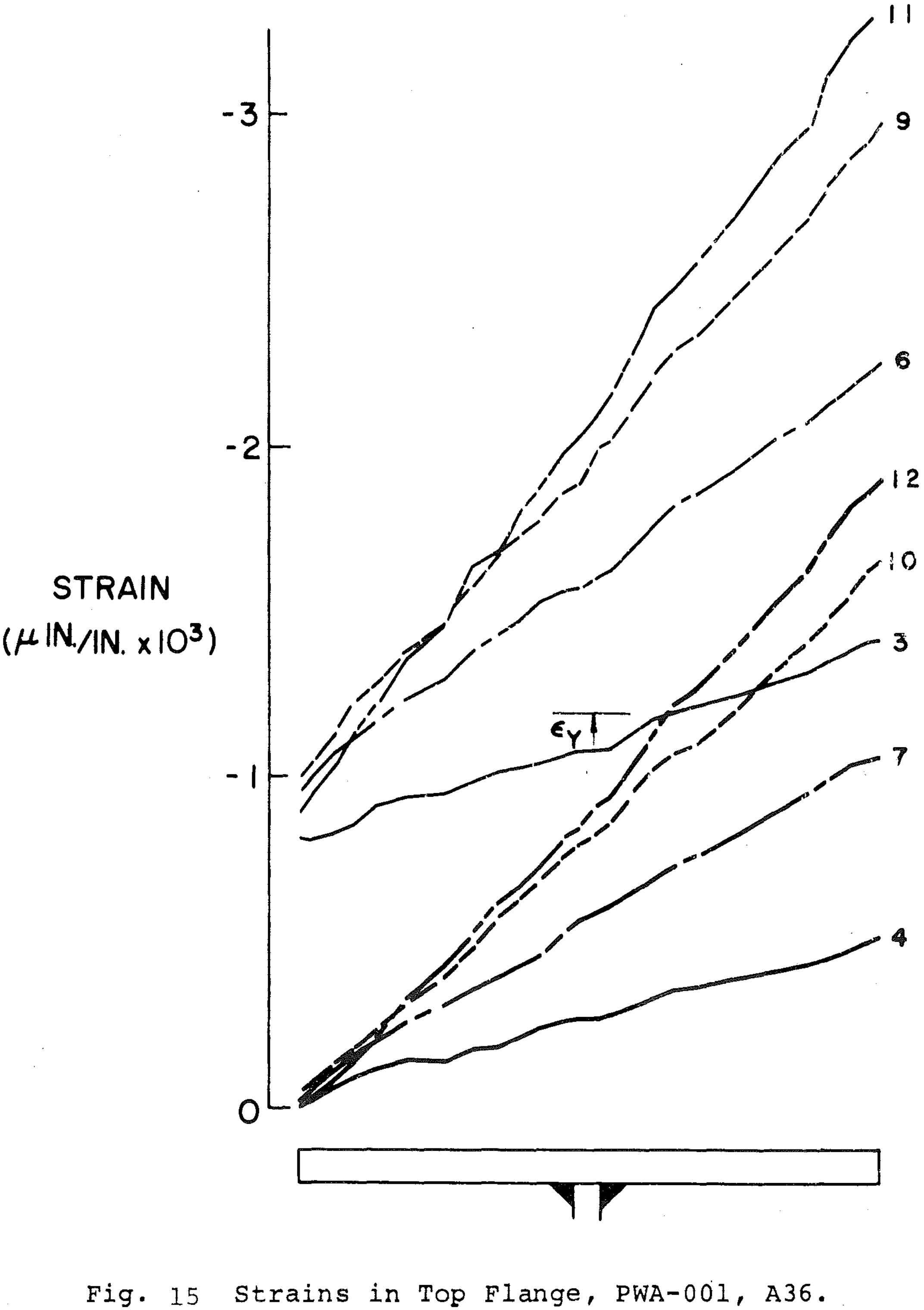

Fig. 15 Strains in Top Flange, PWA-001, A36.
(Loading and Unloading)

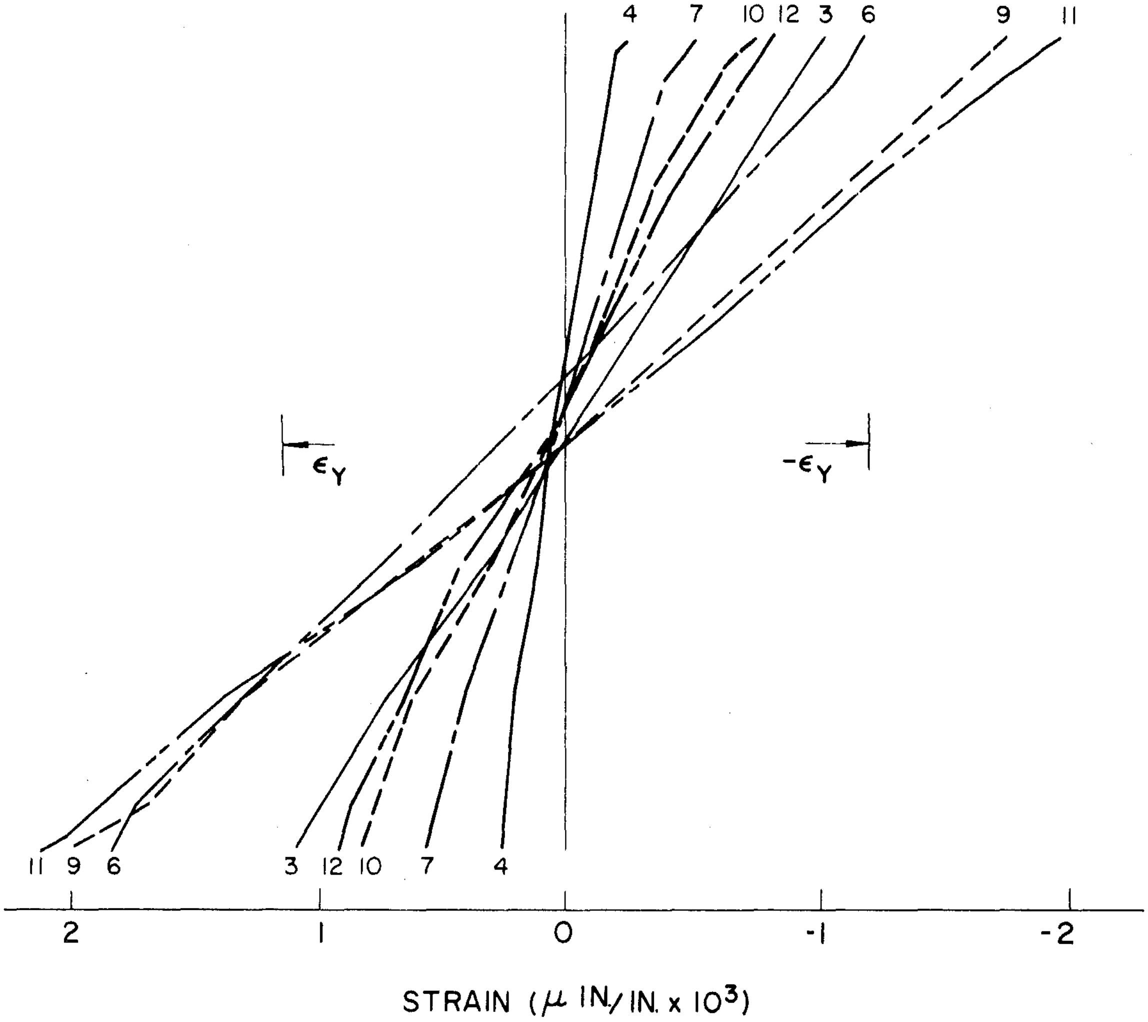

Fig. 16 Strains in Web, PWA-001, A36. (Loading and Unloading)

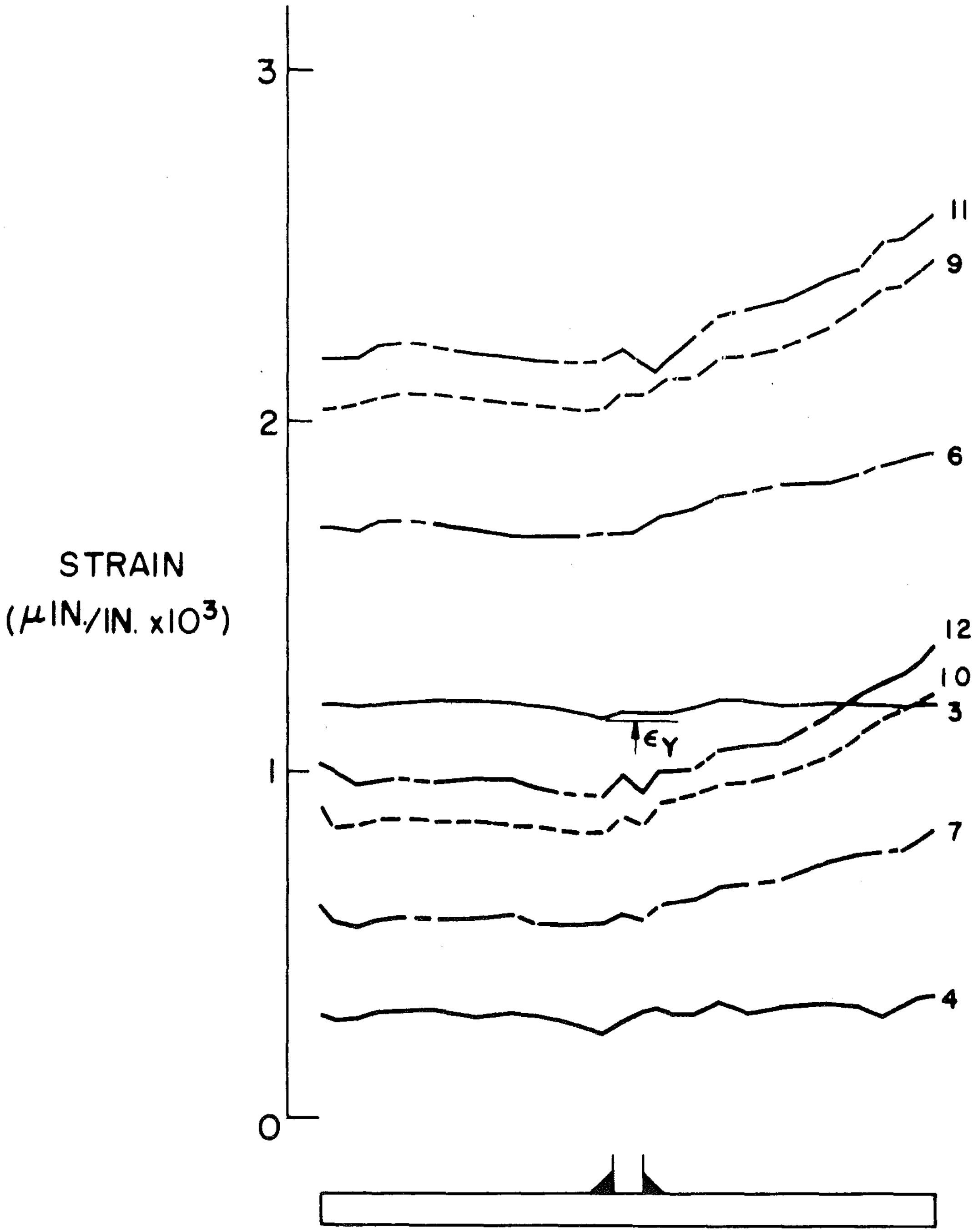

Fig. 17 Strains in Bottom Flange, PWA-001, A36.
(Loading and Unloading)

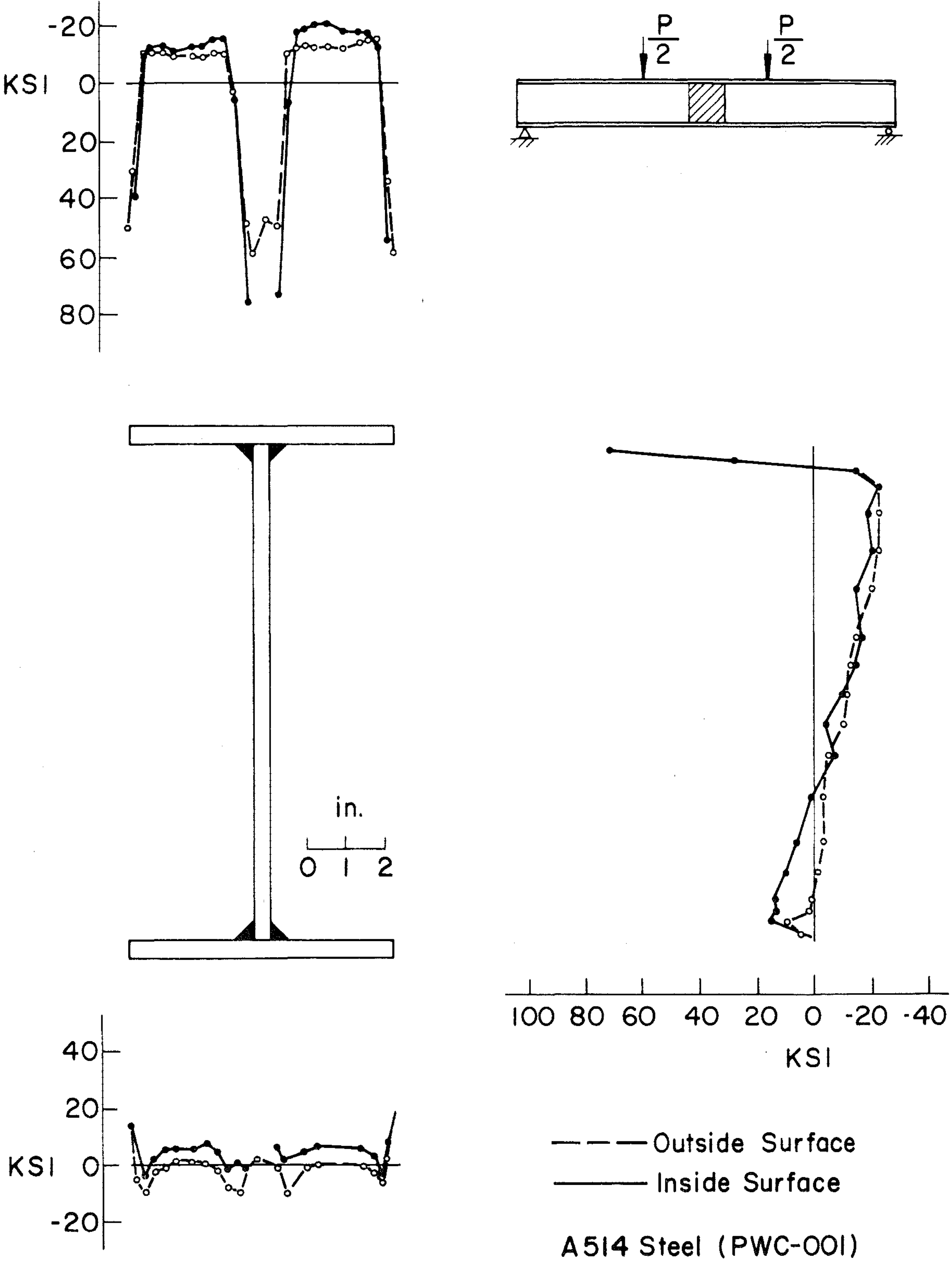

Fig. 18 Residual Stresses in a Welded Shape After 1.04 M_y. PWC-001, A514

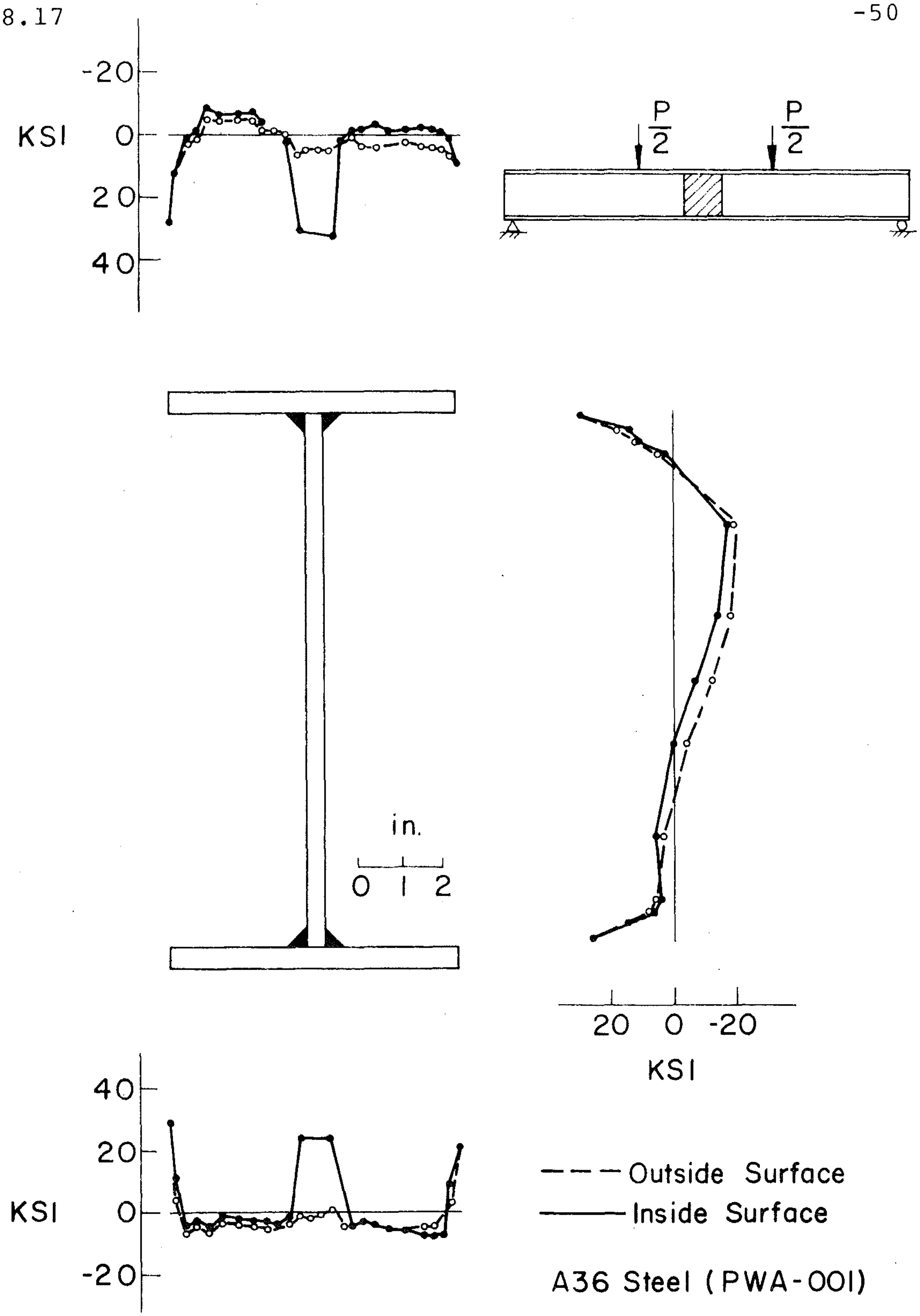

Fig. 19 Residual Stresses in a Welded Shape After 1.10 M_y. PWA-001, A36

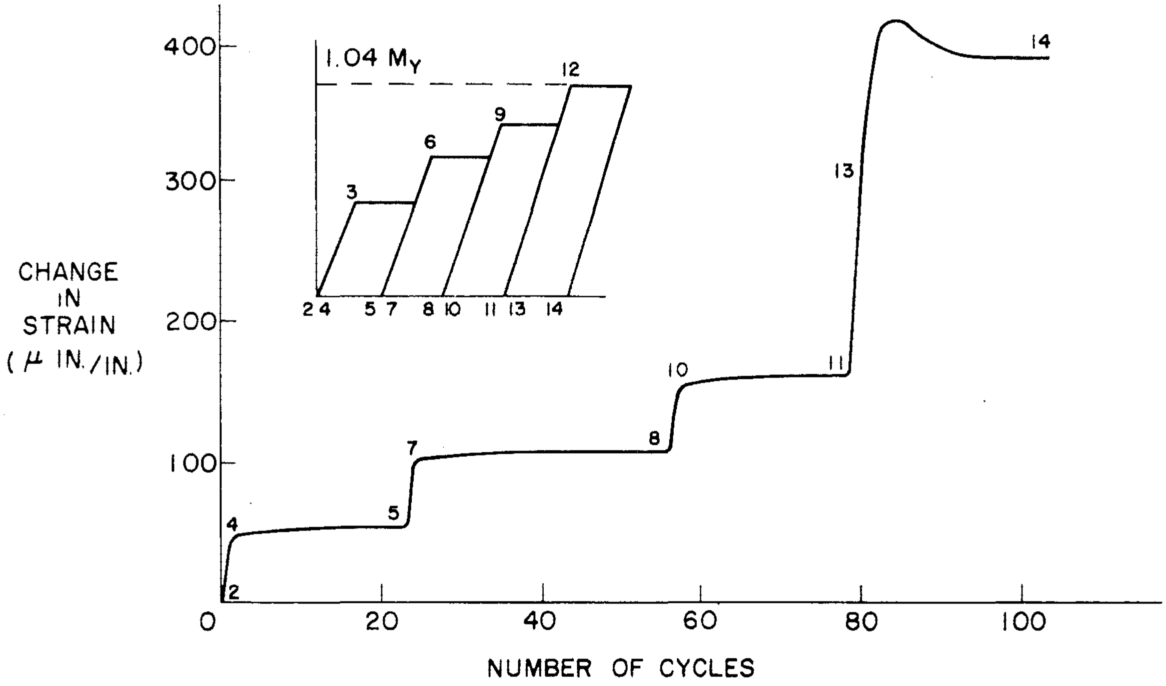

Fig. 20 Residual Strain History of a Point

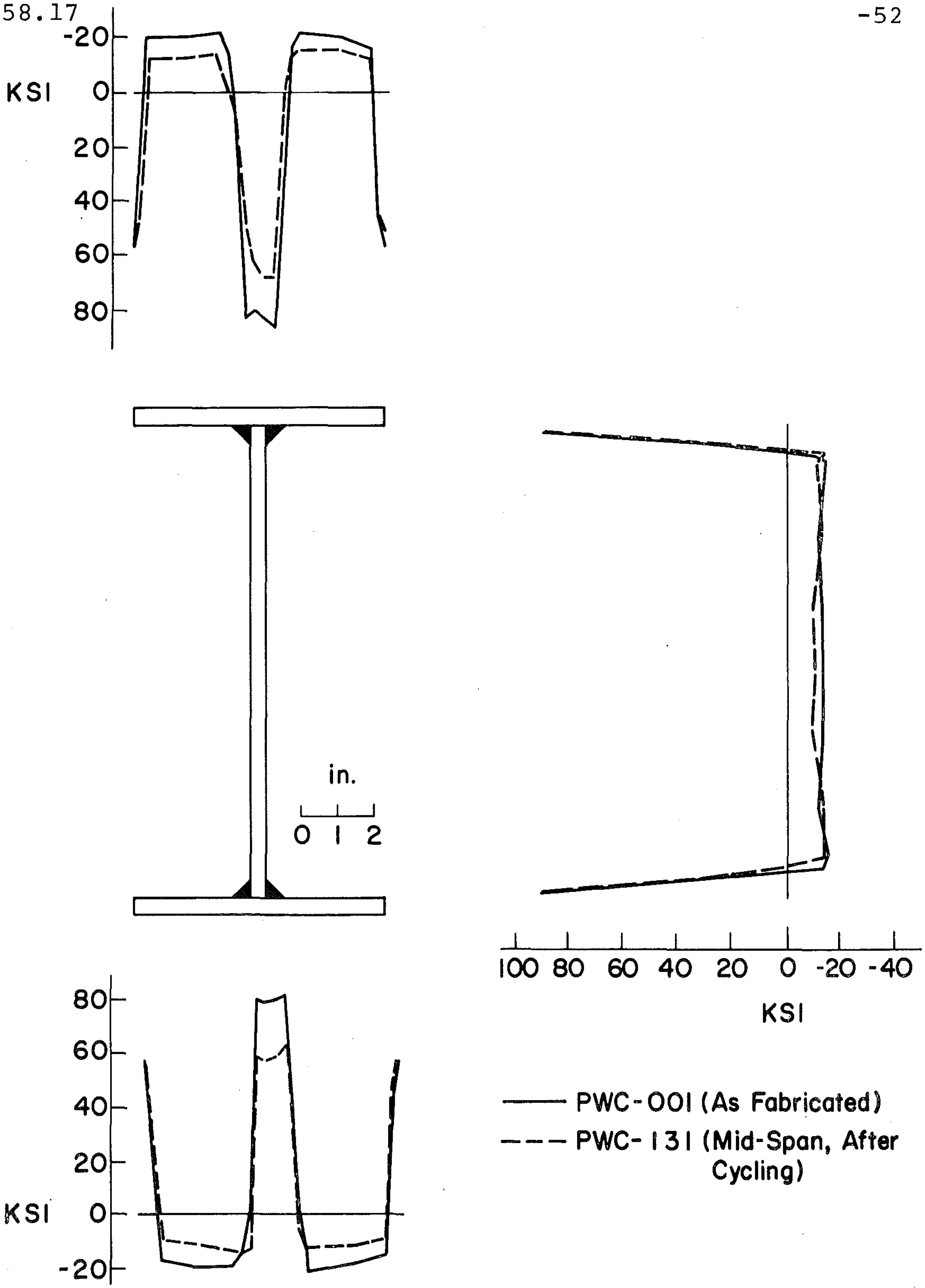

Fig. 21 Comparison of Residual Stresses in As-Welded Shape (PWC-001) and in a Shape After Loading (PWC-131, Mid-Span). A514

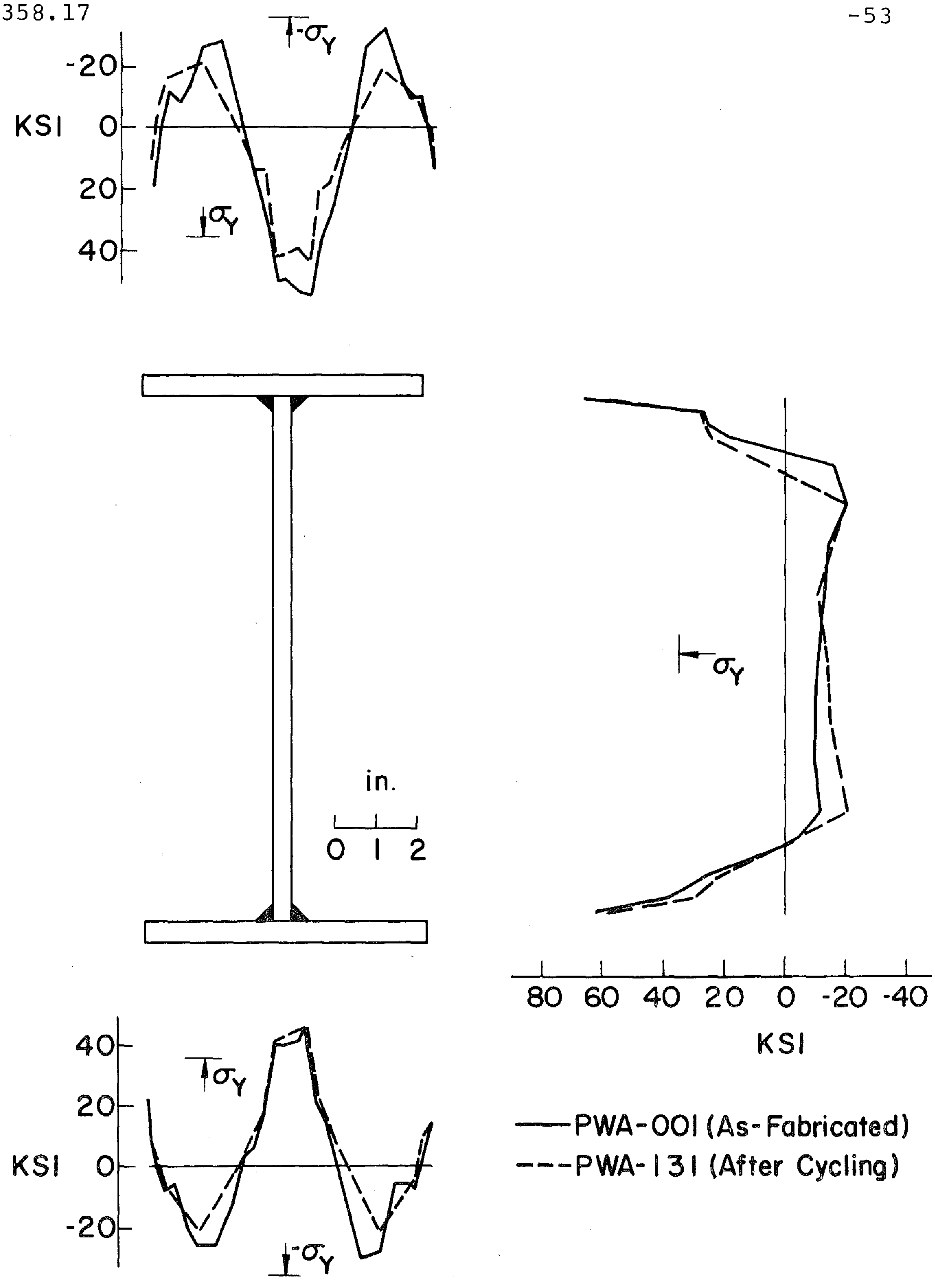

Fig. 22 Comparison of Residual Stresses in As-Welded Shape (PWA-001) and in a Shape After Loading (PWA-131, Shear Span). A36

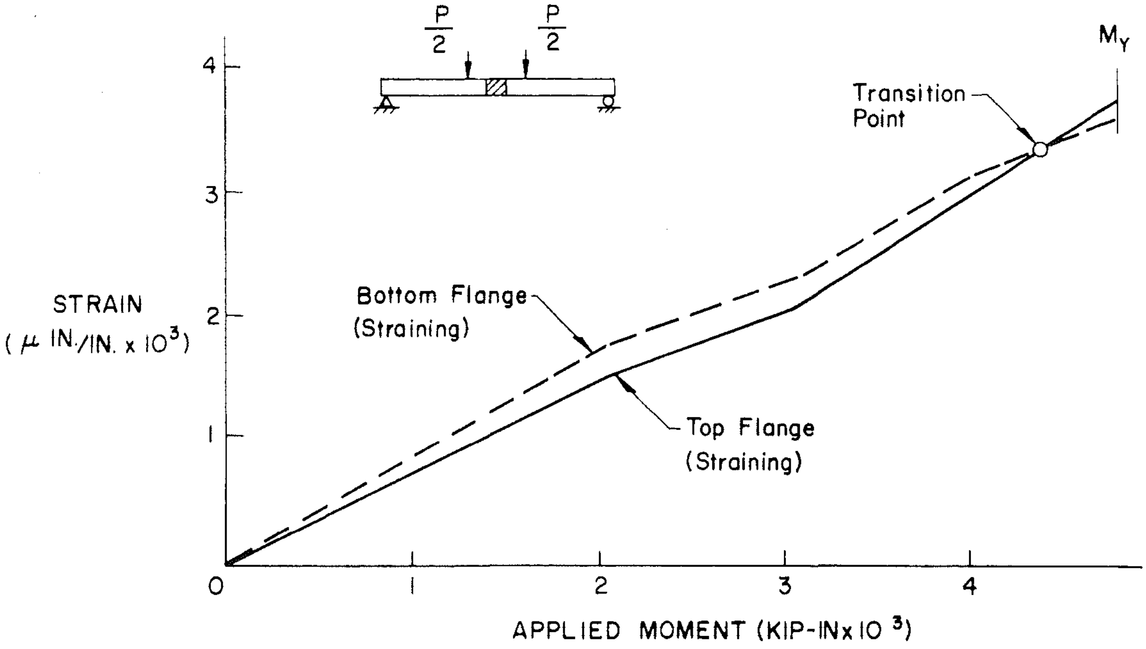

Fig. 23 Strains in the Top and Bottom Flanges Versus Bending Moment

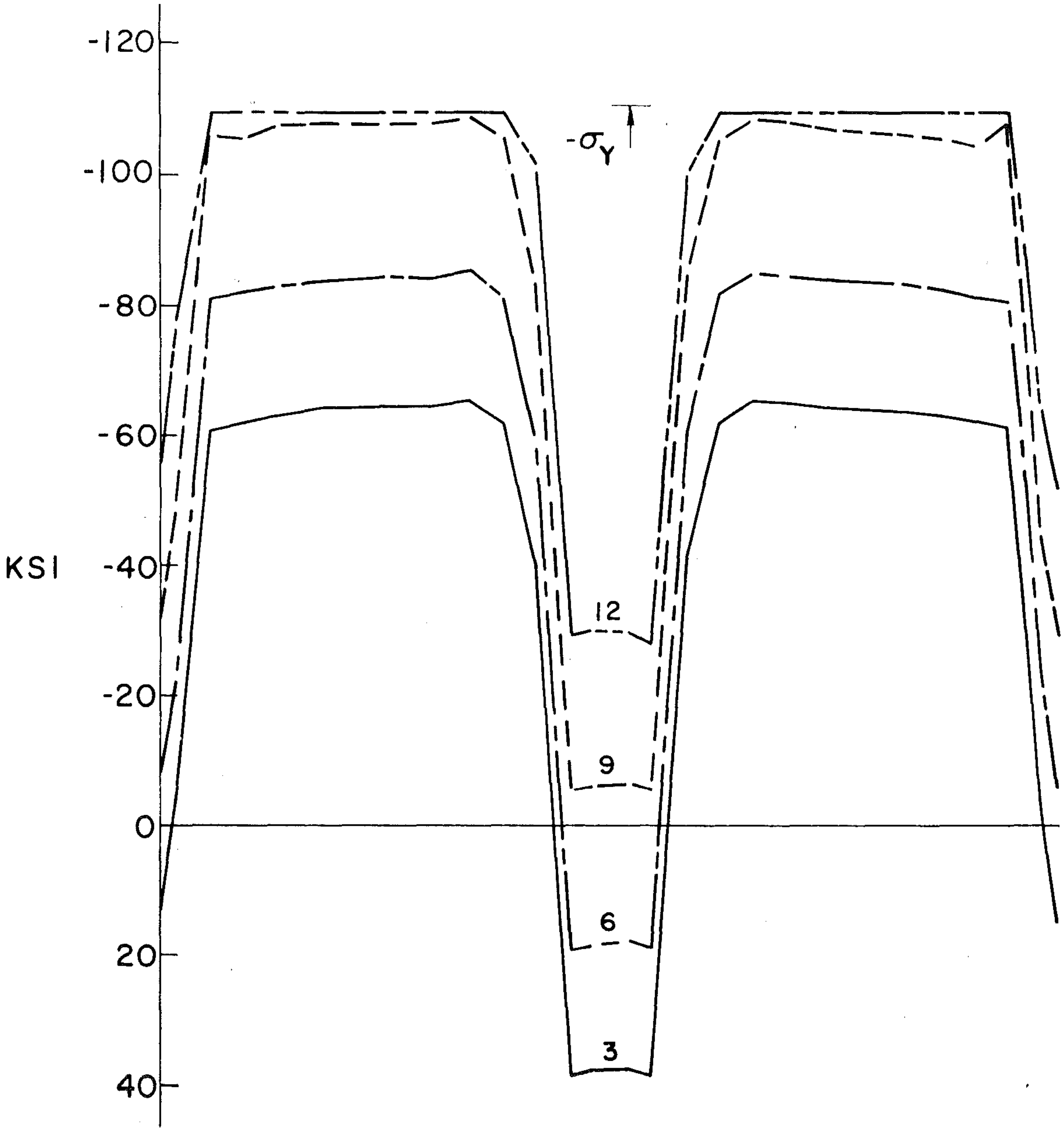

Fig. 24 Stresses Under Load in Top Flange, PWC-001, A514

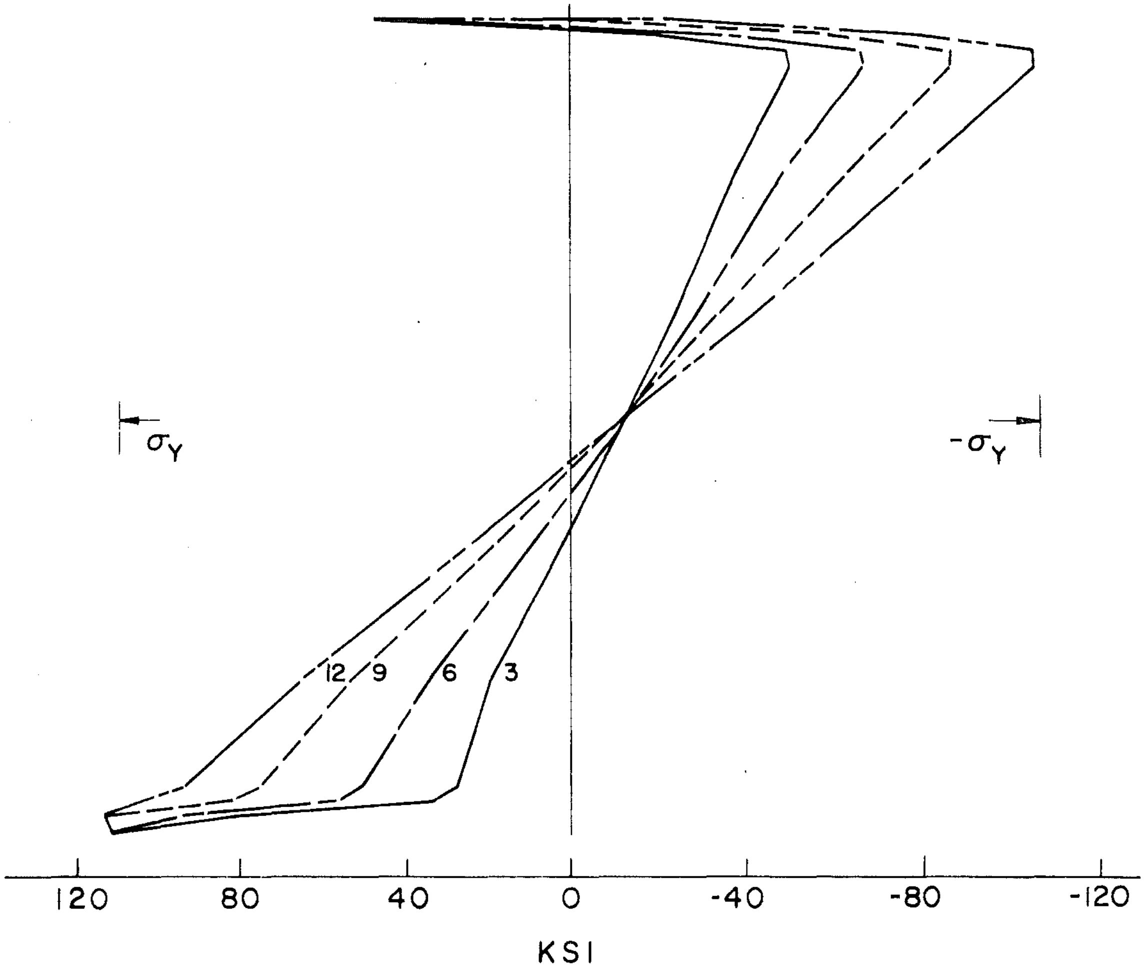

Fig. 25 Stresses Under Load in Web, PWC-001, A514

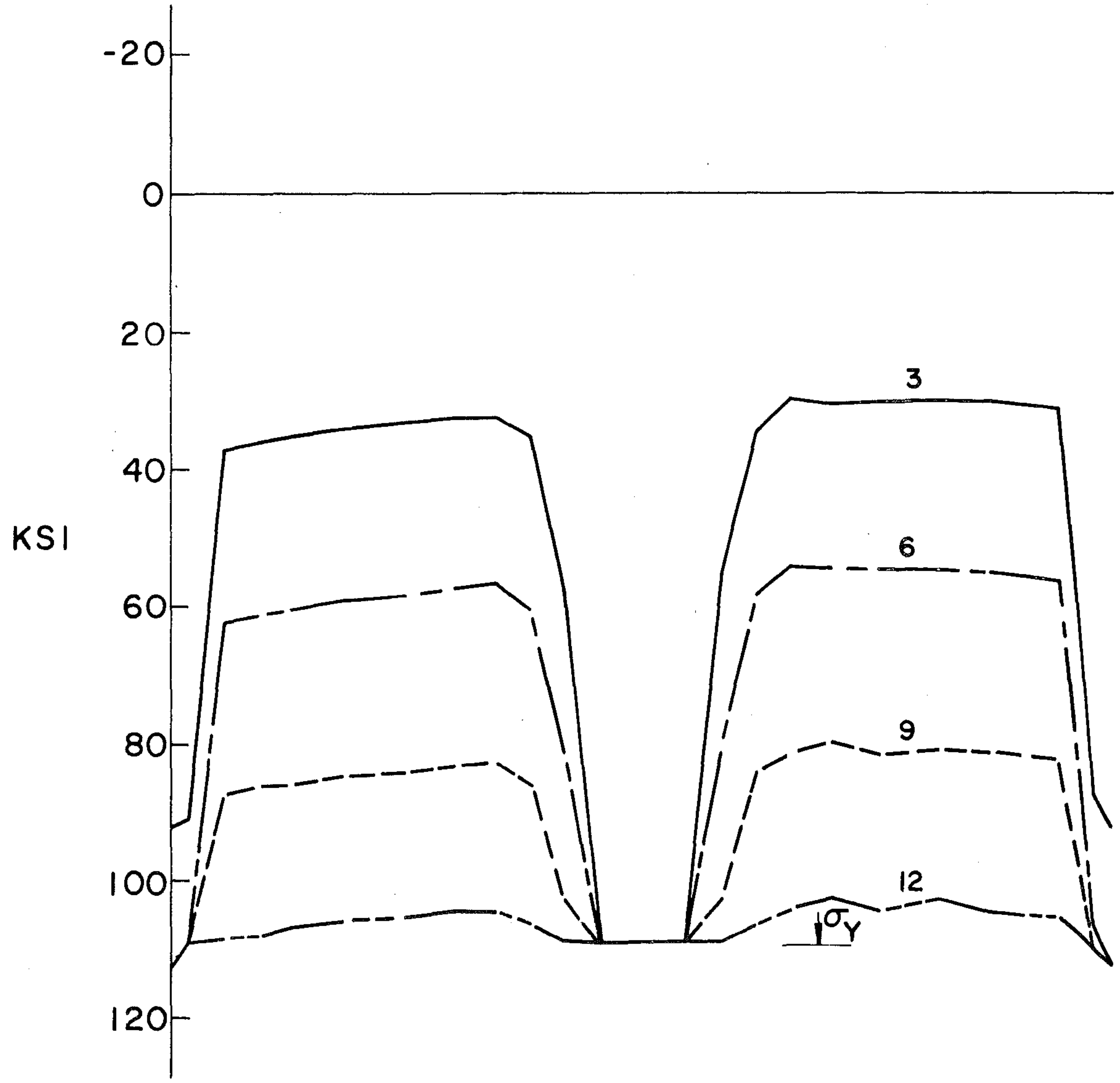

Fig. 26 Stresses Under Load in Bottom Flange, PWC-001, A514

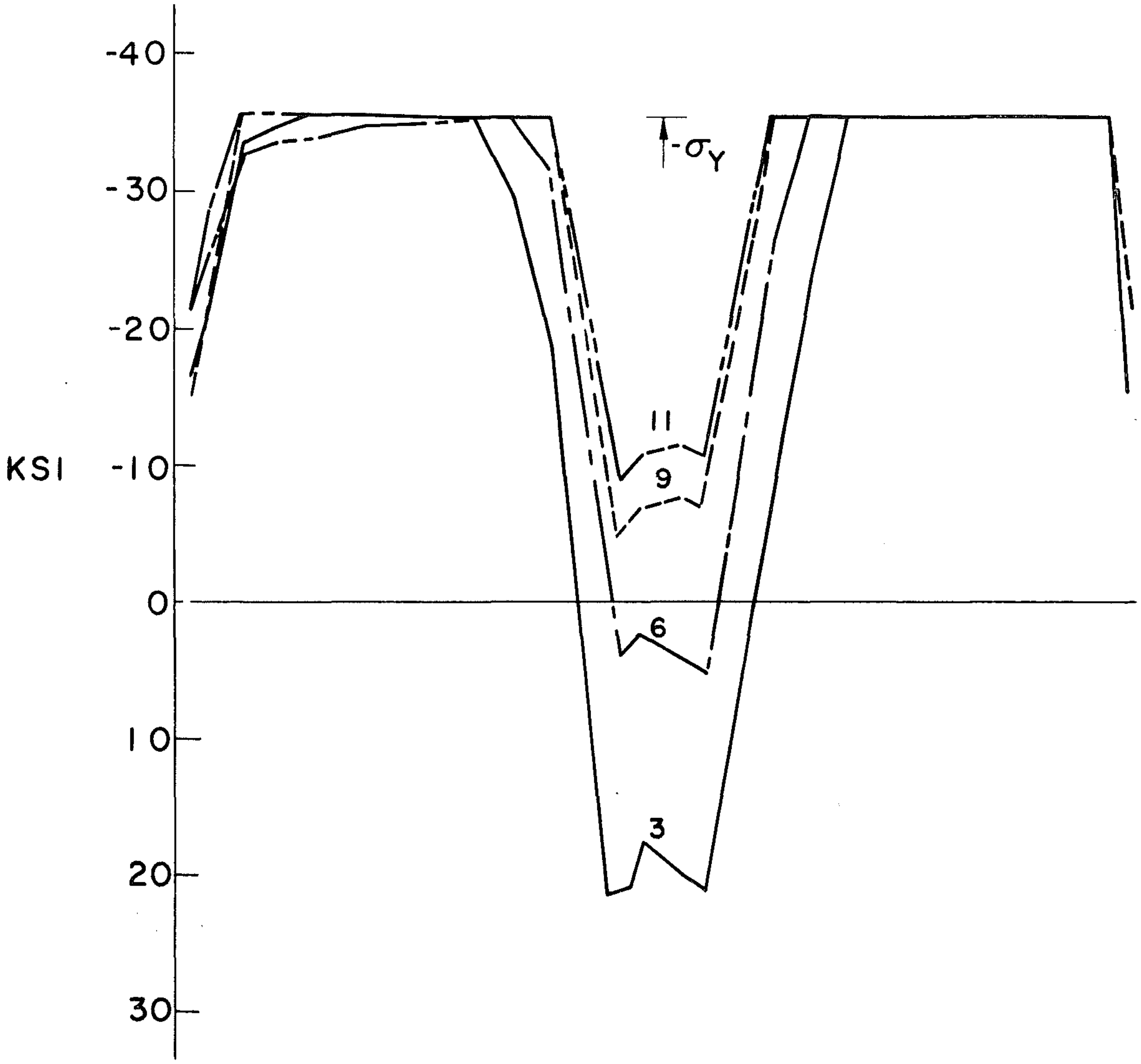

Fig. 27 Stresses Under Load in Top Flange, PWA-001, A36

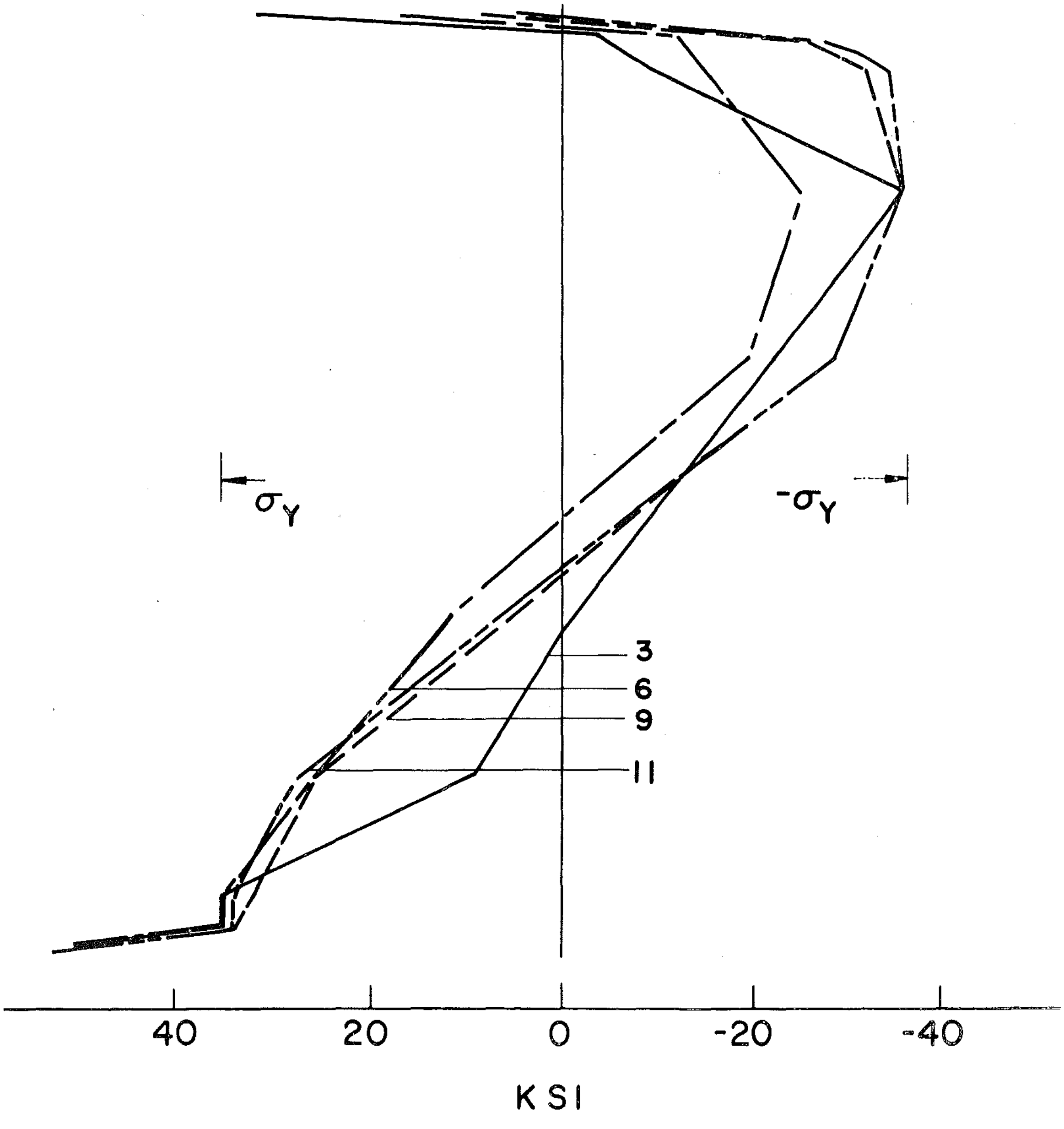

Fig. 28 Stresses Under Load in Web, PWA-001, A36

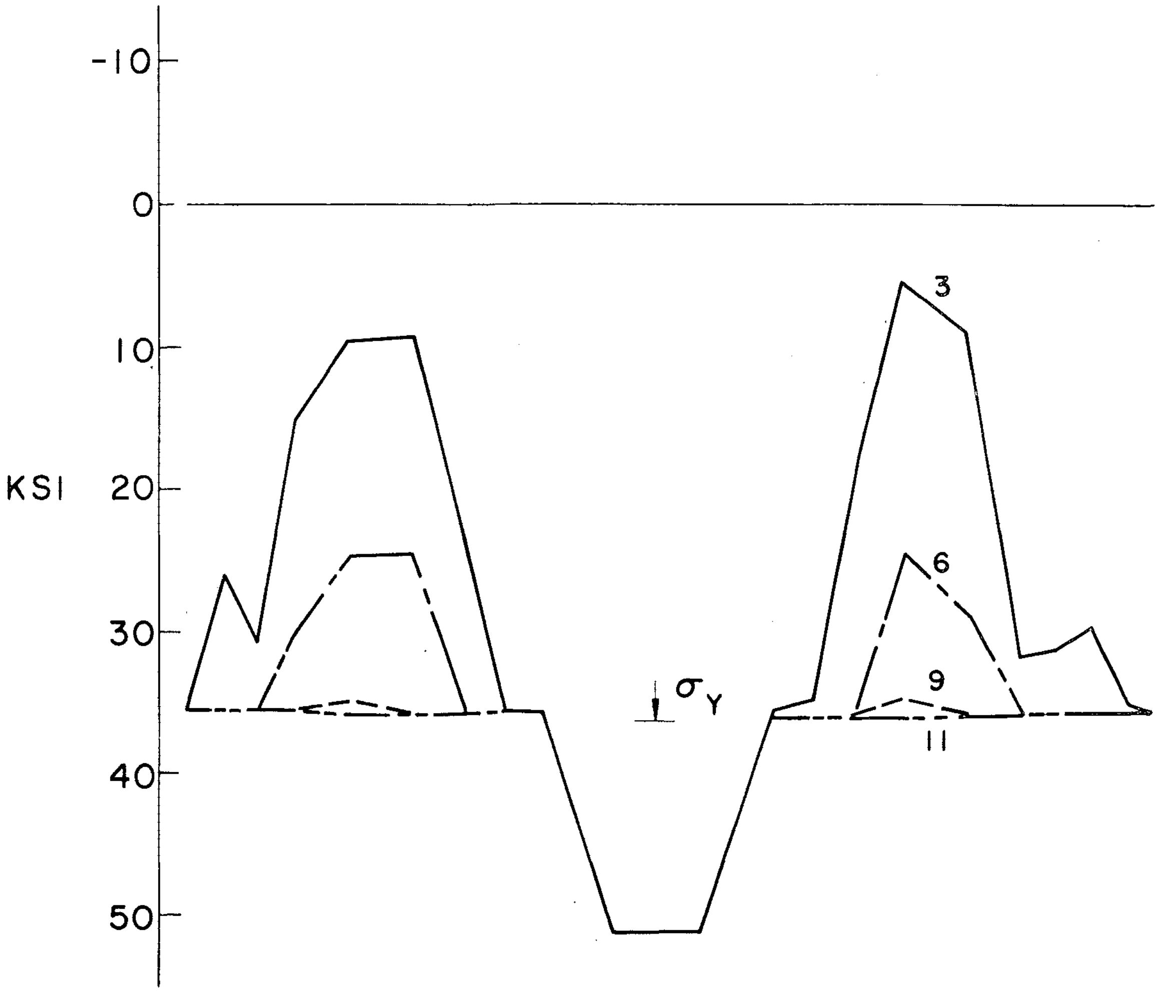

Fig. 29 Stresses Under Load in Bottom Flange, PWA-001, A36

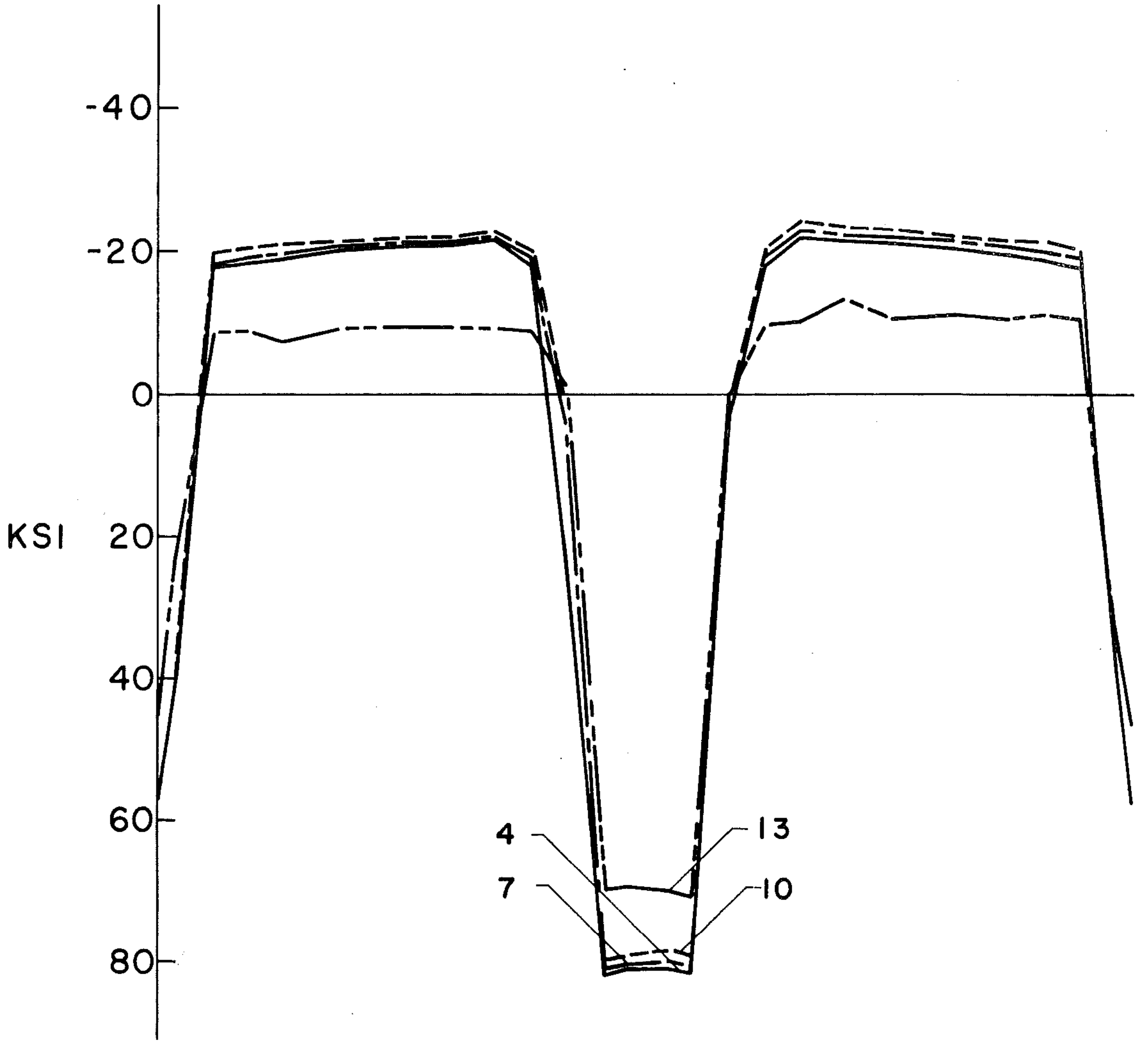

Fig. 30 Residual Stresses After Unloading in Top Flange, PWC-001, A514

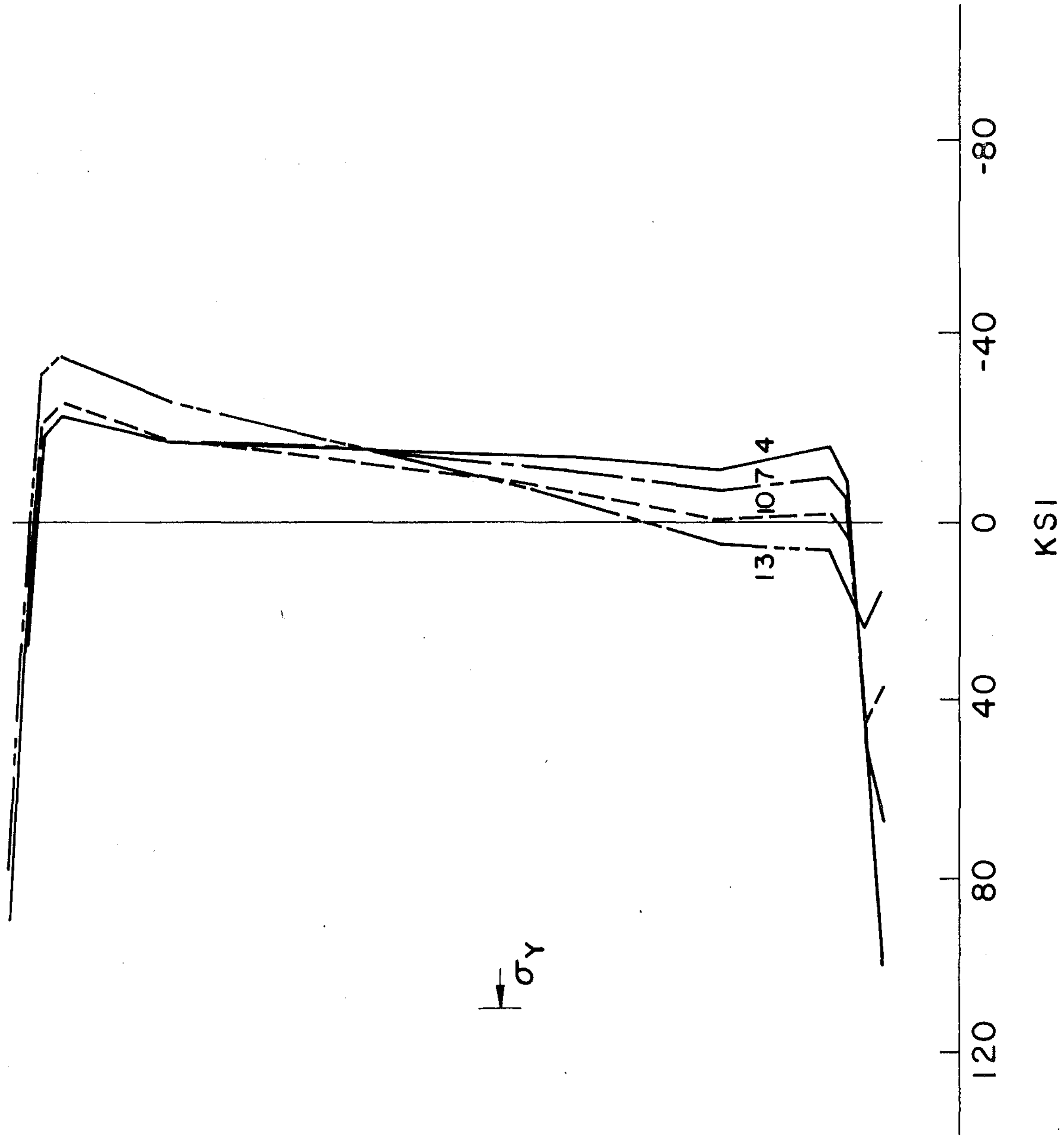

Fig. 31 Residual Stresses After Unloading in Web, PWC-001, A514

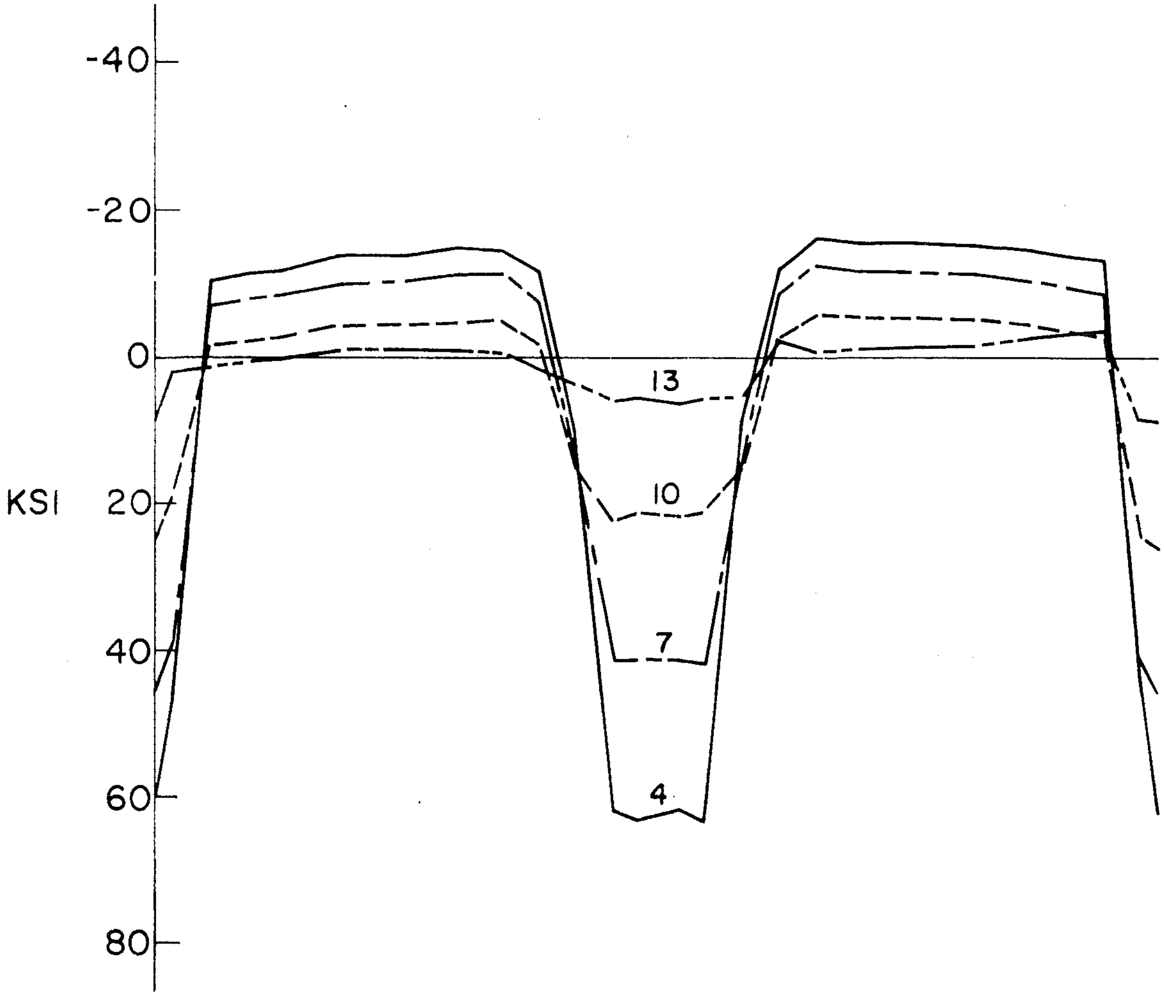

Fig. 32 Residual Stresses After Unloading in Bottom Flange, PWC-001, A514

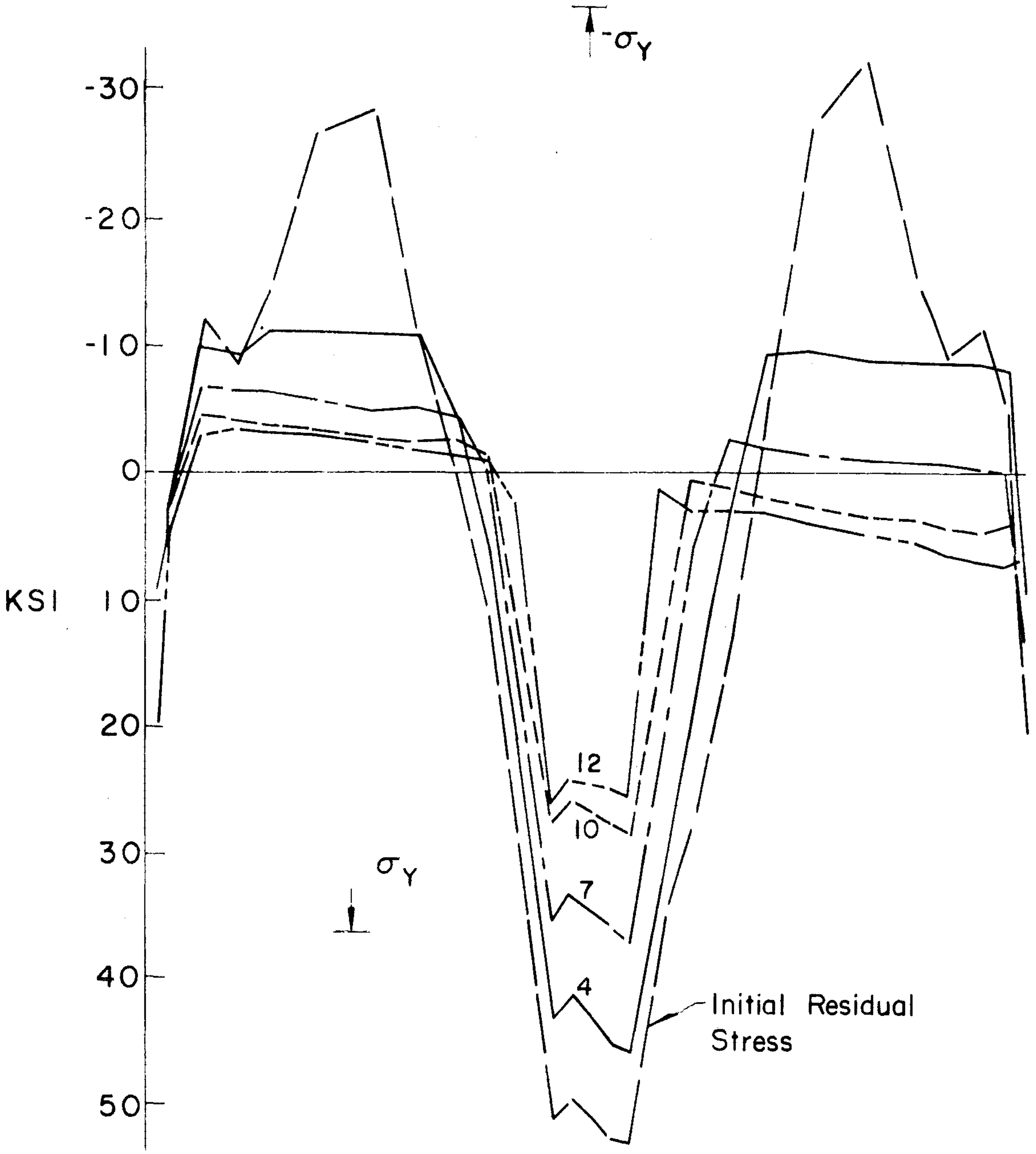

Fig. 33 Residual Stresses After Unloading in Top Flange, PWA-001, A36

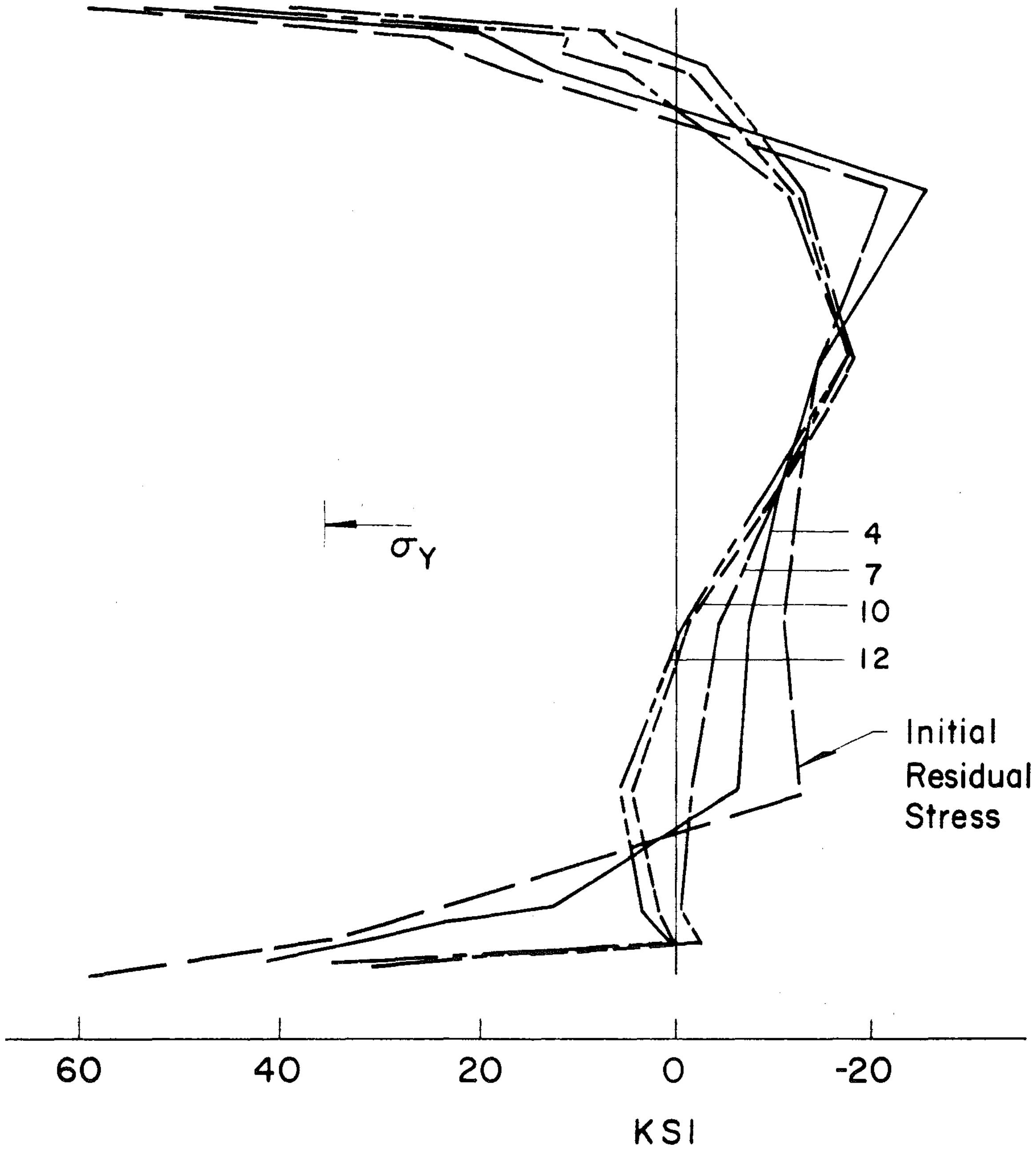

Fig. 34 Residual Stresses After Unloading in Web, PWA-001, A36

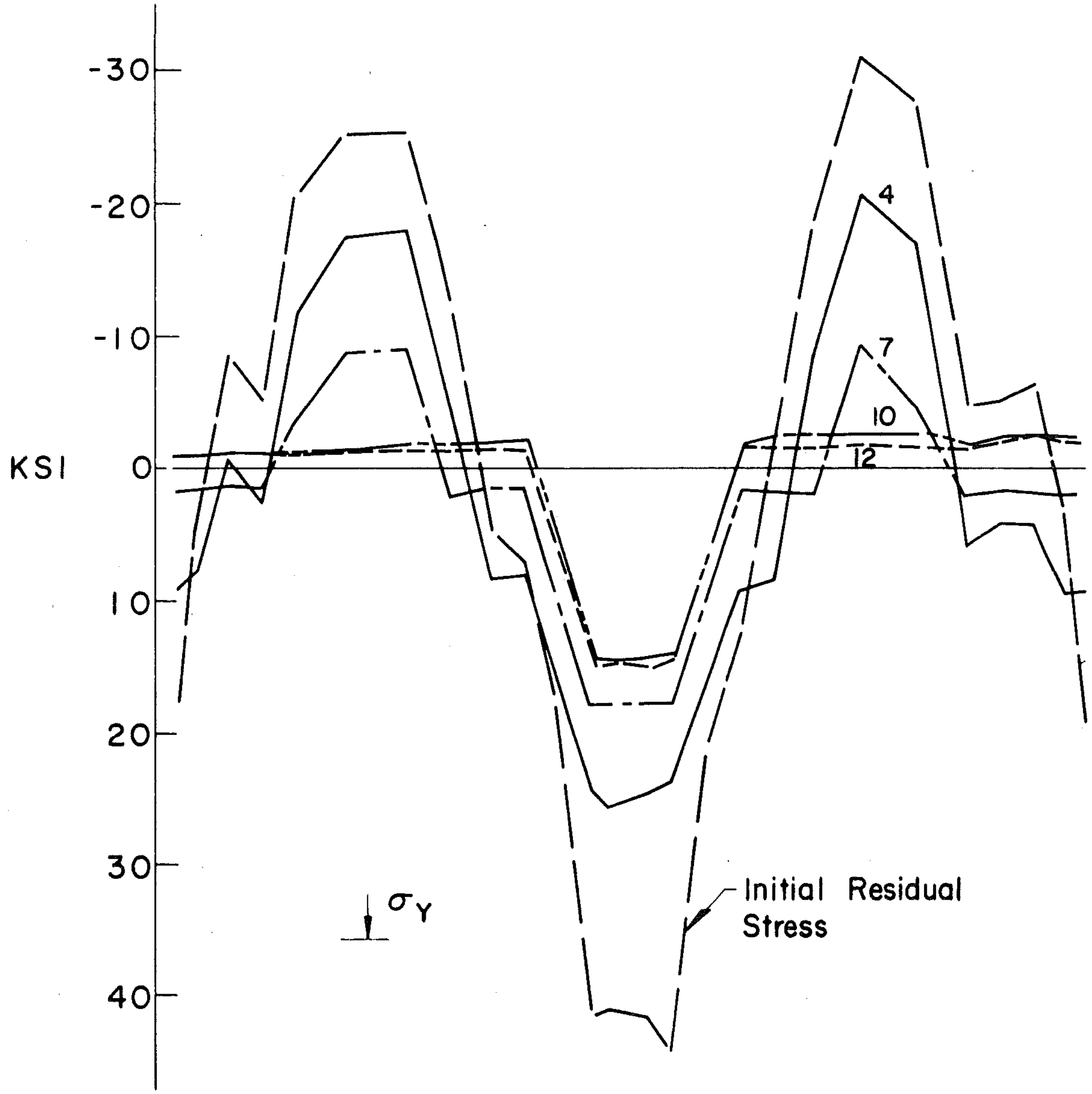

Fig. 35 Residual Stresses After Unloading in Bottom Flange, PWA-001, A36

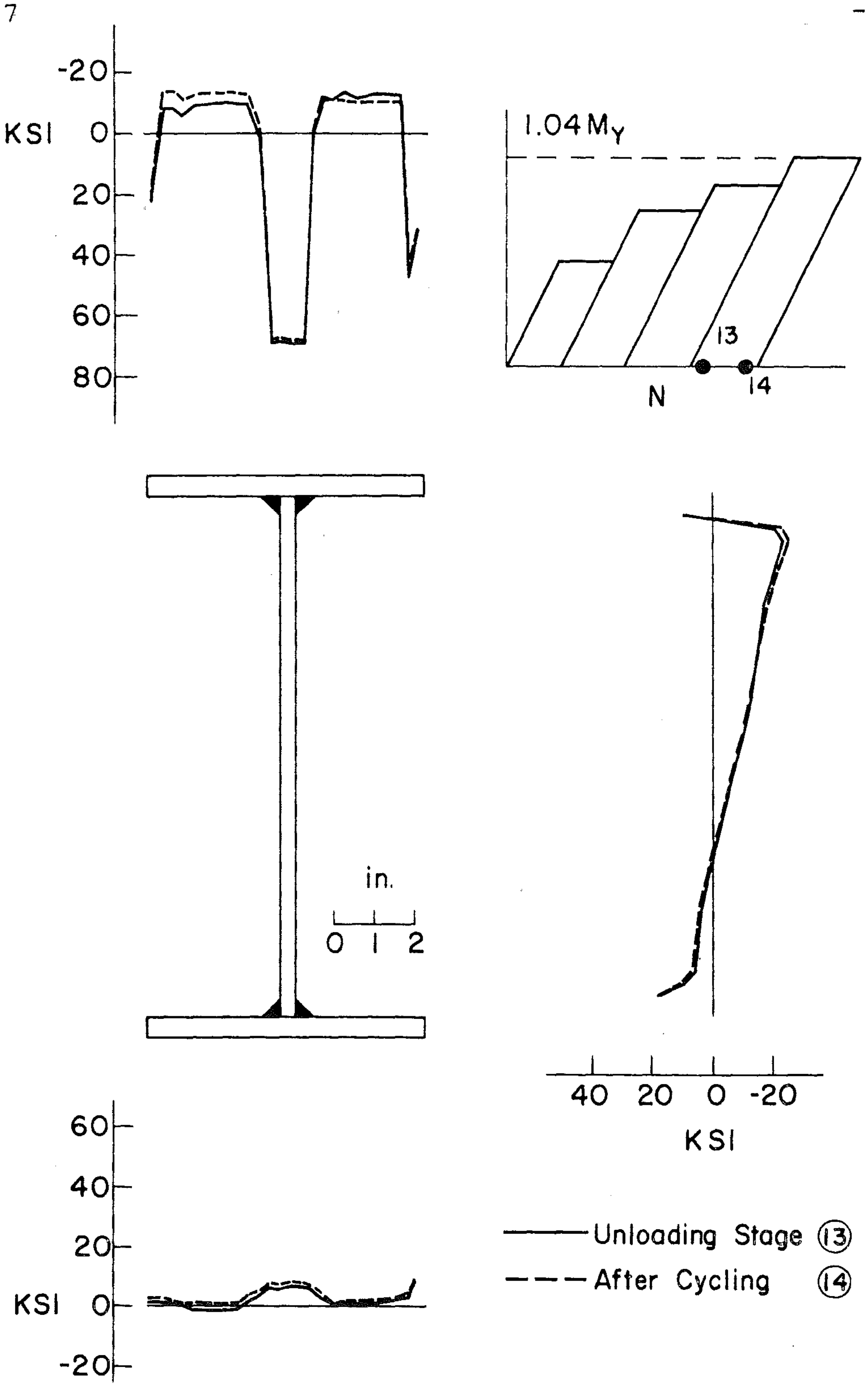

Fig. 36 Effect of Repeated Bending Moment (1.04 M_Y) on Residual Stresses. PWC-001, A514

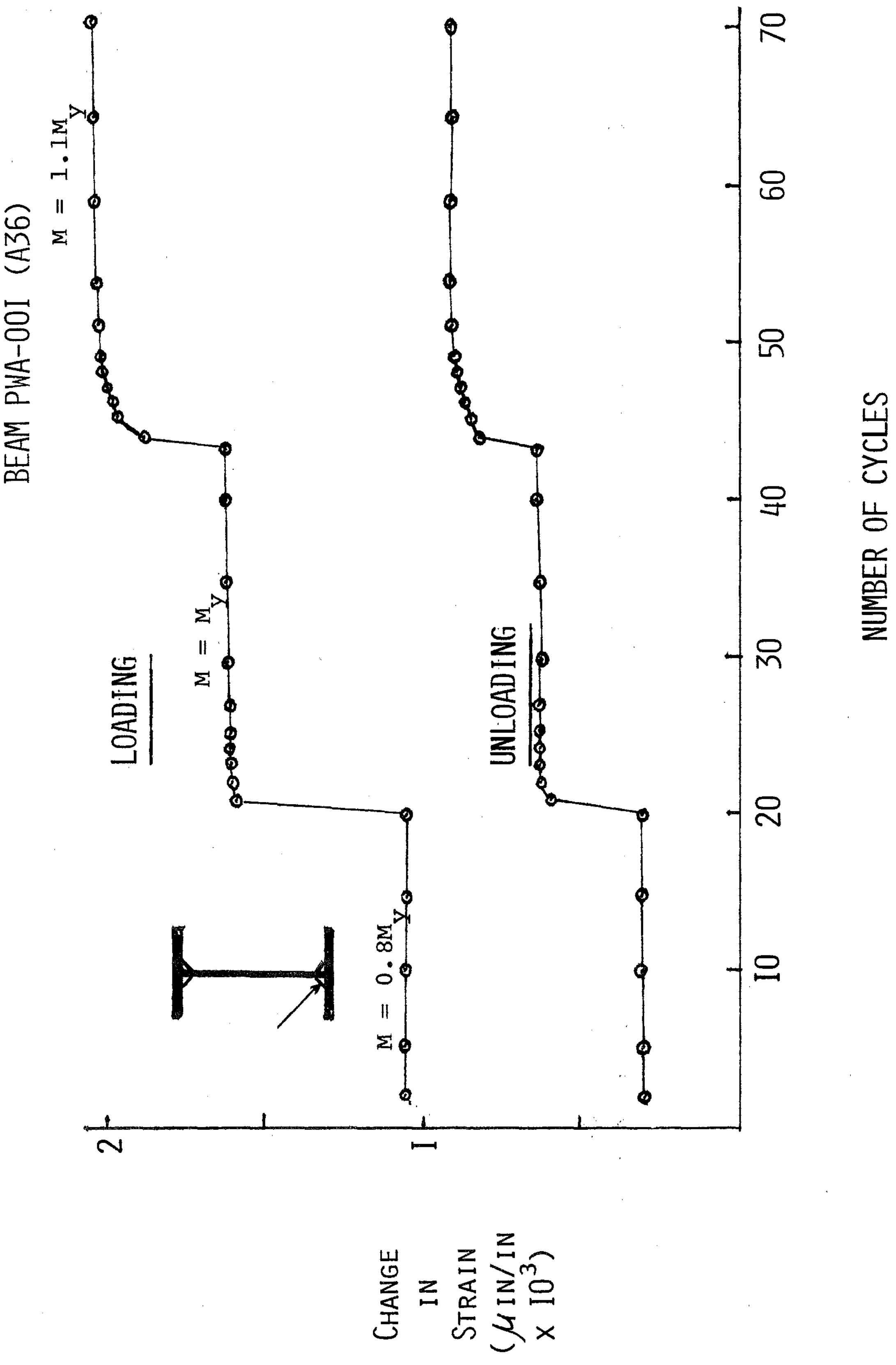

Fig. 37 Strain History of a Point

8. APPENDICES

Appendix 1	Example of Computer Program for Consideration of Strains (Section 2.3)
Appendix 2	Example of Computer Program for Prediction of Stress Distribution (Section 2.4)

Appendix 1 EXAMPLE OF COMPUTER PROGRAM FOR CONSIDERATION OF STRAINS (SECTION 2.3).

```
      DIMENSION DIST(118),AREA(118),Z(118),A(118),B(118),
     1SUMA(118),SUM(118),UNK(118),TSUMA(118),FORCE(118),
     2FMOM(118)
C     STRAIN ON THE TOP FIBER(MICRO INCH/INCH)
      TOPOUT=-3762.
      HH=6.873
      HHH=6.679
C     NEUTRAL AXIS
      DX=6.97
C     NUMBER OF ELEMENTS
      M=118
C     READ AREA OF EACH ELEMENT AS WELL AS ITS RESPECTIVE
C     DISTANCE TO THE OUTSIDE FIBER OF BOTTOM FLANGE
      READ(1,5000) (DIST(I),I=47,59)
      READ(1,5000) (DIST(I),I=106,118)
 5000 FORMAT(8F10.0)
      DO 1430 I=1,24
 1430 DIST(I)=13.843
      DO 1431 I=84,105
 1431 DIST(I)=13.649
      DO 1432 I=25,46
 1432 DIST(I)=0.291
      DO 1433 I=60,83
 1433 DIST(I)=0.097
      READ(1,5000) (AREA(I),I=1,M)
C     READ VIRGIN BEAM AND THE FIRST TWO STAGES.
      READ(1,5000) (Z(I),I=1,M)
      READ(1,5000) (A(I),I=1,M)
      READ(1,5000) (B(I),I=1,M)
C     OBTAIN THE NEW STATE OF RESIDUAL STRESS IN THE
C     VIRGIN BEAM AFTER PUTTING THE STIFFENERS
      DO 1183 I=1,M
 1183 SUMA(I)=0.
      DO 1001 I=1,M
      SUM(I)=B(I)-A(I)
      SUMA(I)=SUMA(I)+Z(I)+SUM(I)
 1001 CONTINUE
      DO 2000 I=1,24
 2000 SUMA(I)=SUMA(I)+TOPOUT
      DO 2001 I=84,105
      UNK(I)=TOPOUT*HHH/HH
 2001 SUMA(I)=SUMA(I)+UNK(I)
      DO 2002 I=47,59
      UNK(I)=-(DX-DIST(I))*TOPOUT/HH
 2002 SUMA(I)=SUMA(I)+UNK(I)
```

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```
      DO 2003 I=106,118
      UNK(I)=-(DX-DIST(I))*TOPOUT/HH
 2003 SUMA(I)=SUMA(I)+UNK(I)
      DELTA=1.
 9000 DO 2004 I=25,46
      UNK(I)=-(TOPOUT*(DX-0.291)/HH)*DELTA*DELTA**2
 2004 SUMA(I)=SUMA(I)+UNK(I)
      DO 2005 I=60,83
      UNK(I)=-(TOPOUT*(DX-0.097)/HH)*DELTA*DELTA**2
 2005 SUMA(I)=SUMA(I)+UNK(I)
      DO 3000 I=1,M
      IF(SUMA(I).LT.-3685.) GO TO 3001
      IF(SUMA(I).GT.3685.) GO TO 3002
      TSUMA(I)=SUMA(I)*0.03
      GO TO 3000
 3001 SUMA(I)=-3685.
      TSUMA(I)=-110.6
      GO TO 3000
 3002 SUMA(I)=3685.
      TSUMA(I)=110.6
 3000 CONTINUE
C     SUMATION OF FORCES(TFORCE)
      DO 7000 I=1,M
 7000 FORCE(I)=TSUMA(I)*AREA(I)
      SFORCE=0.
      DO 1088 I=1,M
 1088 SFORCE=SFORCE+FORCE(I)
      X1=((TSUMA(12)+TSUMA(94))/2.)*AREA(12)
      X2=((TSUMA(13)+TSUMA(95))/2.)*AREA(12)
      X3=TSUMA(94)*0.0312
      X4=TSUMA(95)*0.0312
      X5=((TSUMA(94)+TSUMA(95))/2.)*0.074
      X6=((TSUMA(35)+TSUMA(71))/2.)*AREA(12)
      X7=((TSUMA(36)+TSUMA(72))/2.)*AREA(12)
      X8=TSUMA(35)*.0312
      X9=TSUMA(36)*.0312
      X10=((TSUMA(35)+TSUMA(36))/2.)*0.074
      X11=(TSUMA(50)+TSUMA(51)+TSUMA(109)+TSUMA(110))/4.*
     11.25*0.296
      X12=(TSUMA(51)+TSUMA(52)+TSUMA(110)+TSUMA(111))/4.*
     11.75*0.296
      X13=(TSUMA(52)+TSUMA(53)+TSUMA(111)+TSUMA(112))/4.*
     11.332*0.296
```

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```
      X14=(TSUMA(53)+TSUMA(54)+TSUMA(112)+TSUMA(113))/4.*
     11.332*0.296
      X15=(TSUMA(54)+TSUMA(55)+TSUMA(113)+TSUMA(114))/4.*
     11.75*0.296
      X16=(TSUMA(55)+TSUMA(56)+TSUMA(114)+TSUMA(115))/4.*
     11.25*0.296
      TFORCE=X1+X2+X3+X4+X5+X6+X7+X8+X9+X10+X11+X12+X13+
     1X14+X15+X16
C     EQUILIBRIUM OF FORCES
      IF(TFORCE.LT.-5.) GO TO 4002
      IF(TFORCE.GT.5.) GO TO 4003
C     SUMATION OF MOMENTS(TFMOM)
      DO 5555 I=1,M
 5555 FMOM(I)=FORCE(I)*DIST(I)
      SAL=0.
      DO 5001 I=1,M
 5001 SAL=SAL+FMOM(I)
      TFMOM= SAL+X1*13.649+X2*13.649+X3*13.427+X4*13.427+X5
      *13.427+  X6*.291+X7*.291+X8*.513+X9*.513+X10*.513+
      X11*11.927+X12*9.927+ X13*7.886+X14*6.054+X15*4.013
      +X16*2.013
      WRITE(2,9036) TFORCE,TFMOM
 9036 FORMAT(1H1,F10.3,10X,F15.3)
      GO TO 200
C     INCREMENT
 4002 DELTA=1.005
      GO TO 9000
 4003 DELTA=0.995
      GO TO 9000
  200 CALL EXIT
      END
```

Appendix 2 EXAMPLE OF COMPUTER PROGRAM FOR PREDICTION OF STRESS DISTRIBUTION (SECTION 2.4)

(Flow Chart included in Ref. 1)

```
      DIMENSION A(132),B(132),EX(132),F(132),FR(132),
     1DF(132),FF(132),FUN(132),FM(132),EXD(132),DFF(132),
     2TSUMA(132),FRR(132),FORCE(132),FMOM(132),FFM(132),
     3TFUN(132),BYY(5)
      DATA (BYY(L),L=1,5)/750.0,2050.0,3050.0,4050.0,4800.0/
C     WF=FLANGE WIDTH,TF=FLANGE THICKNESS,H=DEPTH OF BEAM
C     TW=WEB THICKNESS,FY=YIELD STRESS,BMAX=MAX APPLIED
C     MOMENT
      READ(5,10) WF,TF,H,TW,FY,BMAX,DDM,FRM
   10 FORMAT(8F10.0)
C     READ INITIAL RESIDUAL STRESS
      READ(5,17)  (FR(I),I=1,132)
   17 FORMAT(8F10.0)
      WRITE(6,800)
  800 FORMAT(1H1)
C     WRITE INITIAL RESIDUAL STRESS
      WRITE(6,91)  (FR(I),I=1,40)
      DO 230 I=41,92
  230 WRITE(6,310)  I,FR(I)
  310 FORMAT(120X,I2,4X,F5.1)
      WRITE(6,91)  (FR(I),I=93,132)
   91 FORMAT(2X,20(F6.1))
      HW=H-2.*TF
      AOF=WF*TF/80.
      EF1=H-TF/4.
      EF2=H-0.75*TF
      EF3=0.75*TF
      EF4=0.25*TF
      AOW=TW*HW/(2.*52.)
      EEW=TF+HW/104.
C     TRANSFORMATION OF RESIDUAL STRESS TO RESIDUAL STRAIN
      DO 8020 I=1,132
 8020 FRR(I)=FR(I)/0.03
      DO 362  I=1,132
  362 FF(I)=FRR(I)
C     DISTANCES FROM ELEMENTS TO OUTSIDE SURFACE OF BOTTOM
C     FLANGE AND AREAS OF EACH ELEMENT
      DO 11 I=1,20
      A(I)=AOF
   11 EX(I)=EF1
      DO 12 I=21,40
      A(I)=AOF
   12 EX(I)=EF2
      EDW=0.
      DO 13 I=41,92
      A(I)=AOW
      EX(I)=H-EEW-EDW
   13 EDW=HW/52.+EDW
```

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```
      DO 14 I=93,112
      A(I)=AOF
   14 EX(I)=EF3
      DO 15 I=113,132
      A(I)=AOF
   15 EX(I)=EF4
C     SUMATION OF FORCES AND INTERNAL MOMENTS
      DO 7000 I=1,40
      FORCE(I)=FR(I)*A(I)*2.
 7000 FMOM(I)=FORCE(I)*EX(I)
      DO 7001 I=41,92
      FORCE(I)=FR(I)*A(I)*2.
 7001 FMOM(I)=FORCE(I)*EX(I)
      DO 7002 I=93,132
      FORCE(I)=FR(I)*A(I)*2.
 7002 FMOM(I)=FORCE(I)*EX(I)
      SFORCE=0.
      DO 1088 I=1,132
 1088 SFORCE=SFORCE+FORCE(I)
      X1=(FR(40)*.0312)*2.
      X2=(FR(112)*.0312)*2.
C     TOTAL FORCE(TFORCE)
      TFORCE=SFORCE+X1+X2
      SAL=0.
      DO 7033 I=1,132
 7033 SAL=SAL+FMOM(I)
C     TOTAL INTERNAL MOMENT(TFMOM)
      TFMOM=SAL+X1*13.427+X2*.513
      WRITE(6,9036) TFORCE,TFMOM
 9036 FORMAT(1X,F10.3,10X,F15.3)
      DO 16 I=1,132
   16 B(I)=1.0
C     NEUTRAL AXIS
      DX=6.97
      XI=0.
C     MOMENT OF INERTIA
      DO 891 I=1,132
  891 XI=2.*(A(I)*(EX(I)-DX)**2)+XI
      XII=XI
      DXX=DX
      BBM=750.
      WRITE(6,904)  XII
  904 FORMAT(F12.4)
      DM=BBM
      BM=0.
  110 SUMAEX=0.
      SUMA=0.
```

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```
  111 DO 118 I=1,132
      SUMAEX=A(I)*EX(I)+SUMAEX
  118 SUMA=A(I)+SUMA
C     CALCULATION OF NEW NEUTRAL AXIS(AFTER PLASTIFICATION
C     OF AN ELEMENT)
      DX=SUMAEX/SUMA
      XI=0.
C     CALCULATION OF NEW MOMENT OF INERTIA)
      DO 119 I=1,132
      EXD(I)=EX(I)-DX
      EXD2=EXD(I)*EXD(I)
  119 XI=2.*A(I)*EXD2+XI
  300 IF(XI.EQ.0.)  GO TO 200
C     INCREMENT OF APPLIED MOMENT
  117 DO 120 I=1,132
      DF(I)=DM*(DX-EX(I))*B(I)/XI
C     TRANSFORMATION TO STRAIN
      DFF(I)=DF(I)/.03
C     TOTAL STRAIN STATE UNDER APPLIED LOAD
      F(I)=DFF(I)+FF(I)
C     COMPARISON OF STRAIN STATE UNDER LOAD WITH THE
C     YIELDING STRAIN
      IF(F(I).LT.-3685.) GO TO 3039
      IF(F(I).GT.3685.) GO TO 3039
C     TRANSFORMATION FROM STRAIN TO STRESS
      TSUMA(I)=F(I)*.03
      GO TO 120
C     IF ONE ELEMENT IS YIELDED ITS AREA(A) BECOMES ZERO
 3039 A(I)=0.
      B(I)=0.
      GO TO 110
  120 CONTINUE
      BM=BM+DM
C     FF(I) IS MADE EQUAL TO F(I),SO FOR THE NEW STRAIN
C     STATE UNDER LOAD,JUST THE INCREMENT WILL BE CONSIDERED
      DO 155 I=1,132
  155 FF(I)=F(I)
C     UNLOADING STAGE
      DO 179 I=1,132
      FM(I)=BM*(DXX-EX(I))/XII
C     TRANSFORMATION TO STRAIN
  179 FFM(I)=FM(I)/.03
C     RESIDUAL STRESS AFTER UNLOADING
      DO 7777 I=1,132
      TFUN(I)=F(I)-FFM(I)
 7777 FUN(I)=TFUN(I)*.03
```

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```
      DO 1032 L=1,5
      IF(BM.EQ.BYY(L)) GO TO 7778
 1032 CONTINUE
      GO TO 8885
 7778 WRITE(6,129) BM
  129 FORMAT(1H1,1X,*LOADING MOMENT BM=*,F8.2)
      WRITE(6,133)DX
  133 FORMAT(1X,*NEUTRAL AXIS DX=*,F8.4)
      WRITE(6,135)  (TSUMA(I),I=1,40)
  135 FORMAT(2X,20(F6.1))
      WRITE(6,128)  (TSUMA(I),I=41,92)
  128 FORMAT(2X,13(F6.1))
      WRITE(6,136)  (TSUMA(I),I=93,132)
  136 FORMAT(2X,20(F6.1))
      WRITE(6,199)  (FUN(I),I=1,40)
  199 FORMAT(2X,20(F6.1))
      WRITE(6,187)  (FUN(I),I=41,92)
  187 FORMAT(2X,13(F6.1))
      WRITE(6,195)  (FUN(I),I=93,132)
  195 FORMAT(2X,20(F6.1))
 8885 DM=25.
      DO 1001 L=2,4
      BBB=L*1000.
      IF(BM.GT.BBB) DM=DM/2.0
 1001 CONTINUE
C     INCREMENT OF BENDING MOMENT
      BBM=BM+DM
      IF(BBM.GT.BMAX) GO TO 200
      GO TO 117
  200 CALL EXIT
      END
```

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13. ABSTRACT

This study presents some results of an investigation of residual stress distribution and redistribution in welded beams subjected to bending moments which generate flexural stresses in the elastic and inelastic ranges.

The experiments include testing of two beams of different steel grades and measuring strains before loading, under load and after unloading. Repeated bending moments were applied and their effects on strain distribution observed. For low applied moments, the redistribution of residual stresses occurred only in local areas and at the first loading cycle. When applied moments produced nominal stresses near or above the yield point of the beam material, gradual change of residual stress took place from one load to the next but stabilized after a few cycles.

The computer analyses included programs for the evaluation and prediction of the residual stress distribution after any applied load as well as for the prediction of the state of stresses under load.

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