AD A 021537

COAST GUARD

OFFICE OF RESEARCH & DEVELOPMENT

PROJECT 793105/002

INVESTIGATION OF DISTORTION REMOVAL IN WELDED STRUCTURES

BY

RICHARD A. WALSH
DAVID K. DUFFY
KOICHI MASUBUCHI

DEPARTMENT OF NAVAL ARCHITECTURE & MARINE ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASS., 02139

FINAL REPORT

Prepared for: COMMANDANT (DAT)
U.S. COAST GUARD HEADQUARTERS
WASHINGTON, D.C., 20591

51

DATE: MAR 3 1 1971

This report has been submitted in fulfillment of contract DOT-CG-92,784-B and is promulgated subject to the following qualifications:

The contents of this report reflect the views of Richard A. Walsh, David K. Duffy and Koichi Masubuchi of Department of Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, Cambridge, Mass., 02139, which is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policy of the Coast Guard. This report does not constitute a standard, specification or regulation.

J. R. Iversen

J. R. IVERSEN
Captain, U. S. Coast Guard
Chief, Applied Technology Division
Office of Research and Development
U. S. Coast Guard Headquarters
Washington, D. C. 20591

TABLE OF CONTENTS

ABSTRACT

The objective of this study is to investigate mechanisms of flame straightening with emphasis on its effectiveness on high-strength-steel structures. The study was conducted at the Department of Naval Architecture and Marine Engineering of the Massachusetts Institute of Technology to fulfill thesis requirements for two officers of the U. S. Coast Guard, Lt. R. A. Walsh and Lt. D. K. Duffy.

In the Phase 1 study an investigation was made of mechanisms of flame straightening on simple weldments in low-carbon steel and HY-80 steel (quenched and tempered steel with specified minimum yield strength of 80,000 psi). Flame straightening was two to three times more effective on low-carbon steel specimens than on HY-80 steel specimens.

In the Phase 2 study an investigation was made of mechanisms of flame straightening on framed panel structures. The specimens were made in low-carbon steel (AISI 1020), low-alloy high-strength steel (U. S. Steel CORTEN), and quenched and tempered steel (U. S. Steel T-1). It was also found that flame straightening techniques were more effective on low-carbon steel specimens than on high-strength steel specimens.

Introduction and Background

Welding is used extensively in ship fabrication because of its advantages over other assembly methods. However, control of residual stresses and distortion is a problem in the fabrication of welded structures. A recent Welding Research Council Bulletin prepared by Masubuchi[1] presents a review of the state-of-the-art of the analysis and control of weld distortion.

The recognized first step to the control distortion is to minimize distortion by proper design and careful selection of welding procedures. However, sometimes distortion exceeds acceptable limits; then it must be removed.

Flame straightening techniques, which involve spot or line heating by an oxyacetylene torch followed by water spraying, have been used widely for removing distortion. However, present practices in shipyards are based on experience and very few studies have been made of mechanisms of removing distortion. There is a strong need for establishing a scientific basis for the flame straightening technique. The need is especially keen on structures made in quenched and tempered high-strength steels because:

(1) Flame straightening may cause material degradation

(2) Flame straightening may or may not be effective in reducing distortion on these steels as it is on low-carbon-steel structures.

The objective of the M.I.T. study conducted under Purchase Order No. CG-92, 784-B is to investigate mechanisms of flame straightening with emphasis on its effectiveness on high-strength-steel structures.*

The study, which was initiated in January, 1969 and completed in June, 1970, was conducted to fulfill thesis requirements in Naval Architecture and Marine Engineering at M.I.T. The Phase 1 study on simple weldments was conducted by Lt. Richard A. Walsh who graduated in June, 1969. The Phase 2 study on complex weldments was conducted by Lt. David K. Duffy, who graduated in June, 1970. Theses written by Walsh[2] and Duffy[3] describe details of the M.I.T. study. This report summarizes important findings obtained in this study.

Phase 1: Study on Simple Weldments**

Objective and Procedures

The objective of the Phase 1 study was to investigate mechanisms of flame straightening on simple weldments.

---

*The M.I.T. study does not cover material degradation during flame heating, because this problem is being studied at Battelle Memorial Institute for Ship Structures Committee under Project SR-185.

**Details of the Phase 1 study are given in the thesis by R. A. Walsh.[2]

Geometric configurations of the specimens are illustrated in Figures 1 and 2. Specimens were made in low-carbon steel and HY-80 steel plates 1/2 inch thick.***

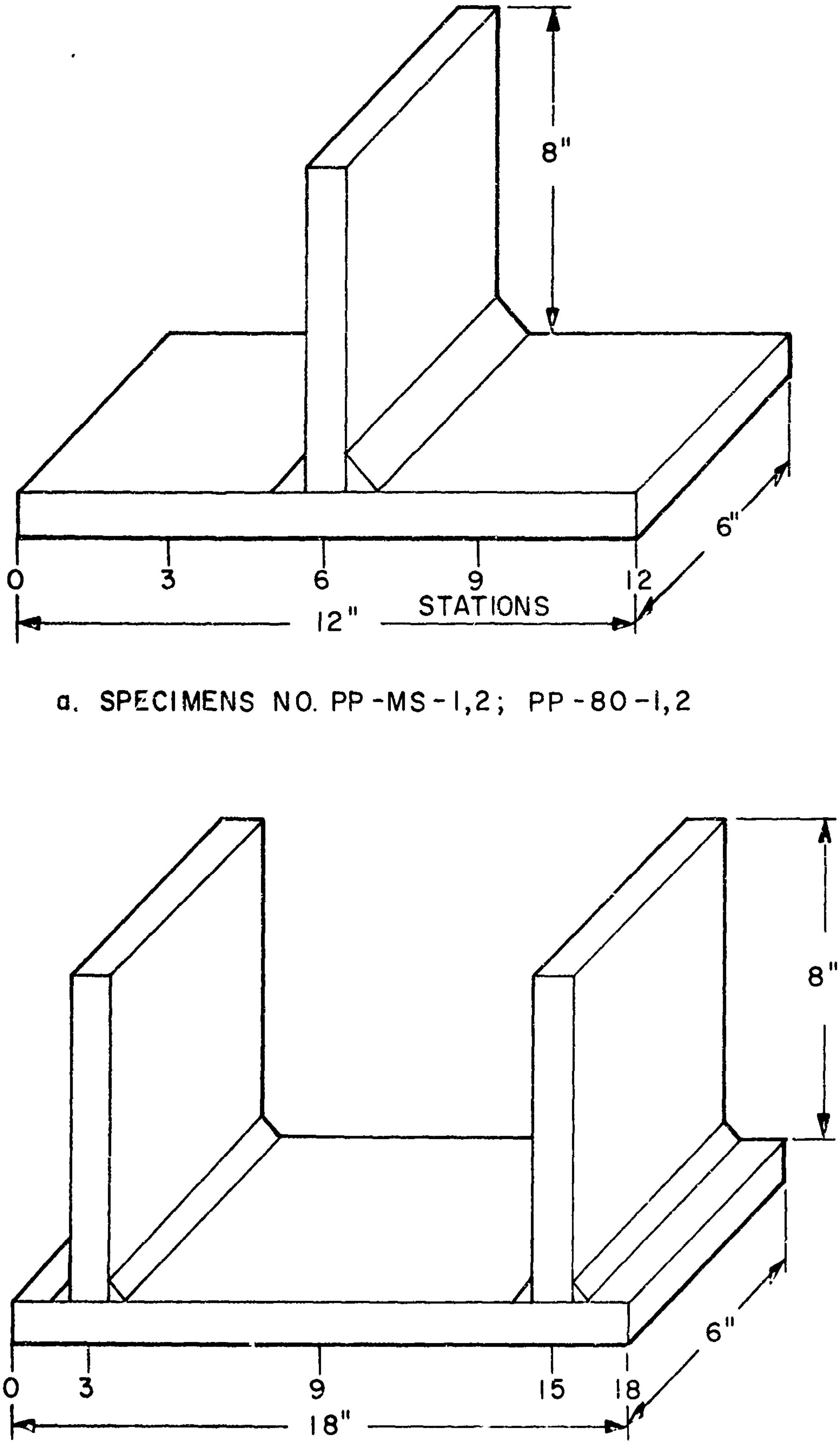
Specimens in Figure 1 represent simple fillet welds. Specimens in Figure 2 represent models of structural components. In rigid-end specimens (Figure 2b), ends of the vertical plates were welded to an H-beam. Table 1 presents the welding characteristics used in the preparation of specimens. Specimen designations used in the accompanying figures and tables are:

PP	-	perpendicular plate
SF	-	structure, free end
SR	-	structure, rigid end
MS	-	mild steel
80	-	HY-80 steel
1, 2, etc.	-	specimen number

A total of 14 specimens were prepared: 8 specimens in low-carbon steel and 6 specimens in HY-80 steel.

After specimens had been welded, they were subjected to flame straightening treatments under various conditions. Table 2 lists heating position, maximum heating temperature, heating station, and fillet weld station (the distance in inches from one end of a specimen) for each specimen.

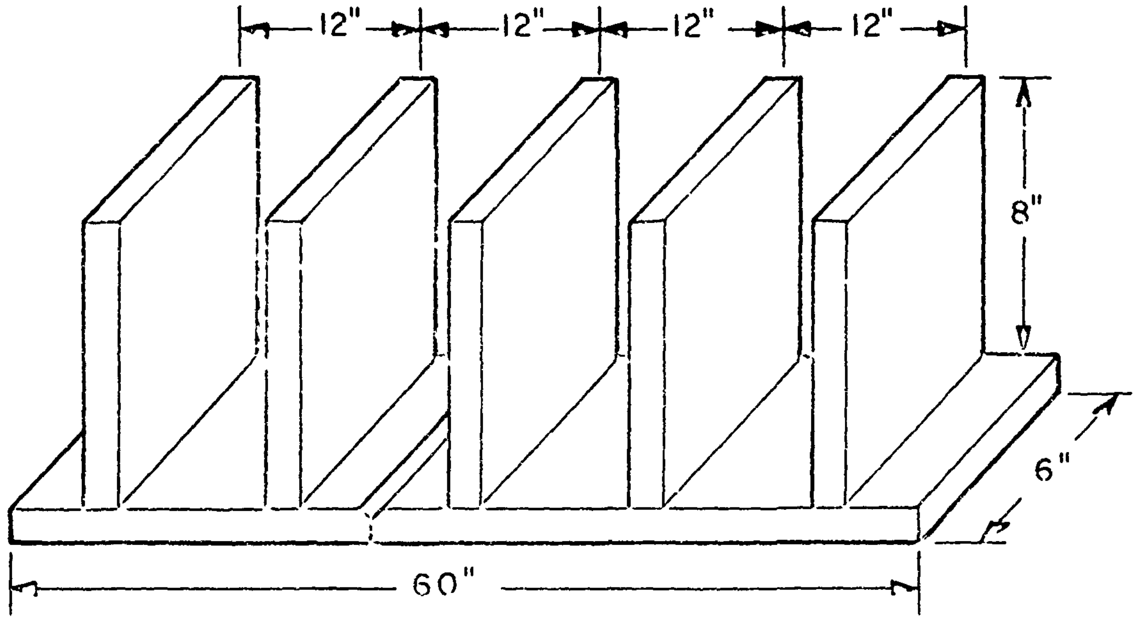
***HY-80 steel is a quenched and tempered steel with the minimum specified yield strength of 80,000 psi (MIL-S-16216). The steel has been used extensively for submarine construction.



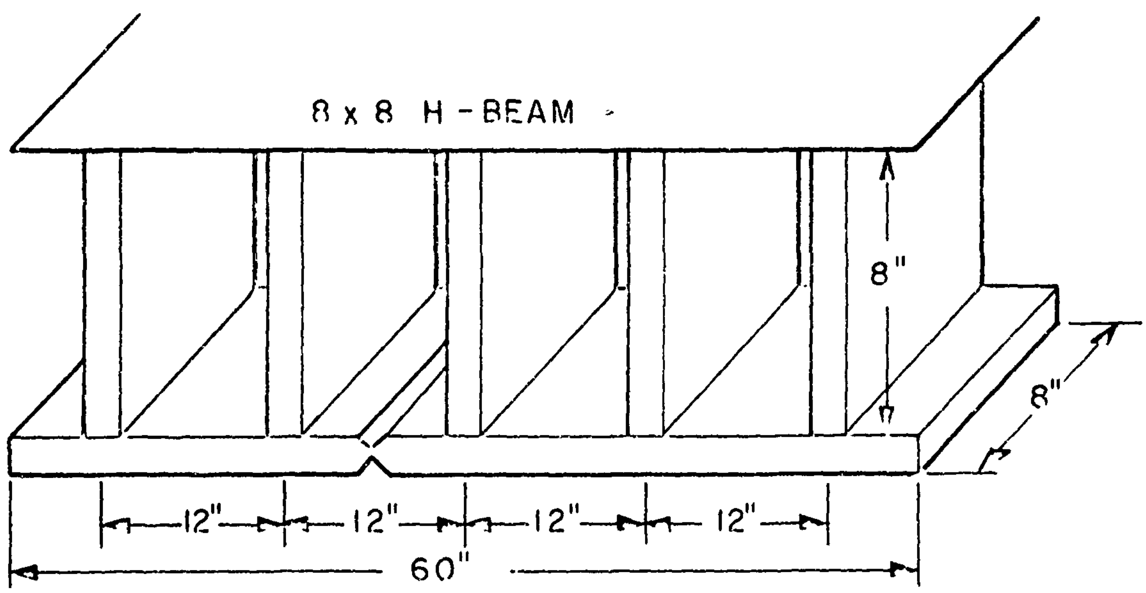
a. SPECIMENS NO. PP-MS-1,2; PP-80-1,2

b. SPECIMENS NO. PP-MS-3,4; PP-80-3,4

FIGURE 1 PERPENDICULAR PLATES



a. FREE END SPECIMENS (NO. SF-MS-1,2)



b RIGID END SPECIMENS (NO. SR-MS-1,2; SR-80-1,2)

FIGURE 2 STRUCTURAL SPECIMENS

TABLE 1

WELDING CHARACTERISITCS

FOR PHASE 1 STUDY

	Specimen		
Characteristic	PP-MS	SF-MS SR-MS	PP-80 SR-80
1. Electrode Type	E 7014	E 7018	E 9018
diameter	3/16"	1/8"	1/8"
tensile strength	72,000- 82,000 psi	78,000 psi	94,400 psi
yield point	62,000- 72,000 psi	69,000 psi	84,600 psi
current range (for designated diameter)	180-280 amps	90-150 amps	90-150 amps
polarity	straight	reverse	reverse
type current	D.C.	D.C.	D.C.
2. I	190 amps	150 amps	150 amps
3. V	20 volts	20 volts	20 volts
4. Welding Position	horizontal	horizontal	horizontal
5. Number of passes			
2	PP-MS-1,2,4,	SR-MS-1 SF-MS-1,2	--
3	PP-MS-3	SR-MS-2	PP-80-1,2,3,4 SR-80-1,2

TABLE 2

FLAME STRAIGHTENI'G PROCEDURES

USED IN PHASE 1 STUDY

Specimen	Fillet Weld Station (S)	Heating Station (S)	Heating Position	Maximum Temperature (T_H)
PP-MS-1 PP-80-2	6	6	bottom	1250 F.
PP-MS-2 PP-80-1	6	1,11	bottom	1250 F.
PP-MS-3 PP-80-4	3,15	9	top	1250 F.
PP-MS-4 PP-80-3	3,15	3,15	bottom	1250 F.
SR-MS-1 SR-80-1	8,20,32,44,56	14 26 38 50	top bottom top bottom	1200 F. 1200 F. 1480 F. 1480 F.
SR-MS-2 SR-80-2	6,18,30,42,54	6 18 30 42	bottom bottom bottom bottom	1200 F. 1250 F. 1480 F. 1500 F.
SF-MS-1	8,20,32,44,56	14 26 38 50	top bottom top bottom	1200 F. 1200 F. 1480 F. 1480 F.
SF-MS-2	8,20,32,44,56	8 20 32 44	bottom bottom bottom bottom	1200 F. 1250 F. 1480 F. 1500 F.

Flame heating was performed with an oxyacetylene torch using a number 30 size tip. Water quench rate was held constant as was water quench temperature for all flame straightening procedures. For heating position, top refers to the side of the horizontal plate with the fillet joint, and bottom refers to the side without the fillet joint.

Horizontal plate deformation measurements were taken after welding and completion of flame straightening procedures. Graphical plots and tables were made for the individual specimens.

Results

Details of results obtained in the Phase 1 study are described in the thesis by Walsh.[2] The following summarizes important findings obtained in the Phase 1 study:

1. Flame straightening was two to three times more effective on mild steel specimens than HY-80 steel specimens, as shown in Figures 3 and 4.
2. Varying the position of flame straightening techniques from plate midspan to fillet weld area produced no significant differences in reducing distortion.
3. There was no significant change in angular distortion at the fillet welds in rigid-end strucutres as a result of flame straightening.

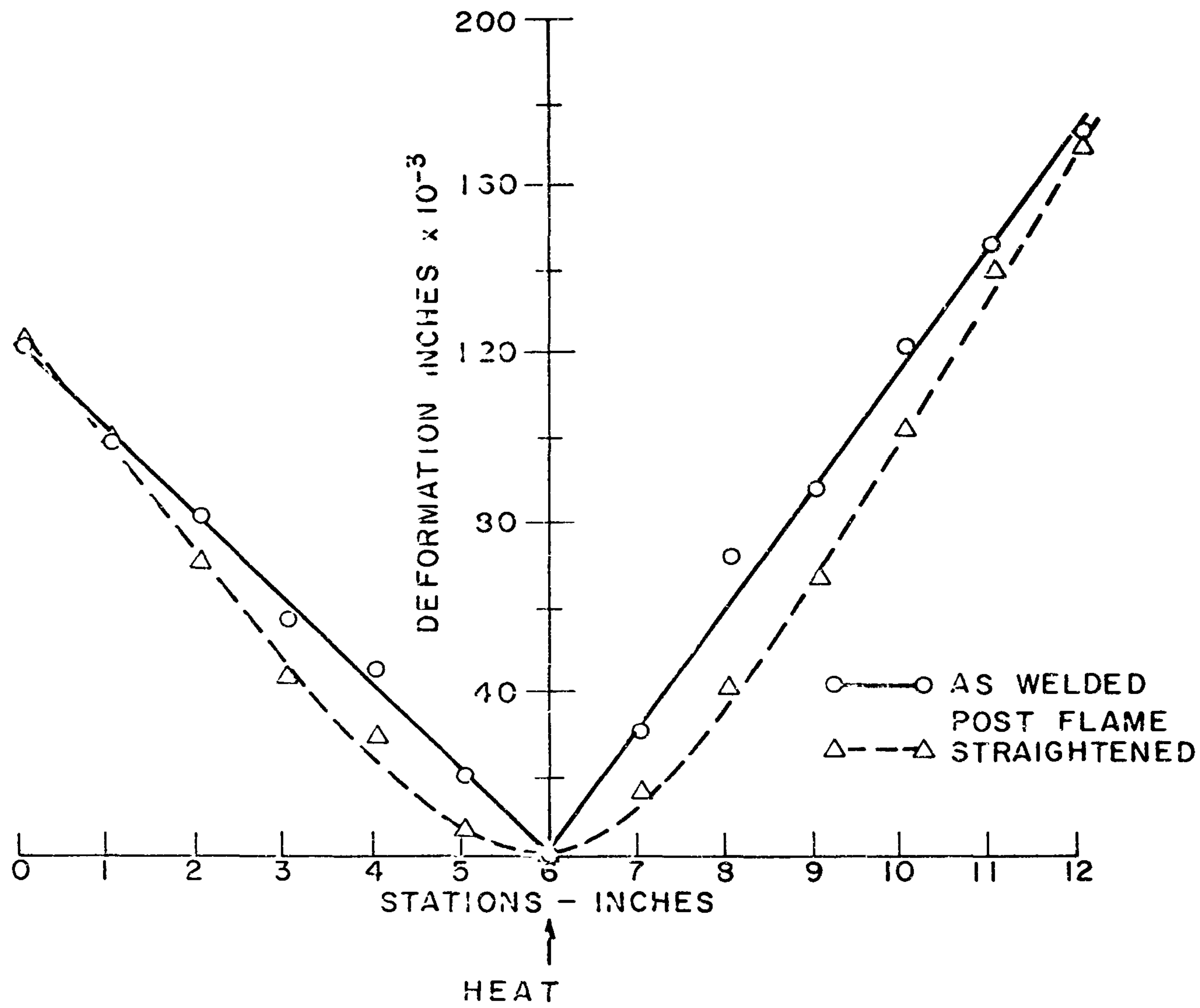


FIGURE 3 DISTORTION OF SPECIMEN NO. PP-MS-1

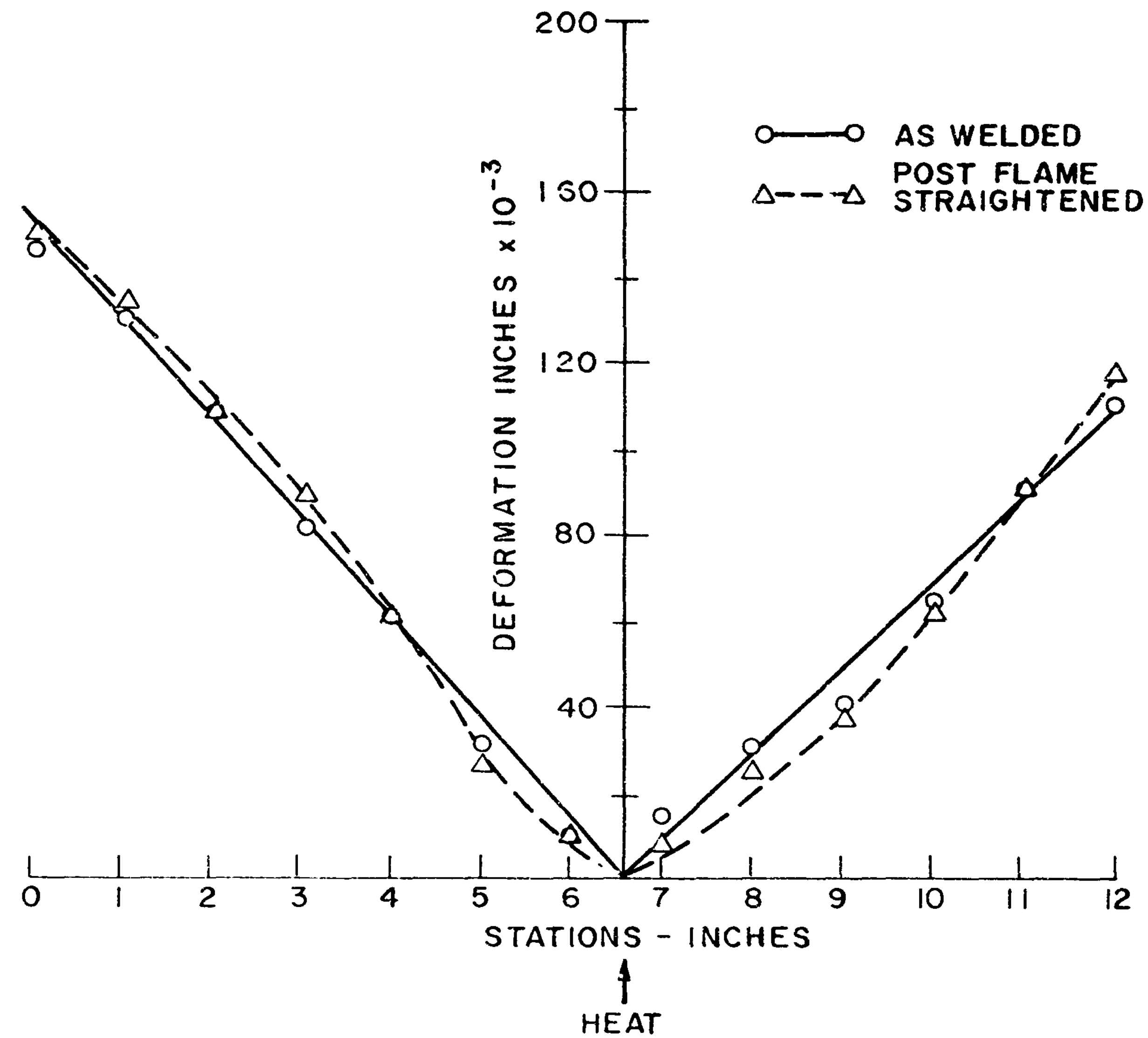


FIGURE 4 DISTORTION OF SPECIMEN NO. PP-80-2

Phase 2: Study on Complex Weldments

Background and Objective

Results of the Phase 1 study showed that flame straightening was not very effective on HY-80 steel weldments. However, a recent investigation conducted at Battelle Memorial Institute showed conflicting results.

The Battelle Study. The purpose of the Battelle study (SR-185 for the Ship Structure Committee) was to study the effect of flame straightening and mechanical straightening on the properties of steels used in shipbuilding. The four types of steels used were: ASTM A-517 Grade A, ASTM A-537, ASTM A-441, and ABS-B having yield strengths of 110,000, 52,000, 57,000, and 40,000 psi, respectively. Plate thickness was varied from 3/8 inch to 3/4 inch.

In the Battelle study, distortion was produced in flat plates with no edge supports either by mechanical pressing or by a single butt weld. To straighten the plates, they were fastened with one edge clamped on a back-up plate, the other edge being free to move. Results of the Battelle investigation are as follows:

1. Spot heating and quenching was unsatisfactory because the plates buckled as soon as they were quenched.

2. Linear heating was more effective although much of the straightening effect was lost when the plates were quenched.
3. Distortion in welded and unwelded plates was generally removed with equal facility.
4. In general, the A-517 Grade A plate was the easiest to straighten and the ABS-B was the most difficult.
5. The notch toughness behavior of ship steels is adversely affected by the heat of flame straightening.

Objective of Phase 2 Study. Because of recommendations for further study contained in the Phase 1 study, it was decided to make an attempt to determine if, in fact, there was a corridor of yield strengths for which the flame straightening was effective. One disconcerting fact, however, was the observations obtained at Battelle that the higher strength steels were easier to straighten.

Considering these conflicting results, it was decided that experiments be made on models which simulate an actual ship structure. Since most of the problems in shipyards occur on bulkheads and on hull plating, it was felt that a panel type model with stiffeners around the panel edges would be the best answer.

Experimental Procedure and Results

Test Models. Figure 5 shows the panel type model used in the Phase 2 study. Longitudinal and transverse frames, 6 inches high, were fillet welded to a flat plate 36 by 24 inches; the size of the panel was 32 by 20 inches. Panels were prepared in 3/8-inch thick plates in three types of steel:

(1) Low-carbon steel, AISI 1020

(2) Low-alloy, high-strength steel, U. S. Steel CORTEN

(3) High-strength, quenched and tempered steel, U. S. Steel T-1 (which is specified as ASTM A-517).

Table 3 shows chemical compositions and mechanical properties of these steels.

Welding. Table 4 shows electrode types and welding conditions used to fabricate the test panels. E7024 electrodes were used for the low-carbon steel panel, while E10018 electrodes were used for the high-strength steel panels. Double fillet welds were used to join stiffeners to the panel and to each other. All three models were maintained in a position such that welds were made in the downhand position. Welds were made in two passes.

Distortion After Welding. After each weld pass, the weldment panels were placed on a surface plate with the stiffeners of the model down against the surface plate. The out-of-plane deflection of the test panel was measured by a dial indicator. The deflection of the entire panel (36 by 24 inches) was determined by measuring deflections along a grid system.

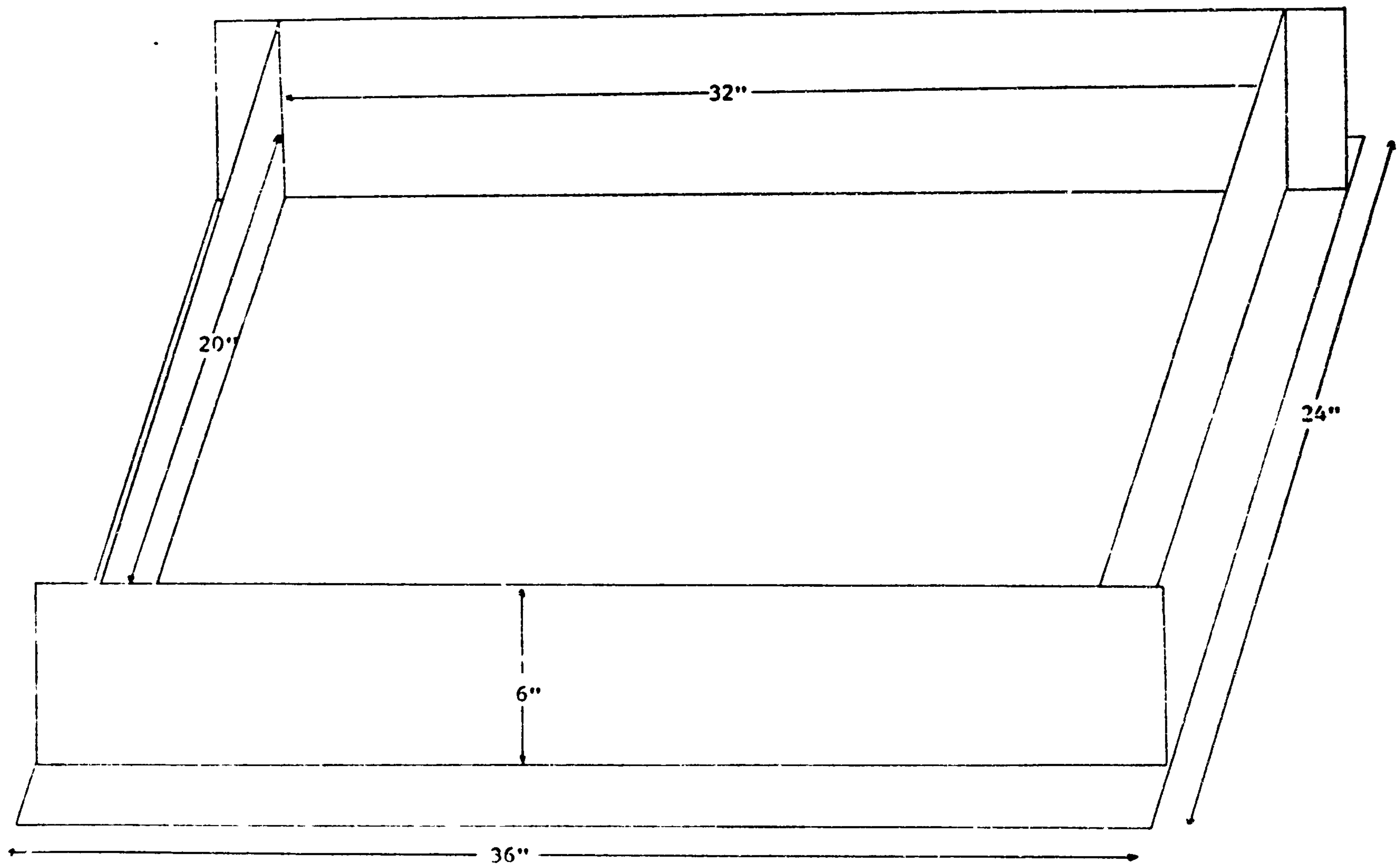


Figure 5 Panel Type Model Used in Phase 2 Study

TABLE 3

Chemical Composition and Mechanical Properties of Steels
Used in the Phase 2 Study

Material	Chemical Composition, %[(a)]				Mechanical Properties	
	C	Mn	P	S	Yield Strength psi	Ultimate Tensile Strength, psi
Low-carbon steel AISI 1020	.06	.31	.002	.024	32,000	58,000
Low-alloy, high-strength steel (U. S. Steel Corten)	.09	.36	.09	.032	51,300	72,600
High-strength, quenched-and-tempered steel (U. S. Steel T-1)	.18	.90	.010	.023	118,500	134,100

(a) Chemical compositions of only four elements are listed here.

TABLE 4

Electrodes and Welding Characteristics for Panel Type Models

Base Plate Material	1020	CORTEN	T-1
Electrodes used	E7024	E10018	E10018
Electrode diameter, inch	5/32-3/16 (1)	5/32	5/32
Current type	DC reverse	DC reverse	DC reverse
Welding current, amperes	140-160	140	140
Arc voltage, volts	20	20	20
Weight of electrodes consumed, W (2)			
After #1 Pass	0.268 oz/in (2.99 gr/cm)	0.320 oz/in (3.57 gr/cm)	0.294 oz/in (3.28 gr/cm)
After #2 Pass	0.464 oz/in (5.18 gr/cm)	0.640 oz/in (7.14 gr/cm)	0.614 (6.86 gr/cm)

(1) Electrodes 5/32" in diameter were used on #1 Pass and electrodes in 3/16" in diameter were used on #2 Pass on the 1020 model.

(2) Weight of electrode consumed, W, includes metals in both sides of the fillet joint.

1 oz/in = 11.16 gr/cm

Figures 6, 7, and 8 show distributions along the longitudinal centerline of panels in 1020, CORTEN, and T-1 steel, respectively. Figure 9 shows relationships between the maximum deflection at the panel center and the amount of electrode consumed for these three specimens. Less distortion was produced with a specimen made in higher yield strength. This phenomenon is shown in Figure 10 which presents relationships between the yield strength of the base plate and the maximum deflection at the panel center after welding the first pass and the second pass. Here results are normalized to give deflection at an equal amount of electrode consumed; 0.28 ounces/inch for the first pass and 0.56 ounces/inch for the second pass. As shown in Figure 10, weld deflection decreases as the yield strength of the base metal increases.

The Appendix of this report summarizes further attempts for analyzing distortion of a welded panel. A study was made by R. C. Gularte, a graduate student at M.I.T. to analyze the exact shape of out-of-plane distortion of a stiffened panel, as shown in Figure 6. He used the "STRUDL" Finite Element Computer Program for the analysis. He also compared distortion measurements obtained at M.I.T. with those obtained in Japan by Hirai and Nakamura. It was found that:

(1) The shape of out-of-plane distortion of a stiffened panel can be calculated very accurately using the finite-element computer program

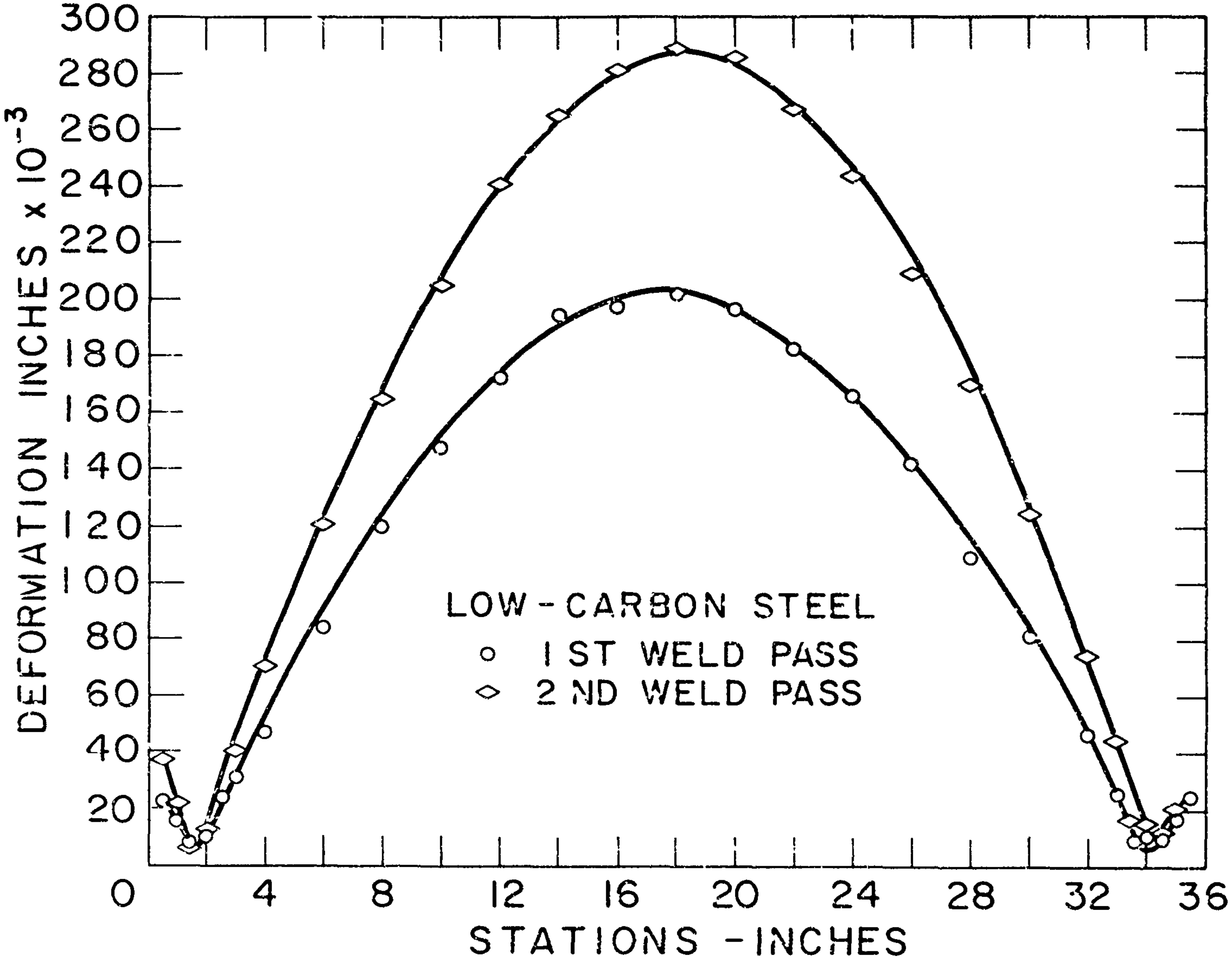


FIGURE 6 DEFLECTIONS ALONG THE CENTER LINE OF PANEL MADE IN LOW-CARBON STEEL

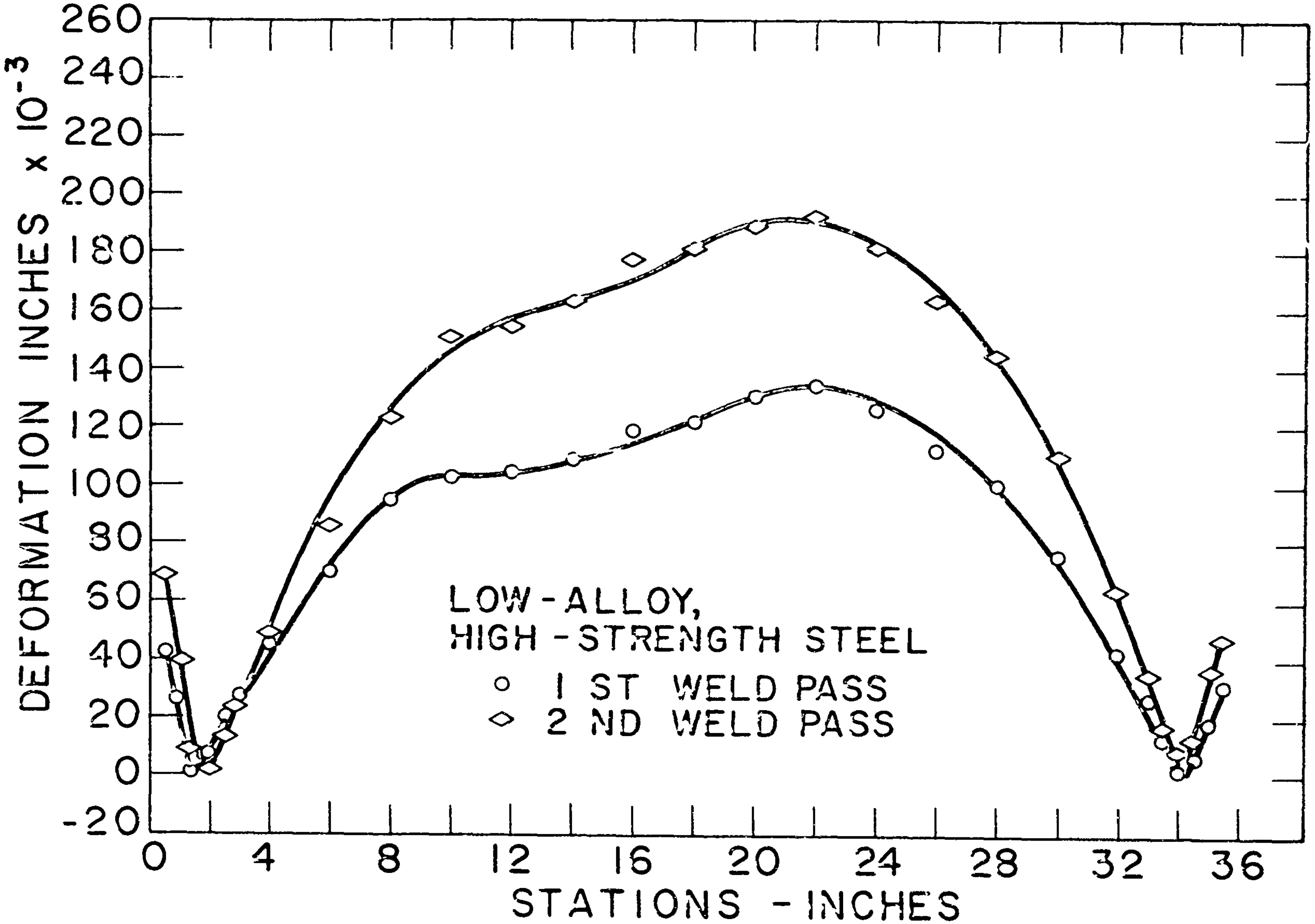


FIGURE 7 DEFLECTIONS ALONG THE CENTER LINE OF PANEL MADE IN LOW-ALLOY, HIGH-STRENGTH STEEL

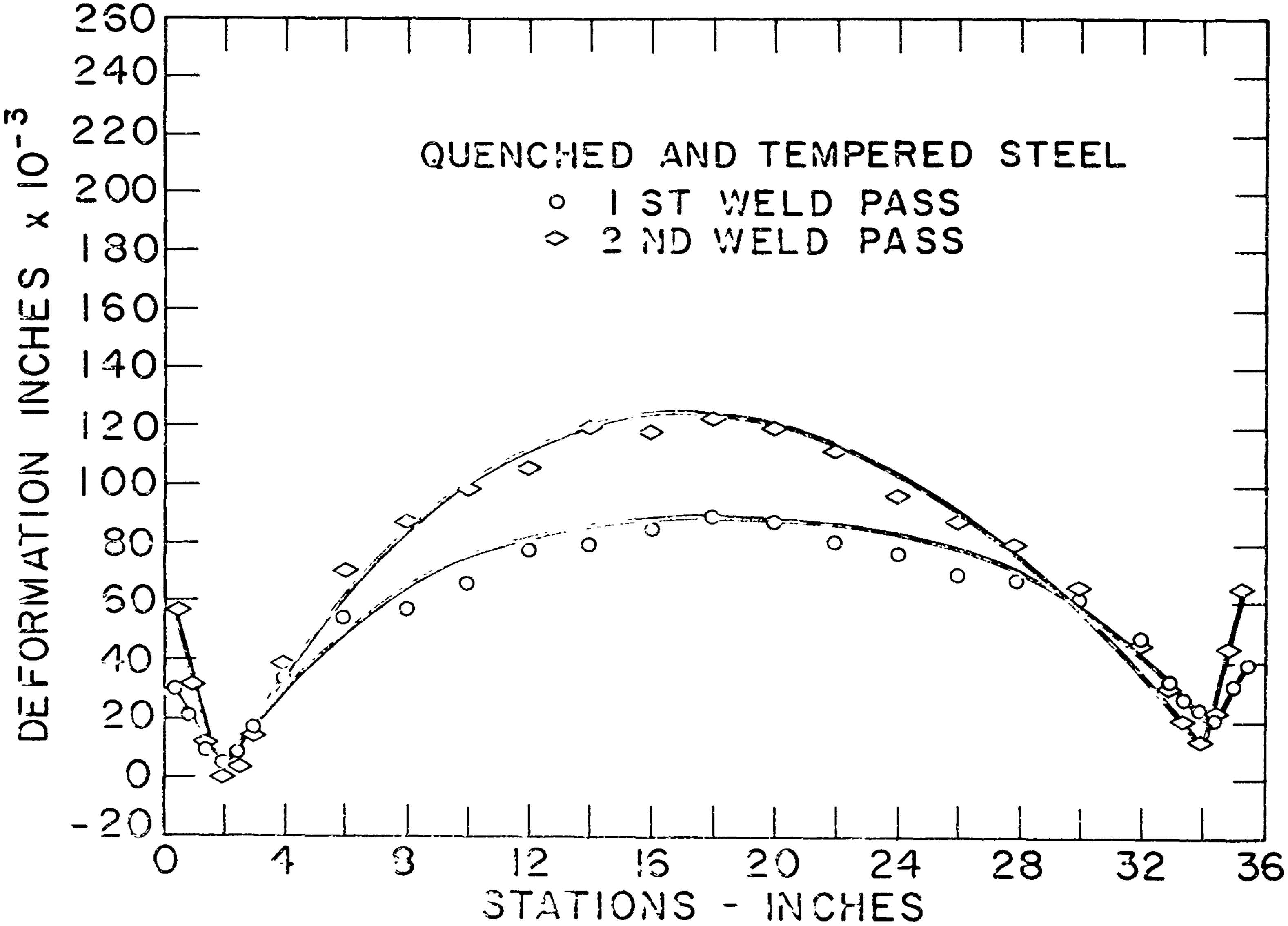


FIGURE 8 DEFLECTIONS ALONG THE CENTER LINE OF PANEL MADE IN QUENCHED AND TEMPERED STEEL

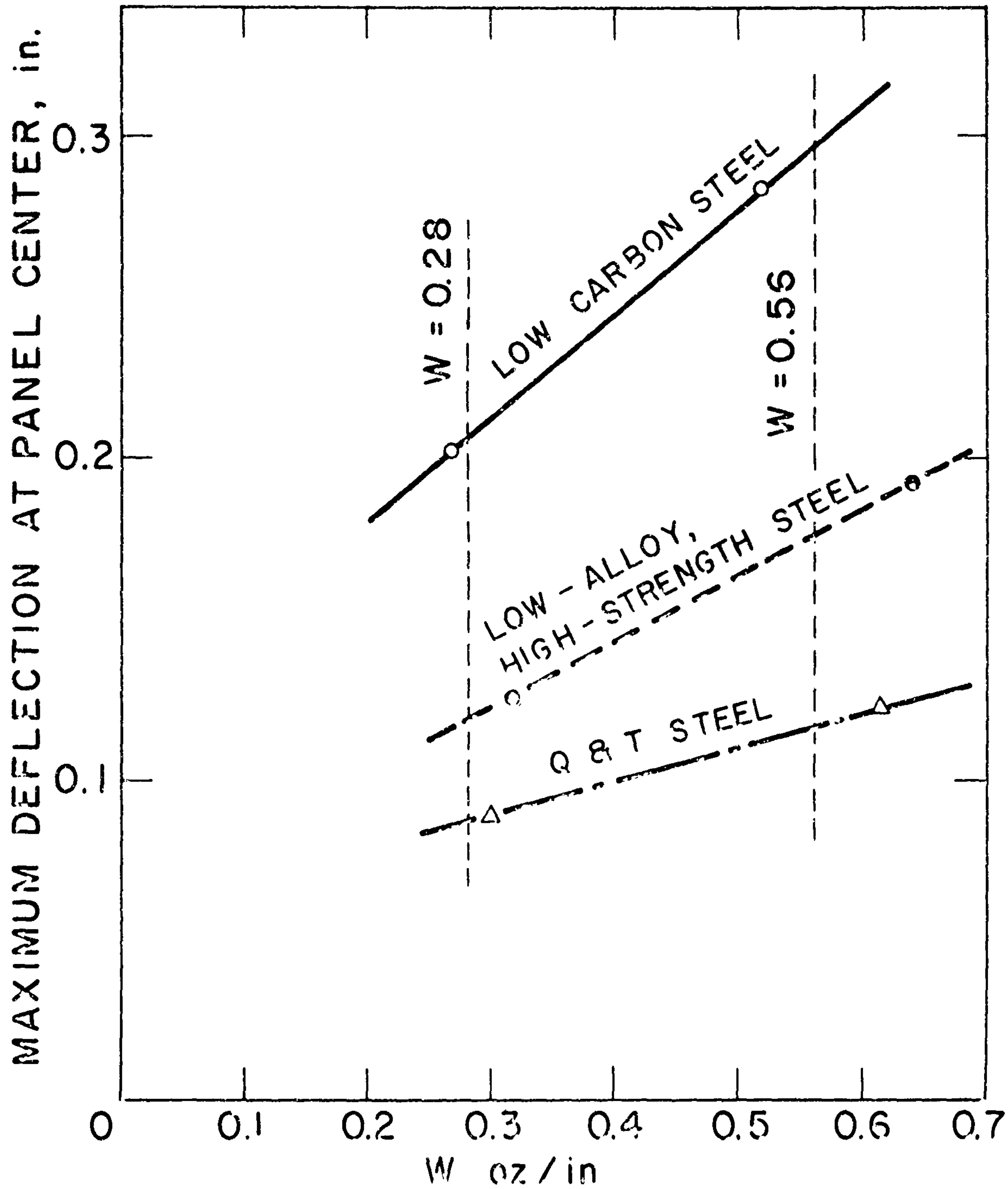


FIGURE 9 RELATIONSHIPS BETWEEN MAXIMUM DEFLECTION AT THE PANEL CENTER AND THE AMOUNT OF ELECTRODES CONSUMED, W (oz/in)

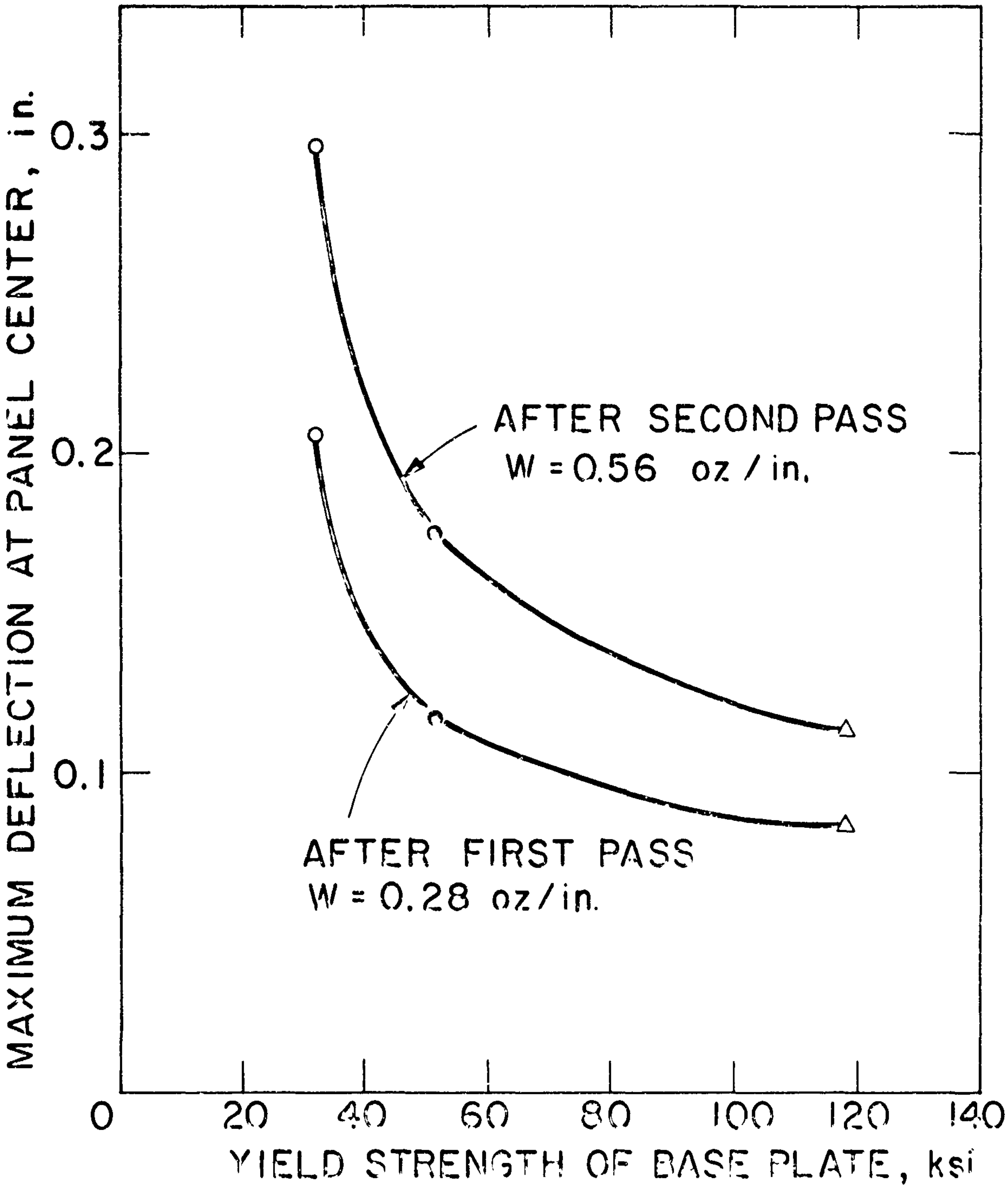


FIGURE 10 RELATIONSHIP BETWEEN THE YIELD STRENGTH OF BASE METAL AND MAXIMUM DEFLECTION AT THE PANEL CENTER

(2) Calculated distortions based upon experimental results obtained by Hirai and Nakamura agree well with results obtained at M.I.T.

The study by Gularte shows that the present state-of-the-art for predicting and analyzing distortion due to welding is fairly accurate.

Flame Straightening. After the panels had been welded, they were subjected to flame heating. Due to indications from the Battelle investigation that quenching was not effective in flame straightening and also because of a desire to eliminate as many variables as possible, it was decided to first attempt the procedure without a water quench. Linear heating was used in the following manner.

The first straightening attempt was made by heating the panel from the convex side along the mid-span of the long side. The torch was slowly moved along the heating line for about 10 minutes until the line was heated uniformly to 1,200° F. The panels were then allowed to air cool.

The second straightening attempt was to heat the panel surface along the back of the fillet welds. Due to lack of success with this technique on 1020 and CORTEN, it was not attempted on the T-1 panel.

The third straightening procedure tried was the use of a water quench technique. The panels were again heated in a linear manner from the concave side, a total of three heats (along three different locations) being made on each panel. The torch was moved slowly along the lines until the required 1,200° F was reached throughout. After each heat, a water quench was applied with the use of a water soaked cloth.

After each flame heating treatment, distortion measurement was conducted. Figures 11, 12, and 13 show deflections along the longitudinal center line of the three panels after heat passes done in the following ways:

1020 and CORTEN panels:

First heat pass--heating along the mid-span
Second heat pass--heating along the back of fillet weld
Third heat pass--linear heating and water quenching

T-1 panel:

First heat pass--heating along the mid-span
Second heat pass--linear heating and water quenching

The first heating attempt by heating the panel from the convex side along the mid-span of the long side only caused an increase in deflection rather than straightening. For example, the maximum deflection at the panel center of the 1020 model after welding was 0.29 inch. However, the deflection increased to 0.60 inch after the first heating.

The second attempt by heating along the back of the fillet welds also caused an increase of deflection.

The only method which produced favorable results was heating and quenching (the third heat pass on 1020 and CORTEN models and the second heat pass on the T-1 model). Table 5

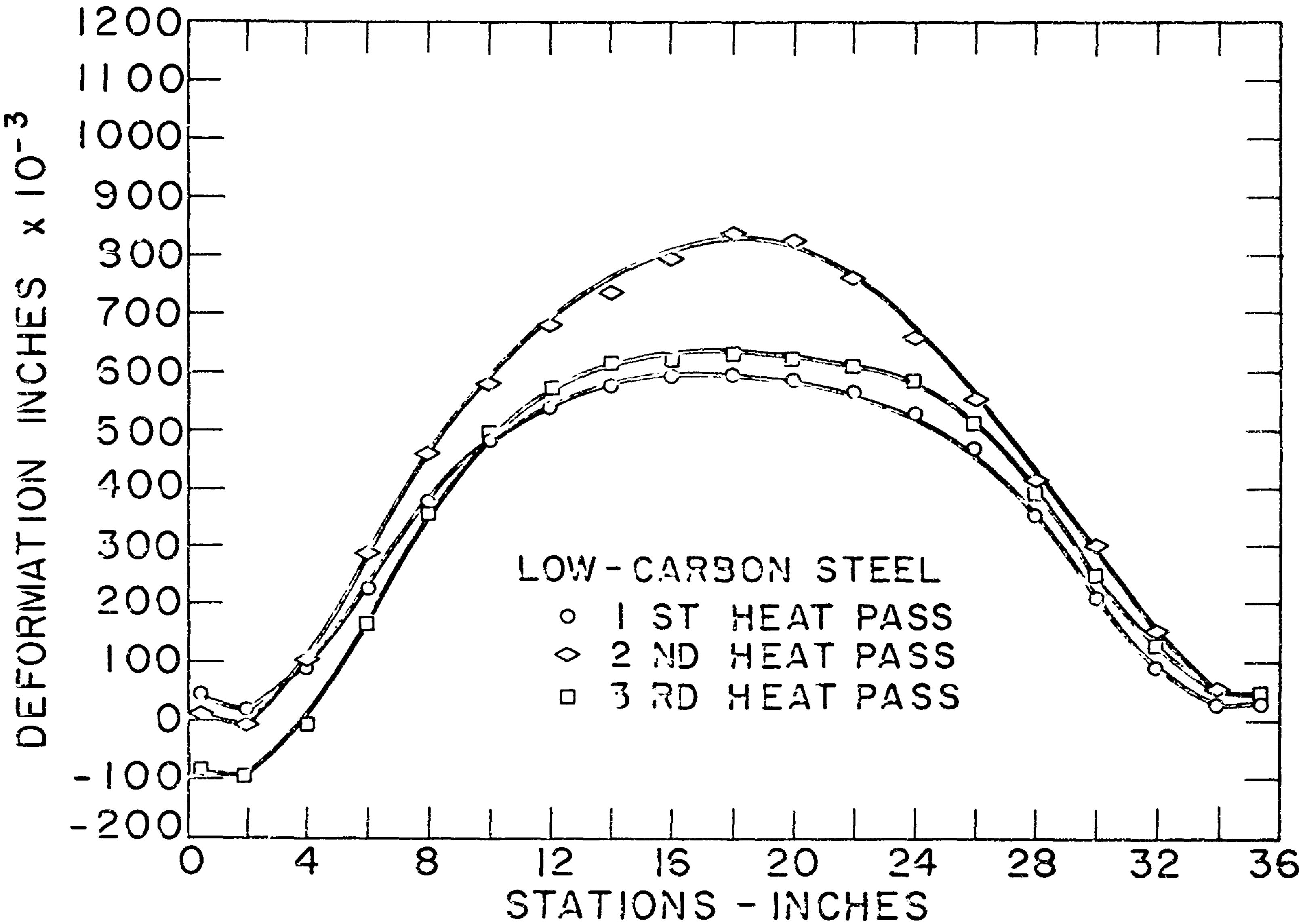


FIGURE II DEFLECTIONS ALONG THE CENTER LINE OF THE 1020 PANEL AFTER FLAME HEATING TREATMENTS

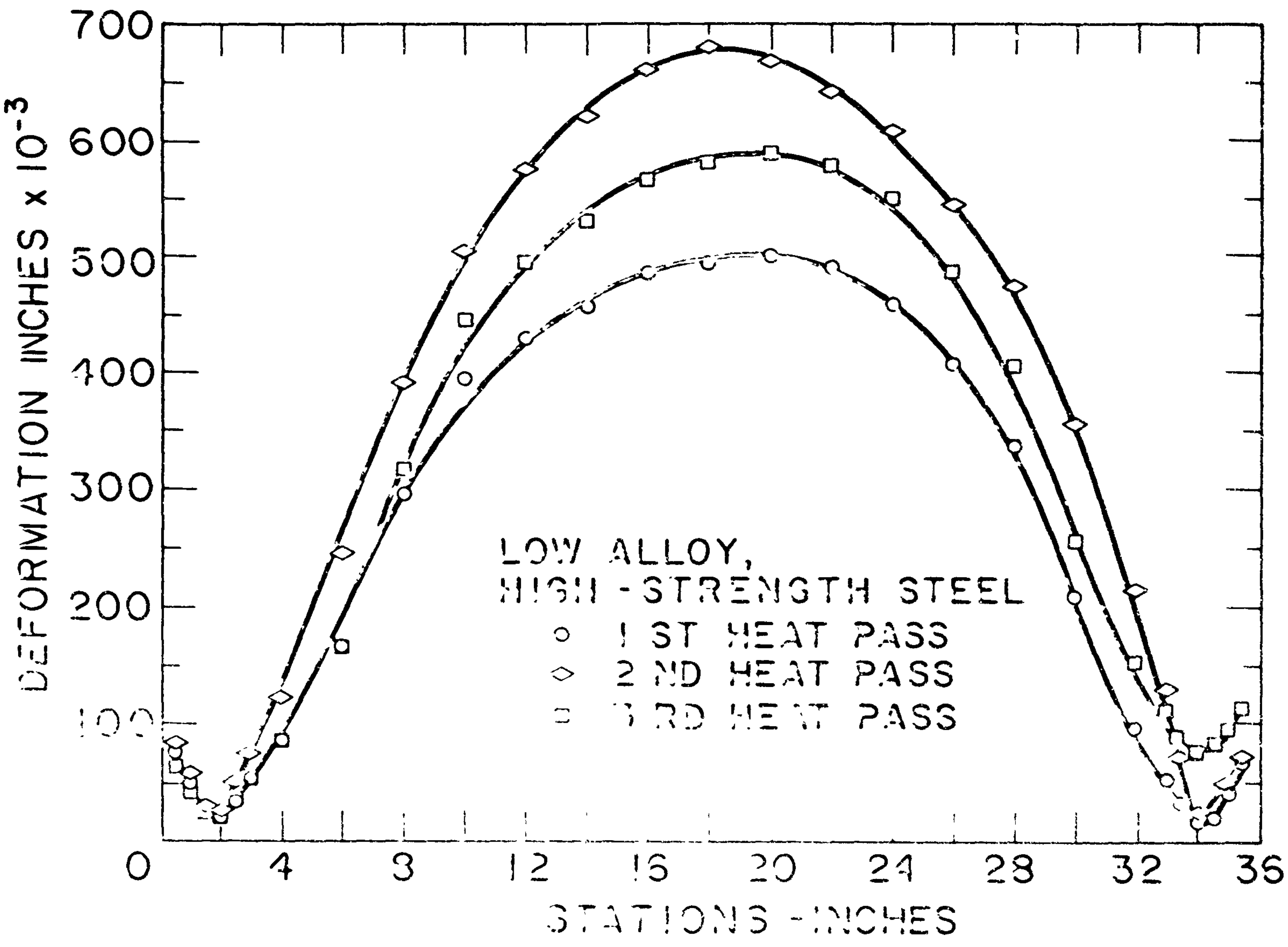


FIGURE 12 DEFLECTIONS ALONG THE CENTER LINE OF THE LOW-ALLOY, HIGH-STRENGTH STEEL PANEL AFTER FLAME HEATING TREATMENTS

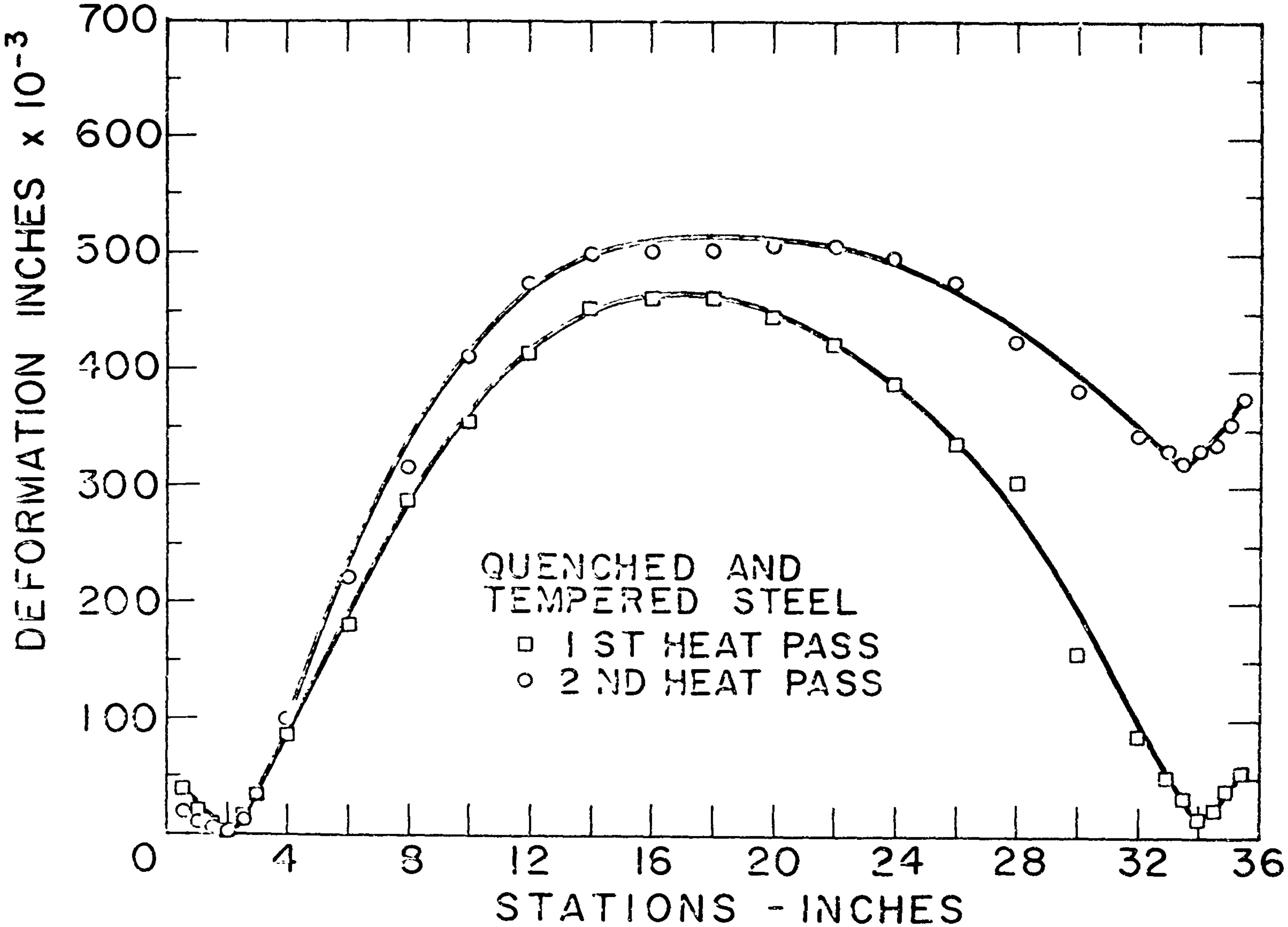


FIGURE 13 DEFLECTIONS ALONG THE CENTER LINE OF THE QUENCHED AND TEMPERED STEEL PANEL AFTER FLAME HEATING TREATMENTS

TABLE 5

Reduction in Deflection due to Flame Heating Followed by Water Quenching

	Materials		
	Low-carbon steel	Low-alloy High-strength steel	Quenched and Tempered steel
Maximum deflection before heating and quenching, inch	0.83	0.68	0.51
Maximum deflection after heating and quenching, inch	0.64	0.59	0.46
Reduction in deflection, inch	0.19	0.09	0.05
Percent reduction in deflection	23%	13%	10%

shows reduction in deflection due to flame heating followed by water quenching. The flame straightening techniques were more effective on low-carbon steel than on high-strength steels.

Summary of Experimental Results and Conclusions

Experimental conditions and important results obtained in Phases 1 and 2 of the M.I.T. study and the Battelle study are summarized as follows:

1. M.I.T. Phase 1 Study

   a. Experimental conditions: Simple fillet welds (Figure 1), and free-end and rigid-end structural specimens (Figure 2). Heating was conducted at various locations (Table 2)

   b. Important results: Flame straightening was two to three times more effective on mild steel specimens than HY-80 steel specimens.

2. M.I.T. Phase 2 Study

   a. Experimental conditions: Panel type modes (Figure 5) were used. Three types of heating were applied.

   b. Important results: Line heating followed by water quenching produced reduction in deflection. As shown in Table 5, the flame straightening techniques (with water quenching) were more effective on low-carbon steels than on high-strength steels. However, heating followed by air cooling only caused increase in distortion.

3. Battelle Study (SR-185)

   a. Experimental conditions: Plate specimens were used. One edge of a specimen was clamped, but but the other edge was kept free during heating.

b. Important results: The A-517 plate was easier to straighten than low-carbon steel plate. Water quenching reduces the effectiveness for straightening of line heating.

As mentioned above, results in these studies are somewhat conflicting. As far as the M.I.T. studies are concerned, flame straightening techniques were more effective on low-carbon steel than on high-strength steels. However, the reverse trend was found in the Battelle study.

Water quenching after heating was found to be effective for straightening in the M.I.T. study (Phase 2), while the reverse trend was found in the Battelle study.

These conflicting results indicate the following:

(1) Mechanisms of flame straightening are quite complicated. The effectiveness of flame straightening techniques is affected by a number of parameters including heating and cooling conditions, mechanical properties of the base metal, and structural constraint (how a panel is constrained in a structure), etc.

(2) Our knowledge on mechanisms of flame straightening is very limited. There is a strong need for developing fundamental knowledge on the mechanisms of flame straightening.

As shown in the Appendix, the situation is quite different as far as the analysis of distortion due to welding is concerned. The present state-of-the-art is fairly well developed and the accuracy of the present analysis is very good.

It is important to mention that the art of analysis of weld distortion has been developed significantly during the last ten years by a number of investigators in the world. During the last few years several computer programs have been developed at M.I.T. and elsewhere to calculate thermal stresses during welding.

On the basis of recent developments in the analysis of weld distortion, it should be possible to develop better means for analyzing basic mechanisms of flame straightening techniques. Computers should be useful for handling complex mathematical analyses involved. Such a fundamental study should be very useful in further developing the art of flame straightening.

Acknowledgement

The investigators wish to thank Mr. A. J. Zona of the Welding Laboratory of M.I.T. and Messrs. David Ramsay, C. O'Hara and A. Mosman of Ramsay Welding Research, Inc., Cambridge, Massachusetts, for their assistance in performing experimental work.

References

(1) Masubuchi, K., "Control of Distortion and Shrinkage in Welding," Welding Research Council Bulletin, No. 149 April, 1970

(2) Walsh, R. A., "Investigation of Distortion Removal in Welded Structures," M.S. Thesis, Department of Naval Architecture and Marine Engineering, M.I.T., May, 1969

(3) Duffy, D. K., "Distortion Removal in Structural Weldments," M.S. Thesis, Department of Naval Architecture and Marine Engineering, M.I.T., May, 1970

(4) Pattee, H. E., Evans, R. M., and Monroe, R. E., "Experimental Flame and Mechanical Straightening and Its Effects on Base Metal Properties," Report on Project SR-185, Battelle Memorial Institute, Columbus Laboratories, July, 1969

APPENDIX

Distortion of Framed Panel Structures due to Angular Changes at Fillet Welds

Analysis of Distortion of Simple Framed Structures

Figure A-1 shows distortion caused by angular changes in two types of fillet welded structures. If a fillet joint is free from outer constraint, the joint simply bends to a polygonal form having a knuckle at the weld, as shown in Figure A-1a. However, if the joint is constrained by some means, a different type of distortion is produced. For example, when the movement of stiffeners welded to a plate is prevented, wavy distortion of the plate, as shown in Figure A-1b, results.

Masubuchi et al have found that the problem of analyzing wavy distortion and the associated stresses can be handled as a problem of stress in a rigid frame. In the simplest case of a uniform distortion, the relationship between angular change at the weld, ϕ, and distortion, δ, is given as follows (see Figure A-2):

$$\frac{\delta}{\ell} = \left[\frac{1}{4} - \left(\frac{x}{\ell} - \frac{1}{2}\right)^2\right]\phi \qquad (1)$$

The amount of angular change, ϕ, in a restrained structure is smaller than that in a free joint, ϕ_o. The amount of ϕ also changes when the rigidity of the bottom plate, $D = \frac{Et^3}{12(1-\nu^2)}$, and the length of span, ℓ, change. The following equation has been obtained:

$$\phi = \frac{\phi_o}{1 + \frac{2D}{\ell} \cdot \frac{1}{C}} \qquad (2)$$

where C is a coefficient determined by welding conditions and plate thickness.

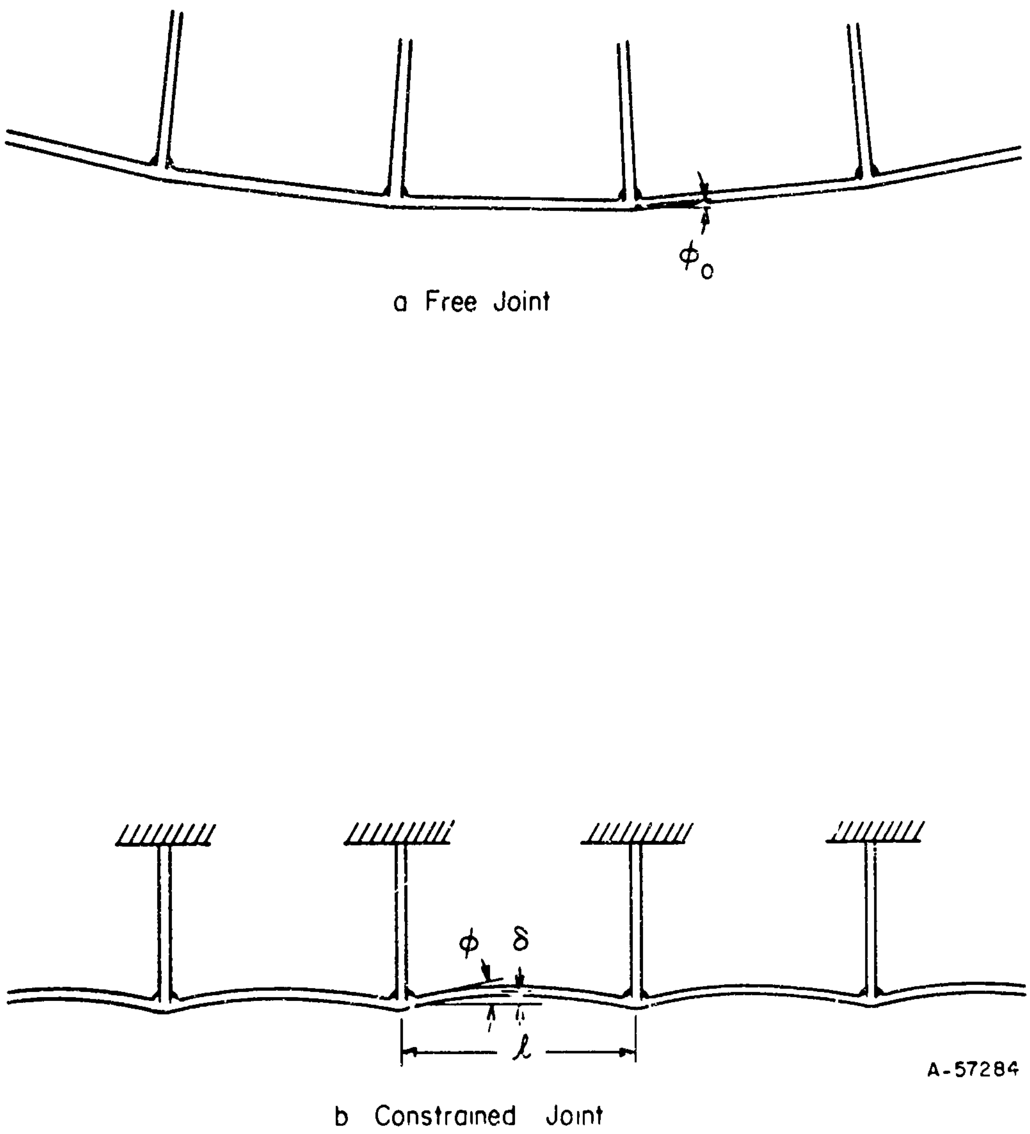


FIGURE A-1 DISTORTION CAUSED BY ANGULAR CHANGE IN TWO TYPES OF FILLET WELDED STRUCTURES

Hirai and Nakamura conducted an investigation to determine values of ϕ_o and C under various conditions. Figure A-2 shows values of ϕ_o as a function of plate thickness, t (mm), and weight of electrode consumed per weld length, w (g/cm). In this particular experiment, using covered electrodes 0.2 inch (5 mm) in diameter, maximum angular changes were obtained when plate thickness was around 0.35 inch (9 mm). When the plate was thinner than 0.35 inch, the amount of angular change was reduced as the plate thickness was reduced. This was because the plate was heated more evenly in the thickness direction thus reducing the bending moment. When the plate was thicker than 0.35 inch, the amount of angular change was reduced as the plate thickness increased because of the increase of rigidity of the plate. The following formula has been proposed to calculate the C value:

$$C = \frac{t^4}{1 + \frac{w}{5}} \qquad (3)$$

where t = plate thickness, mm, and w = weight of weld metal deposited per unit of weld length, gram/cm. By using equations 1 through 3, it is possible to calculate the distortion that occurs when a given structure is fabricated with a given welding procedure.

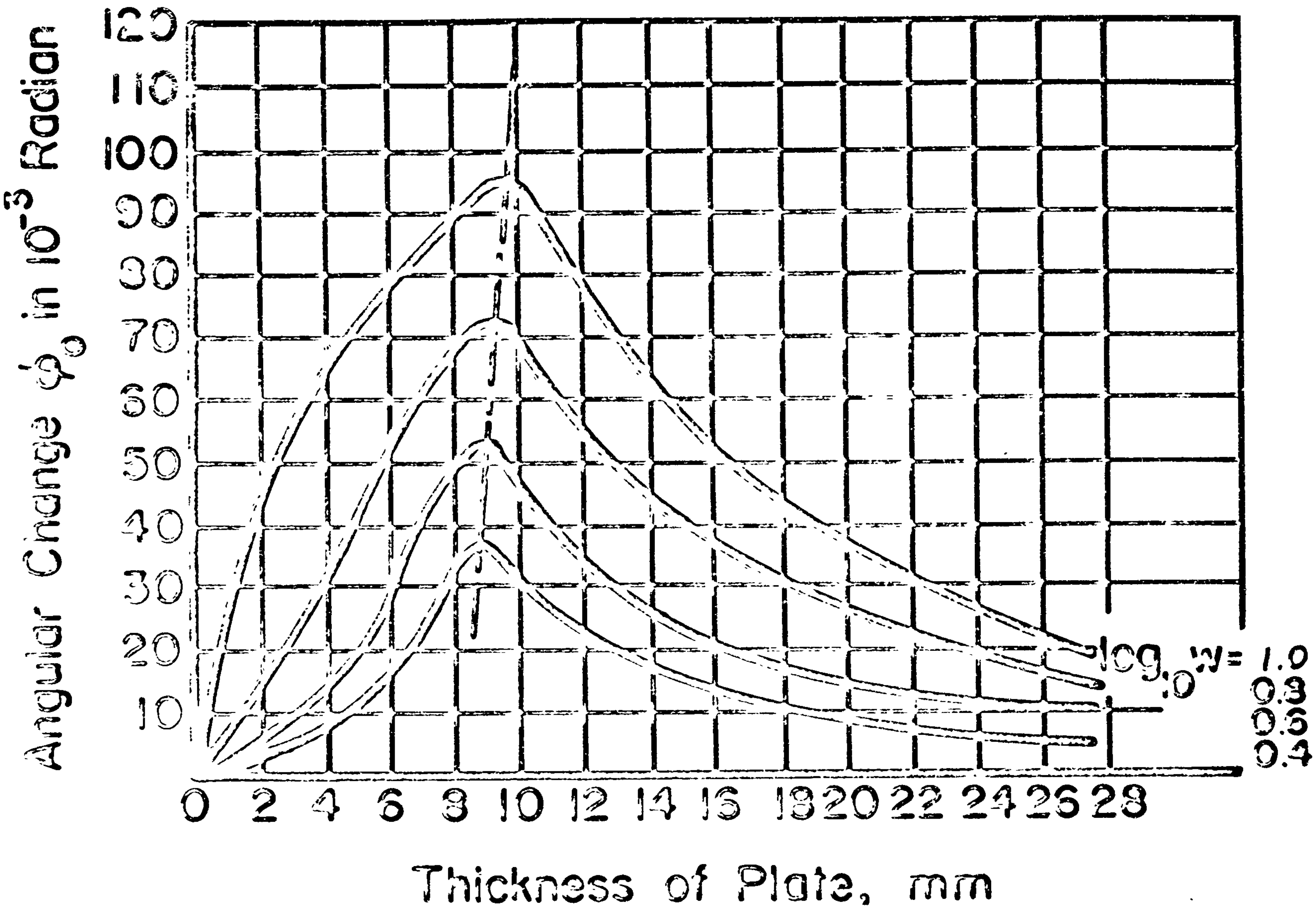


FIGURE A-2. VARIATION OF ANGULAR CHANGE OF FREE FILLET WELDS, ϕ_o, AS A FUNCTION OF PLATE THICKNESS, t, AND WEIGHT OF ELECTRODE CONSUMED PER WELD LENGTH, W (HIRAI AND NAKAMURA)

Data on Out-of-Plane Distortion of Panel Structures

Several studies have been made of the out-of-plane distortion of welded panel structures.

1. Experimental Data Obtained on Low-carbon Steel Structures in Different Sizes

Masubuchi et al conducted an experimental study on distortion of welded specimens. Longitudinal and transverse girders were fillet welded to the bottom plate in low-carbon steel in 14 mm(0.55 inch) thick. Results were reported in: "Investigation on the Corrugation Failure of Bottom Plating of Ships," Report of Shipbuilding Research Association of Japan, No. 19, 1957.

2. Experimental Data Obtained on Structures in Medium- and High-Strength Steels

An investigation was conducted at the Massachusetts Institute of Technology [1] on distortion of panel structures made in three types of steel:

(1) Low-carbon steel, AISI 1021

(2) Low-alloy high-strength steel, U. S. Steel Corten

(3) High-strength, quenched-and-tempered steel, U. S. Steel T-1.

Figure A-3 shows the specimen geometry. Longitudinal and transverse frames six inches high were fillet welded to a flat plate 36 by 24 inches (the size of the free panel was 32 by 20 inches). Plates 3/8 inch thick were used because

---

[1] Duffy, David K., "Distortion Removal in Structural weldments," M.S. Thesis, Department of Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, May, 1970.

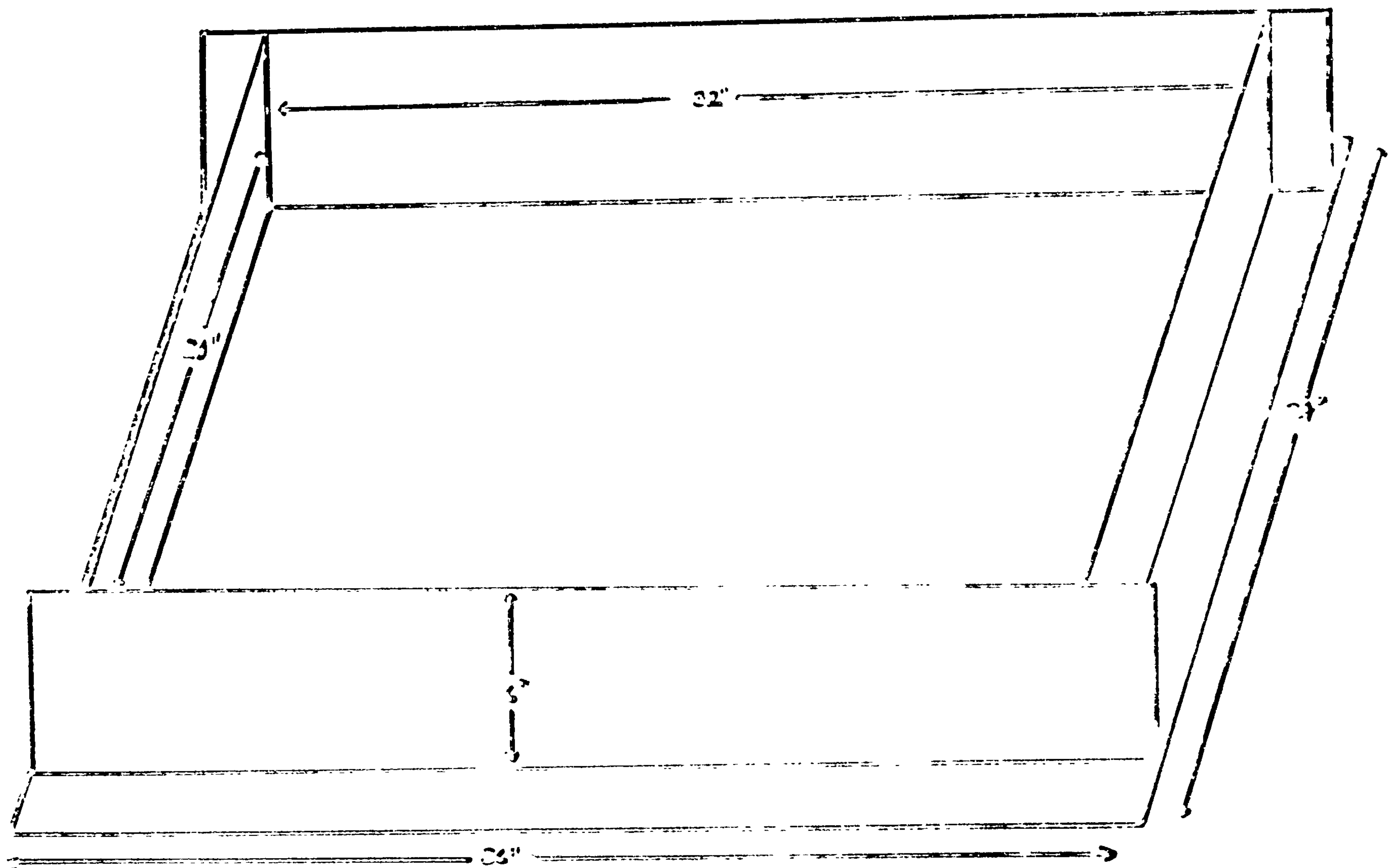


FIGURE A-3. PANEL STRUCTURE STUDIED AT M.I.T.

they produce maximum angular change when covered electrodes are used (see Figure A-2).

Figure A-4 shows distributions along the longitudinal centerline of the 1020 steel specimen after welding the first and the second pass. Less distortion was produced with a specimen made in steel with higher yield strength.

An attempt also was made to compare results obtained at M.I.T. and those shown in Figure A-2. More precisely, a comparision was made between:

(1) Angular change of the free edge of a panel with b = 1200 mm and

(2) Angular change of fillet welds for 14 mm thick plate given in Figure A-2.

Results are as follows:

Angular Change in Radian

	Free edge of a panel with b = 1200 mm, Figure A-4	Free fillet welds in 14 mm thick, Figure A-2
Log w = 0.4	0.022	0.017
Log w = 0.6	0.033	0.026
Log w = 0.8	0.044	0.043
Log w = 1.0	0.055	0.064

The above list shows that values of angular changes for the two conditions compared agree reasonably well. This indicates that the degree of constraint of the free edge near the center of the 1200 mm (47 inches) span was very small.

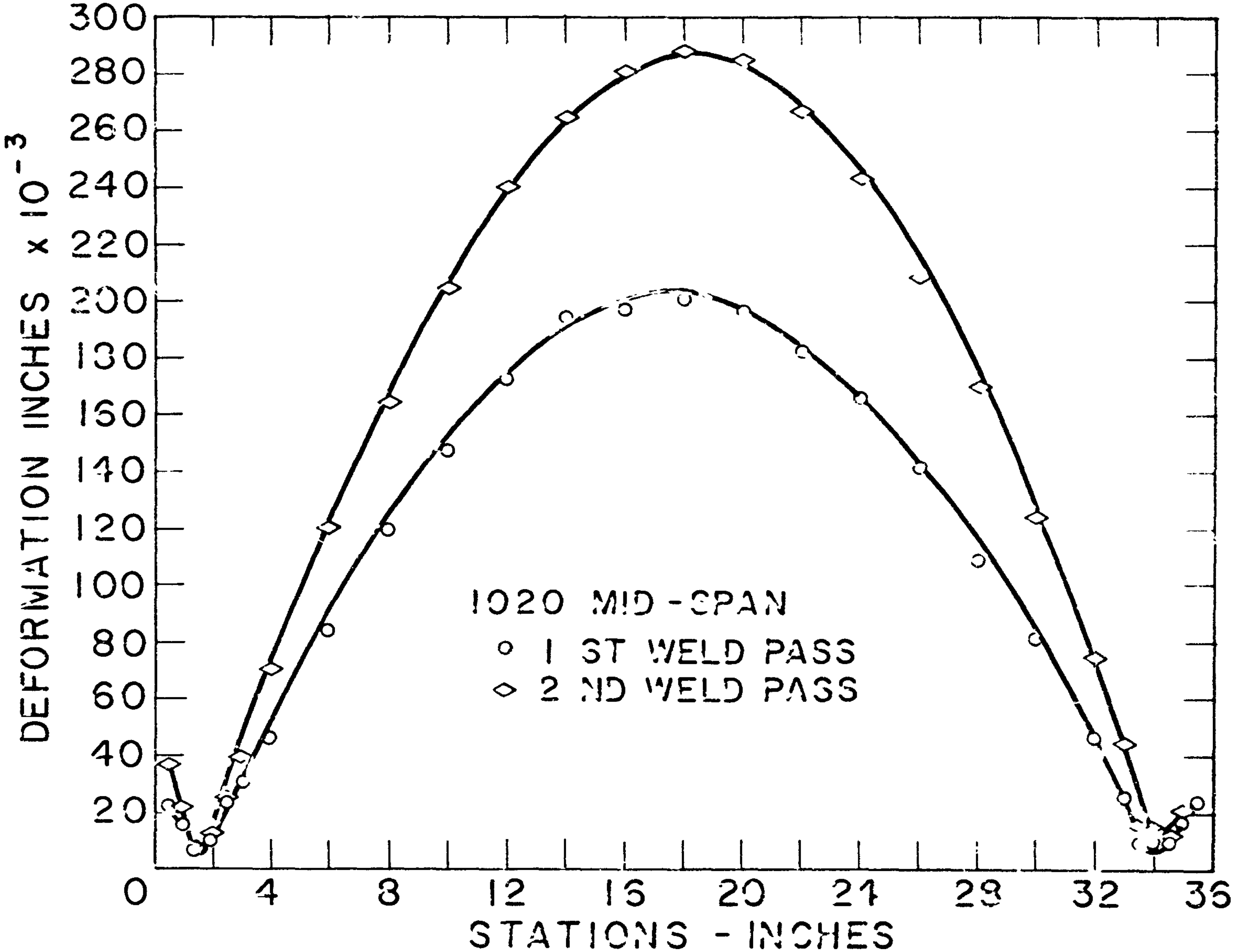


FIGURE A-4 DISTORTION ALONG THE LONGITUDINAL CENTER LINE OF PANEL IN LOW-CARBON STEEL

3. Detailed Analysis by Computer of Exact Shape of Distortion

A study was made by Gularte, a graduate student at Massachusetts Institute of Technology to analyze the exact shape of out-of-plane distortion of a stiffened panel. The analysis was made of the low-carbon steel specimen shown in Figure A-3; experimental results are shown in Figure A-4.

The analysis uses the "STPUDL" Finite Element Computer Program developed at the Department of Civil Engineering of M.I.T., whose user's instructions have been published.

Figure A-5 shows comparision of computed and measured defelctions after welding the first pass. Details of the computation are given in the following paper:

> Gularte, R. C., "Finite Element Approach to Distortions Caused by Angular Change in Fillet Welding," to Professor K. Masubuchi for Subject 13.71, Special Problem in Naval Architecture and Marine Engineering, Massachusetts Institute of Technology, May, 1970.

The computations were made using data given in Figure A-2. The maximum distortion at the center of the plate (node 54) was 0.215 inch. The actual measured value was 0.201 inch or within approximately 7 percent. More important than the difference between the calculated and measured deflection at specific points is the similarity between the calculated and experimental shapes as illustrated in Figure A-5.

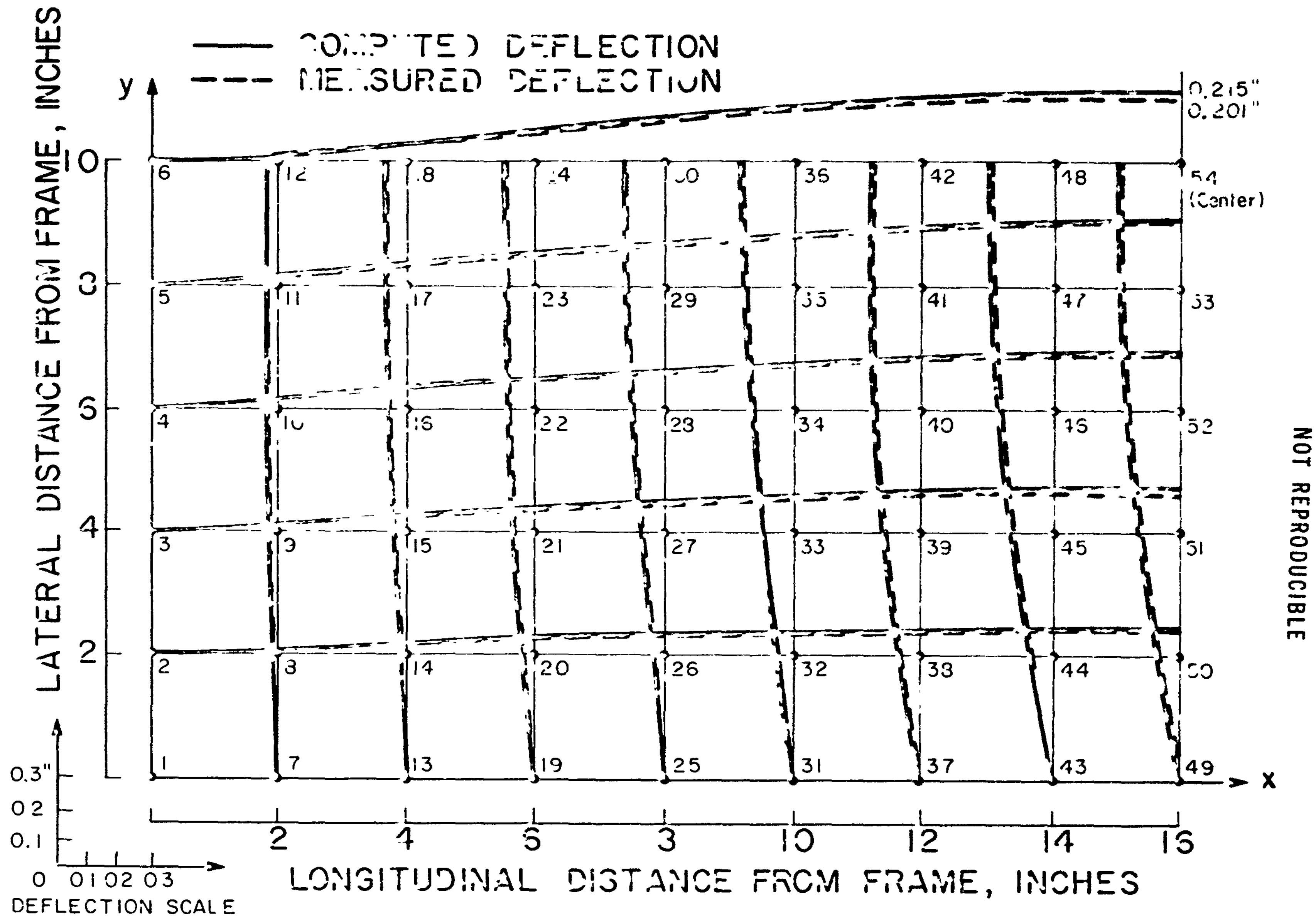


FIGURE A-5. COMPARISON OF COMPUTED AND MEASURED DEFLECTIONS AFTER FINAL WELDING PASS

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)

Department of Naval Architecture and Marine Engineering
Mass. Inst. of Technology
Cambridge, Mass., 02139

2a. REPORT SECURITY CLASSIFICATION

UNCLASSIFIED

2b. GROUP

13/10

3. REPORT TITLE

Investigation of Distortion Removal
In Welded Structures

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical, November 1970

5. AUTHOR(S) (First name, middle initial, last name)

Richard A. Walsh
David K. Duffy
Koichi Masubuchi

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
November 1970	50	4

8a. CONTRACT OR GRANT NO. CG-92,784-B

b. PROJECT NO. 793105/002

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

Unlimited

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

Applied Technology Division
U. S. Coast Guard Headquarters

13. ABSTRACT

The objective of this study is to investigate mechanisms of flame straightening with emphasis on its effectiveness on high-strength-steel structures. The study was conducted at the Department of Naval Architecture and Marine Engineering of the Massachusetts Institute of Technology to fulfill thesis requirements for two officers of the U. S. Coast Guard, LT. R. A. WALSH and LT. D. K. DUFFY.

In the Phase 1 study an investigation was made of mechanisms of flame straightening on simple weldments in low-carbon steel and HY-80 steel (quenched and tempered steel with specified minimum yield strength of 80,000 psi). Flame straightening was two to three times more effective on low-carbon steel specimens than on HY-80 steel speciments.

In the Phase 2 study an investigation was made of mechanisms of flame straightening on framed panel structures. The specimens were made in low-carbon steel (AISI 1020), low-alloy high-strength steel (U. S. Steel CORTEN), and quenched and tempered steel (U. S. Steel T-1). It was also found that flame straightening techniques were more effective on low-carbon steel specimens than on high-strength steel specimens.

DD FORM 1 NOV 65 1473

UNCLASSIFIED
Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Distortion Removal						
Flame Straightening						
High-Strength-Steel Structures						
Low Carbon Steel Weldments						
HY-80 Steel Weldments						
Welding Characteristics						
Complex Weldments						
Flame Straightening Low Carbon Steel (AISI 1020)						
Flame Straightening High Strength Steel (U. S. Steel CORTEN)						
Flame Straightening Quenched and Tempered Steel (U. S. Steel T-1)						