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Evaluation of Advanced Gas Metal Arc Welding and Distortion Mitigation Techniques

Kent Leclair

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EVALUATION OF ADVANCED GAS METAL ARC WELDING AND DISTORTION MITIGATION TECHNIQUES

FINAL REPORT

July 31, 2008

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REPORT: Evaluation of Advanced Gas Metal Arc Welding and Distortion Mitigation Techniques for Thin Panel Steel and Aluminum Structures

DATE: July 31, 2008

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ESAB
Hobart Brothers

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EXECUTIVE SUMMARY

The US Navy is in the process of transforming their surface combatant fleet with highly capable, multi-mission Destroyers, advanced Cruisers and a new breed of focused mission ships, such as the Littoral Combat Ship (LCS). The Lockheed Martin LCS design is a survivable, semi-planing steel monohull that provides outstanding maneuverability with proven sea-keeping characteristics to support launch and recovery operations, mission execution and optimum crew comfort. The LCS1 will be the first surface combatant to be classed under the new Naval Vessel Rules by the American Bureau of Shipping. The LCS1 is currently being built by Marinette Marine Corporation (MMC). Bollinger Shipyards constructed one of the LCS1's stern modules. The General Dynamics (GD) LCS design features an innovative, high-speed trimaran aluminum hull that is based on a proven Austal (Henderson, Australia) design. The LCS2 is being built by GD Bath Iron Works (GDBIW) at Austal USA in Mobile, Alabama.

Each LCS features thin light weight steel and aluminum alloy materials that are highly sensitive to welding induced distortion that when not controlled can lead to costly fit-up and rework efforts throughout the build process. To address this issue, researchers have been examining welding processes such as Friction Stir Welding (FSW) and laser or laser hybrid processes for consideration in full production. Although very effective at reducing distortion, the current technology for FSW does not allow for weld joints to be completed at a high rate of productivity. The laser and/or laser hybrid welding processes provide a good combination of distortion control and enhanced productivity and has been proven in Europe to be effective in shipbuilding applications, however the equipment and required maintenance is very costly. Furthermore, for each of these processes weld joint fit-up needs to be precisely controlled to be effective in production and therefore extensive tooling is required.

In addition to the distortion issues, there are requirements in LCS construction that most primed steel structures not have their primers removed prior to welding. In order to produce sound welds when welding over primers welding processes such as flux cored arc welding (FCAW) with special electrode formulations have been traditionally used. Slow welding speeds are employed to allow the gases generated from the decomposed primers to sufficiently escape the weld prior to solidification. The slow welding speeds result in higher heat inputs that generate increased levels of distortion in thin panel structures as well as low production rates. In commercial shipbuilding it is common practice to remove the primers prior to welding by grit blasting and then reapply after the welding operations are complete. This method of construction adds time and money to the build process and shipyards are always looking for productive methods to effectively weld over primers to reduce their costs.

To increase the productivity of welding, processes with high deposition rates need to be employed; however, to reduce distortion high travel speeds and low heat inputs are required. Welding processes that provide a suitable balance between productivity and distortion control need to be considered as well as provide a significant return on the equipment investment. In addition, methods that increase the level of restraint in the structure need to be investigated that have the potential to reduce distortion in thin panel structures. The methods that are discussed following have been investigated in this project to resolve the aforementioned issues without sacrificing quality, and these are:

<u>Controlled Dip Transfer Welding:</u> The controlled dip transfer welding processes (such as Lincoln Electric's Surface Tension Transfer (STT) and Miller Electric's Regulated Metal Deposition (RMD)) have been tested on the first LCS at MMC and have proven appropriate for a limited set of welds on distortion sensitive areas. This process provides low heat input welds with little to no spatter and excellent weld geometries; however, the process is not suited for a large range of applications. This report provides detailed guidelines and procedures for the application of the STT process. Although the process is successful in producing welds with low distortion, it is not highly productive and therefore does not provide a suitable balance between productivity and distortion for many applications such as welding of stiffeners to base plates in panel line production.

<u>Superpulse Technology:</u> ESAB has recently released a series of new GMAW technologies including pulse/pulse, pulse/short, and pulse/spray. The pulse/pulse technology has similar attributes to the STT and RMD processes; however, unlike the STT and RMD processes it can be applied to the welding of aluminum structures. Optimal procedures were developed for aluminum welding of stiffener assemblies with the pulse/pulse, pulse/short, and the pulse spray transfers. The pulse/pulse mode of transfer produced improved bead appearance and profile, as well as significantly lower distortion (greater than 30% reduction) compared to the conventional CV process. The trade-off was productivity as the pulse/pulse technology resulted in a 40% decrease in travel speed compared to the conventional CV process.

<u>Tandem Gas Metal Arc Welding (T-GMAW):</u> T-GMAW uses two wires which are fed through a single torch, into the weld pool simultaneously. The T-GMAW process results in a significant increase in deposition rate, requiring higher rates of travel speeds to complete welds of various types and sizes. The higher travel speeds generate lower heat inputs and resulting distortion. The use of metal cored electrodes with the T-GMAW process (referred to as T-MCAW) resulted in a 221% increase in travel speed compared to the benchmark FCAW procedure. With no clean-up operations to remove slag after welding, the actual productivity improvements are estimated at 250%.

Procedures for T-MCAW were developed for welding over primers to utilize the elongated puddle of the tandem arc to extend the degasification period allowing higher travel speeds to be employed without generating weld defects. These procedures resulted in an increase of 140% in travel speed compared to the benchmark FCAW procedure. Porosity counts on fractured weld samples revealed that the T-MCAW process was capable of achieving porosity requirements; however, variations in the primer coating thickness resulted in sections of weld where resulting porosity was not acceptable. It appears that the T-MCAW process is less tolerant to the amount of primer on the material compared to the benchmark FCAW process. It is believed that a mechanical process to mill the edge of the stiffener square, removing primer from only the bottom surface of the stiffener and eliminating ridges where primer settles would make the T-MCAW more feasible. Joint fit-up would be improved with the machine edge reducing the amount of rework and productivity would be improved due to the increased travel speeds achieved with the T-MCAW process.

<u>Mechanical Tensioning:</u> The very nature of the arc welding process, viz., local and non-uniform heating and cooling, is such that it is usually accompanied by distortion of the structure being fabricated. The magnitude of the distortion is controlled in practice within specified tolerances, not only for aesthetic purposes but also to maintain the structural integrity in service. It is preferable to implement techniques and procedures that minimize distortion in the first place since its correction at a later stage entails substantial hidden costs, including an adverse effect on the quality of the subsequent welds and of the overall fabrication (e.g., poor fit-up, greater amount of weld volume, possibly higher residual stresses, etc).

Mechanically applied tension loading parallel to the weld axis during welding has been used by fabricators to minimize the buckling of thin plate during butt welding. Kawasaki Heavy Industries developed several methods to reduce out-of-plane distortion involving mechanical tensioning, and the methods were so successful that they were called the “Kawasaki Perfect Panel Production” method. The tension load forces the weld and thermally upset zone alongside to stretch longitudinally and transverse to the weld to conform to the geometry of the balance of the sheet.

BMT developed a mechanical tensioning set-up for a mock panel line to investigate the effects of pre-tensioned panels on distortion. Results were inconclusive for groove weld operations joining panels together; however, success was achieved in the use of mechanical tensioning to align the fit-up of the panels to be welded.

The mechanical tensioning process was successful in reducing distortion (greater than 30% reduction) in stiffener welding applications of both steel and aluminum applications.

Further work is required to develop a mechanical tensioning arrangement that can provide equal tension along the entire width of the plates to be joined as well as restrain the plates longitudinally during welding. It is believed that a set-up like this would have the potential to produce improved distortion results for seam welding operation of large plates as well as overall improvement in distortion for plates greater than 10” wide.

Further work is also required to develop a process where the bottom edge of stiffeners is machined prior to welding, and welding over primer procedures with T-MCAW utilized to achieve highly productive welds meeting porosity requirements with repeatability. The improved mechanical tensioning arrangement would be employed for welding of stiffeners on large base plates with reduced distortion throughout the assembly.

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ACRONYMS

AWS	American Welding Society
CTTD	Contact Tip To Work
CV	Constant Voltage
DCEN	Direct Current Electrode Negative
DCEP	Direct Current Electrode Positive
FCAW	Flux Cored Arc Welding
FSW	Friction Stir Welding
GMAW	Gas Metal Arc Welding
HSLA	High Strength Low Alloy
IPM	Inches Per Minute
MCAW	Metal Core Arc Welding
MMC	Marinette Marine Corp.
NSRP	National Shipbuilding Research Program
RMD	Regulated Metal Deposition
SAW	Submerged Arc Welding
STT	Surface Tension Transfer
T-GMAW	Tandem Gas Metal Arc Welding
WFS	Wire Feed Speed
WPDS	Welding Procedure Data Sheet

1. INTRODUCTION

1.1 Problem to be Addressed

Ships such as the LCS feature thin light weight steel and aluminum alloy materials that are highly sensitive to welding induced distortion that when not controlled can lead to costly fit-up and rework efforts throughout the build process. Shipyards such as MMC are looking for cost effective solutions and/or technologies that can be incorporated into their existing panel line operations to achieve distortion within tolerances and avoid costly fit-up and rework.

In addition to the distortion issues, there are requirements in LCS construction that welding be performed over the primed plates and stiffeners. The FCAW process using special electrode formulations have been traditionally used to produce sound welds over primed surfaces. The FCAW procedures utilize slow welding speeds for degasification of the decomposing primer. The slow welding speeds result in higher heat inputs that generate increased levels of distortion in thin panel structures as well as low production rates. In commercial shipbuilding it is common practice to remove the primers prior to welding by grit blasting and then reapply after the welding operations are complete. This method of construction adds time and money to the build process and shipyards are always looking for productive methods to effectively weld over primers to reduce their cost.

To increase the productivity of welding, processes with high deposition rates need to be employed; however, to reduce distortion high travel speeds and low heat inputs are required. Welding processes that provide a suitable balance between productivity and distortion control need to be considered as well as provide a significant return on the equipment investment. In addition, methods that increase the level of restraint in the structure need to be investigated that have the potential to reduce distortion in thin panel structures. The following methods that are proposed have the potential to resolve the above issues without sacrificing quality, and these are: Controlled Dip Transfer Welding (including ESAB Superpulse Technology), Tandem Gas Metal Arc Welding (T-GMAW), and Mechanical Tensioning.

1.2 Scope

Many shipyards use the GMAW and FCAW processes for various applications in their panel lines. In some cases, shipyards have investigated laser or laser-hybrid joining technologies to further improve productivity and improve subsequent block fit-up efforts through distortion reduction. However, these processes are quite costly (initial cost of equipment and extensive fit-up efforts) and it is for this reason most shipyards are reluctant to use these in production, although many European shipyards have had great success to-date. The T-GMAW technology proposed in this study is a low cost solution with a greater margin of return on the investment, compared to other advanced joining methods. The weld metal deposition rates achieved with this process are typically twice that compared to single electrode welding. Greater deposition rates require higher travel speeds to complete a weld of a given size, and therefore higher productivity rates are achieved. Higher travel speeds result in lower heat inputs and less welding induced distortion. T-GMAW has the potential to enhance welding speeds while welding over primers without introducing weld defects.

Metal cored electrodes for GMAW are manufactured using a mild steel jacket with a core of specifically selected iron and other metal powders and alloys. The current is carried only by the thin sheath surrounding the electrode, thereby increasing resistive heating of the electrode, resulting in increased deposition rates and thus higher productivity. Stabilizers and arc enhancers are added to its core, typically providing a wider operating window compared to welding with solid wires. Formulations have been developed specifically for welding over primers.

Aluminum’s coefficient of thermal expansion is approximately six times greater that that of steel, and therefore makes it much more susceptible to welding induced distortion in comparison. Processes such as Pulse/Pulse and other SuperPulse GMAW modes need to be investigated to reduce heat input and distortion as well as improve productivity rates.

2. PROJECT OBJECTIVES

The main objective of the proposed investigation is to utilize recent technological advancements in GMAW processes and consumable design to improve productivity rates and reduce the construction costs of both commercial and naval vessels in US shipyards. Secondly, mechanical tensioning may reduce distortion in thin panel structures and therefore reduce the cost of fit-up and rework efforts.

The benefits of this project to the sponsor group vary based upon the interests of the sponsoring organization. The NSRP will expect to increase the quality and economy of ship construction completed in US shipyards. This will both make naval platforms and commercial vessels more affordable and improve the structural integrity of ships built in US shipyards. The sponsoring shipyards would expect to be able to reduce their fabrication costs through higher productivity and lower rework and scrap rates.

The shipyard sponsors will appreciate that the proposed welding equipment can be easily implemented into any of their existing panel lines that use the SAW, FCAW, or GMAW process, with minimal modifications.

The project metrics are shown in Table 2.1

Table 2.1: Project Metrics

Metric	"As-is" Baseline	Project Goal	Tracking and Reporting Plan
Weld Completion Rates for Aluminum and Non-primed steel structures	Current Weld Metal Deposition Rates and Travel Speeds per Unit Length of Weld	Increase Weld Completion Rates by 200%	Select and evaluate current welding procedures for panel line welding of same materials and thickness; Compare results with those using the proposed technologies.
Reduce Distortion Through Heat Inputs and Tension Loads	Current Levels	Reduce by 30%	Collect data from shipyards on current levels of distortion. Produce welds in lab with new welding processes and mechanical tensioning and measure resulting distortion
Extend Travel Speeds for Welding Over Primers	Current Levels	Increase by up to 50%	Collect data from shipyards on current practice for welding over primers. Produce welding procedures with T-GMAW process and compare productivity rates.

3. TASK 1: DEFINITION OF BENCHMARK WELDING PROCEDURES

The first task of the project was to collect and analyze results of the current practices for welding on "thin" panel steel and aluminum structures (5mm thick), including welding over primers. The welds produced using the benchmark procedures were used to compare the differences in both distortion and productivity. The GMAW-STT, FCAW, and SAW procedures provided by MMC were used as a guideline for producing benchmark procedures for welding on the 5mm thick steel plate with the GMAW-STT, FCAW, and SAW processes. Procedures were not provided by MCC for welding of aluminum. The desired fillet weld size was known so typical parameters for the wire size were used (based on manufacturers recommendations) and travel speed was fine tuned to achieve the desired fillet weld size.

The first step was to build a structural steel frame large enough to support two 4' x 10' plates and accommodate the tensioning apparatus and the load cell. The steel frame needed to be flat and sitting level on the shop floor. A frame was also custom built to support the 16' beam to form the welding gantry. An upgraded motor was installed to run on the beam capable of travel speed up to 100 inches per minute. Fixturing was designed and fabricated for mounting of all the required control boxes, feeders, servo motors and slides, welding torch, and wire spool holders. Figure 3.1 illustrates the welding gantry and frame set-up.

Figure 3.1: Welding Gantry and Frame Set-up

Distortion readings are taken using a self leveling laser to project a beam across the plate, level with the working surface. Reading are taken for every point on the plate (plate distortion measurement grid) and recorded on a spreadsheet for use in creating tables, charts, and ANSYS models of the plate and the displacements. Measurements are also taken of the frame for reference to corresponding location on the plate for accurate displacement results. Distortion readings were taken of all benchmark plates before and after welding for later comparison with tension cases. Figure 3.2 shows the self-leveling laser level and Figure 3.3 shows the beam projected on the steel rule.

Figure 3.2: Self Leveling Laser Level

Figure 3.3: Beam Projected on Steel Rule

Plates for the benchmark procedures were first fitted and tacked to form a butt joint with no preparation and no gap. Chalklines were made at predetermined spacing along the width and length of the plate. Figure 3.4 shows the plate distortion measurement grid used for the benchmark plate as well as the tension cases. The benchmark plates were free to rest on the test frame during welding.

Figure 3.4: Plate Layout

Stiffener Assemblies for the benchmark procedures were fitted and tacked so that the stiffener was at 90 degrees with the base plate. Tack welds were performed at predetermined points for all assemblies so there was no variance in displacement readings due to the tack welding operations. Stiffeners were fit tight to the base plate so there were no gaps. Points were marked on the base plate and stiffener following the distortion matrix grid for taking distortion readings. Figure 4.22 (FCAW 10" Base Plate), Figure 6.4 (Aluminum) and Figure 7.19 (FCAW 4' Base Plate) show the plate distortion measurement grid used for the benchmark plate as well as the tension cases. The benchmark plates were free to rest on the test frame during welding. Figures 3.5 to 3.7 show the various assembly layouts.

Figure 3.5: Stiffener Assembly Layout (Steel)

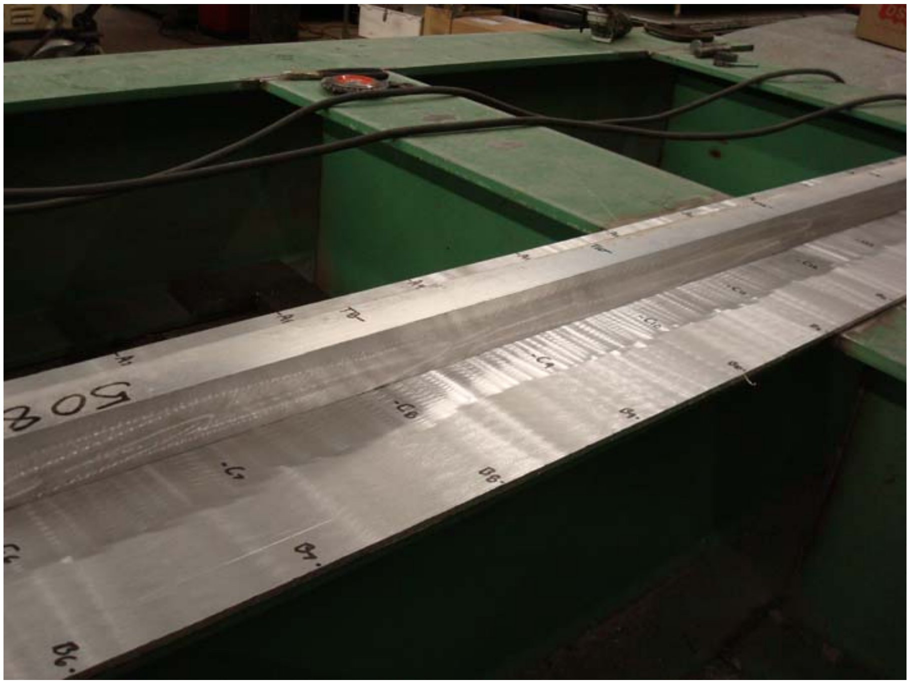


Figure 3.6: Stiffener Assembly Layout (Aluminum)

Figure 3.7: Stiffener Assembly Layout (Steel 10' Base Plate)

Welding parameters used for the benchmark procedures have been summarized in the form of welding procedure data sheets as shown in Figures 3.8 through 3.11. Distortion results are discussed later in the report as the benchmark distortion data is used to compare with the distortion results of the tension cases.

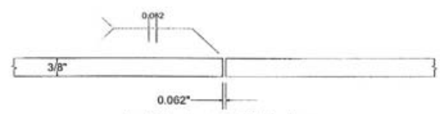
CWB Form 160E/99-1

BMT Fleet Technology — **WELDING PROCEDURE DATA SHEET**

WPDS NO.:	SAW 1G
DATE:	10-Jul-08
Rev.:	
Company Name:	BMT Fleet Technology
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:	
Ref. WPS:	

Welding Processes:	1 SAW Pulsed: ☐ Yes ☑ No / 2 Pulsed: ☐ Yes ☐ No
Shielding Gas Type:	N/A
Positions:	Flat
Process Mode:	☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto
Joint Type:	☑ Butt ☐ Tee ☐ Corner ☐ Lap ☐ Edge
Penetration:	☑ Complete ☐ Partial ETT= ☐ Fillet
Backing:	Material: N/A Thickness: N/A
Backgouging:	☐ Yes Method: N/A / ☐ No Depth: N/A
Electrode Extension:	contact tip to work distance = 19mm to 25mm
Nozzle Diameter(s):	7/8"
Flux Classification:	F9A6-EM2-M2-H8
Tungsten Electrode:	Type: N/A Dia.: N/A
Cleaning Procedures	As Required
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Root Opening is 1/16" Maximum

SAW both sides - no back gouge

Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	MIL-S-24645 HSLA 80	3/16"	
II	MIL-S-24645 HSLA 80	3/16"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
SAW	ESAB SpoolArc 95	MIL-100S-1		

Welding Parameters

Thickness (In.)	Weld Size/ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Burn-Off Rate ( )	Gas Flow Rate (CFH	Heat Input (kJ/in)
		Side 1											
3/16	3/16	1	1	SAW	3/32	N/A	320	30	DCEP	24	N/A	N/A	24.0
		Side 2											
		1	1	SAW	3/32	N/A	350	30	DCEP	24	N/A	N/A	26.3

Heat treatment :

Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

CWB Acceptance

Company Authorization

Date:

Figure 3.8: Welding Procedure Data Sheet for Benchmark SAW

CWB Form 160E/99-1

BMT Fleet Technology

WELDING PROCEDURE DATA SHEET

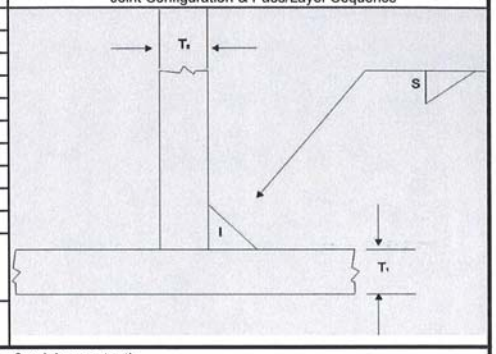
WPDS NO.: FCAW-2F
DATE: 26-Jun-08 Rev.:

Company Name: BMT Fleet Technology
Address: 311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:
Ref. WPS:

Welding Processes:	1	FCAW	Pulsed: ☐ Yes ☑ No
Shielding Gas Type:		100% C02	
	2		Pulsed: ☐ Yes ☐ No

Positions:	Horizontal (2F)
Process Mode:	☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto
Joint Type:	☐ Butt ☑ Tee ☐ Corner ☐ Lap ☐ Edge
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet
Backing:	Material: N/A Thickness: N/A
Backgouging:	☐ Yes Method: N/A ☐ No Depth: N/A
Electrode Extension:	contact tip to work distance = 19mm to 25mm
Nozzle Diameter(s):	7/8" to 3/4"
Flux Classification:	N/A
Tungsten Electrode:	Type: N/A Dia.: N/A
Cleaning Procedures	As Required: Chipping, wire brush, wire wheel
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material (for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	HSLA 80	3/16"	
II	HSLA 80	3/16"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
FCAW	Trimark	MIL-101TM		

Welding Parameters

Thick-ness (In.)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Burn-Off Rate ( )	Gas Flow Rate (CFH)	Heat Input (kJ/in)
Base Material in Primed Condition													
3/16	3/16	1	1	FCAW	.045	350	210	30	DCEP	25	N/A	40	15
Base Material with Primer Removed													
3/16	3/16	1	1	FCAW	.045	320	205	27.5	DCEP	28	N/A	40	12

Heat treatment :				**CWB Acceptance**	**Company Authorization**
Preheat min:	Ambient	Interpasstemp.max.:	N/A		
		Interpasstemp.min.:	N/A		
					Date:

Figure 3.9: Welding Procedure Data Sheet for Benchmark FCAW

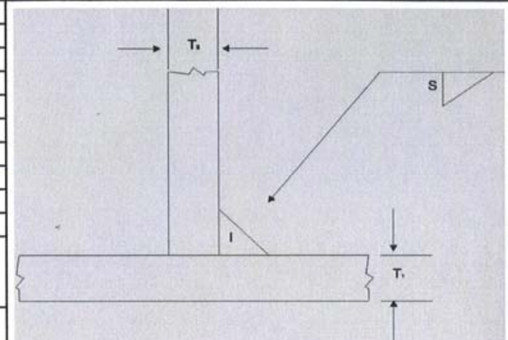
BMT Fleet Technology

WELDING PROCEDURE DATA SHEET

WPDS NO.:	STT-035-C02-2F		
DATE:	12/19/2007	Rev.:	
Company Name:	BMT Fleet Technology	Ref. Standards:	
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8	Ref. WPS:	

Welding Processes:	1	GMAW-STT	Pulsed: ☐ Yes ☑ No
Shielding Gas Type:		100% CO2	
	2		Pulsed: ☐ Yes ☐ No
Positions:	Horizontal (2F)		
Process Mode:	☐ Manual ☑ Semi-Auto ☑ Machine ☐ Auto		
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge		
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet		
Backing:	Material: N/A	Thickness: N/A	
Backgouging:	☐ Yes Method: N/A ☐ No Depth: N/A		
Electrode Extension:	contact tip to work distance = 3/8"		
Nozzle Diameter(s):	1/2" to 5/8"		
Flux Classification:	N/A		
Tungsten Electrode:	Type: N/A	Dia.: N/A	
Cleaning Procedures	Wiire wheel		
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only		

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	HSLA 80	3mm to 5mm	
II	HSLA 80	3mm to 5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-STT	ESAB Spoolarc 95	ER100S-1		

Welding Parameters

Thickness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Program number	Gas Flow Rate (CFH	Heat Input (kJ/in)
T	3.0	1	1	STT	.035	210	115	16	DCEP	13	131	30	8.5
T	4.8	1	1	STT	.035	210	115	16	DCEP	10	131	30	11.0

Heat treatment :

Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Power Source: Lincoln Powerwave 455
Arc Control: 8.0, Trim: 1.0
Run-in: 100ipm, burnback: 0.03sec, preflow: 0.5sec
Work angle: 40 degrees, Travel angle: 0 degrees

5mm plate is the limitation of this process. Use of STT transfer on plate above 5mm in thickness may result in lack of fusion or lack of penetration. Contact tip to work distance of 3/8" must be maintained to achieve acceptable weld profile and penetration profile.

Acceptance

Company Authorization

Date:

Figure 3.10: Welding Procedure Data Sheet for Benchmark STT

BMT Fleet Technology

WELDING PROCEDURE DATA SHEET

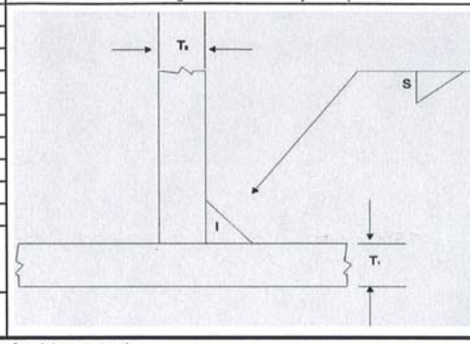
WPDS NO.: CV-Argon-2F
DATE: 02/04/2008 Rev.:

Company Name: BMT Fleet Technology
Address: 311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:
Ref. WPS:

Welding Processes:	1	GMAW	Pulsed: ☐ Yes ☑ No
Shielding Gas Type:		100% Argon	
	2		Pulsed: ☐ Yes ☐ No

Positions:	Horizontal (2F)
Process Mode:	☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet
Backing:	Material: N/A Thickness: N/A
Backgouging:	☐ Yes Method: N/A ☐ No Depth: N/A
Electrode Extension:	contact tip to work distance = 3/4"
Nozzle Diameter(s):	Tandem Torch Noxxle
Flux Classification:	N/A
Tungsten Electrode:	Type: N/A Dia.: N/A
Cleaning Procedures	Stainless wire wheel, stainless sanding disk, stainless wire brush as required
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	5086 H116	5mm	
II	5086 H116	5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW	OK Autrod 5356	ER5356		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (mm)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Data Set	Gas Flow Rate (CFH)	Heat Input (kJ/in)
T	5	1	1	GMAW	1.2	600	259	19.8	DCEP	50	5	45	6.2

Heat treatment :

Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Power Source: ESAB Aristomig 450
Drive Unit: Mech/Mek
Pendant: ESAB U8
Work Angle: 40°, Travel Angle: 0°
Program Info: Mig/Mag, Dip/Spray, Al/Mg, Ar, 1.2mm

Acceptance

Company Authorization

Date:

Figure 3.11: Welding Procedure Data Sheet for Benchmark GMAW of Aluminum

4. TASK 2: DEVELOP OPTIMUM TENSION PROFILES 2

4.1 Design of Tension System

The first step in this task was to determine the hole locations required for tensioning the plates. The concern was tear out and plastic deformation of the plate material so modeling was done with different dimensions for (a) and (b) shown on Figure 4.1. The air cylinder has a maximum capacity of 30 tonne; however, it was expected that actual loads would be closer to 10 tonnes. Figure 4.2 shows modeling results for the lateral displacement for different values of (a) and (b) using a 10 tonne tension load. The lateral displacement using a 3" value for a and a 3" value for b was approximately 0.2mm, very low, so it was decided to use a value of 2.5" for both a and b dimensions. Once this was established the clevices were fabricated along with the 1" diameter pins.

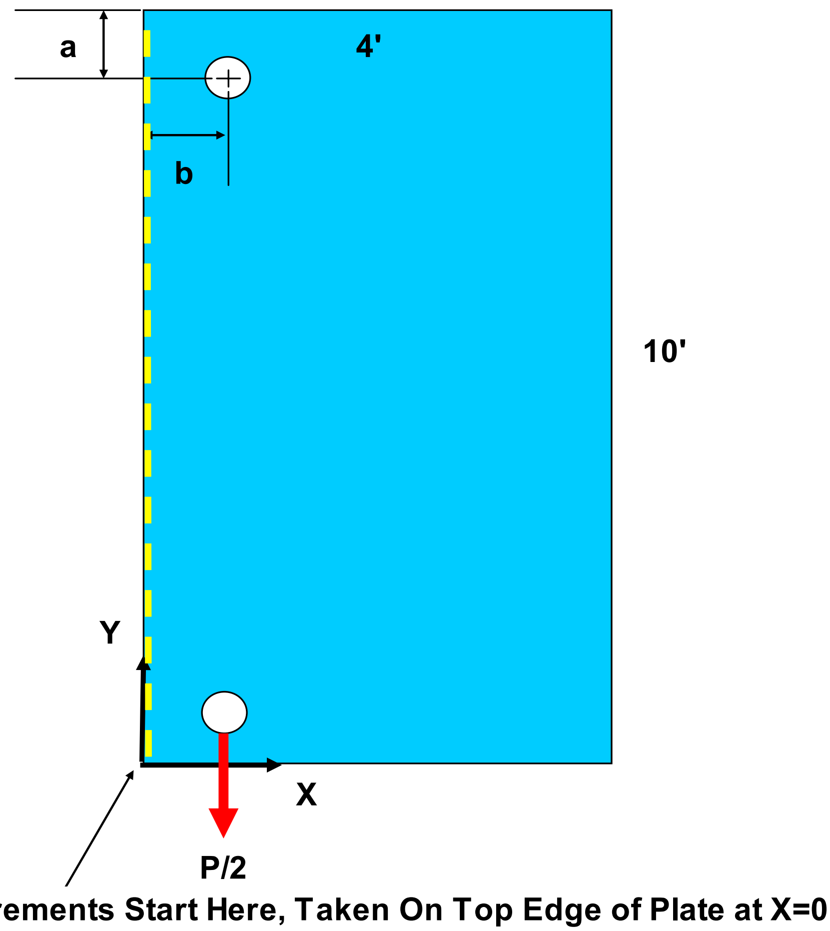


Figure 4.1: Hole Locations in Plate for Mechanical Tensioning

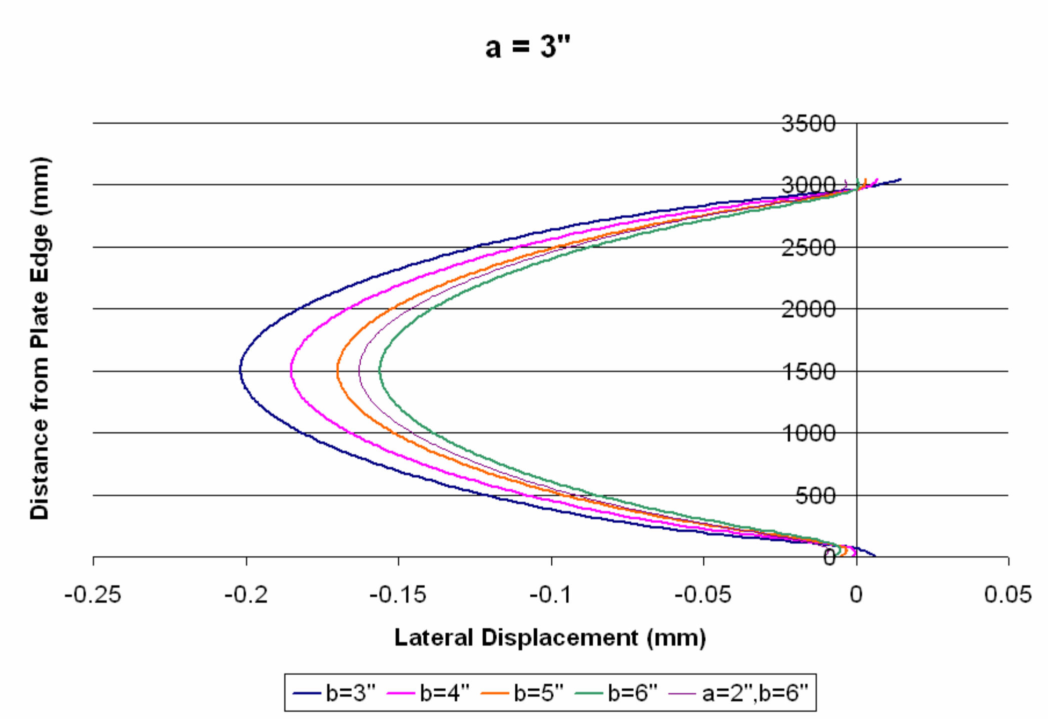


Figure 4.2: Distance from Plate Edge vs. Lateral Displacement for Hole Locations

Figures 4.3 through 4.5 show the operation of the clevice system in how they attach to the plates through hardened 1" diameter pins and locate the plates in proper orientation for welding while providing desired tension load. A load cell is connected to the clevice at the bottom of Figure 4.5 and is connected to a laptop computer to provide tension load information. The tension load is monitored during welding and the load adjusted as required to maintain a constant load throughout the welding of the plate.

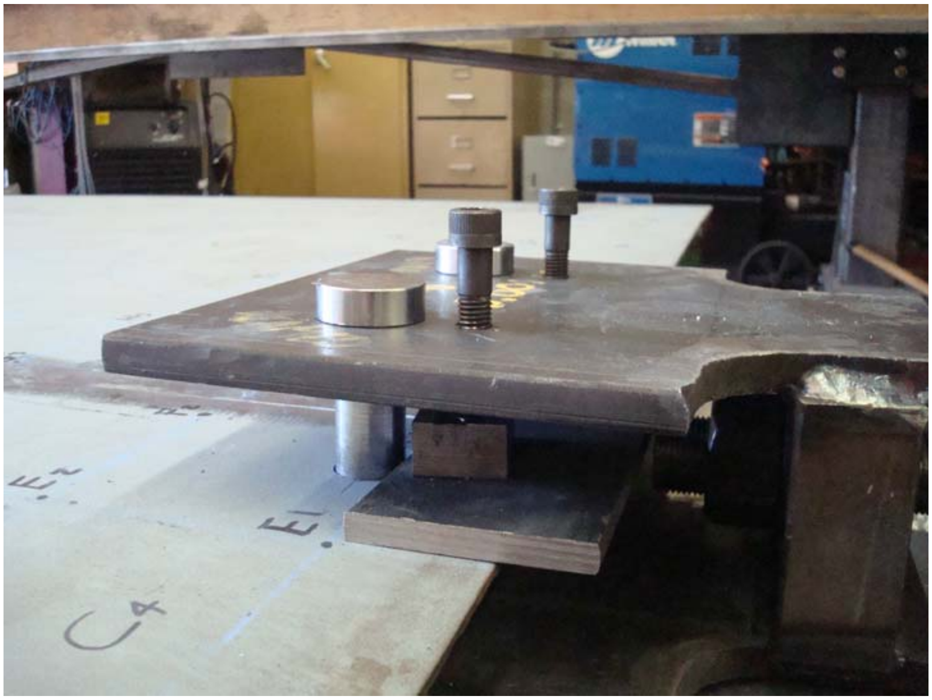


Figure 4.3: Side View of Clevice with Plate under Tension

Figure 4.4: Top View of Clevice with Plate under Tension

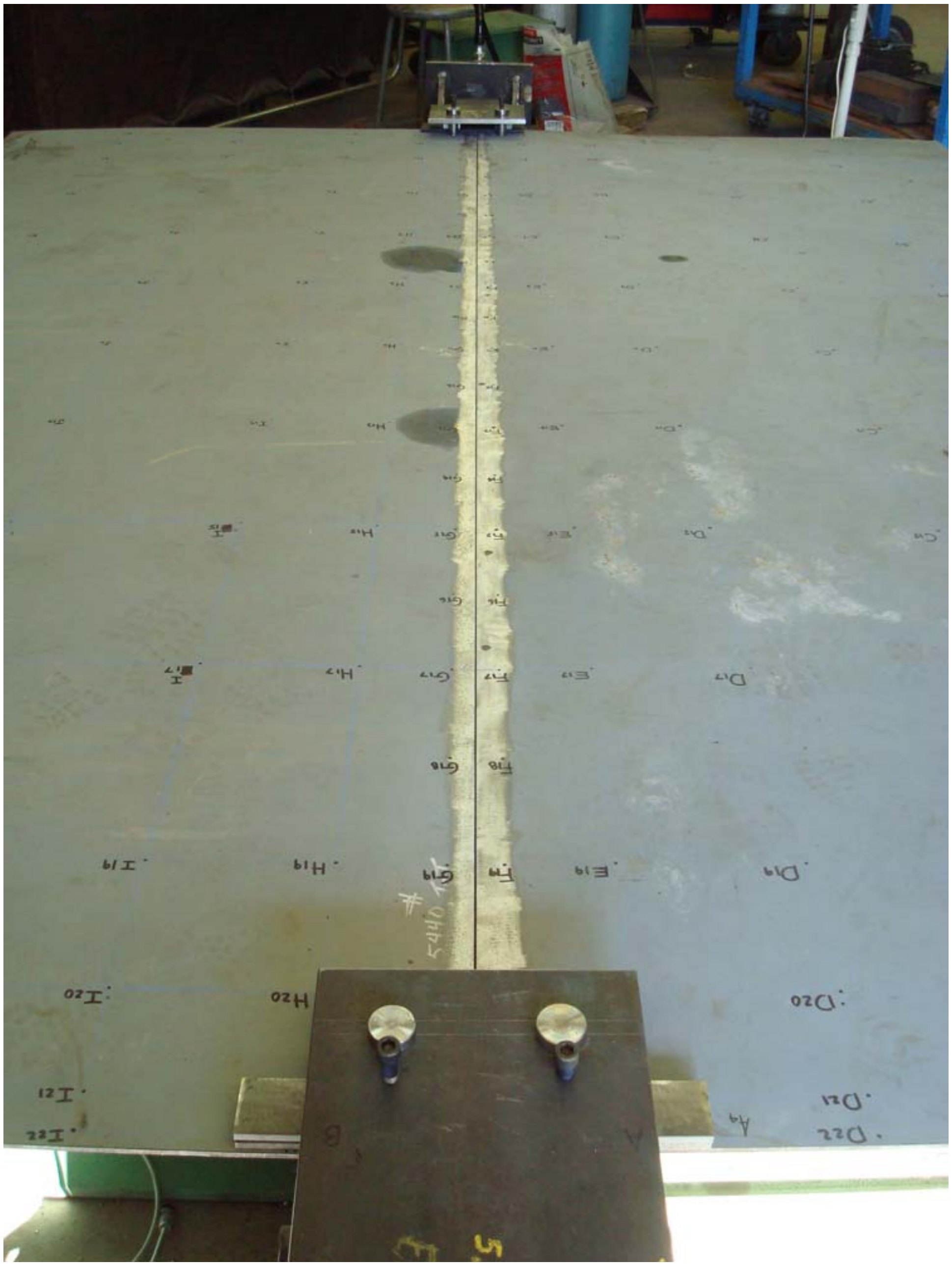


Figure 4.5: View of Entire Plate Assembly under Tension

4.2 Plate Assembly Results

All test plates to be welded are marked up as illustrated in Figure 4.6. Plate distortion (vertical displacement) measurements are recorded for every point between A to L along the width and 1 to 22 along the length, using a laser level. For all plates to be welded under mechanical tension, plate distortion data is recorded at all three stages:

1. Before welding
2. Before welding under tension
3. After welding

For benchmark plates in absence of tension, data is recorded before and after completion of welding. In addition, a similar measurement grid was setup for the test support frame upon which the plate to be welded are supported.

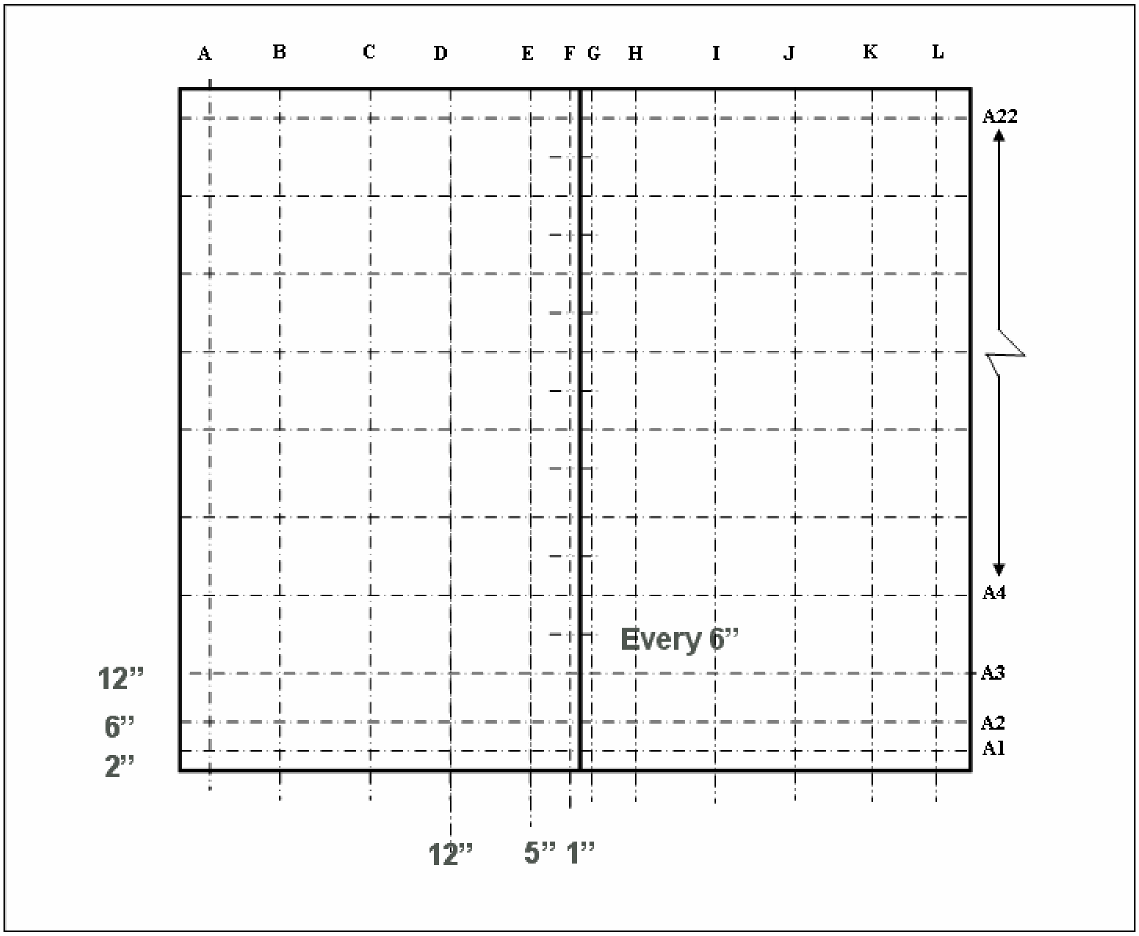


Figure 4.6: Plate Distortion Measurement Grid

Table 4.1 summarizes the test cases that were analyzed as part of the on-going research. Applied tension loads under 10, 000 lbs achieved a straightening effect on plates that were distorted. Tension loading was increased at increments of 5,000 lbs to determine the optimal tension load profile.

Table 4.1: Test Summary

Specimen No.	Side	Applied Tension (lbs)	Test Type
1	1, 2	-	Benchmark
6	1, 2	-	
2	1	10,000	Mechanical Tensioning
3	1, 2	15,000	
5	1, 2	15,000	
4	1,2	30,000	

Figure 4.7, 4.8 and 4.9 illustrate the benefits of mechanical tensioning on straightening and alignment of plates to be welded. In Figures 4.7 and 4.8, a high low situation up to approximately 1" exists between the plates to be welded. With the use of less than 10,000lbs of tension, the plate are brought within tolerance and ready for welding as shown in Figure 4.9. Figure 4.10 shows the vertical displacement of the plates with no tension and Figure 4.11 shows the vertical displacement of the plates under 10,000lbs of tension.

Figure 4.7: Fit-Up of Plates before Pre-Tensioning

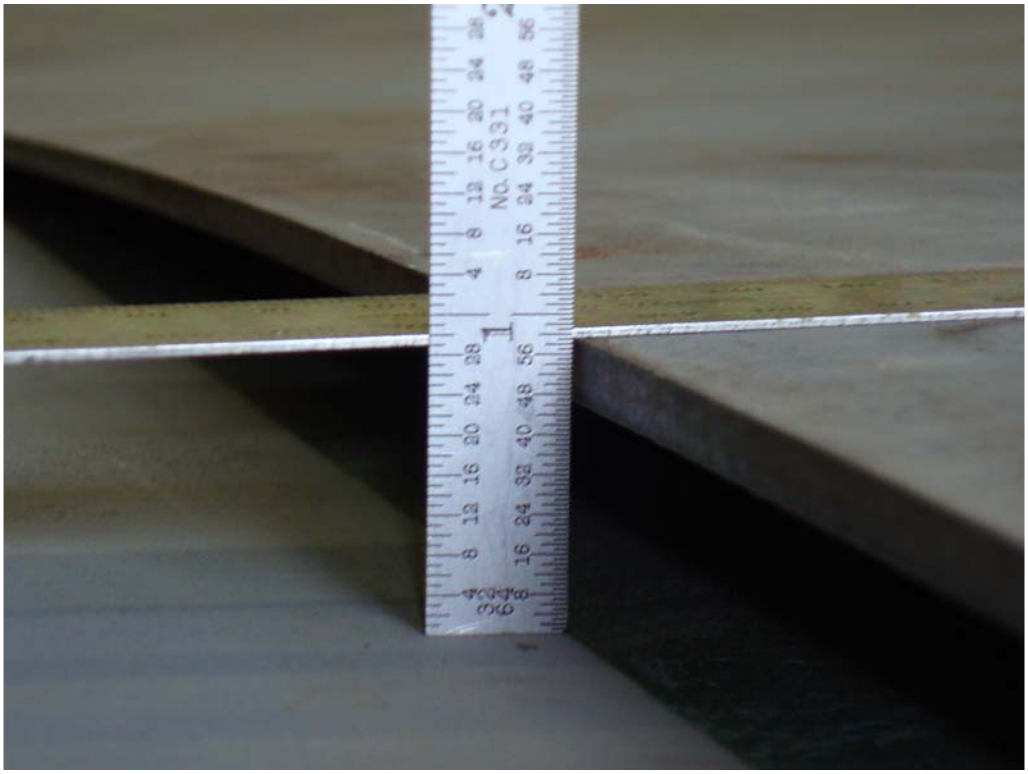


Figure 4.8: High Low in Plates before Pre-Tensioning

Figure 4.9: Fit-Up of Plates after Pre-Tensioning

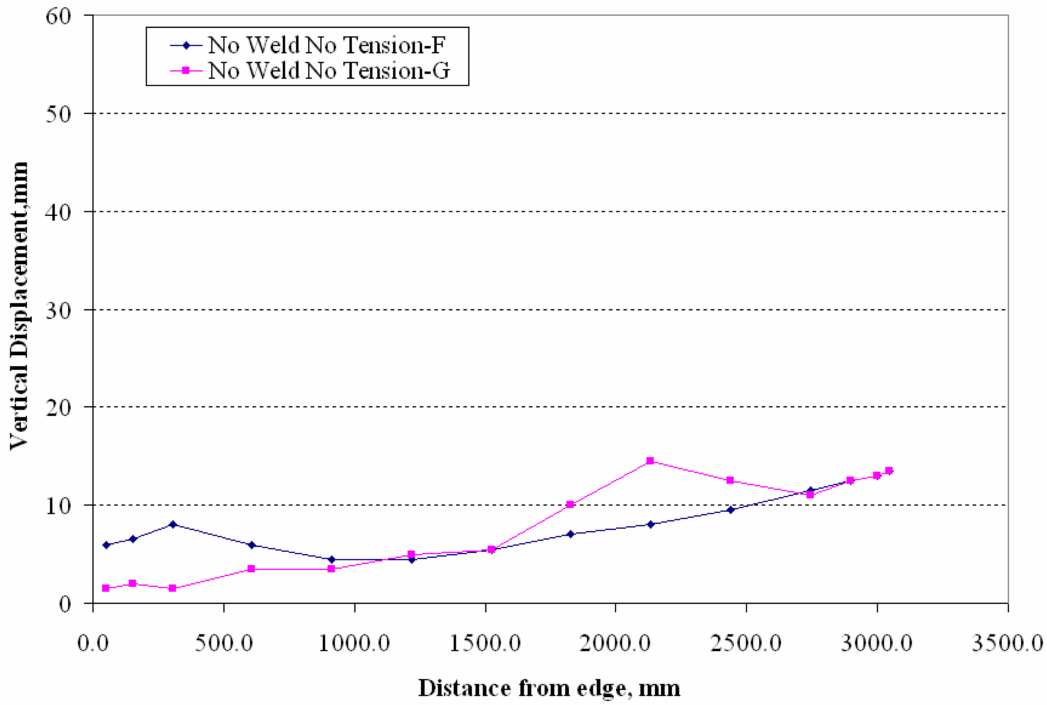


Figure 4.10: Plate Distortion Measurement Grid

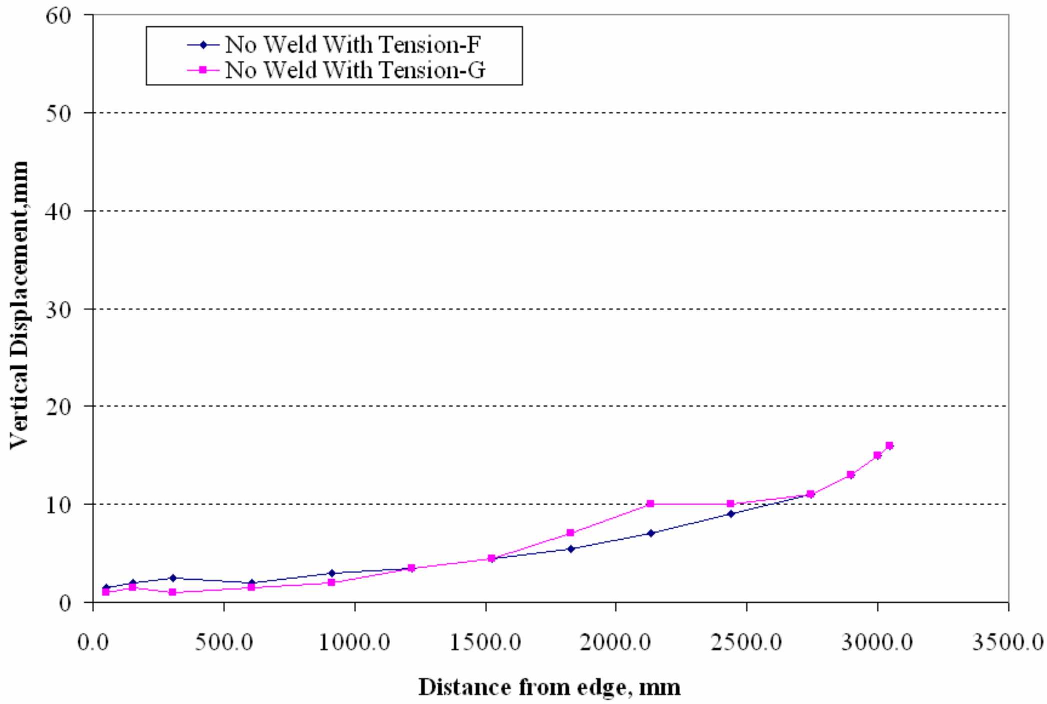


Figure 4.11: Plate Distortion Measurement Grid

In order to measure the effectiveness of mechanical tensioning approach, the net displacement of each marked point on the plate with respect to the corresponding point on the test frame is compared at each of the above stages. Figures 4.12 and 4.13 compare the net displacement along transverse and longitudinal sections for benchmark Plate 1-Side 1. Figure 4.14 is a 3-dimensional ANSYS model that shows the net displacement after welding for Plate 1-Side 1. Additional plots are provided in **Appendix A**.

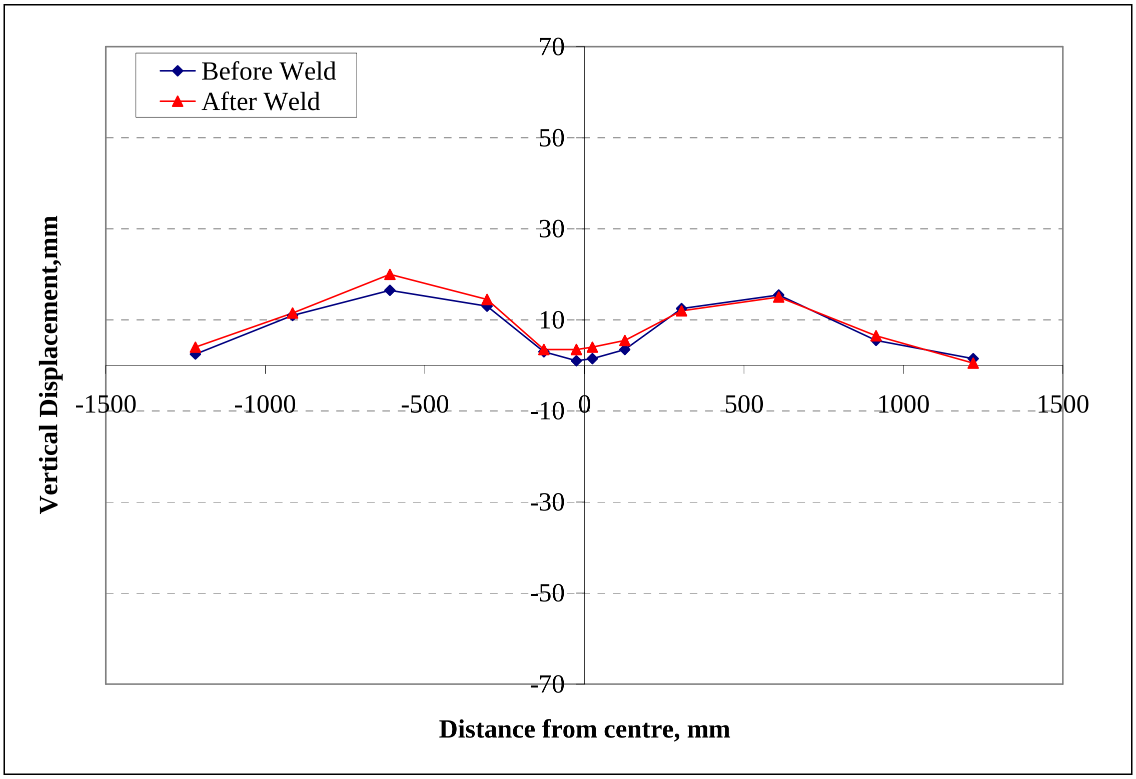


Figure 4.12: Net Displacement along Transverse Section A11 for Plate 1-Side1

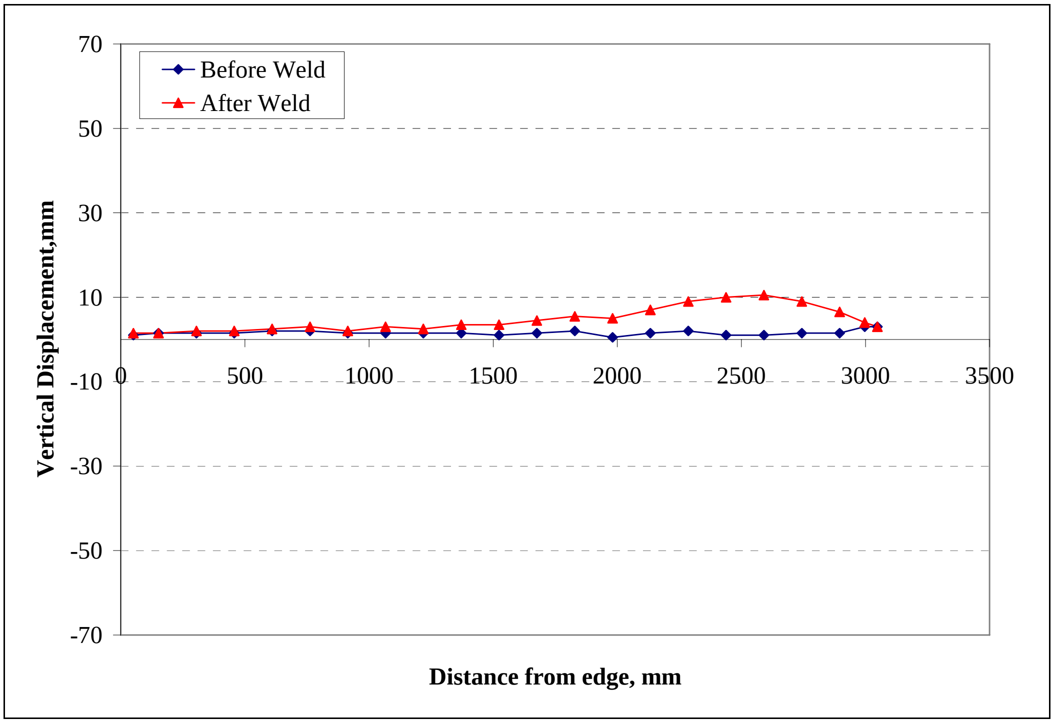


Figure 4.13: Net Displacement along Longitudinal Section F for Plate 1-Side1

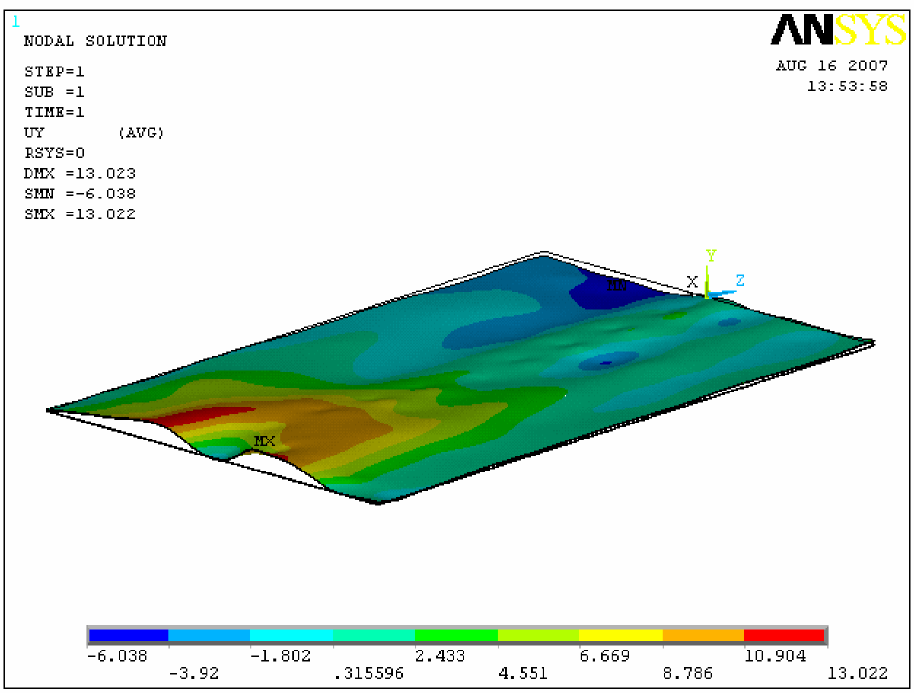


Figure 4.14: Net Plate Deformation after Welding Plate 1-Side1

Figures 4.15 and 4.16 compare the net displacement along transverse and longitudinal sections for Plate 4-Side 1. Figures 4.17 and 4.18 are 3-dimensional ANSYS models that show the net displacement before and after welding for Plate 4-Side 1. Additional plots are provided in **Appendix A**.

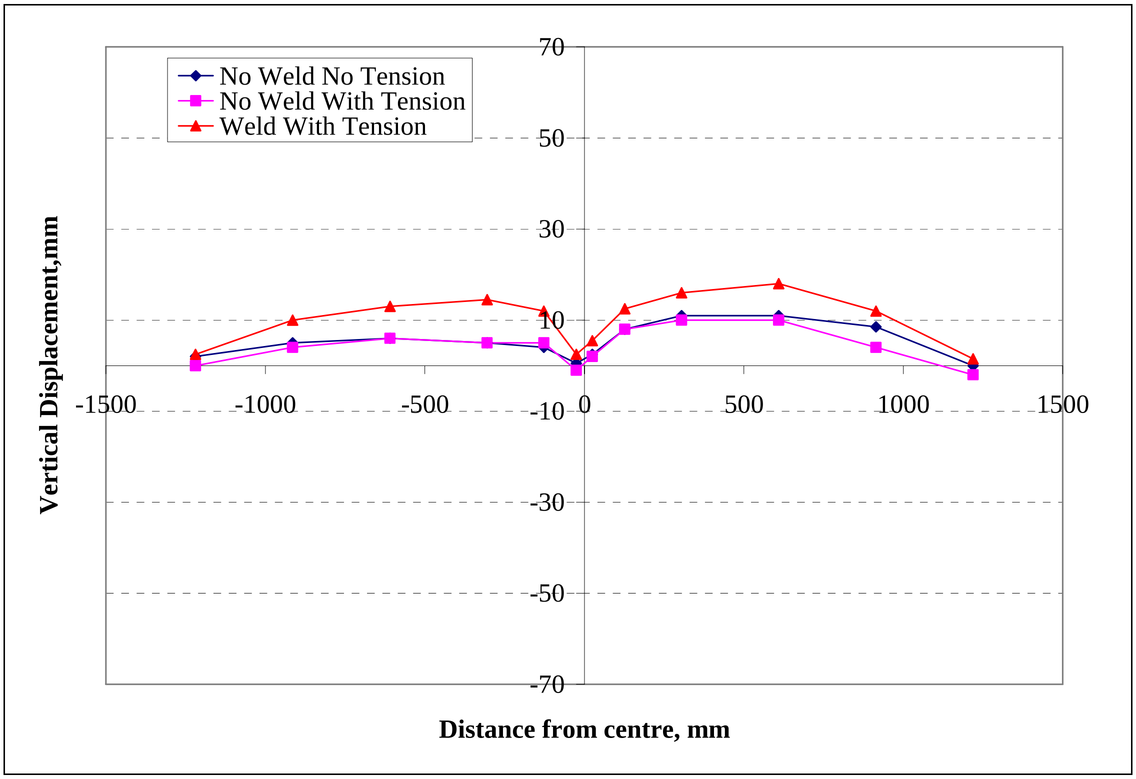


Figure 4.15: Net Displacement along Transverse Section A11 for Plate 4-Side1

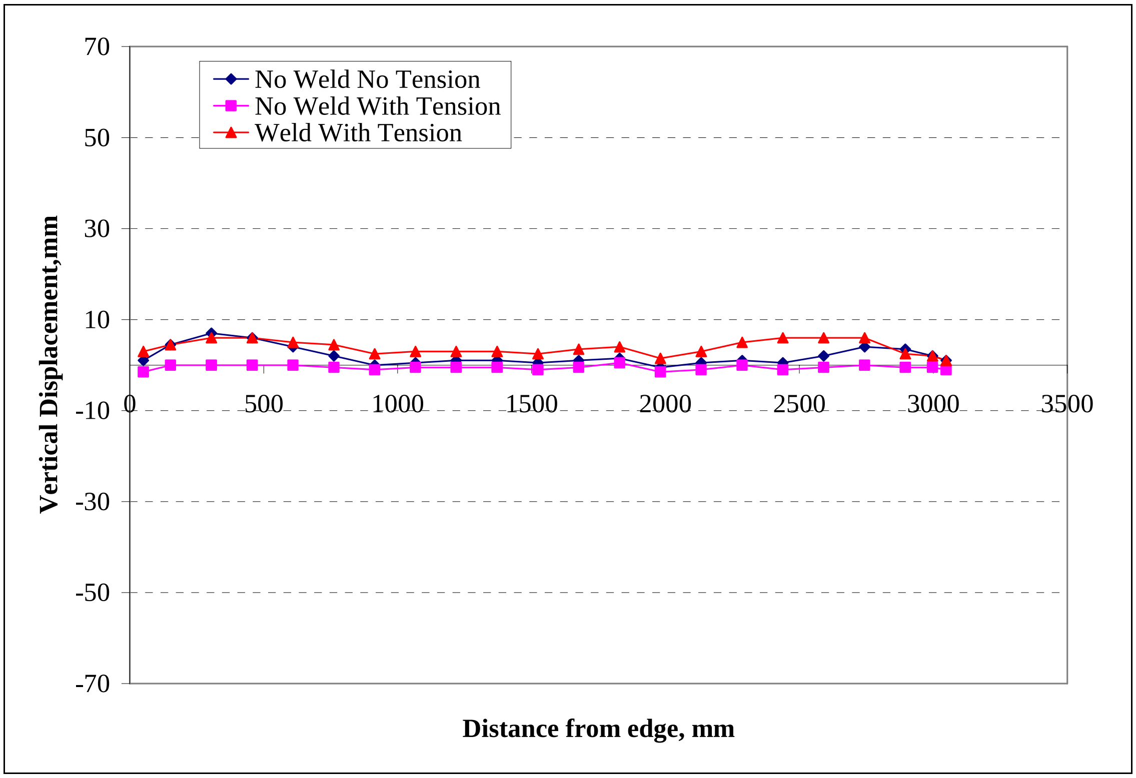


Figure 4.16: Net Displacement along Longitudinal Section F for Plate 4-Side1

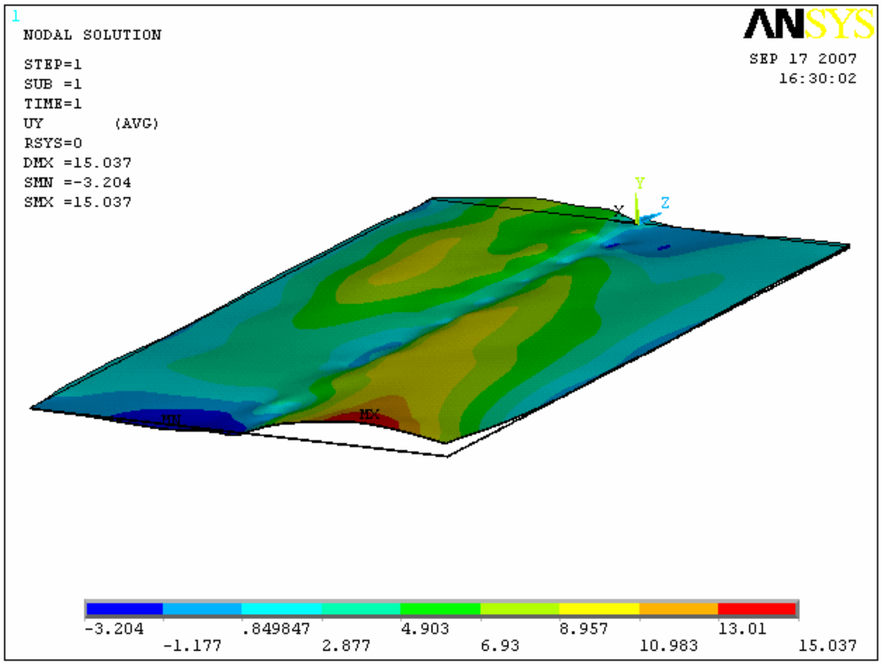


Figure 4.17: Net Plate Deformation (No Weld No Tension -Weld under Tension)

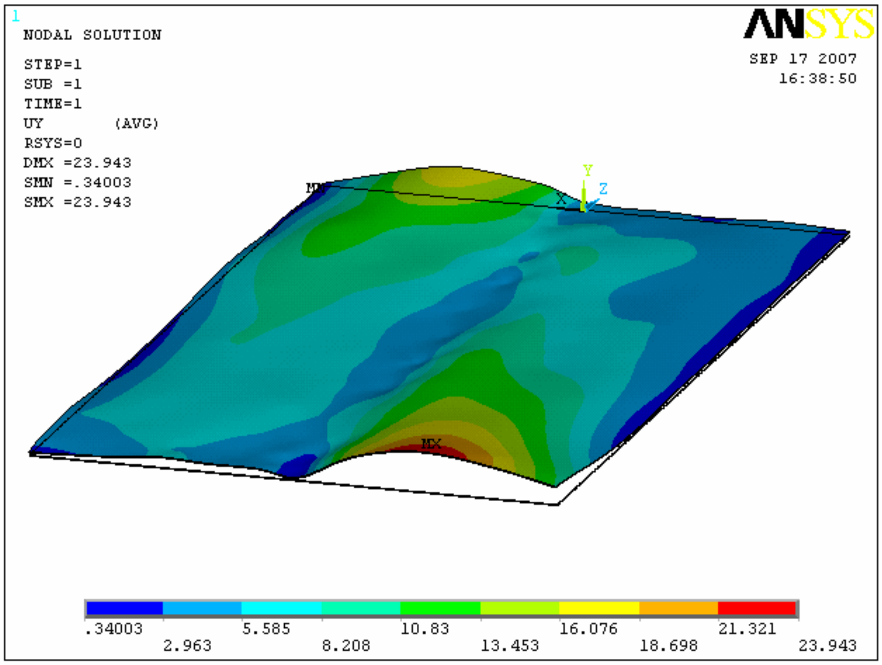


Figure 4.18: Net Plate Deformation after Welding (Tension Case)
(No Weld with Tension-Weld under Tension)

4.3 Volume due to Plate Deformation

The original measured displacement values were offset by value of 10 to account for negative values. Figures 4.19 and 4.20 compare the displacement data before and after offset correction. These offset corrected values are used to calculate the area under the curve.

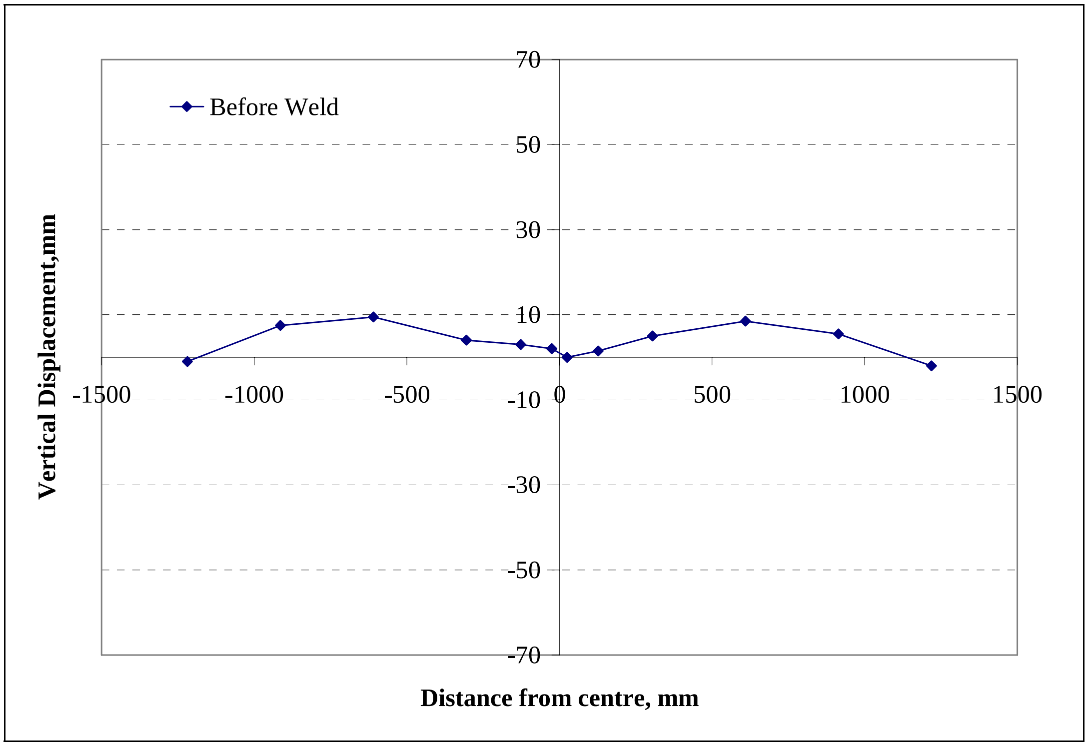


Figure 4.19: Net Displacement along Transverse Section A1 for Plate 6-Side1

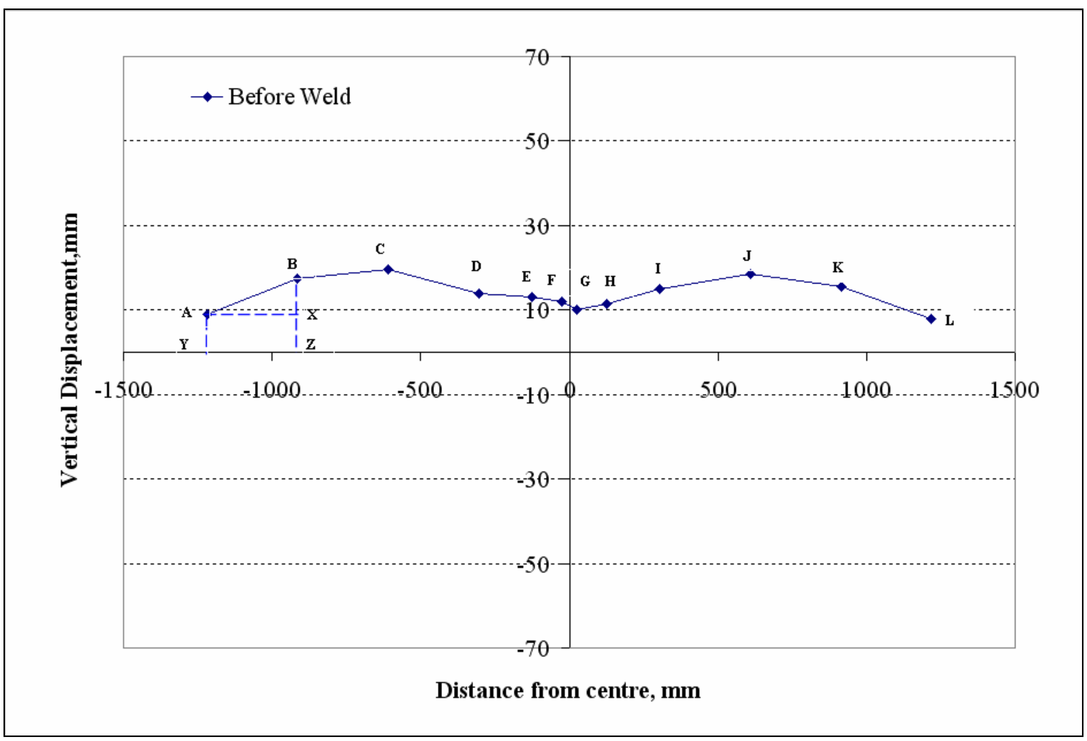


Figure 4.20: Offset Net Displacement along Transverse Section A1 for Plate 6-Side1

The approach used to calculate plate volume due to plate geometry is as follows:

1. Calculate area under each of the segment of the curve (before and after welding)
   Ex: Area segment AB = Area AXZY + Area AXB
2. Total area under the curve AL is summation of areas under segment AB, BC, CD, DE, EF,FG, GH, HI, IJ, JK and KL respectively.
3. Total volume between transverse sections Total area AL times the spacing between transverse sections A1 and A2 gives.
4. Volumes for sections A2 to A22 are calculated using similar approach.
5. Total volume generated due to plate geometry is summation of all transverse sectional volumes.
6. Plate volumes are calculated before and after welding operation.
7. The net change in plate volume is difference in plate volume before and after welding

The results of above approach are illustrated in Figure 4.21.

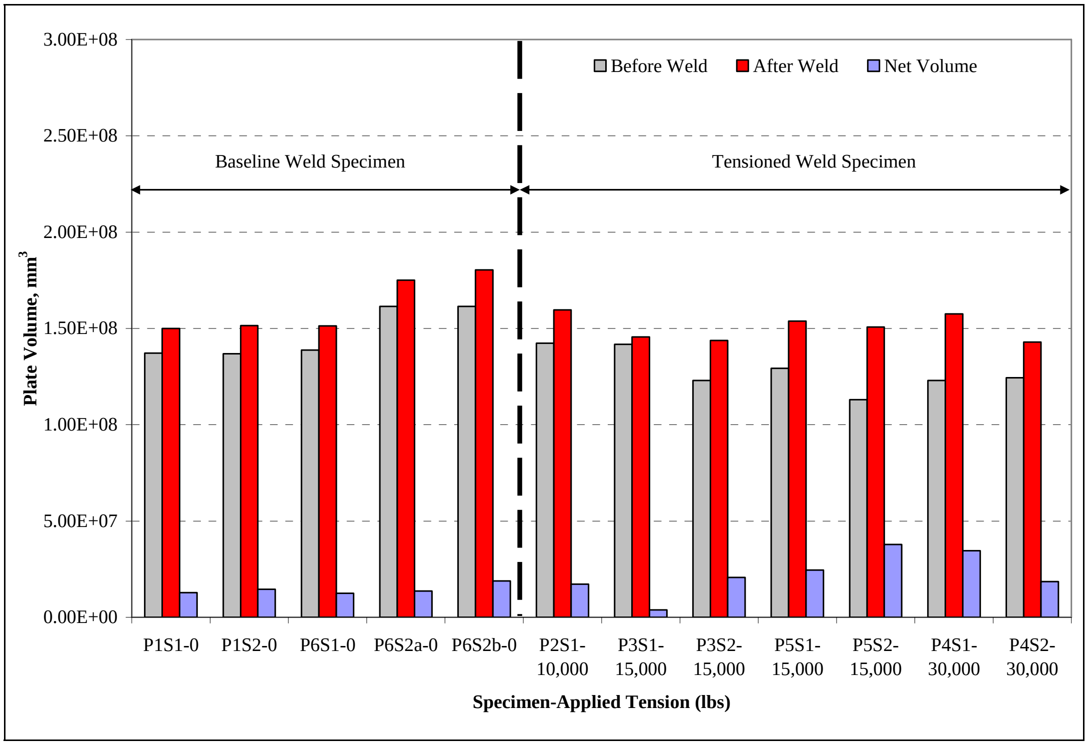


Figure 4.21: Net Plate Volume

It can be seen that the mechanical tensioning approach as applied to groove welding of high strength steel during panel line operation doesn't seem to provide significant advantage to counter deformation, at least within the methods it's applied in this study. The results are not consistent for the benchmark assemblies or for the tension assemblies. Benchmark plate 1 resulted in a similar 'net volume change' (volume after welding subtracted by volume before welding) of distortion for side one and side two. Plate 6 was a repeated benchmark attempt to determine consistency of results and it resulted in a similar first side result with significantly more 'net volume change' of distortion on the second side. Two separate reading were taken from side two as shown in Figure 4.21 to determine whether the ‘net volume change’ distortion results would differ depending on how the plate was buckled; the end results were similar. Plates three and five were performed at 15, 000lbs of tension which was determined to be the best tension profile for this application. Plate three and five show a similar trend in reduction of net displacement after welding compared to net displacement before welding; However, the ‘net volume change’ of displacement on average is greater than with the benchmark procedures. The best comparison for distortion is probably to compare between the net displacement before welding for side one and the net displacement after welding side two. Using this method the plates would rank in this order from least distortion to greatest distortion:

1. Plate 3 (Tension Case)
2. Plate 1 (Non Tension)
3. Plate 4 (Tension Case)
4. Plate 5 (Tension Case)
5. Plate 6 (Non Tension))

Further work with a modified tension set-up where the entire width of the plates is tensioned and length of the plates restrained is proposed for future work. The mechanical tension was effective at straightening the seam to be welding, helping with the fit-up operations.

4.4 FCAW Stiffened Panel Assembly (10” Wide Base Plate) Results

Welding of stiffener assemblies was performed using the STT process and FCAW process and the 10” wide base plates for comparison of tension profiles to the benchmark assembly. CSA 300W base plate was used for this comparison to conserve the 4’ wide primed HSLA 80 base plate for the final testing.

All the stiffened panels (5mm thick) to be welded were marked up as illustrated in Figure 4.22. Panel distortion (vertical displacement) measurements are recorded for points A, B and T along the width and T1 to T23 along the length, using a laser level. For all plates to be welded under mechanical tension, the distortion data is recorded at all three stages:

1. Before welding
2. Before welding under tension
3. After welding

For benchmark stiffener assembly in absence of tension, data is recorded before and after completion of welding. In addition, a similar measurement grid was setup for the test support frame upon which the stiffener assembly to be welded are supported.

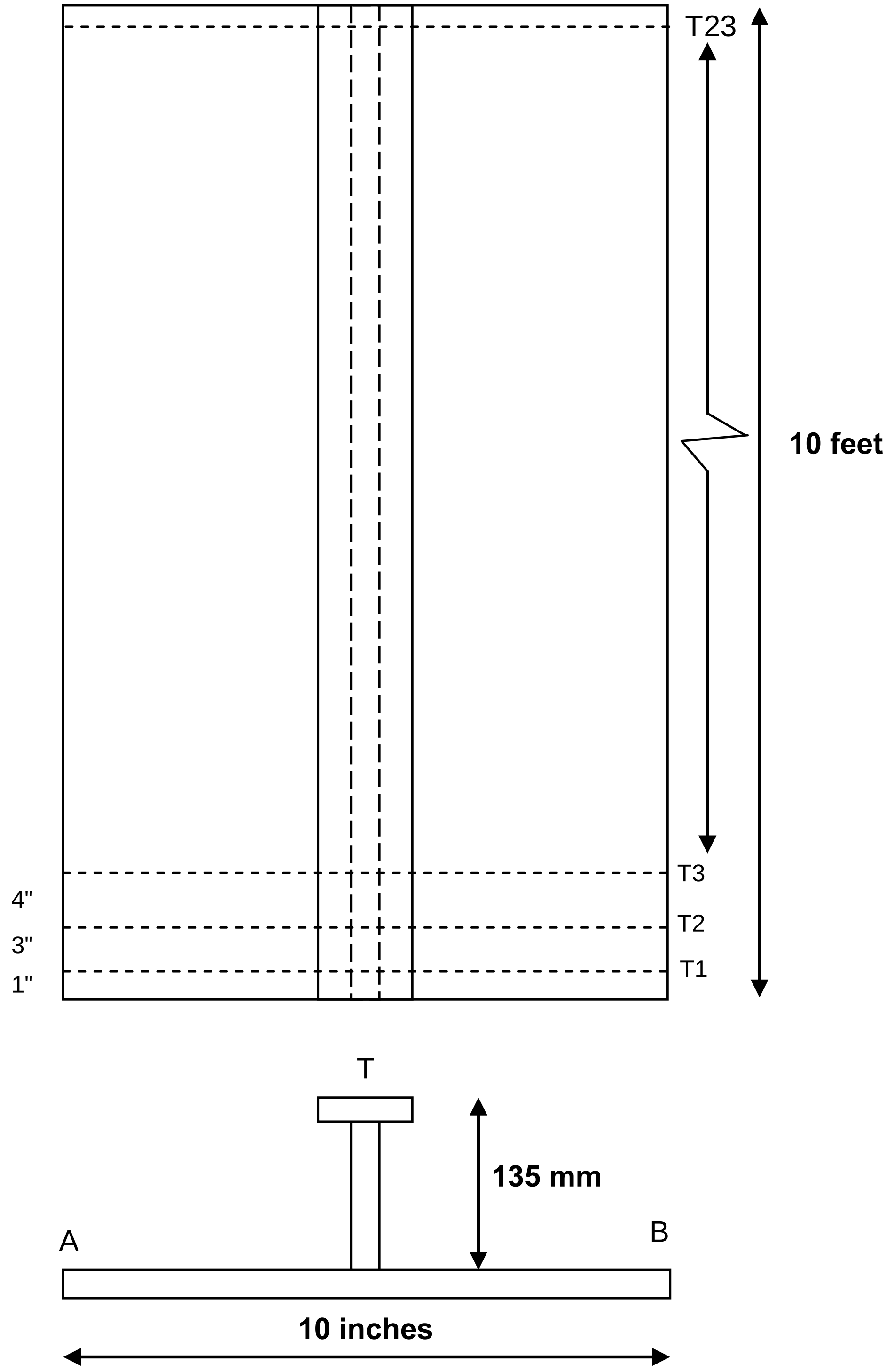


Figure 4.22: Stiffened Panel Distortion Measurement Grid

STT and FCAW techniques were used to set up two benchmark stiffener assemblies. Table 4.2 summarizes the test cases that were analyzed. Tables 4.3 through 4.5 summarize the measured distortion data for stiffener assemblies at locations A and B. The data is color-coded red and yellow to help better visualize the assembly distortion (torsion). The color red indicates a higher distortion compared to color yellow, whereas light green indicates no change in displacement. Additional test data is provided in **Appendix B.**

Table 4.2: Test Summary

Stiffener Assembly	Applied Tension (lbs)
STT_Stiff_1_Benchmark	0
FCAW_Stiff_1_Benchmark	0
FCAW_Stiff_2	10,000
FCAW_Stiff_3-worst case	10,000
FCAW_Stiff_4	10,000

Table 4.3: STT_Stiff_1_Benchmark Distortion Data

Before Weld					After Weld				
Displacement w.r.t to Frame, mm					Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff		A	T	B	Abs Diff
1	9	67	6.5	2.5	1	6.5	65.5	5	1.5
2	8.5	66.5	6	2.5	2	6.5	65	5	1.5
3	6.5	65	4.5	2	3	5.5	64	3.5	2
4	6	63.5	4	2	4	5.5	63	4	1.5
5	5	62	3	2	5	5	61.25	3.5	1.5
6	3.5	60.5	1.5	2	6	3.5	59.5	2.5	1
7	2.5	59.25	0.5	2	7	3	58.5	2	1
8	2	58	0.5	1.5	8	2.5	57.5	1.5	1
9	1.5	56.75	0.5	1	9	2	56.5	2	0
10	0	55.5	0	0	10	1.5	55.5	1.5	0
11	1	55.25	0	1	11	2	55.5	1.5	0.5
12	1	55	0.5	0.5	12	2.5	55.5	2	0.5
13	1.5	54.5	0.5	1	13	2.5	55	2	0.5
14	1	54	0.5	0.5	14	2	54.5	2	0
15	1.5	54.25	0.5	1	15	2.5	54.75	2.5	0
16	2.5	54.5	1.5	1	16	3.5	55	3	0.5
17	3	55	1.5	1.5	17	4	55.25	3	1
18	3.5	55.5	2.5	1	18	4.5	55.5	4	0.5
19	5.5	56.5	3.5	2	19	5.5	56.25	5	0.5
20	6.5	57.5	5	1.5	20	6.5	57	6	0.5
21	8	58.5	6	2	21	6.5	57.5	6	0.5
22	9	59	7	2	22	6.5	58	6.5	0
23	10	59.5	8	2	23	7.5	58.5	7.5	0

Table 4.4: FCAW_Stiff_1_Benchmark Distortion Data

	Before Weld				After Weld			
	Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff	A	T	B	Abs Diff
1	7	55	9.5	2.5	3.5	53	9	5.5
2	6.5	55	9	2.5	3	53	8.5	5.5
3	5	54	7.5	2.5	2.5	52.25	7	4.5
4	4.5	53	6.5	2	2	51.5	6.5	4.5
5	3.5	51.75	5.5	2	2	50.5	5.5	3.5
6	2.5	50.5	3.5	1	2	49.5	4	2
7	2	50	3	1	2	49.25	3.5	1.5
8	1.5	49.5	2	0.5	2	49	3	1
9	1.5	49	1.5	0	2	48.75	2.5	0.5
10	0.5	48.5	0.5	0	2	48.5	2	0
11	1	49	1	0	2.5	49	2	0.5
12	1.5	49.5	1.5	0	3	49.5	2.5	0.5
13	1.5	49.5	1.5	0	3	49.5	2.5	0.5
14	1	49.5	1.5	0.5	2.5	49.5	2	0.5
15	2	50.5	2	0	3	50.25	2.5	0.5
16	2.5	51.5	3	0.5	3	51	3	0
17	3	52.5	3.5	0.5	3	51.5	3.5	0.5
18	3.5	53.5	5	1.5	3.5	52	4.5	1
19	5	55	6	1	4.5	53	5	0.5
20	6.5	56.5	7.5	1	4.5	54	6	1.5
21	7.5	58	8.5	1	3.5	54.5	5	1.5
22	8	58.75	9	1	4.5	55	5	0.5
23	8.5	59.5	9.5	1	5	55.5	5.5	0.5

Table 4.5: FCAW_Stiff_2 Distortion Data

	Before Weld				Tension No Weld				After Weld			
	Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff	A	T	B	Abs Diff	A	T	B	Abs Diff
1	10	57.5	10	0	5	54.5	4	1	3	52.5	2.5	0.5
2	9	57	8	1	5	54.5	4	1	3	52.5	2.5	0.5
3	7	56.25	6.5	0.5	4	53.5	3	1	2	51.5	1.5	0.5
4	6.5	55.5	5.5	1	4.5	52.5	3	1.5	3	50.5	2.5	0.5
5	5	54	4.5	0.5	3.5	51.25	2	1.5	2.5	49.75	2	0.5
6	4	52.5	3	1	2	50	0.5	1.5	1.5	49	1	0.5
7	3	51.5	2	1	1	49.5	0	1	1.5	48.75	1	0.5
8	2	50.5	1.5	0.5	0.5	49	0	0.5	1.5	48.5	1	0.5
9	1.5	50	1	0.5	0	48.5	0	0	1.5	48.5	1	0.5
10	1	49.5	0.5	0.5	0	48	0	0	1.5	48.5	1	0.5
11	1.5	50	0.5	1	0.5	48.75	0	0.5	1.5	49	1	0.5
12	1.5	50.5	0.5	1	0.5	49.5	0	0.5	2	49.5	1.5	0.5
13	2	50.5	1	1	1	49.25	0	1	2	49.75	1.5	0.5
14	1.5	50.5	1	0.5	0.5	49	0	0.5	2	50	1	1
15	2	51.25	1	1	1	50.25	0	1	2.5	50.5	2	0.5
16	2	52	1.5	0.5	1	51.5	0	1	2.5	51	2	0.5
17	2.5	52.75	1.5	1	1	51.75	0.5	0.5	2.5	51.5	2	0.5
18	4	53.5	2.5	1.5	2.5	52	1.5	1	3.5	52	2.5	1
19	5.5	54.75	3	2.5	3.5	53.75	2.5	1	5	53	3.5	1.5
20	7	56	4.5	2.5	4.5	55.5	3.5	1	5	54	3.5	1.5
21	8	58	4.5	3.5	2.5	56	2	0.5	3	56	1.5	1.5
22	8.5	58.5	6	2.5	2.5	57	2	0.5	3	56.25	1.5	1.5
23	9.5	59	7	2.5	2.5	58	2	0.5	3	56.5	1.5	1.5

Figures 4.23 through 4.26 illustrate the net displacements for two benchmark stiffener assemblies. It can be seen that of the two benchmark stiffener assemblies, net distortion is higher using FCAW technique than STT technique; also these distortions are more prominent along the edges. Therefore it would be more beneficial to use the mechanical tensioning approach in conjunction with FCAW technique to better demonstrate the ability of mechanical tensioning to counter plate distortion.

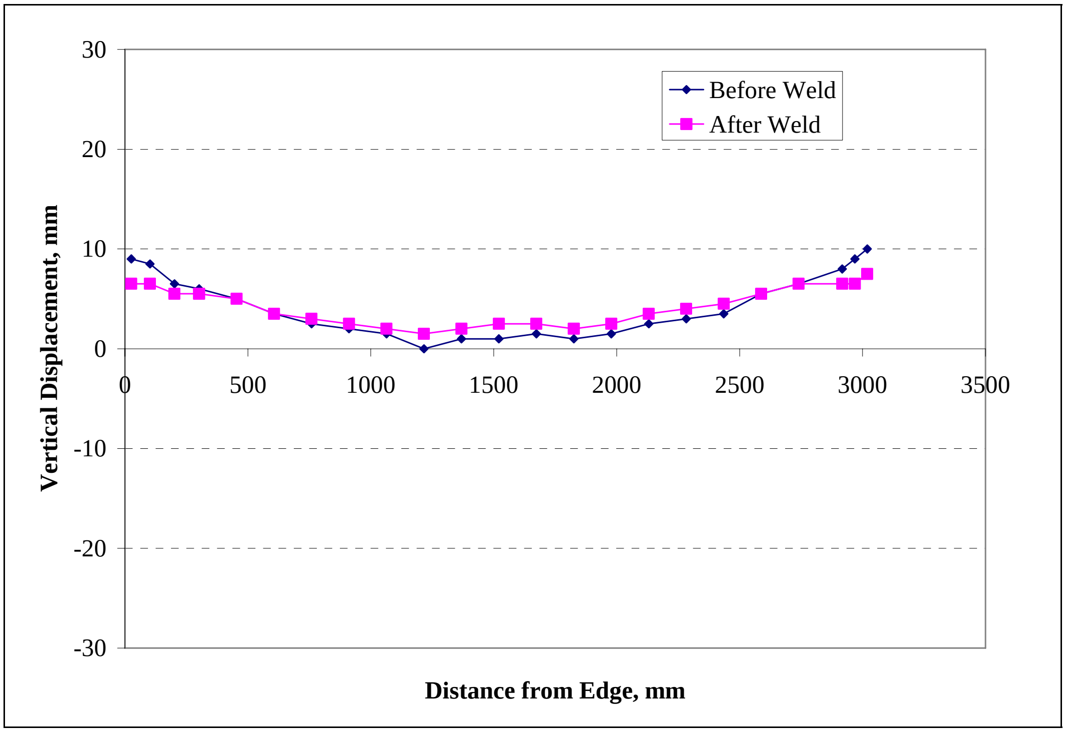


Figure 4.23: Net Displacement along Longitudinal Section A for STT Stiffener Benchmark Assembly

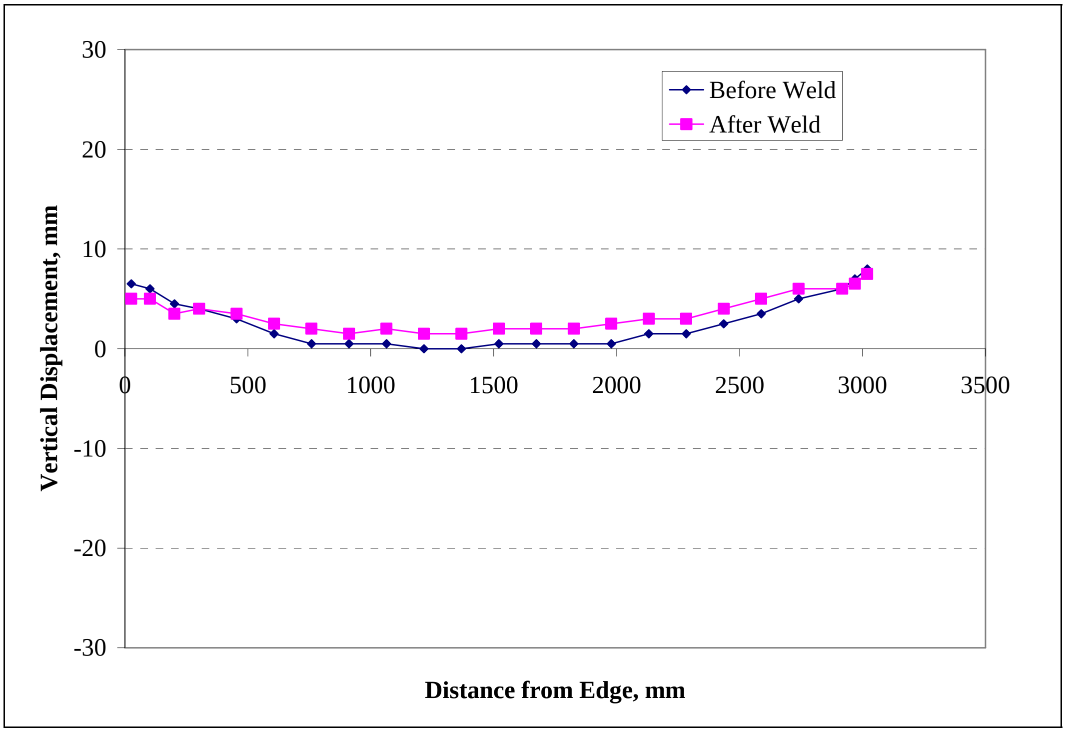


Figure 4.24: Net Displacement along Longitudinal Section B for STT Stiffener Benchmark Assembly

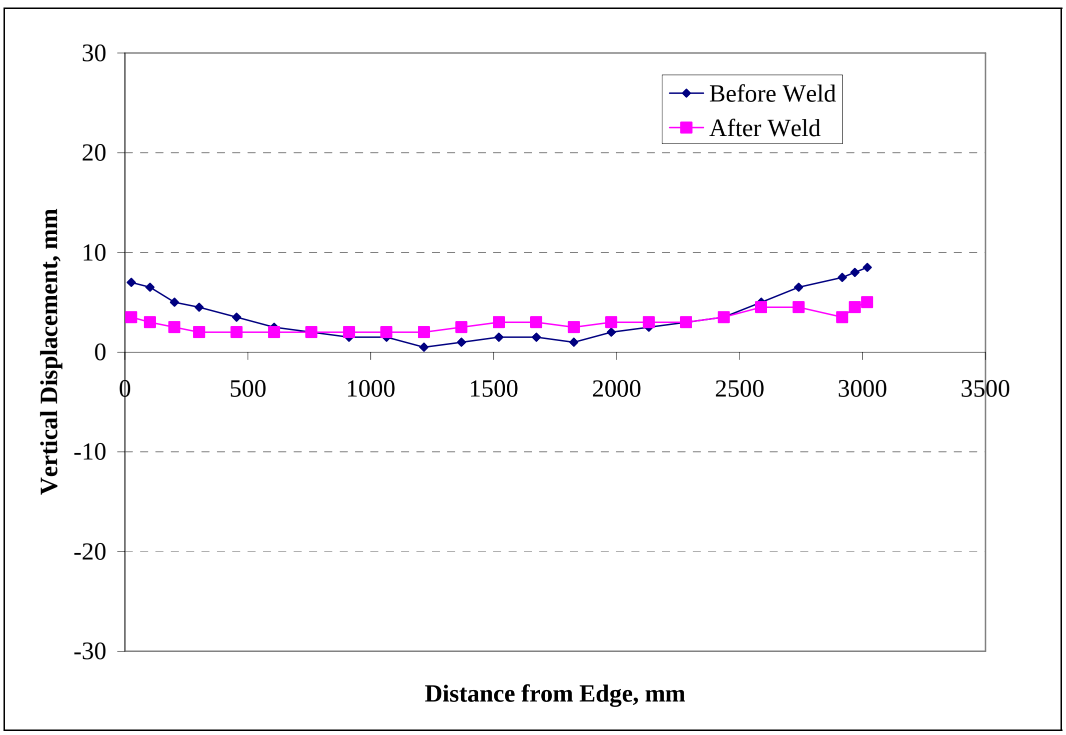


Figure 4.25: Net Displacement along Longitudinal Section A for FCAW Stiffener Benchmark Assembly

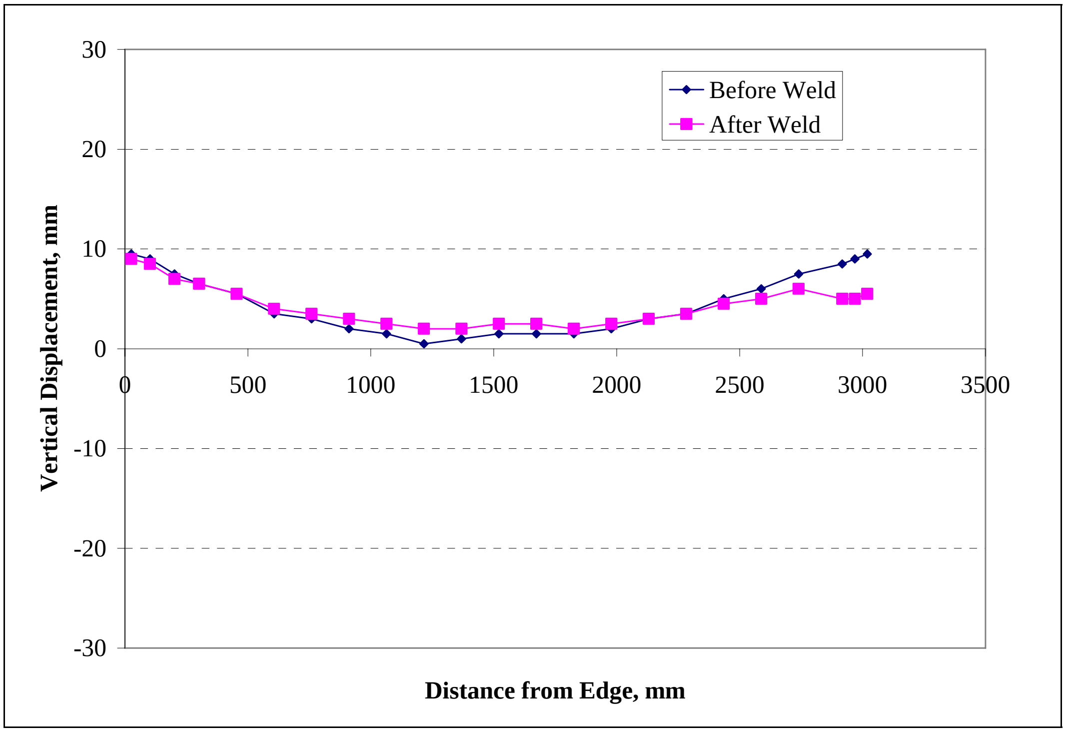
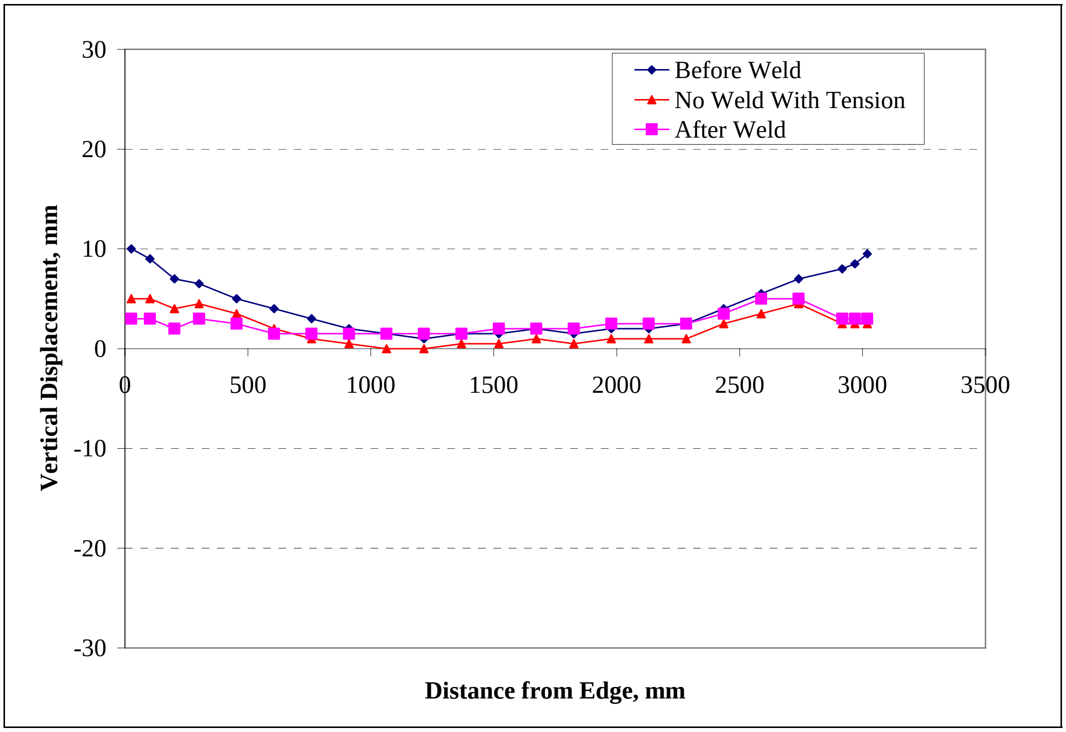


Figure 4.26: Net Displacement along Longitudinal Section B for FCAW Stiffener Benchmark Assembly

In order to measure the effectiveness of mechanical tensioning approach, the net displacement of each marked point on the assembly (Figure 4.22) with respect to the corresponding point on the test frame is compared at each of the above stages. Figures 4.27 and 4.28 compare the net displacement along the longitudinal sections for FCAW Stiffener Assembly subjected to a tension load of 10,000 lbs. additional plots are provided in **Appendix B.**



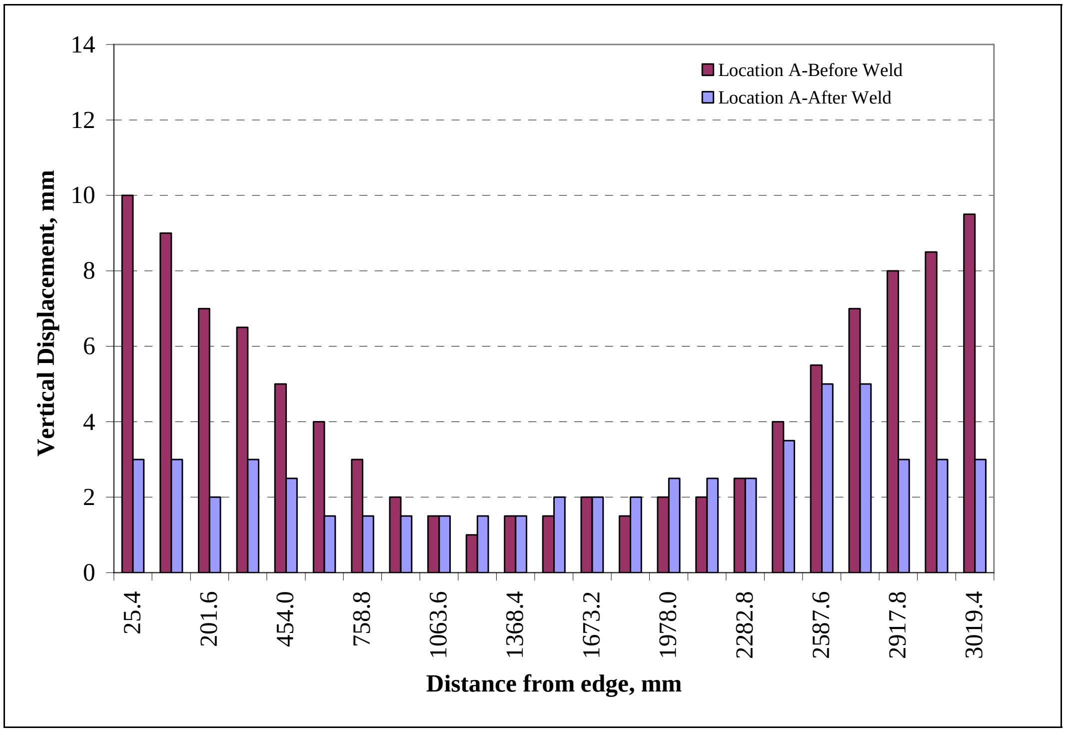
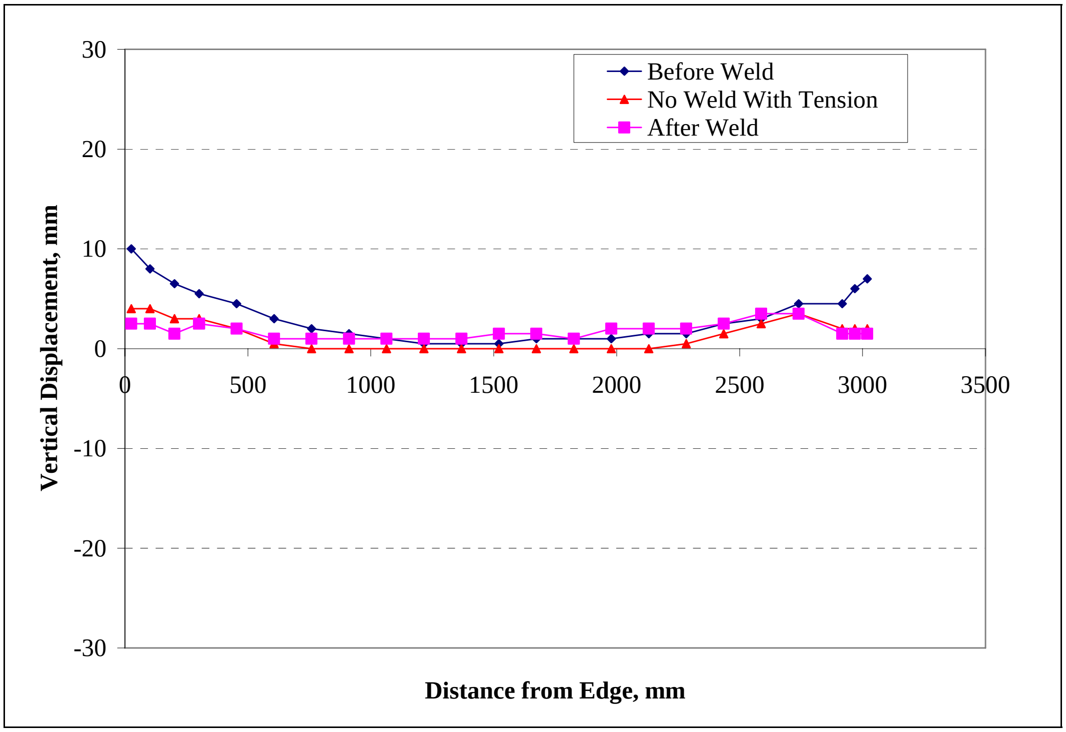


Figure 4.27: Net Displacement along Longitudinal Section A for FCAW Stiffener Assembly 2.



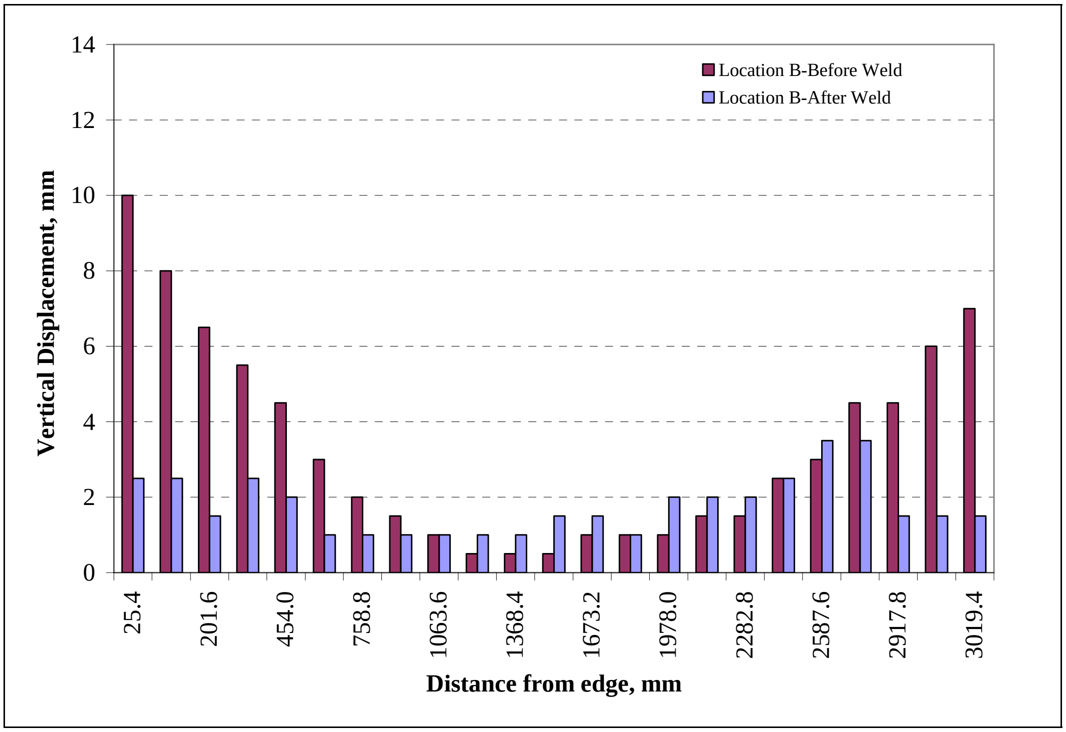


Figure 4.28: Net Displacement along Longitudinal Section B for FCAW Stiffener Assembly 2

4.4.1 Net Improvement

The distortion data in Table 4.6 and Figures 4.29 through 4.31 compare the overall net improvement achieved in controlling distortion under applied tension with respect to the benchmark assembly. The negative values, color coded blue indicates location where tensioning has been effective to counter distortion due to welding. Also cells color coded light green indicate no change in distortion and yellow indicates a marginal increases in distortion. Additional plots and tables are provided in **Appendix B.**

Table 4.6: FCAW_Stiff_2 Net Displacement

Net Displacement, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	-7	-5	-7.5	0.5
2	-6	-4.5	-5.5	0.5
3	-5	-4.75	-5	0
4	-3.5	-5	-3	0.5
5	-2.5	-4.25	-2.5	0
6	-2.5	-3.5	-2	0.5
7	-1.5	-2.75	-1	0.5
8	-0.5	-2	-0.5	0
9	0	-1.5	0	0
10	0.5	-1	0.5	0
11	0	-1	0.5	0.5
12	0.5	-1	1	0.5
13	0	-0.75	0.5	0.5
14	0.5	-0.5	0	0.5
15	0.5	-0.75	1	0.5
16	0.5	-1	0.5	0
17	0	-1.25	0.5	0.5
18	-0.5	-1.5	0	0.5
19	-0.5	-1.75	0.5	1
20	-2	-2	-1	1
21	-5	-2	-3	2
22	-5.5	-2.25	-4.5	1
23	-6.5	-2.5	-5.5	1

Net Displacement, mm				
Benchmark				
	A	T	B	Abs Diff
1	-3.5	-2	-0.5	3
2	-3.5	-2	-0.5	3
3	-2.5	-1.75	-0.5	2
4	-2.5	-1.5	0	2.5
5	-1.5	-1.25	0	1.5
6	-0.5	-1	0.5	1
7	0	-0.75	0.5	0.5
8	0.5	-0.5	1	0.5
9	0.5	-0.25	1	0.5
10	1.5	0	1.5	0
11	1.5	0	1	0.5
12	1.5	0	1	0.5
13	1.5	0	1	0.5
14	1.5	0	0.5	1
15	1	-0.25	0.5	0.5
16	0.5	-0.5	0	0.5
17	0	-1	0	0
18	0	-1.5	-0.5	0.5
19	-0.5	-2	-1	0.5
20	-2	-2.5	-1.5	0.5
21	-4	-3.5	-3.5	0.5
22	-3.5	-3.75	-4	0.5
23	-3.5	-4	-4	0.5

Net Improvement, mm		
Benchmark		
-3.5	-3	-7
-2.5	-2.5	-5
-2.5	-3	-4.5
-1	-3.5	-3
-1	-3	-2.5
-2	-2.5	-2.5
-1.5	-2	-1.5
-1	-1.5	-1.5
-0.5	-1.25	-1
-1	-1	-1
-1.5	-1	-0.5
-1	-1	0
-1.5	-0.75	-0.5
-1	-0.5	-0.5
-0.5	-0.5	0.5
0	-0.5	0.5
0	-0.25	0.5
-0.5	0	0.5
0	0.25	1.5
0	0.5	0.5
-1	1.5	0.5
-2	1.5	-0.5
-3	1.5	-1.5

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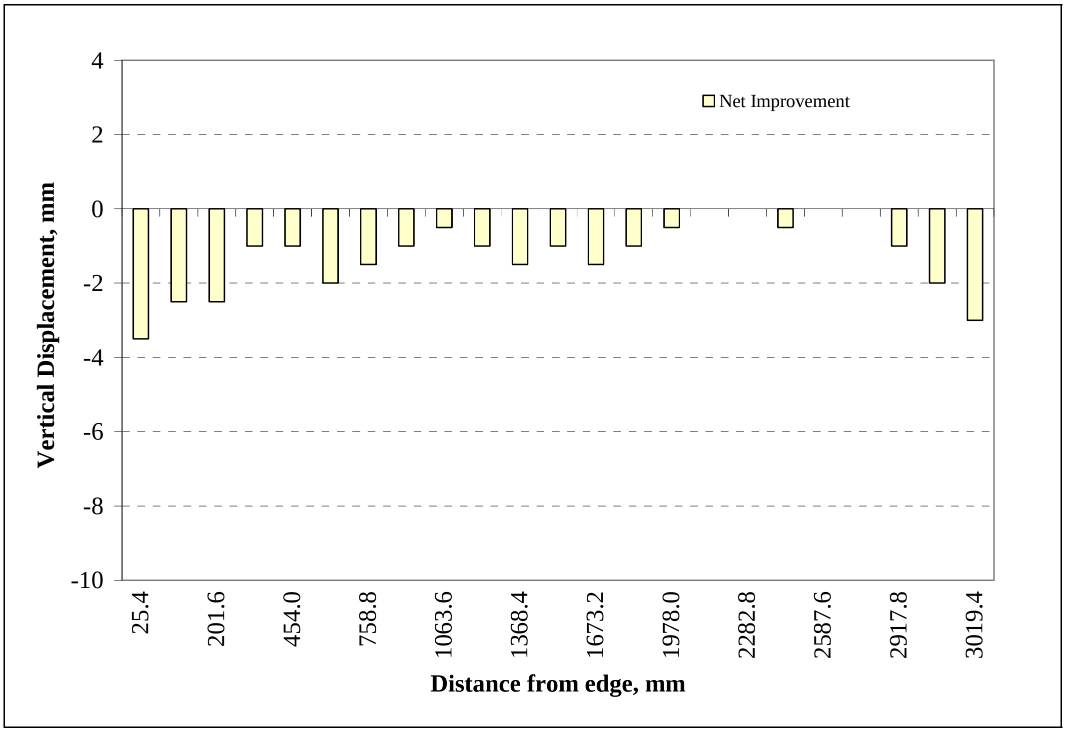


Figure 4.29: FCAW_Stiff_2 -Net Improvement at Location A.

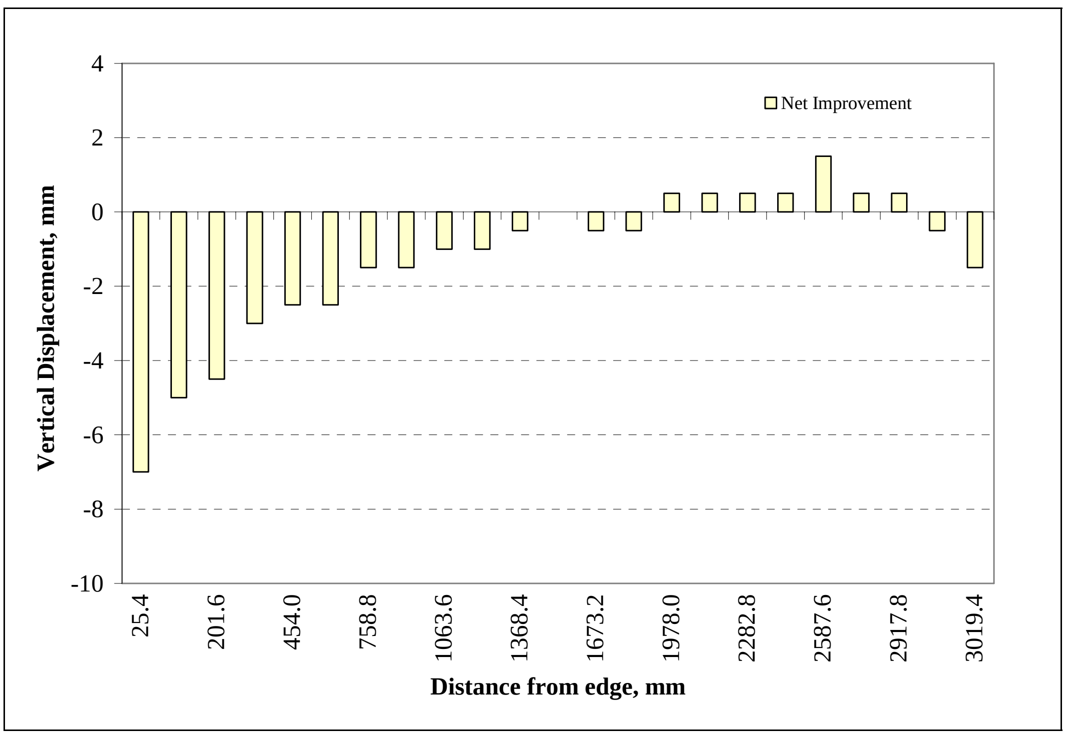


Figure 4.30: FCAW_Stiff_2 -Net Improvement at Location B.

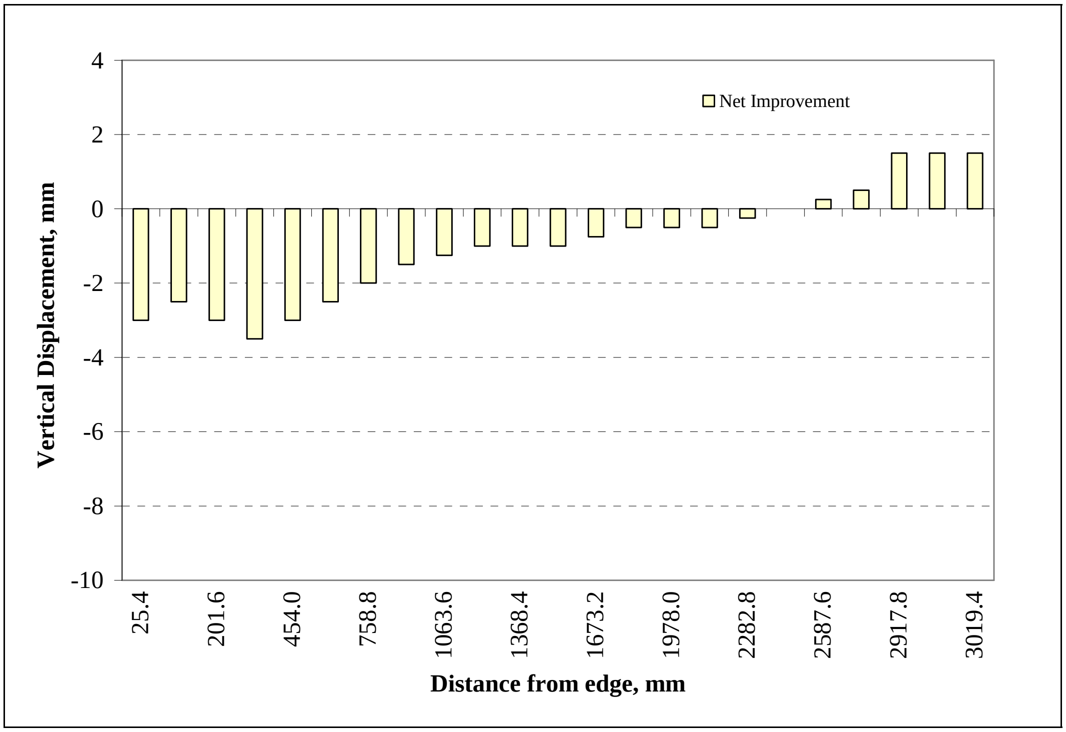


Figure 4.31: FCAW_Stiff_2 -Net Improvement at Location T

From the data presented it can be concluded that the mechanical tensioning approach as applied to fillet welding of high strength steel stiffener assemblies does provide significant advantage to counter deformation. Figures 4.29 through 4.31 demonstrate this with the majority of values showing as negative vertical displacement, negative is a positive effect on reducing distortion. Table 4.6 also shows the effect of mechanical tensioning on distortion with the blue indicating locations where tensioning has been effective to counter distortion due to welding. Comparing the net displacements for FCAW_Stiff_2 (10,000lbs tension) vs. FCAW Stiff_1 (Benchhmark), a reduction in distortion of 144% results from the use of mechanical tensioning.

In summary, mechanical tensioning of plate assemblies did not result in a significant reduction in distortion, with results inconsistent to one another. The mechanical tensioning of stiffener assemblies resulted in a significant reduction in distortion on the stiffened panel assemblies, with clear and repeatable results.

The results of mechanical tensioning of aluminum stiffener assemblies are discussed in Task 4.

5. TASK 3: DEVELOP OPTIMIZED WELDING PROCEDURE AND GUIDELINES FOR CONTROLLED DIP TRANSFER WELDING OF STEEL STRUCTURES

5.1 Surface Tension Transfer

This report provides the results on the independent evaluation of the surface tension transfer (STT) process conducted at BMT Fleet Technology for the application of distortion control on thin panel high strength fillet welds used in light weight combatants. The objective in this task was to determine the operating limitations of the process as well as provide guidance on its potential use in regular production.

STT is a modified short circuit transfer (also known as controlled dip transfer) using inverter power source technology with waveform control to provide a better welding solution than traditional short circuiting GMAW. Unlike conventional GMAW power sources, the STT power source does not use a voltage control knob. Current controls are used to adjust the heat independent of the wire feed speed, so changes in electrode extension do not affect heat. Low heat input welds can therefore be produced without overheating or even burning through thin plate. Distortion is also limited due to the low heat input. Figure 5.1 shows what is happening to the consumable wire at the welding arc at different stages of the waveform. Marinette Marine Corp. (MMC) is currently using this process for some applications and provided data sheets for use as benchmark and reference data. A series of welds were performed using 0.035” diameter wire and 0.045” diameter wire with 100% C02 shielding gas and 75Ar / 25 C02 shielding gas. Welding procedure data sheets and user guidelines have been established for procedures that successfully achieved acceptable penetration profile, acceptable weld profile, acceptable arc stability, and operating characteristics. The power source used was a Lincoln Powerwave 455 with pre-loaded software. Wavedesigner 2000 software can be used to modify waveforms in an effort to optimize them for specific applications. There is limited support available for wavedesigner software through Lincoln Electric, and efforts to modify the waveform did not result in improved arc characteristics. For this reason, the preloaded software was used with no modification of the waveform other than adjustment to the synergic controls such as trim and arc control. It is possible that other Lincoln STT power sources such as the Lincoln Invertec STT II (used by MMC) will allow for further fine tuning of the waveform or even broader parameter range, however this is an assumption and such procedures shall be evaluated and qualified prior to use with alternative power sources. The welding procedure data sheets may need to be adjusted as well for synergic controls if used on other types of controlled dip transfer power supplies, such as with Miller Electric’s Regulated Metal Deposition (RMD) technology.

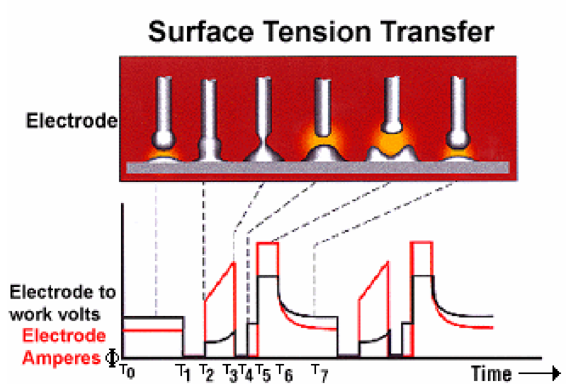


Figure 5.1: Lincoln STT Process

Table 5.1 shows the various wire/gas and program combinations evaluated with the STT process. The ranking system takes into account operating characteristics of the arc and resulting bead profile. A five star ranking is the best and a one star ranking is the worst. The current MMC procedure uses 0.035” diameter wire with CO2 shielding gas to produce a 1/8” fillet weld size on 3/8” thick plate. This is an unlikely weld size to achieve with STT transfer and maintain adequate penetration and fusion. The STT transfer is recommended for fillet welds on material thickness up to 3/16.” All procedure development welding was performed on 5mm plate thickness (slightly greater than 3/16”). The wire feed speeds shown are optimal for the wire size and achieving acceptable arc characteristics and weld profile for producing a 1/8” fillet weld. Of all the combinations experimented with, Sample ID #9 with 0.045” diameter wire, C25 (75Ar / 25C02) shielding gas, and program 118 resulted in the greatest flexibility with wire feed speeds ranging from 125 to 175 inches per minute. Acceptable operating characteristics and weld profiles were achieved with both wire diameters; however, the penetration profile of the welds performed with the 0.045” diameter wire exhibited better penetration and fusion. Both five star ranking welds (C02 and C25 shielding gas) for the 0.045” diameter wires resulted in good penetration and fusion, with good bead profile. The only five star ranking weld with the 0.035” diameter wire resulted in a penetration profile that was not acceptable.

Table 5.1: STT Procedure Development Parameters

WFS (IPM)	Trim	Arc C	Avg. Amps	wire θ	Gas	Program	T.S. (IPM)	Weld Profile	Penetration /Fusion	Weld Size	Sample ID#	Ranking* (five star)
200	0.8	7.5	100	0.035	C02	111				1/8		***
200	0.7	7.5	100	0.035	C02	131	10.9	Good	Acceptable	1/8	2	****
200	0.7	7.5	100	0.035	C02	127	9.9	Good	Not acceptable	1/8	1	*****
200	0.8	6	110	0.035	C25	112	N/A	Not Desirable	N/A	1/8		**
200	1.4	9	118	0.035	C25	131	9.9	Convex	Not acceptable	1/8	4	***
200	1.5	9.5	118	0.035	C25	127	10.3	Good	Minimal	1/8	3	****
125	1.4	7.5	135	0.045	C02	117	13.8	Good	Acceptable	1/8	8	*****
125	1.18	8.5	130	0.045	C02	129	11.5	Not Desirable	Acceptable	1/8	7	**
125	1.25	5	135	0.045	C02	133	11.6	Good	Acceptable	1/8	6	****
110	1.15	5	120	0.045	C02	133	10	Good	Acceptable	1/8 +	5	****
125	1.4	7.5	135	0.045	C25	118	13.8	Good	Acceptable	1/8 +	9	*****
150	1.4	7.5	150	0.045	C25	118	Trial to determine operating range of procedure.					*****
175	1.44	5	175	0.045	C25	118	Trial to determine operating range of procedure.					****
125	1.5	10	140	0.045	C25	133	11.5	Convex	Acceptable	1/8 +	10	**
125	1.5	10	140	0.045	C25	129	13.2	Good	Acceptable	1/8	11	***

Macro sections were extracted from each of the welds deposited with the parameters in Table 5.1, and are shown in Figures 5.2 to 5.12. Specimens 1 and 4 as seen in Figure 5.2 and Figure 5.5 have lack of fusion along the horizontal leg of the fillet. Convexity is apparent for specimens 4, 7, and 10 as seen in Figures 5.2, 5.5 and 5.8. Porosity was not observed in any of the welded test specimens and spatter was minimal. In conclusion, 0.045" diameter consumable wire using C02 or C25 shielding gas appears to be the most suitable choice for welding 1/8" fillet welds on 5mm t-stiffeners. No less than 125IPM of wire feed speed should be used on this procedure to ensure adequate root penetration and sidewall fusion.

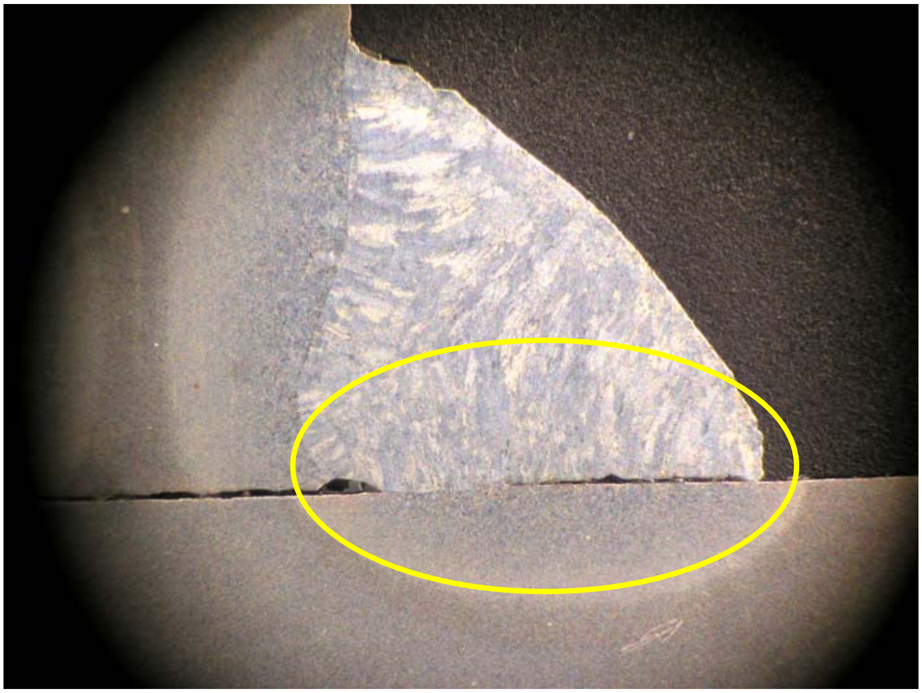


Figure 5.2: Sample ID #1 – 0.035" Dia. Wire, C02 Gas, Program 127

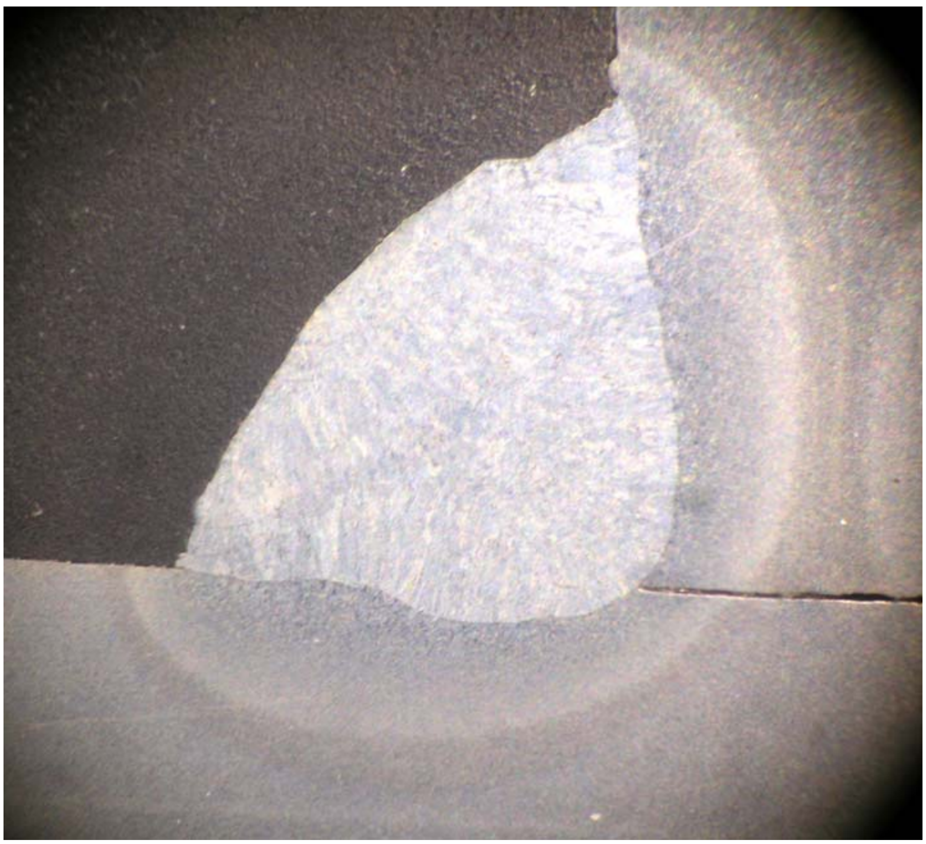


Figure 5.3: Sample ID #2 – 0.035" Dia. Wire, C02 Gas, Program 131

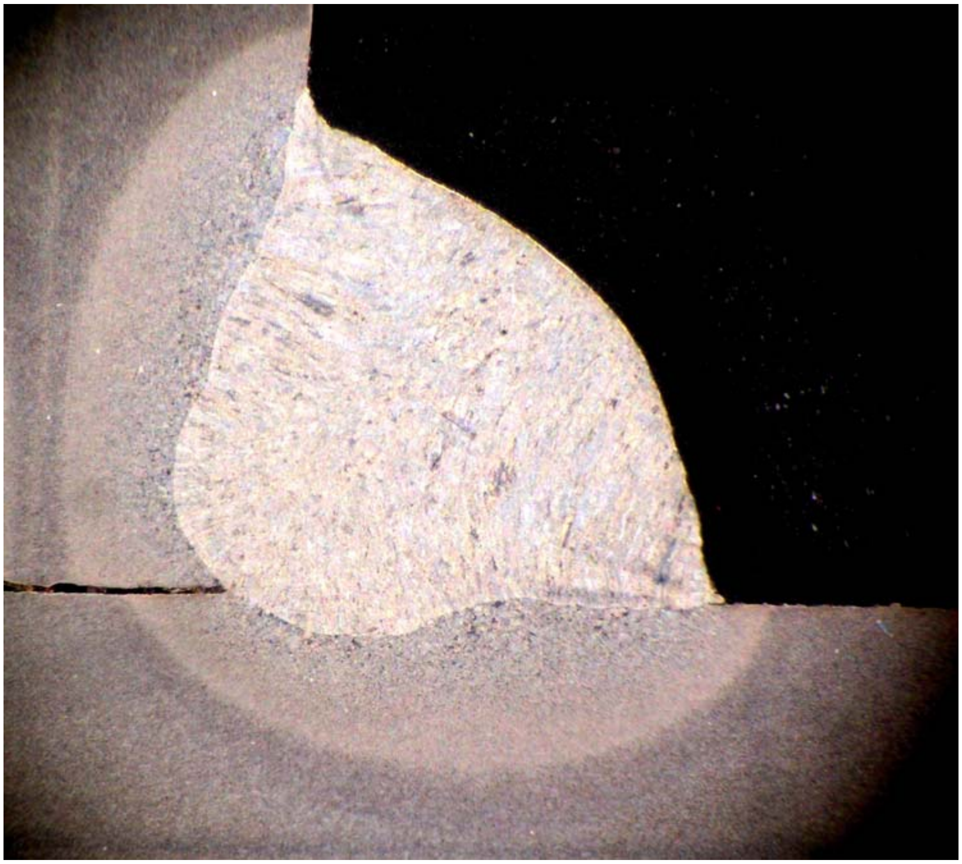


Figure 5.4: Sample ID #3 – 0.035" Dia. Wire, C25 Gas, Program 127

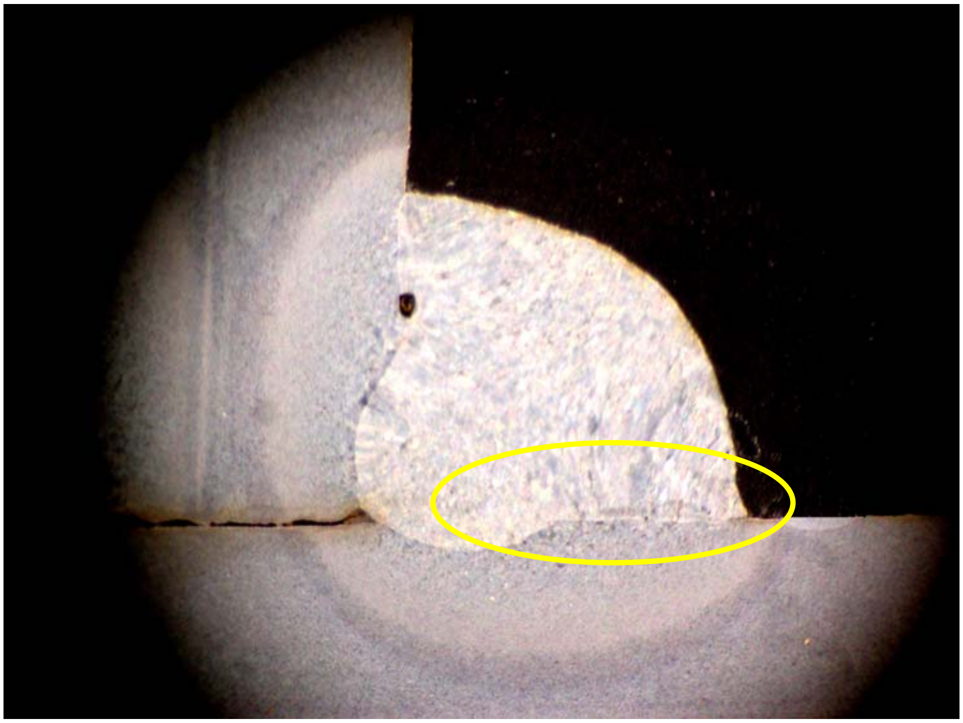


Figure 5.5: Sample ID #4 – 0.035" Dia. Wire, C25 Gas, Program 131

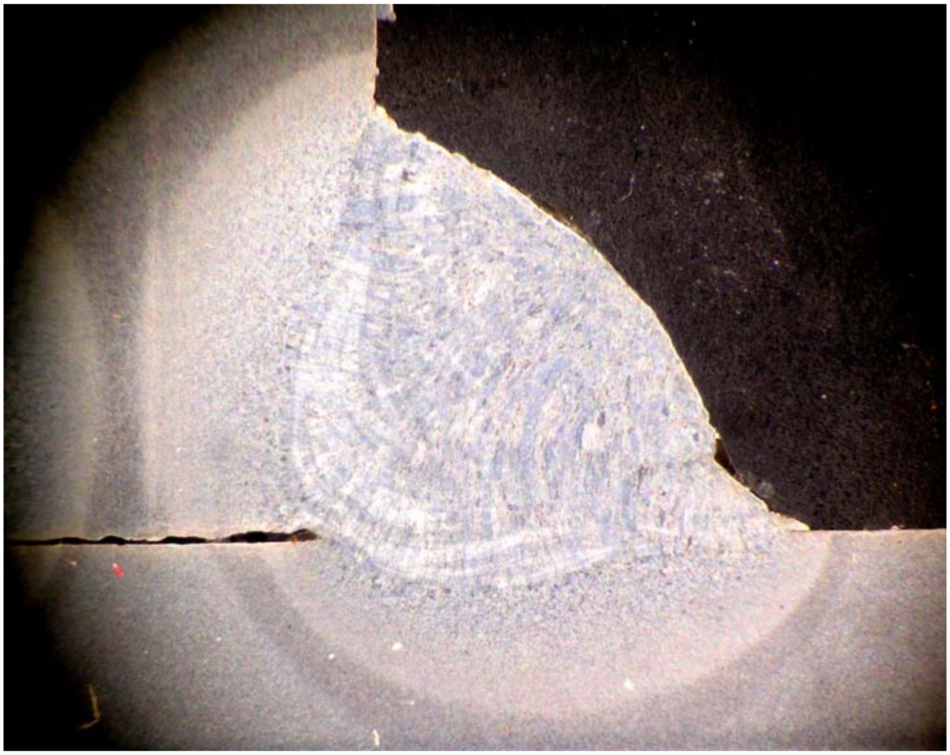


Figure 5.6: Sample ID #5 – 0.045" Dia. Wire, C02 Gas, Program 133

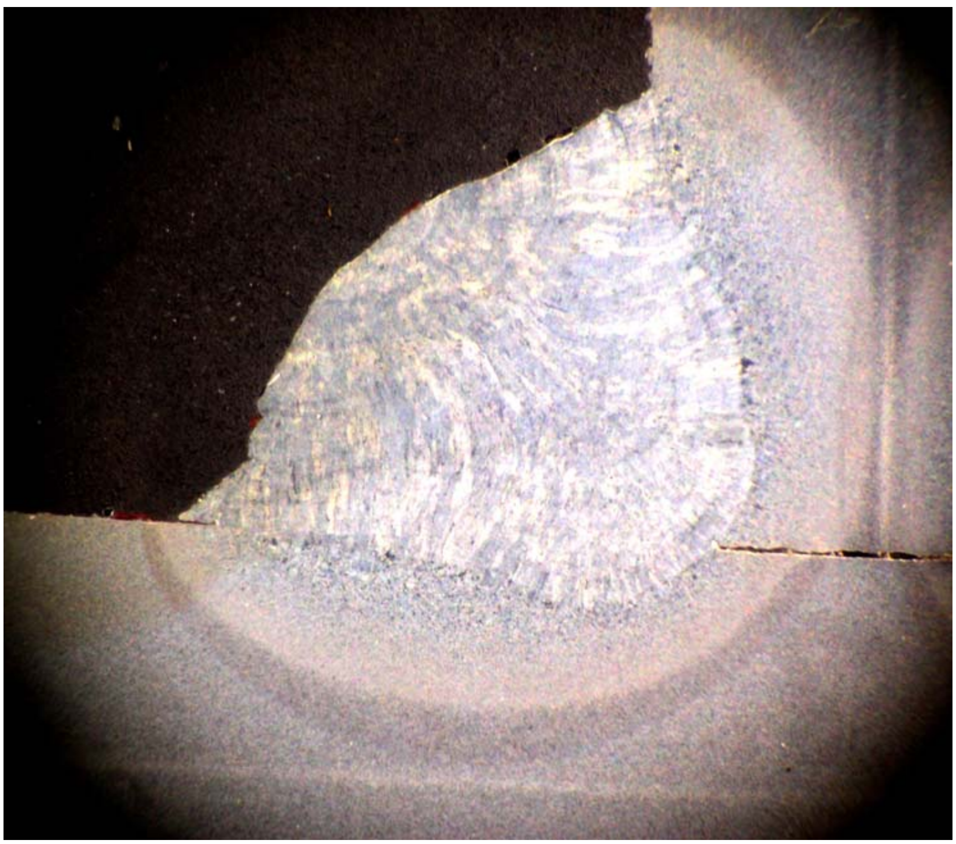


Figure 5.7: Sample ID #6 – 0.045" Dia. Wire, C02 Gas, Program 133

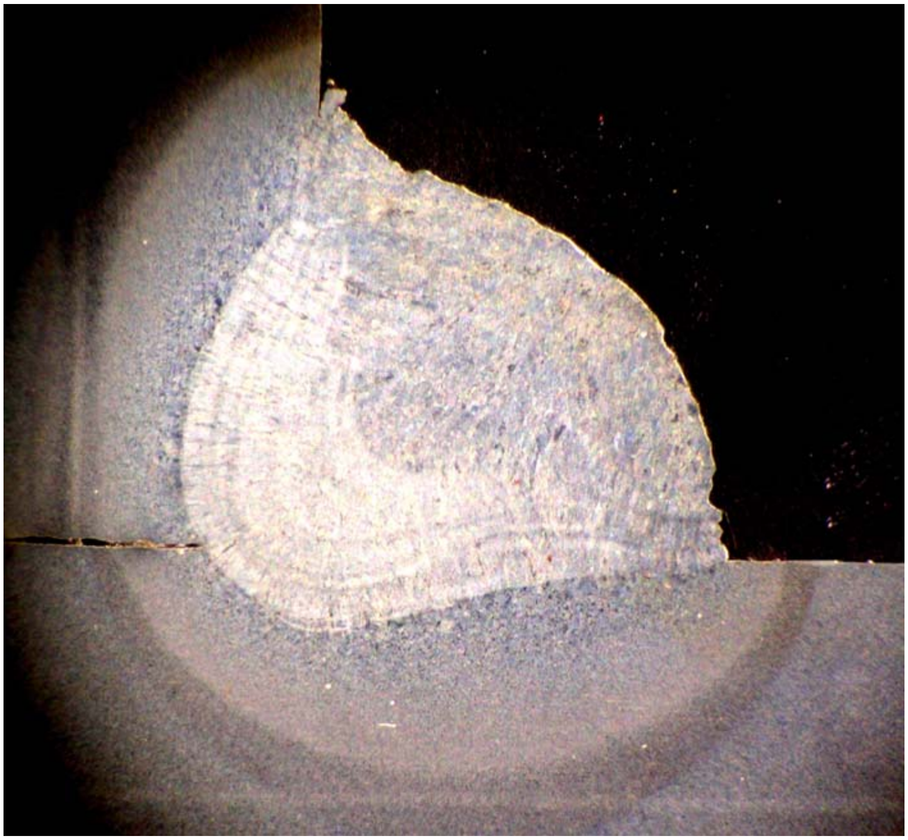


Figure 5.8: Sample ID #7 – 0.045" Dia. Wire, C02 Gas, Program 129

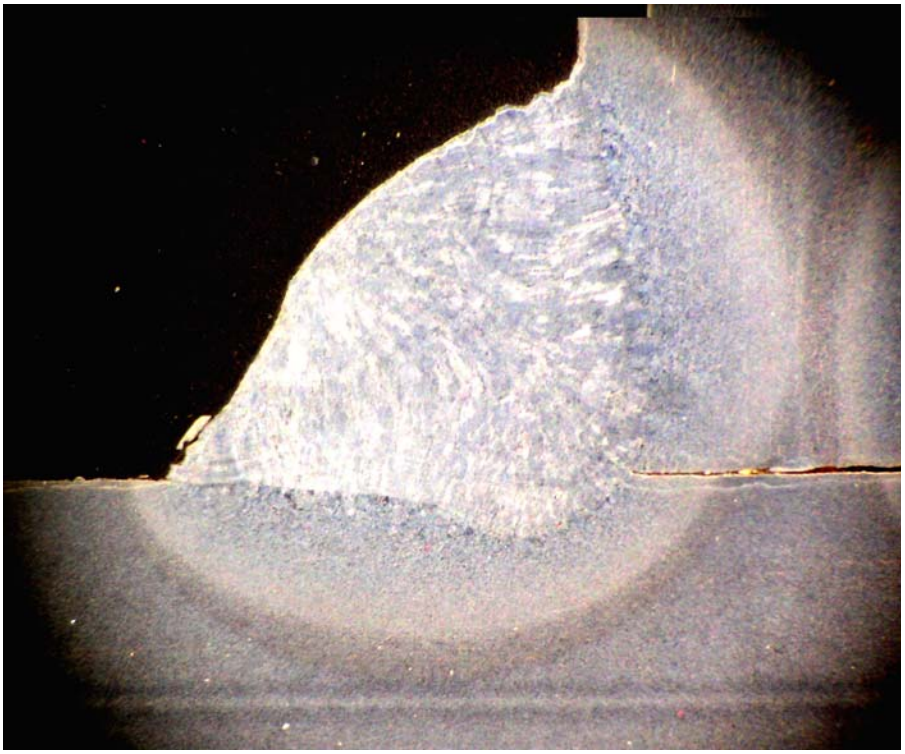


Figure 5.9: Sample ID #8 – 0.045" Dia. Wire, C02 Gas, Program 117

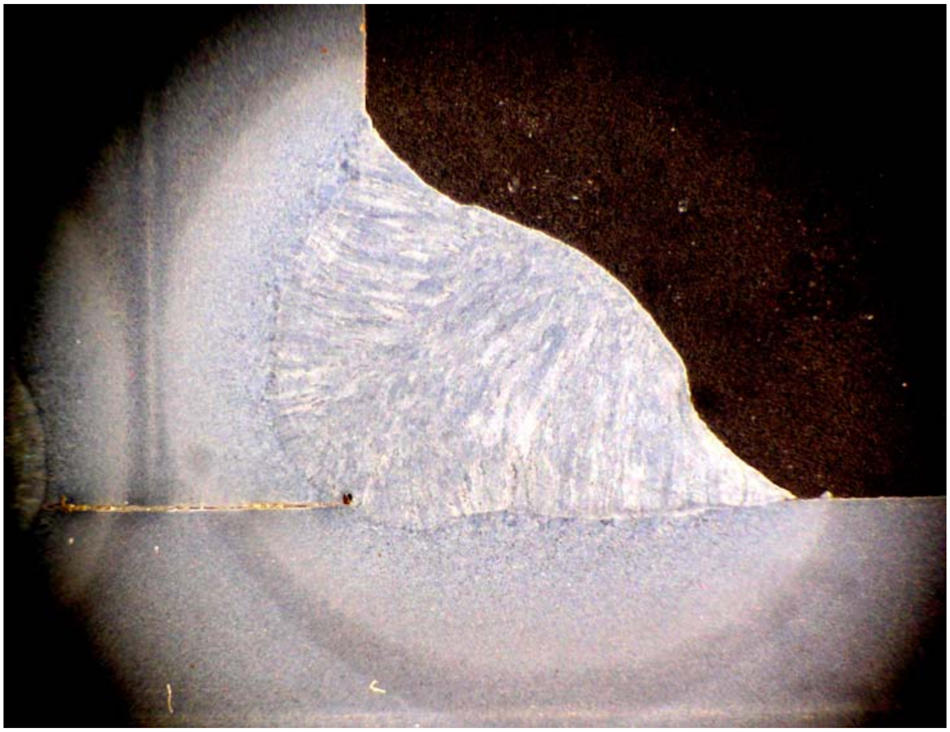


Figure 5.10: Sample ID #9 – 0.045" Dia. Wire, C25 Gas, Program 118

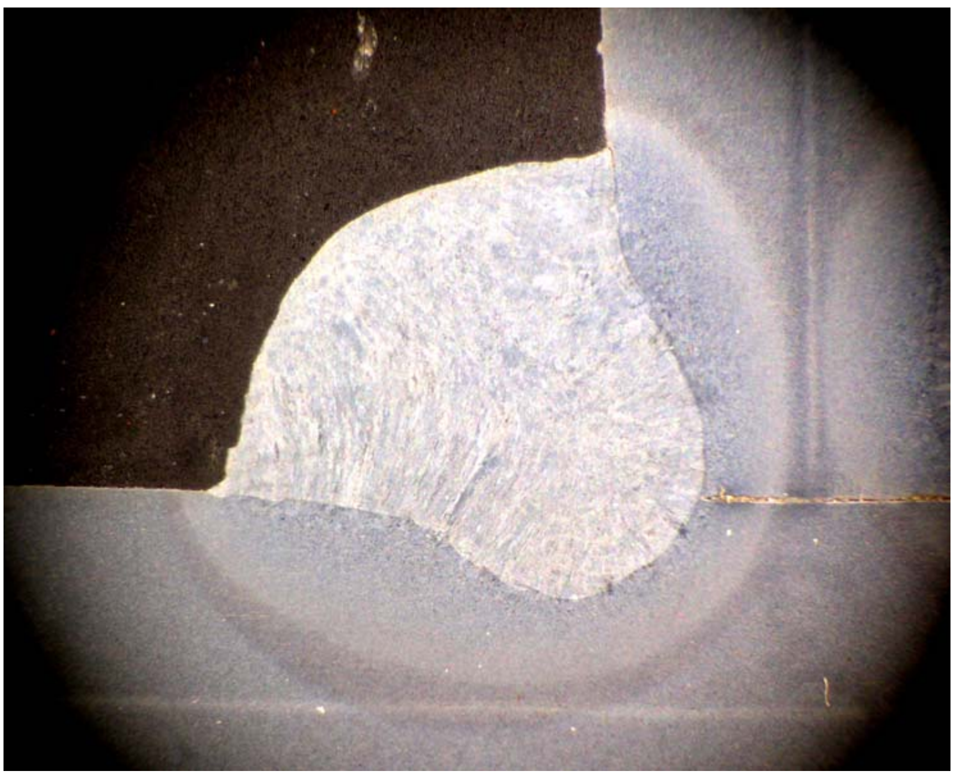


Figure 5.11: Sample ID #10 – 0.045" Dia. Wire, C25 Gas, Program 133

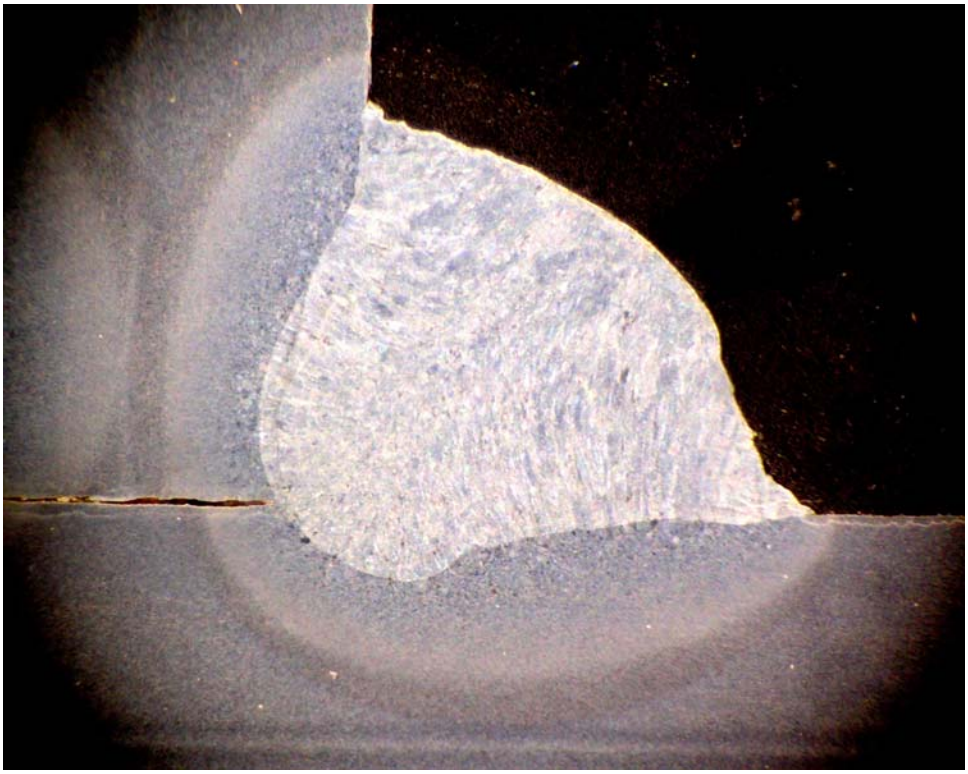


Figure 5.12: Sample ID #11 – 0.045" Dia. Wire, C25 Gas, Program 129

Recommendations for STT welding are provided in **Appendix C** along with preferred welding procedure data sheets (WPDS's) for welding with both .035" and .045" diameter ER100S-1 electrodes and C02 and C25 gases.

Distortion measurements were taken of welded t-stiffeners using benchmark parameters, before and after welding in the as-welded condition (see Table 4.3**,** Figures 4.23 and 4.24). The distortion results of the STT welded t-stiffener was compared to distortion results of the FCAW welded t-stiffener (see Table 4.3**,** Figures 4.25 and 4.26). Mechanical tensioning was not performed using the STT process, because after reviewing the distortion results of the assembly in the as welded condition it was felt that little advantage would be gained by use of mechanical tensioning. Penetration profiles of the two benchmark processes, STT and FCAW, are seen in Figures 5.13 and 5.14, respectively. Notice the increased sidewall fusion of the weld performed with the FCAW process vs. the STT process. Typical heat input values for the STT process are less than 9 kj/in compared to 12 kj/in for the FCAW process when depositing a 1/8" fillet weld size.

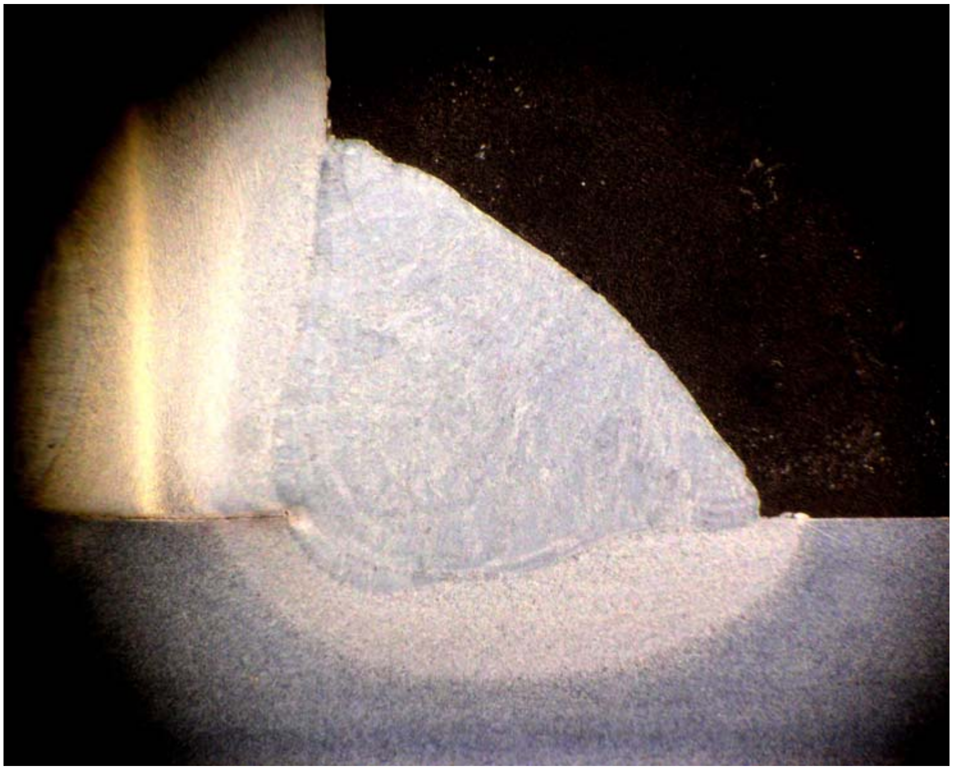


Figure 5.13: Benchmark STT – 0.035" Dia. Wire, C02 Gas, Program 131

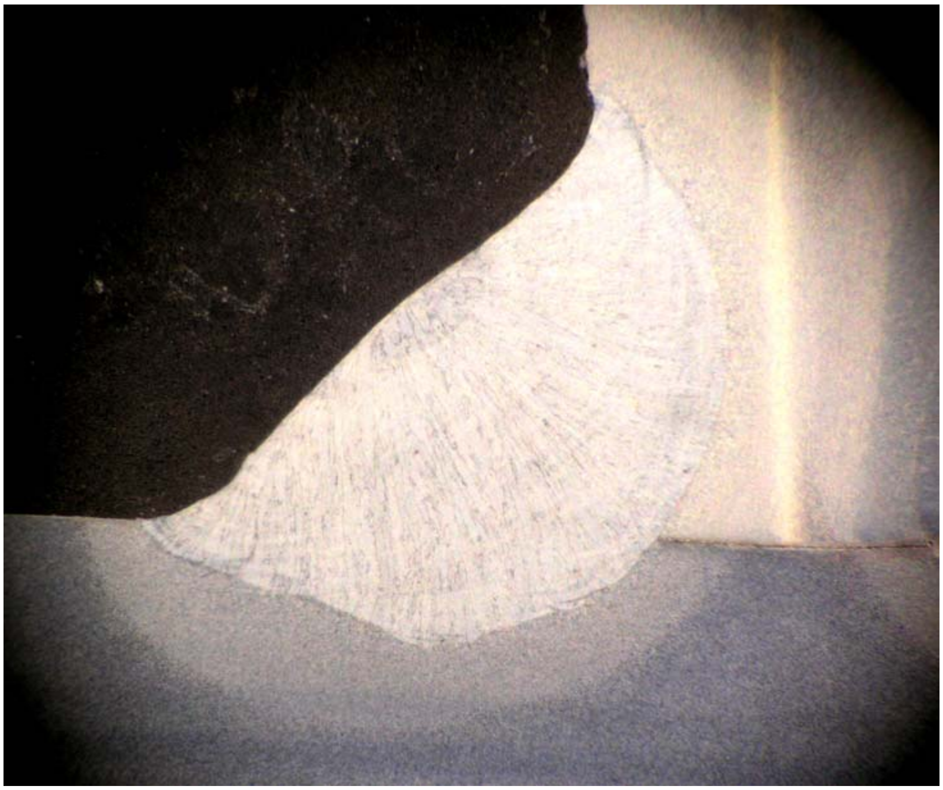


Figure 5.14: Benchmark FCAW

6. TASK 4: DEVELOP OPTIMIZED WELDING PROCEDURES AND GUIDELINES FOR ADVANCED PULSE TRANSFERS FOR ALUMINUM WELDING

6.1 Aluminum Welding with Advanced Processes

This report provides the results on the evaluation and comparison of the ESAB superpulse technology (pulse on pulse, pulse on spray, and pulse on short circuit) with conventional CV and pulse modes of metal transfer for the application of distortion control on aluminum thin panel fillet welds used in light weight combatants. The objective in this task was to develop optimized welding procedures and guidelines for superpulse welding of aluminum structures and compare the distortion results of superpulse with conventional CV and standard pulse processes. The secondary objective was to determine if baseline distortions can be further reduced with the use of mechanical tensioning.

Pulse/pulse technology was created to provide a GMAW solution for aluminum welding that made the process less difficult than standard pulse and therefore required less operator skill. Unlike standard pulse welding, pulse/pulse uses a sequence of varying pulse wave shapes to crate a bead shape and appearance similar to the Gas Tungsten Arc Welding (GTAW) process. Pulse/pulse was primarily designed for welding on aluminum and stainless steels. It utilizes low amperage in one phase for heat reduction and higher amperage in the other phase for enhanced penetration. The phases are named primary and secondary. A typical pulse/pulse waveform is shown in Figure 6.1.

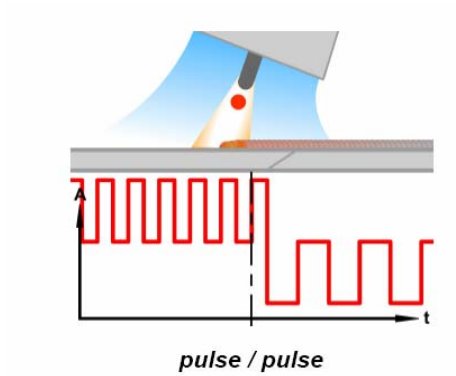


Figure 6.1: Pulse/Pulse Waveform

The Aristo SuperPulse is ESAB's latest development for GMAW that gives access to enhanced welding productivity in an easy to operate system. It is an extension to the pulse/pulse concept with full control over the heat input and arc behavior. The two additional arc modes include pulse arc/short arc, and, spray arc/pulse arc.

6.2 Pulse Arc/Short Arc

The pulse arc/short arc process was developed for welding very thin aluminum and stainless. It utilizes pulse in one phase and short arc in the other phase with very low heat input and a GTAW bead appearance. The phases are called primary and secondary. It can be used in all positions of welding and has low sensitivity to variations in root gap. The process can also be used for root runs from one side in thicker materials without the need for backing. A typical pulse arc/short arc waveform is shown in Figure 6.2.

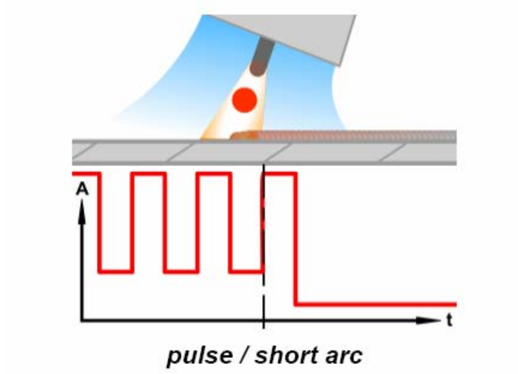


Figure 6.2: Pulse Arc/Short Arc Waveform

6.3 Spray Arc/Pulse Arc

The spray arc/pulse arc process was primarily developed for positional welding of thick materials. It utilizes spray arc transfer in one phase for enhanced penetration and pulse arc in the other phase which serves to cool the weld pool for less heat transfer to the base metal and less distortion. The phases are called primary and secondary. Pulsing in second phase also allows spray type transfer to be achieved in all positions of welding. A typical spray arc/pulse arc waveform is shown in Figure 6.3.

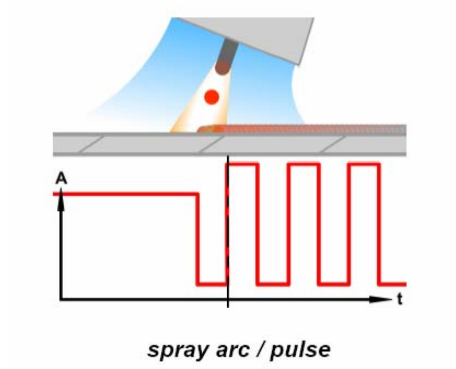


Figure 6.3: Spray Arc/Pulse Arc

6.4 Stiffened Aluminum Panel Assembly

All the stiffened panels (5mm thick) to be welded were marked up as illustrated in Figure 6.4. Panel distortion (vertical) measurements are recorded for points A, B, C and T along the width and T1 to T23 along the length, using a laser level.

For benchmark stiffener assembly in absence of tension, data is recorded before and after completion of welding. In addition, a similar measurement grid was setup for the test support frame upon which the stiffener assembly to be welded are supported.

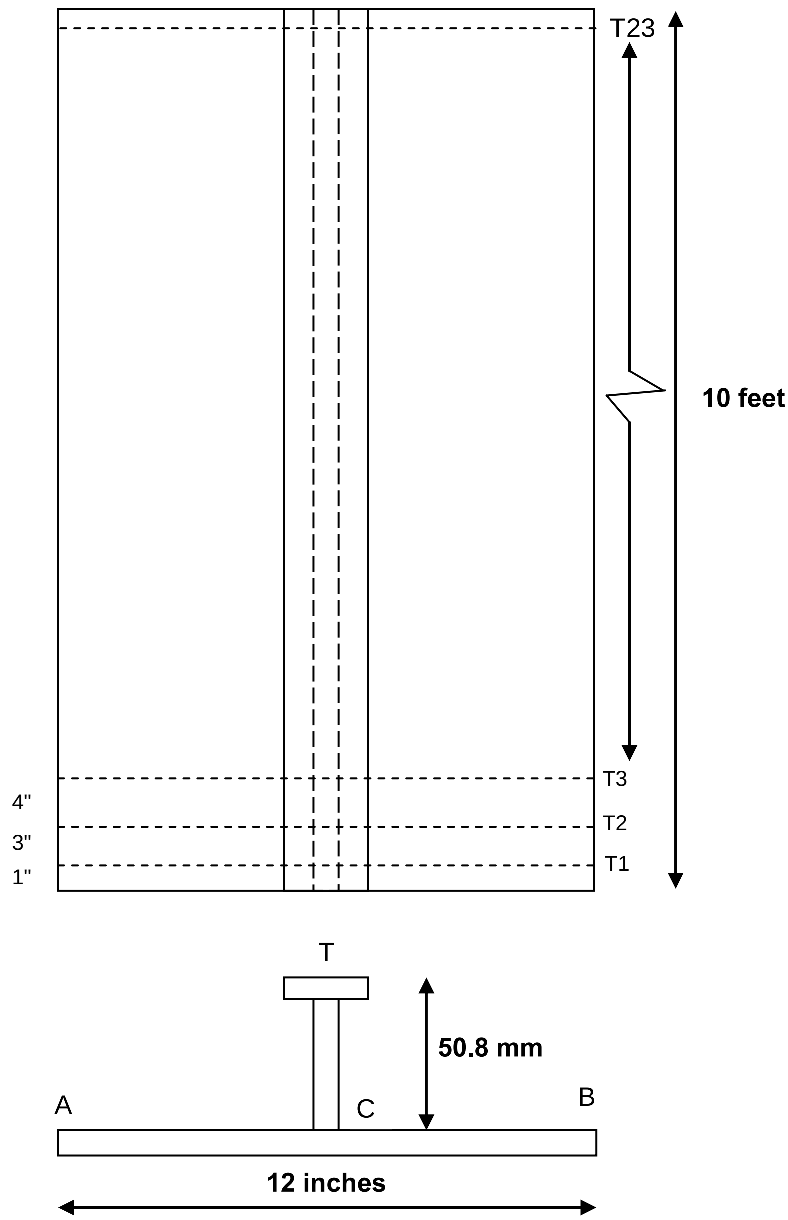


Figure 6.4: Stiffened Panel Distortion Measurement Grid

Figure 6.5 illustrates a typical test assembly is shown with tacks every 12 inches on the back side. Welding is performed on the other side of the assembly. Care is taken when fitting up assemblies so that all tacked assemblies are identical.

Figure 6.5: Tacked Stiffener Test Assembly on Test Frame

The matrix for distortion readings is shown marked on the plate (Figure 6.6).

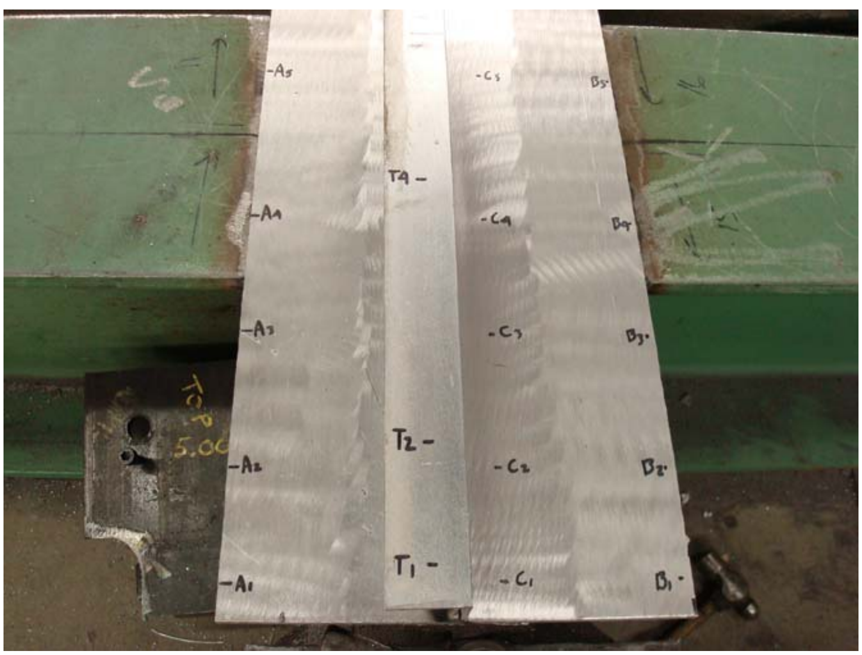


Figure 6.6: Plate Marked for Distortion Readings

Table 6.1 summarizes the benchmark test cases that were analyzed as part of the on-going research. Tables 6.2 through 6.8 summarize the measured distortion data for stiffener assemblies 1 through 5 at locations A, T, C and B respectively. The data is color-coded red and yellow to help better visualize the assembly distortion (torsion). The color red indicates a higher distortion compared to color yellow, whereas light green indicates no change in displacement. The sum of the columns is shown to compare total displacement for a given location along the length of the assembly.

Table 6.1: Test Summary

Benchmark Assembly 1	GMAW Conventional CV
Benchmark Assembly 2	GMAW Pulse on Pulse
Benchmark Assembly 3	GMAW Pulse on Spray
Benchmark Assembly 4	GMAW Pulse on Short Circuit
Benchmark Assembly 4 (Repeat)	GMAW Pulse on Short Circuit
Benchmark Assembly 5	GMAW Pulse
Assembly 6 (6000LBS Tension Case)	GMAW Pulse on Spray

Table 6.2: Benchmark Assembly 1-Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	6	55.2	5.5	0.5
2	6	55.2	5.5	0.5
3	5	54.95	4.5	0.5
4	5	54.7	4.5	0.5
5	4.5	54.2	4.5	0
6	4	53.7	4	0
7	4	53.45	4	0
8	4	53.2	4	0
9	3.5	52.7	3.5	0
10	3	52.2	3	0
11	3.5	52.7	3.5	0
12	4.5	53.2	3.5	1
13	4.5	53.2	3.5	1
14	4	53.2	3.5	0.5
15	4.5	53.45	3.5	1
16	5	53.7	4	1
17	4	53.7	4	0
18	3.5	53.7	4	0.5
19	3.5	53.95	4	0.5
20	4.5	54.2	4.5	0
21	4	53.7	4.5	0.5
22	5	54.7	6	1
23	6.5	55.7	6.5	0
Sum	**102**		**98**	**9**

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	6.5	54.7	4	2.5
2	6	54.2	4	2
3	4.5	53.95	3	1.5
4	5	53.7	3.5	1.5
5	5	53.2	4.5	0.5
6	4.5	52.7	5	0.5
7	5	52.95	5	0
8	5	53.2	5.5	0.5
9	5	52.95	5.5	0.5
10	4.5	52.7	5	0.5
11	5	53.2	5.5	0.5
12	5.5	53.7	6	0.5
13	5.5	53.45	6	0.5
14	5	53.2	6	1
15	5	53.2	6	1
16	5	53.2	6.5	1.5
17	4.5	53.45	6.5	2
18	4.5	53.7	6.5	2
19	5	53.95	7.5	2.5
20	4.5	54.2	6.5	2
21	3.5	53.2	5	1.5
22	3.5	53.2	4.5	1
23	4	53.2	4.5	0.5
	111.5		**122**	**26.5**

Net Displacment, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	0.5	-0.5	-1.5	2
2	0	-1	-1.5	1.5
3	-0.5	-1	-1.5	1
4	0	-1	-1	1
5	0.5	-1	0	0.5
6	0.5	-1	1	0.5
7	1	-0.5	1	0
8	1	0	1.5	0.5
9	1.5	0.25	2	0.5
10	1.5	0.5	2	0.5
11	1.5	0.5	2	0.5
12	1	0.5	2.5	1.5
13	1	0.25	2.5	1.5
14	1	0	2.5	1.5
15	0.5	-0.25	2.5	2
16	0	-0.5	2.5	2.5
17	0.5	-0.25	2.5	2
18	1	0	2.5	1.5
19	1.5	0	3.5	2
20	0	0	2	2
21	-0.5	-0.5	0.5	1
22	-1.5	-1.5	-1.5	0
23	-2.5	-2.5	-2	0.5
	9.5		**24**	**26.5**

Table 6.3: Benchmark Assembly 2-Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	8.5	57.2	7.5	1
2	7.5	57.2	7.5	0
3	6.5	56.45	6.5	0
4	6	55.7	6	0
5	5	54.95	5.5	0.5
6	4.5	54.2	5	0.5
7	4.5	53.7	4.5	0
8	4	53.2	4	0
9	3.5	52.45	3.5	0
10	2.5	51.7	2.5	0
11	3.5	52.45	3	0.5
12	4	53.2	3.5	0.5
13	4	52.95	3.5	0.5
14	3.5	52.7	3	0.5
15	4	53.2	3.5	0.5
16	5	53.7	4.5	0.5
17	4.5	54.2	4.5	0
18	4.5	54.7	5	0.5
19	5	55.7	6	1
20	6.5	56.7	7	0.5
21	6.5	57.2	7	0.5
22	7.5	58.2	9	1.5
23	8.5	59.2	10.5	2
Sum	**119.5**		**122.5**	**11**

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	7.5	55.2	4	3.5
2	7.5	55.2	4	3.5
3	5.5	54.45	2.5	3
4	5.5	53.7	3	2.5
5	5.5	53.45	4.5	1
6	5	53.2	4.5	0.5
7	5.5	53.2	5	0.5
8	5	53.2	5	0
9	5	52.7	4.5	0.5
10	4	52.2	3.5	0.5
11	5	52.95	4	1
12	5.5	53.7	5	0.5
13	5	53.2	5	0
14	4.5	52.7	4.5	0
15	4.5	52.7	5.5	1
16	4.5	52.7	5	0.5
17	4	52.7	5	1
18	3.5	52.7	5.5	2
19	4	53.2	6	2
20	4.5	53.7	6	1.5
21	3.5	53.7	4.5	1
22	4	53.95	4.5	0.5
23	4.5	54.2	5	0.5
	113		**106**	**27**

Net Displacment, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	-1	-2	-3.5	2.5
2	0	-2	-3.5	3.5
3	-1	-2	-4	3
4	-0.5	-2	-3	2.5
5	0.5	-1.5	-1	1.5
6	0.5	-1	-0.5	1
7	1	-0.5	0.5	0.5
8	1	0	1	0
9	1.5	0.25	1	0.5
10	1.5	0.5	1	0.5
11	1.5	0.5	1	0.5
12	1.5	0.5	1.5	0
13	1	0.25	1.5	0.5
14	1	0	1.5	0.5
15	0.5	-0.5	2	1.5
16	-0.5	-1	0.5	1
17	-0.5	-1.5	0.5	1
18	-1	-2	0.5	1.5
19	-1	-2.5	0	1
20	-2	-3	-1	1
21	-3	-3.5	-2.5	0.5
22	-3.5	-4.25	-4.5	1
23	-4	-5	-5.5	1.5
	-6.5		**-16.5**	**27**

Table 6.4: Benchmark Assembly 3-Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	3.5	54.2	5	1.5
2	3.5	54.2	5	1.5
3	3	54.2	4.5	1.5
4	3.5	54.2	5	1.5
5	4	54.45	5	1
6	3.5	54.7	4.5	1
7	3.5	54.2	4.5	1
8	3.5	53.7	4	0.5
9	3.5	53.45	4	0.5
10	2.5	53.2	3.5	1
11	3	53.45	4	1
12	3.5	53.7	4	0.5
13	3.5	53.45	3.5	0
14	3.5	53.2	3.5	0
15	3.5	53.45	4	0.5
16	3.5	53.7	4	0.5
17	3	53.45	3.5	0.5
18	3.5	53.2	3.5	0
19	3.5	53.45	3.5	0
20	4	53.7	4	0
21	3.5	53.2	3.5	0
22	4	53.7	4	0
23	5	54.2	4.5	0.5
Sum	**81**		**94.5**	**14.5**

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	3.5	53.2	3.5	0
2	3.5	53.7	3.5	0
3	3	53.45	3	0
4	3.5	53.2	3.5	0
5	4	52.95	5	1
6	3.5	52.7	5	1.5
7	4	53.7	6	2
8	5	54.7	6.5	1.5
9	6	54.95	7.5	1.5
10	6	55.2	7	1
11	6	55.2	7.5	1.5
12	6.5	55.2	7.5	1
13	6	55.2	7	1
14	5.5	55.2	7	1.5
15	5.5	54.95	7.5	2
16	5	54.7	7	2
17	4.5	54.2	6.5	2
18	4.5	53.7	6.5	2
19	4.5	54.2	6.5	2
20	4.5	54.7	6.5	2
21	3.5	53.7	4.5	1
22	3.5	53.45	4	0.5
23	3.5	53.2	4	0.5
	105		**132.5**	**27.5**

Net Displacment, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	0	-1	-1.5	1.5
2	0	-0.5	-1.5	1.5
3	0	-0.75	-1.5	1.5
4	0	-1	-1.5	1.5
5	0	-1.5	0	0
6	0	-2	0.5	0.5
7	0.5	-0.5	1.5	1
8	1.5	1	2.5	1
9	2.5	1.5	3.5	1
10	3.5	2	3.5	0
11	3	1.75	3.5	0.5
12	3	1.5	3.5	0.5
13	2.5	1.75	3.5	1
14	2	2	3.5	1.5
15	2	1.5	3.5	1.5
16	1.5	1	3	1.5
17	1.5	0.75	3	1.5
18	1	0.5	3	2
19	1	0.75	3	2
20	0.5	1	2.5	2
21	0	0.5	1	1
22	-0.5	-0.25	0	0.5
23	-1.5	-1	-0.5	1
	24		**38**	**26**

Table 6.5: Benchmark Assembly 4-Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	4.5	54.2	4	0.5
2	4	54.2	4	0
3	3	53.95	3	0
4	3.5	53.7	3.5	0
5	4	53.7	4	0
6	3	53.7	3.5	0.5
7	3	53.7	3.5	0.5
8	3.5	53.7	3.5	0
9	3.5	53.2	3.5	0
10	3	52.7	2.5	0.5
11	3.5	53.2	3	0.5
12	3.5	53.7	3.5	0
13	4	53.2	3.5	0.5
14	4	52.7	3	1
15	4	53.2	3.5	0.5
16	4	53.7	3.5	0.5
17	4	53.7	3.5	0.5
18	3.5	53.7	3.5	0
19	3.5	54.2	4	0.5
20	4	54.7	4.5	0.5
21	4	54.7	4	0
22	5	55.45	5.5	0.5
23	6.5	56.2	6.5	0
Sum	**88.5**		**86.5**	**7**

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	5	55.2	4	1
2	4.5	55.2	3.5	1
3	3	54.7	3.5	0.5
4	3.5	54.2	3.5	0
5	4	53.7	5	1
6	4	53.2	5.5	1.5
7	4	53.2	5.5	1.5
8	4.5	53.2	6.5	2
9	5	53.2	6.5	1.5
10	4	53.2	5.5	1.5
11	4.5	53.45	5.5	1
12	5	53.7	5.5	0.5
13	4.5	53.45	5.5	1
14	3.5	53.2	5	1.5
15	4	54.45	5.5	1.5
16	5	55.7	8.5	3.5
17	7	57.95	10.5	3.5
18	9.5	60.2	14	4.5
19	12	62.2	16.5	4.5
20	12.5	64.2	16.5	4
21	11.5	64.2	15.5	4
22	11.5	63.95	15	3.5
23	12.5	63.7	15	2.5
	144.5		**187.5**	**47**

Net Displacment, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	1	1	0	0.5
2	1	1	-0.5	1
3	0	0.75	0.5	0.5
4	0	0.5	0	0
5	0	0	1	1
6	1	-0.5	2	1
7	1	-0.5	2	1
8	1	-0.5	3	2
9	1.5	0	3	1.5
10	1	0.5	3	2
11	1	0.25	2.5	1.5
12	1.5	0	2	0.5
13	0.5	0.25	2	1.5
14	-0.5	0.5	2	2.5
15	0	1.25	2	2
16	1	2	5	4
17	3	4.25	7	4
18	6	6.5	10.5	4.5
19	8.5	8	12.5	4
20	8.5	9.5	12	3.5
21	7.5	9.5	11.5	4
22	6.5	8.5	9.5	3
23	6	7.5	8.5	2.5
	56		**101**	**48**

Table 6.6: Benchmark Assembly 4 (Repeat)-Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	5.5	55.2	4.5	1
2	5	55.2	4	1
3	4	54.95	3.5	0.5
4	4.5	54.7	4	0.5
5	5.5	53.95	4.5	1
6	4	53.2	4	0
7	3.5	52.95	3.5	0
8	3.5	52.7	3.5	0
9	3.5	52.45	3.5	0
10	3	52.2	3	0
11	3.5	52.95	4	0.5
12	4	53.7	4.5	0.5
13	4.5	53.7	5	0.5
14	4.5	53.7	5	0.5
15	4.5	53.95	5	0.5
16	5	54.2	5	0
17	4.5	54.7	5	0.5
18	5.5	55.2	6	0.5
19	6	55.45	7	1
20	6.5	55.7	8	1.5
21	6.5	56.2	8	1.5
22	7.5	57.2	9	1.5
23	9	58.2	10.5	1.5
Sum	**113.5**		**120**	**14.5**

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	5.5	54.7	3.5	2
2	4.5	55.2	3.5	1
3	3.5	54.7	2.5	1
4	4	54.2	4	0
5	4	53.45	5.5	1.5
6	4	52.7	5.5	1.5
7	3.5	52.7	6	2.5
8	1.5	52.7	6	4.5
9	3.5	52.45	6	2.5
10	3.5	52.2	5.5	2
11	4	52.95	6	2
12	4.5	53.7	6.5	2
13	5	53.2	7	2
14	4.5	52.7	6.5	2
15	4	53.2	6.5	2.5
16	4	53.7	7.5	3.5
17	4	53.7	7	3
18	4.5	53.7	7.5	3
19	5	53.7	8.5	3.5
20	4.5	53.7	7.5	3
21	3.5	52.7	5.5	2
22	3.5	52.95	5	1.5
23	4	53.2	5	1
	92.5		**134**	**49.5**

Net Displacment, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	0	-0.5	-1	1
2	-1	0	-0.5	0
3	-1	-0.25	-1	0.5
4	-1	-0.5	0	0.5
5	-1.5	-0.5	1	2.5
6	0	-0.5	1.5	1.5
7	0	-0.25	2.5	2.5
8	-2	0	2.5	4.5
9	0	0	2.5	2.5
10	0.5	0	2.5	2
11	0.5	0	2	1.5
12	0.5	0	2	1.5
13	0.5	-0.5	2	1.5
14	0	-1	1.5	1.5
15	-0.5	-0.75	1.5	2
16	-1	-0.5	2.5	3.5
17	-0.5	-1	2	2.5
18	-1	-1.5	1.5	2.5
19	-1	-1.75	1.5	2.5
20	-2	-2	-0.5	1.5
21	-3	-3.5	-2.5	0.5
22	-4	-4.25	-4	0
23	-5	-5	-5.5	0.5
	-21		**14**	**39**

Table 6.7: Benchmark Assembly 5-Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	4	54.2	3.5	0.5
2	3.5	53.7	4	0.5
3	2.5	53.45	3	0.5
4	3	53.2	3.5	0.5
5	3	52.7	3.5	0.5
6	3	52.2	3	0
7	2.5	52.45	3	0.5
8	3	52.7	3	0
9	3.5	52.95	3.5	0
10	3	53.2	3.5	0.5
11	3	53.45	3.5	0.5
12	3.5	53.7	4	0.5
13	3.5	53.45	4.5	1
14	3.5	53.2	4	0.5
15	3.5	53.7	4.5	1
16	4	54.2	4.5	0.5
17	3.5	54.45	4.5	1
18	4	54.7	5	1
19	4.5	54.95	5.5	1
20	5	55.2	5.5	0.5
21	4.5	55.2	5	0.5
22	5.5	55.7	5.5	0
23	6.5	56.2	6	0.5
Sum	**85.5**		**95.5**	**12**

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	4	53.2	2.5	1.5
2	3.5	53.2	3	0.5
3	2.5	52.7	2.5	0
4	3	52.2	3.5	0.5
5	3.5	51.95	4.5	1
6	2.5	51.7	4.5	2
7	3	52.45	5.5	2.5
8	4	53.2	6.5	2.5
9	5	53.7	7.5	2.5
10	5	54.2	7	2
11	5.5	54.45	7	1.5
12	5.5	54.7	7	1.5
13	5	54.2	7	2
14	4.5	53.7	6	1.5
15	4.5	53.95	6	1.5
16	4	54.2	6	2
17	4	54.7	7	3
18	5.5	55.2	8.5	3
19	6	55.45	9	3
20	5.5	55.7	7.5	2
21	4.5	54.7	4.5	0
22	4	54.45	3.5	0.5
23	4	54.2	3.5	0.5
	98.5		**129.5**	**37**

Net Displacment, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	0	-1	-1	1
2	0	-0.5	-1	1
3	0	-0.75	-0.5	0.5
4	0	-1	0	0
5	0.5	-0.75	1	0.5
6	-0.5	-0.5	1.5	2
7	0.5	0	2.5	2
8	1	0.5	3.5	2.5
9	1.5	0.75	4	2.5
10	2	1	3.5	1.5
11	2.5	1	3.5	1
12	2	1	3	1
13	1.5	0.75	2.5	1
14	1	0.5	2	1
15	1	0.25	1.5	0.5
16	0	0	1.5	1.5
17	0.5	0.25	2.5	2
18	1.5	0.5	3.5	2
19	1.5	0.5	3.5	2
20	0.5	0.5	2	1.5
21	0	-0.5	-0.5	0.5
22	-1.5	-1.25	-2	0.5
23	-2.5	-2	-2.5	0
	13		**34**	**28**

Table 6.8: Assembly 6-Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	6.5	54.7	7	0.5
2	5.5	54.7	6.5	1
3	4	54.45	5	1
4	4	54.2	5	1
5	4	53.95	4.5	0.5
6	4	53.7	4	0
7	4	53.7	4	0
8	4	53.7	4	0
9	4	53.45	3.5	0.5
10	4	53.2	3	1
11	4	53.7	3.5	0.5
12	4.5	54.2	4	0.5
13	4.5	53.95	4	0.5
14	4	53.7	3.5	0.5
15	4.5	53.95	4	0.5
16	5	54.2	4	1
17	4.5	54.2	4	0.5
18	4.5	54.2	4	0.5
19	5	54.7	4.5	0.5
20	5	55.2	5	0
21	4.5	54.7	4	0.5
22	5.5	54.7	5.5	0
23	7	54.7	6.5	0.5
Sum	**106.5**		**103**	**11.5**

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	5.5	54.2	4.5	1
2	5	54.2	4.5	0.5
3	3.5	53.7	3	0.5
4	4	53.2	3.5	0.5
5	4	52.95	4.5	0.5
6	3.5	52.7	5	1.5
7	4	52.95	5	1
8	4	53.2	5.5	1.5
9	4.5	53.2	6	1.5
10	4	53.2	5.5	1.5
11	4.5	53.7	6	1.5
12	5	54.2	6	1
13	5	53.95	6	1
14	5	53.7	6	1
15	4.5	53.7	6	1.5
16	5	53.7	5.5	0.5
17	4.5	53.45	5.5	1
18	4.5	53.2	5.5	1
19	5	54.2	6.5	1.5
20	4.5	55.2	6	1.5
21	3	54.2	4.5	1.5
22	3.5	54.2	4.5	1
23	4	54.2	5	1
	100		**120**	**25**

Net Displacment, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	-1	-0.5	-2.5	1.5
2	-0.5	-0.5	-2	1.5
3	-0.5	-0.75	-2	1.5
4	0	-1	-1.5	1.5
5	0	-1	0	0
6	-0.5	-1	1	1.5
7	0	-0.75	1	1
8	0	-0.5	1.5	1.5
9	0.5	-0.25	2.5	2
10	0	0	2.5	2.5
11	0.5	0	2.5	2
12	0.5	0	2	1.5
13	0.5	0	2	1.5
14	1	0	2.5	1.5
15	0	-0.25	2	2
16	0	-0.5	1.5	1.5
17	0	-0.75	1.5	1.5
18	0	-1	1.5	1.5
19	0	-0.5	2	2
20	-0.5	0	1	1.5
21	-1.5	-0.5	0.5	2
22	-2	-0.5	-1	1
23	-3	-0.5	-1.5	1.5
	-6.5		**17**	**35.5**

Figures 6.7 through 6.10 illustrate the net displacements for benchmark stiffener assembly 1 at edge locations A, T, C and B respectively.

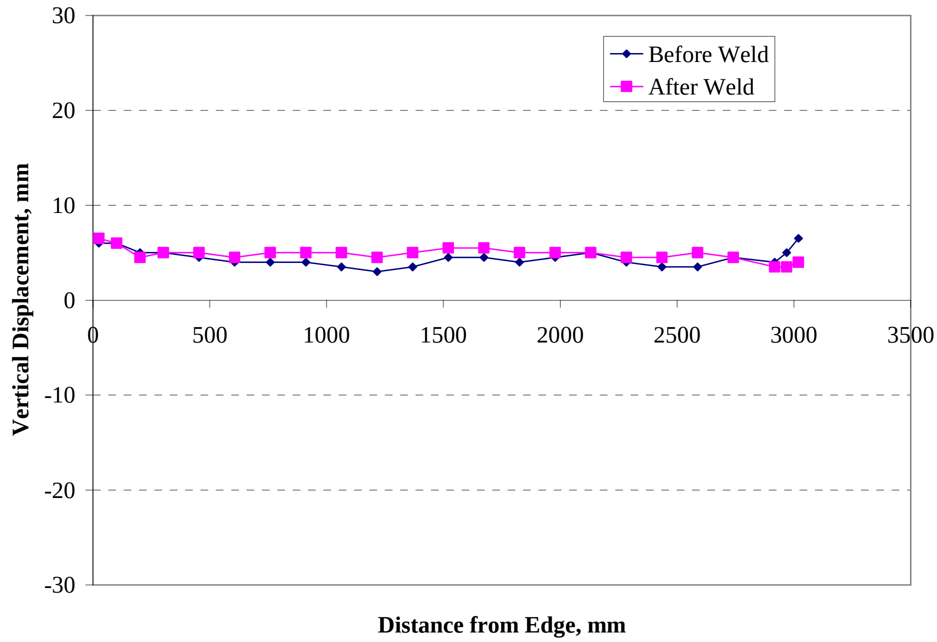


Figure 6.7: Net Displacement along Longitudinal Section A for Benchmark Assembly1

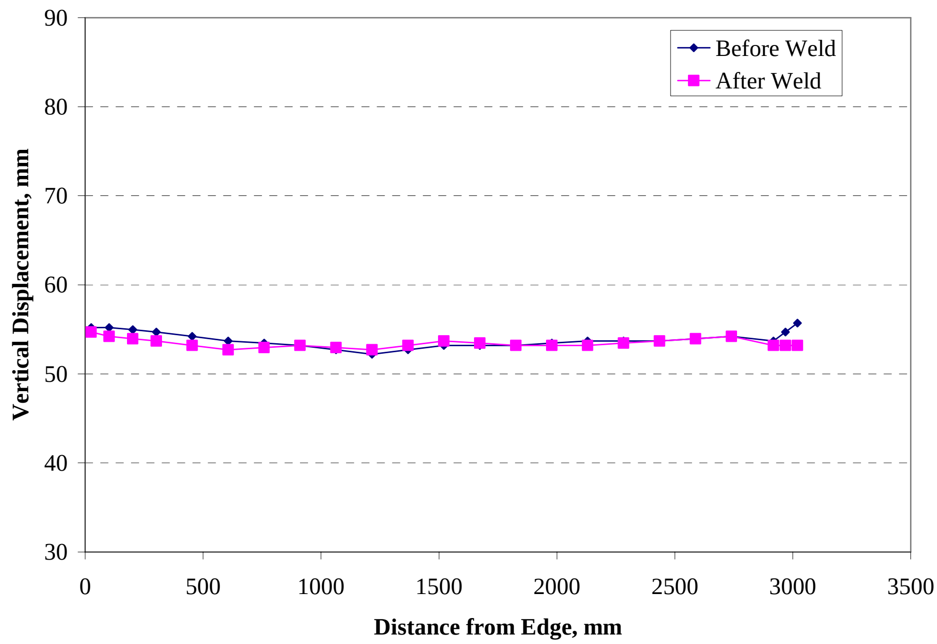


Figure 6.8: Net Displacement along Longitudinal Section T for Benchmark Assembly1

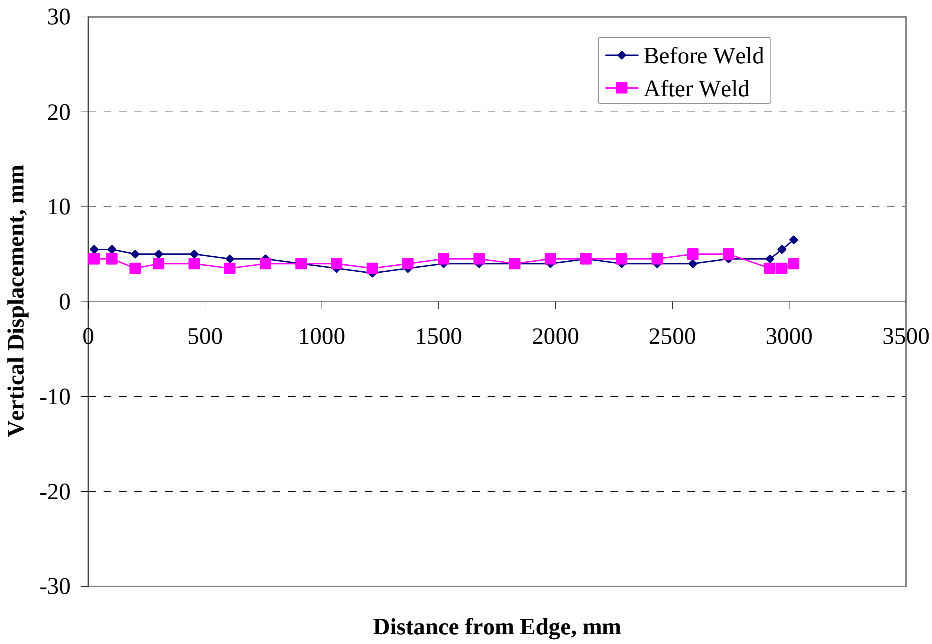


Figure 6.9: Net Displacement along Longitudinal Section C for Benchmark Assembly1

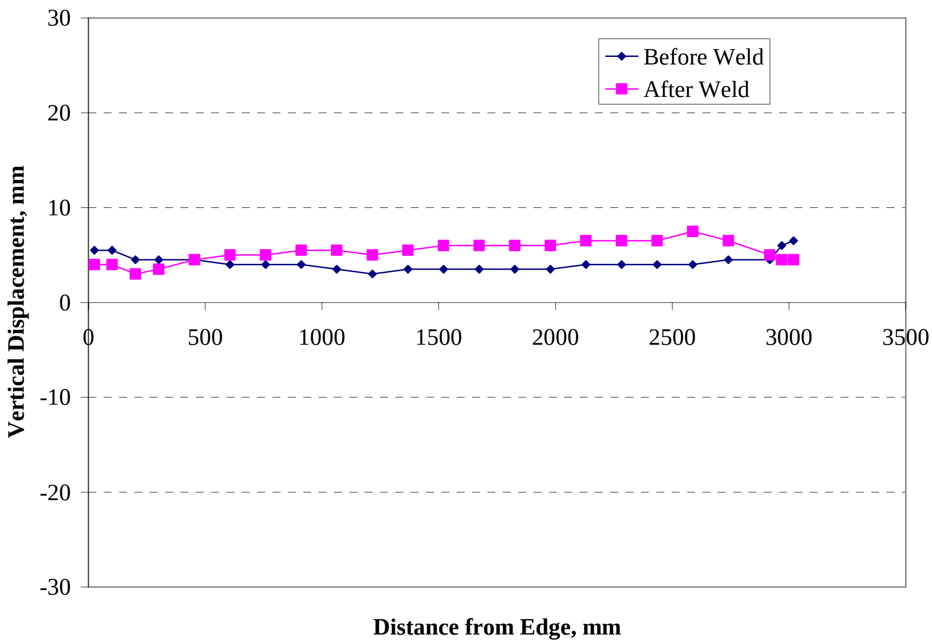


Figure 6.10: Net Displacement along Longitudinal Section B for Benchmark Assembly1

Figures 6.11 through 6.14 illustrate the net displacements for benchmark stiffener assembly 2 at edge locations A, T, C and B respectively

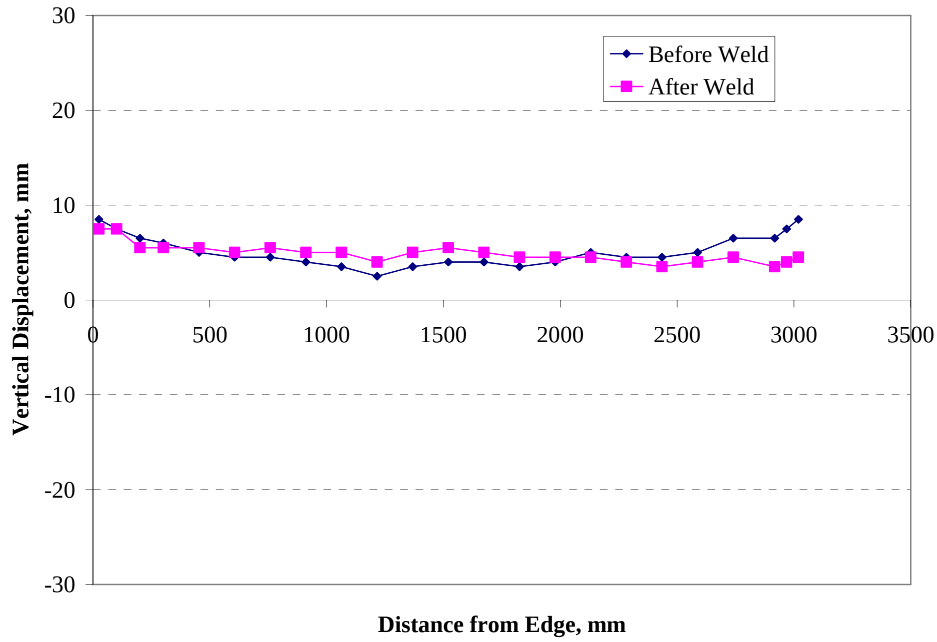


Figure 6.11: Net Displacement along Longitudinal Section A for Benchmark Assembly2

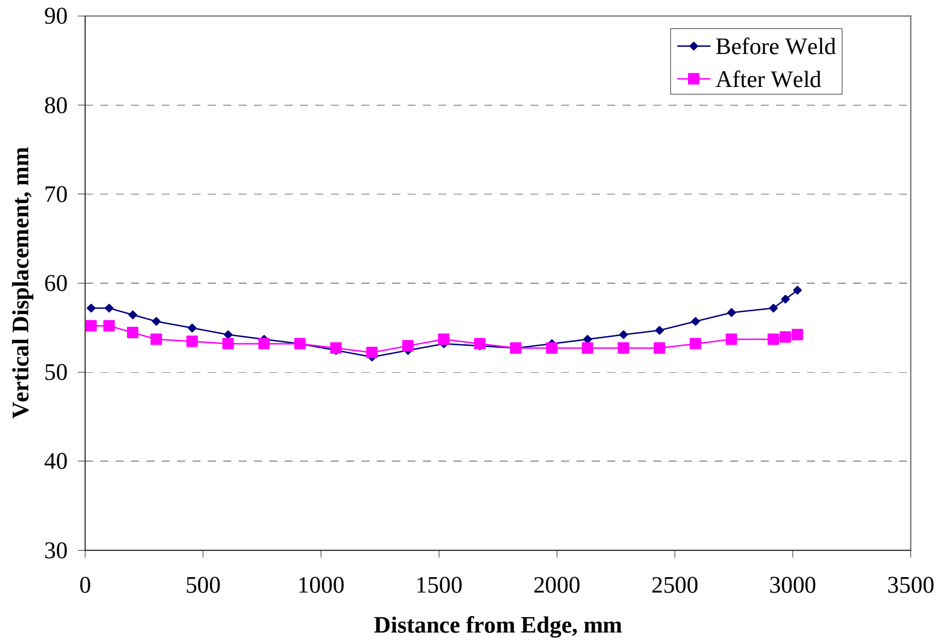


Figure 6.12: Net Displacement along Longitudinal Section T for Benchmark Assembly2

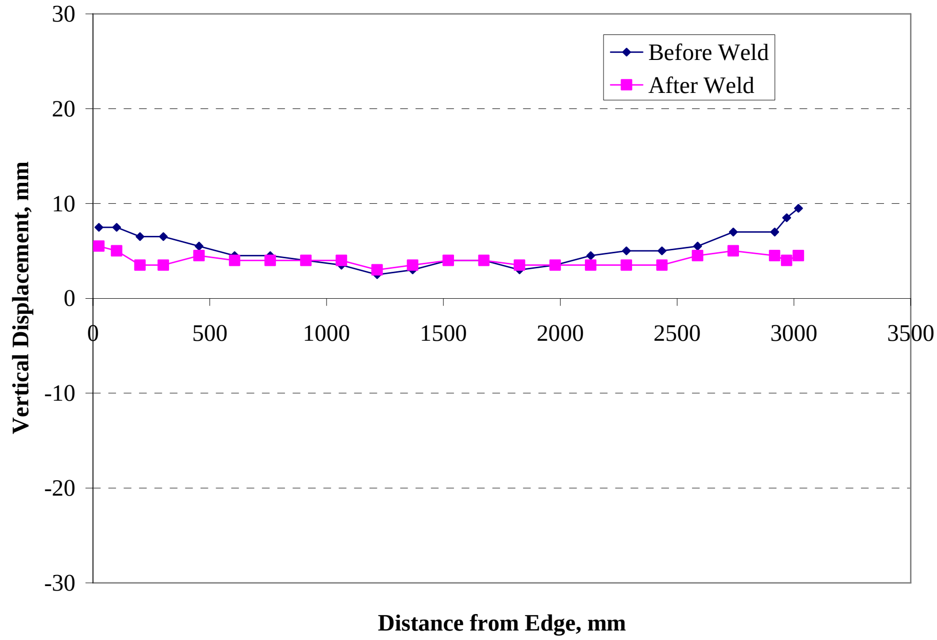


Figure 6.13: Net Displacement along Longitudinal Section C for Benchmark Assembly2

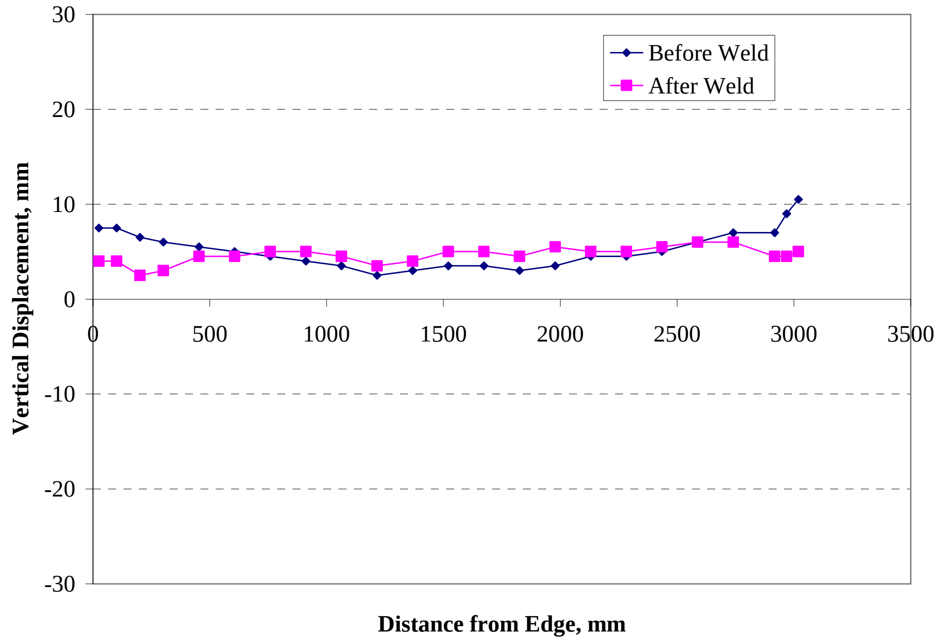


Figure 6.14: Net Displacement along Longitudinal Section B for Benchmark Assembly2

Figures 6.15 through 6.18 illustrate the net displacements for benchmark stiffener assembly 3 at edge locations A, T, C and B respectively

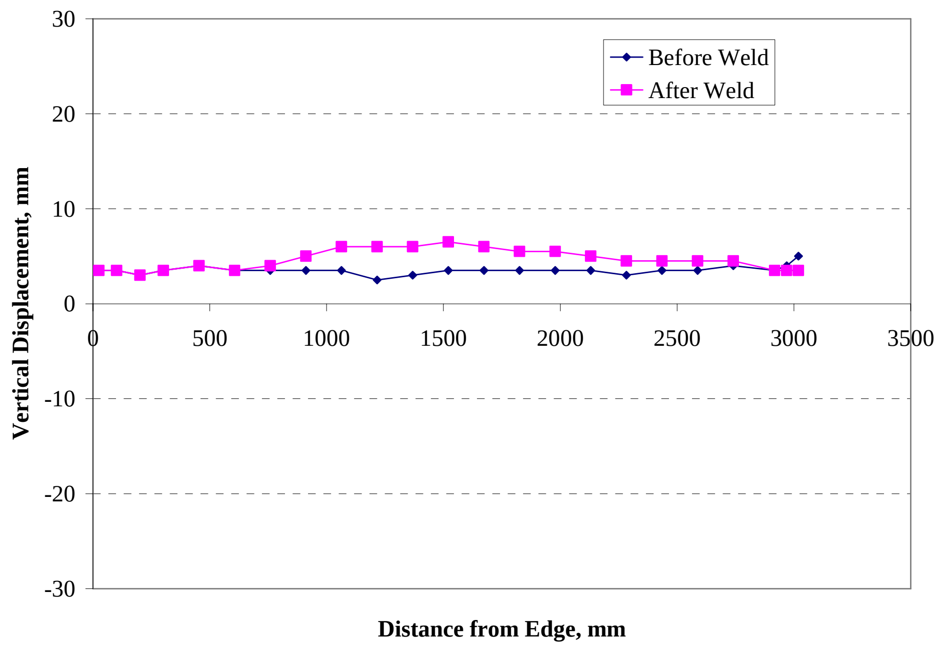


Figure 6.15: Net Displacement along Longitudinal Section A for Benchmark Assembly3

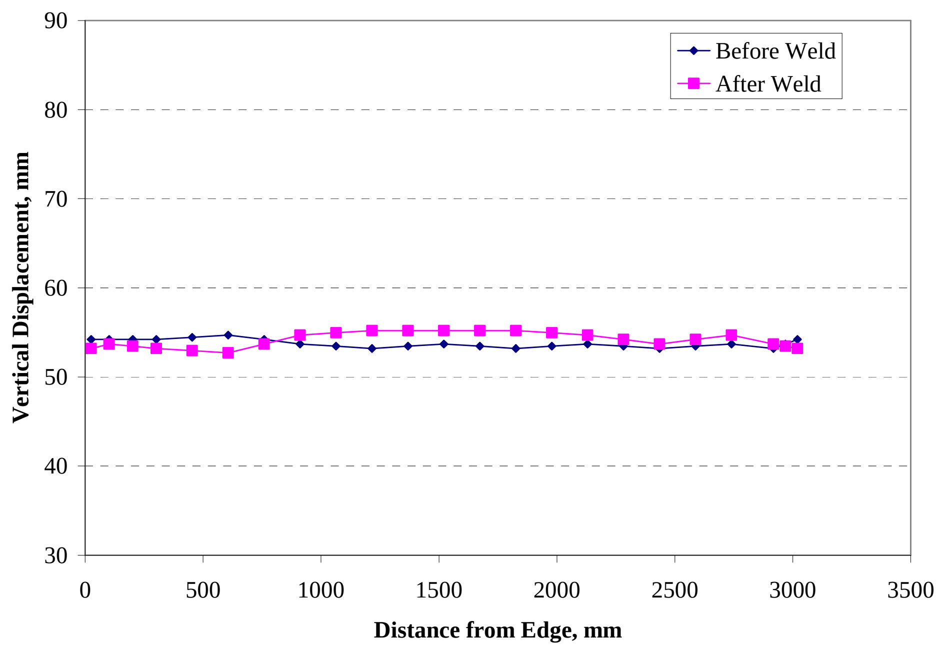


Figure 6.16: Net Displacement along Longitudinal Section T for Benchmark Assembly3

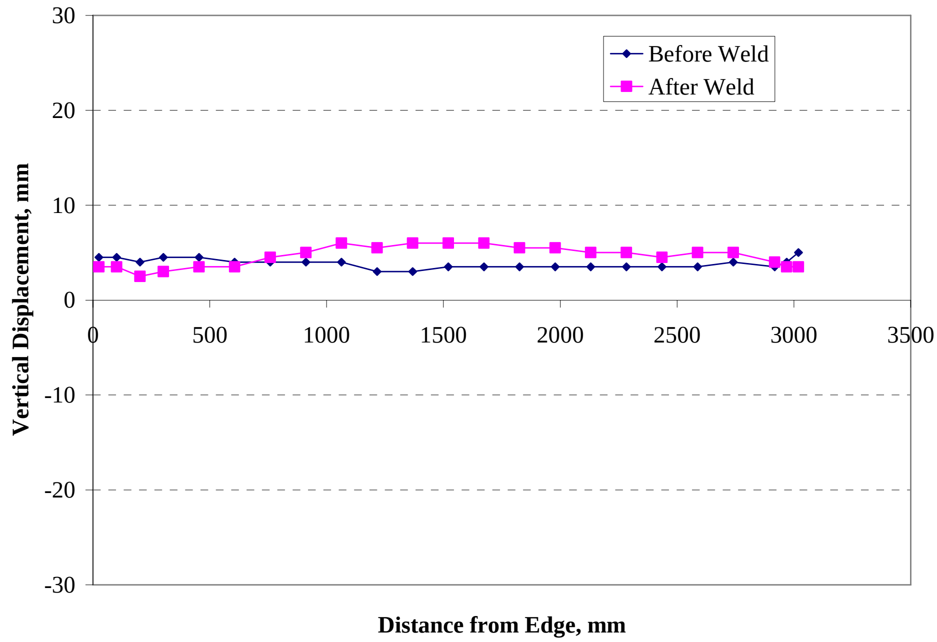


Figure 6.17: Net Displacement along Longitudinal Section C for Benchmark Assembly3

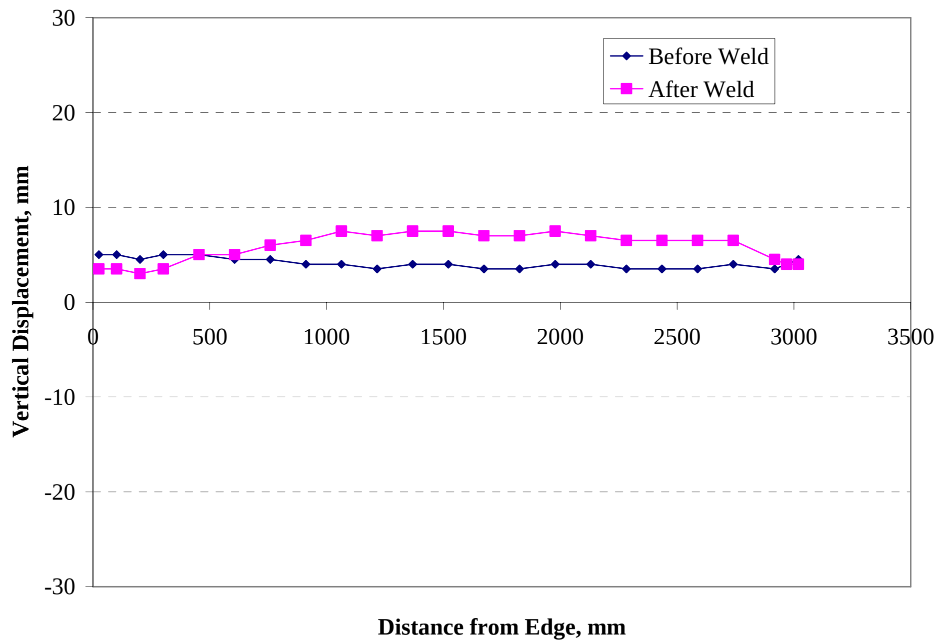


Figure 6.18: Net Displacement along Longitudinal Section B for Benchmark Assembly3

Figures 6.19 through 6.22 illustrate the net displacements for benchmark stiffener assembly 4 at edge locations A, T, C and B respectively.

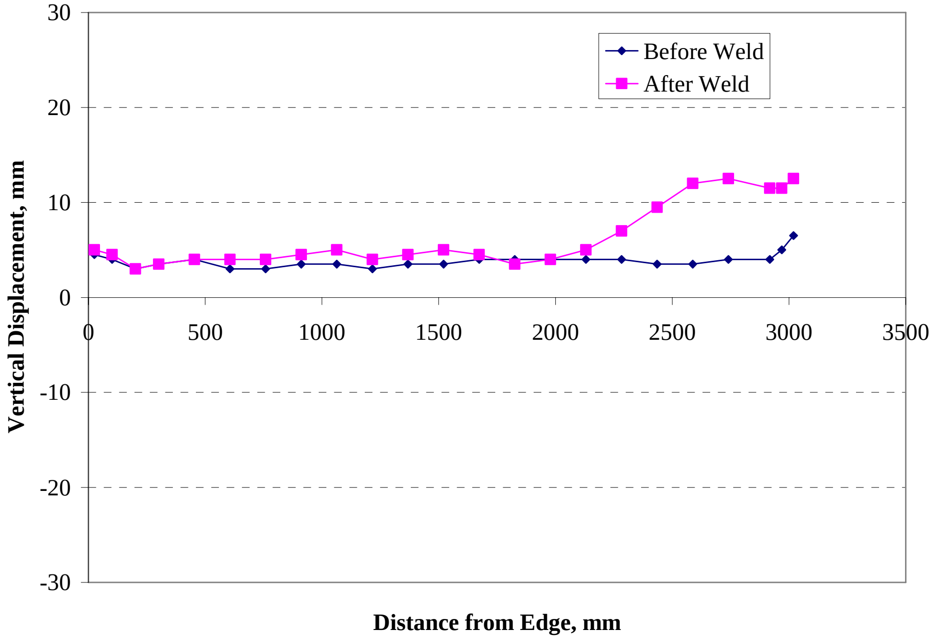


Figure 6.19: Net Displacement along Longitudinal Section A for Benchmark Assembly4

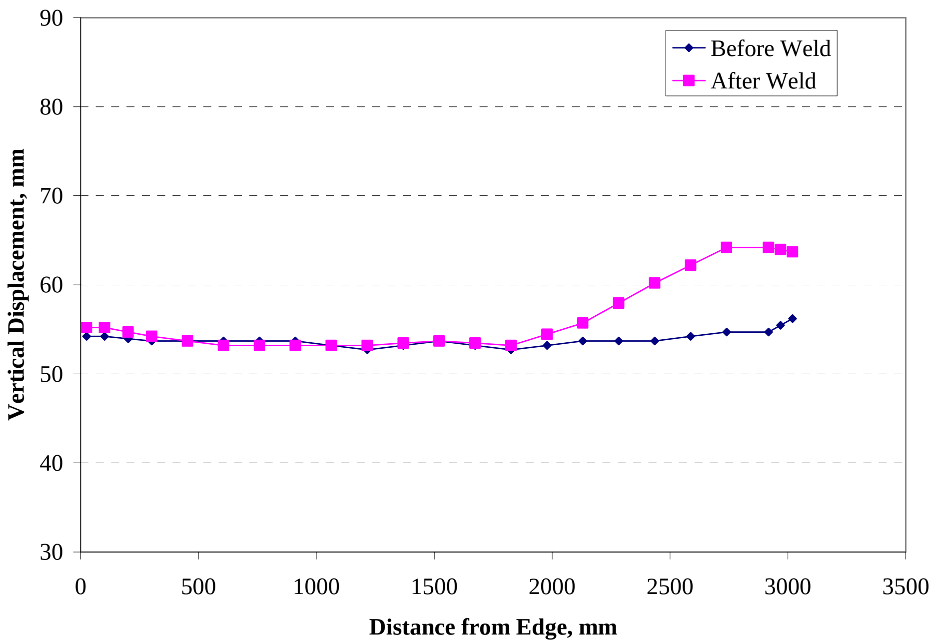


Figure 6.20: Net Displacement along Longitudinal Section T for Benchmark Assembly4

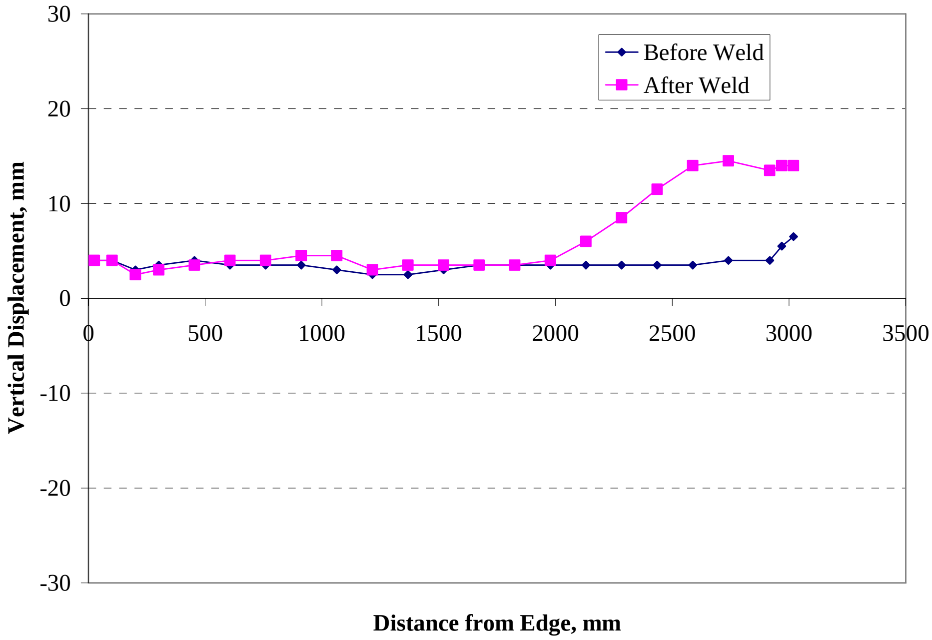


Figure 6.21: Net Displacement along Longitudinal Section C for Benchmark Assembly4

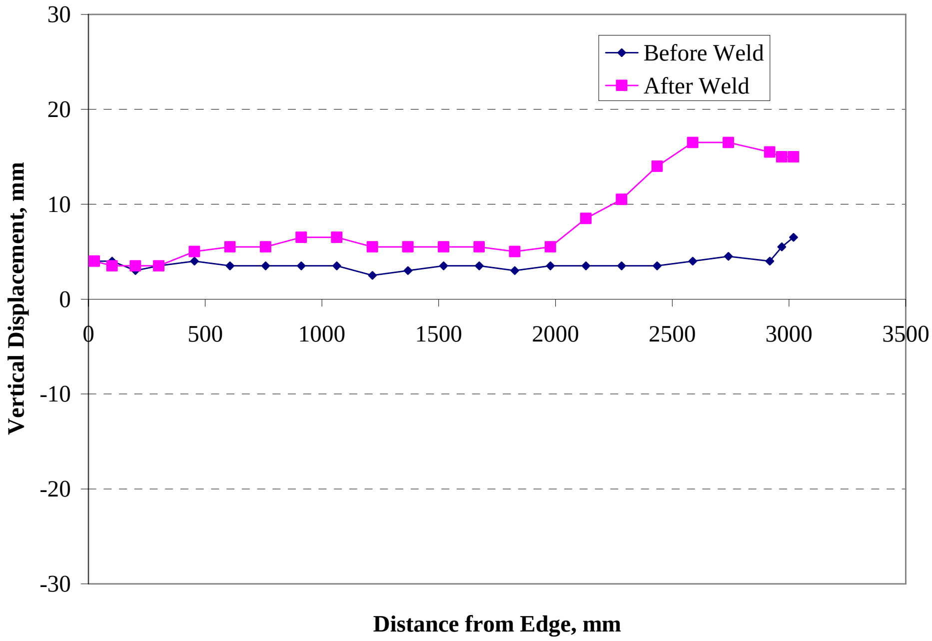


Figure 6.22: Net Displacement along Longitudinal Section B for Benchmark Assembly4

Figures 6.23 through 2.26 illustrate the net displacements for benchmark stiffener assembly 4 (Repeat) at edge locations A, T, C and B respectively. Benchmark Assembly 4 was repeated due to tacks breaking during welding of benchmark assembly 4 starting at approximately the 2200mm region of the assembly.

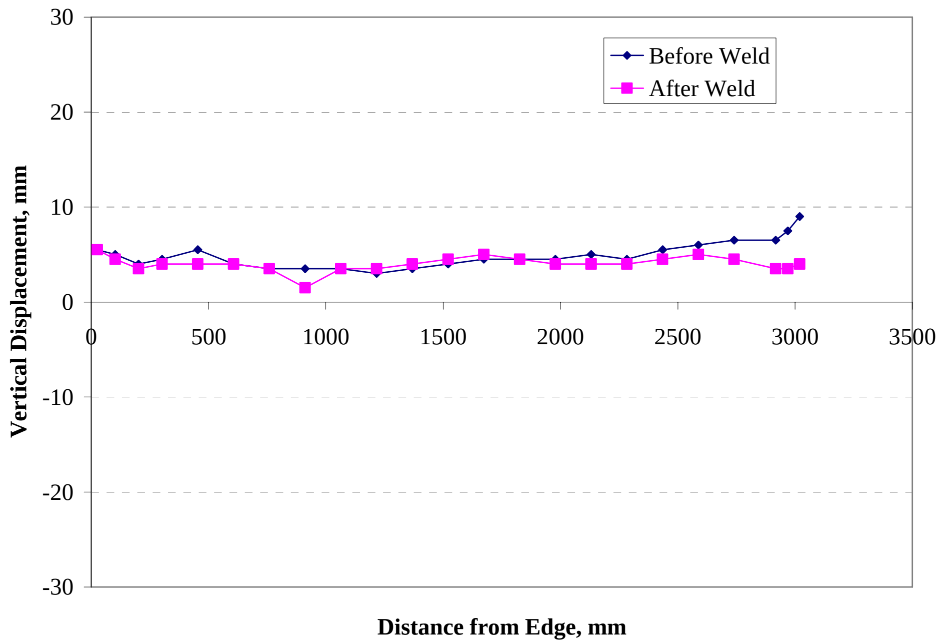


Figure 6.23: Net Displacement along Longitudinal Section A for Benchmark Assembly4 (Repeat)

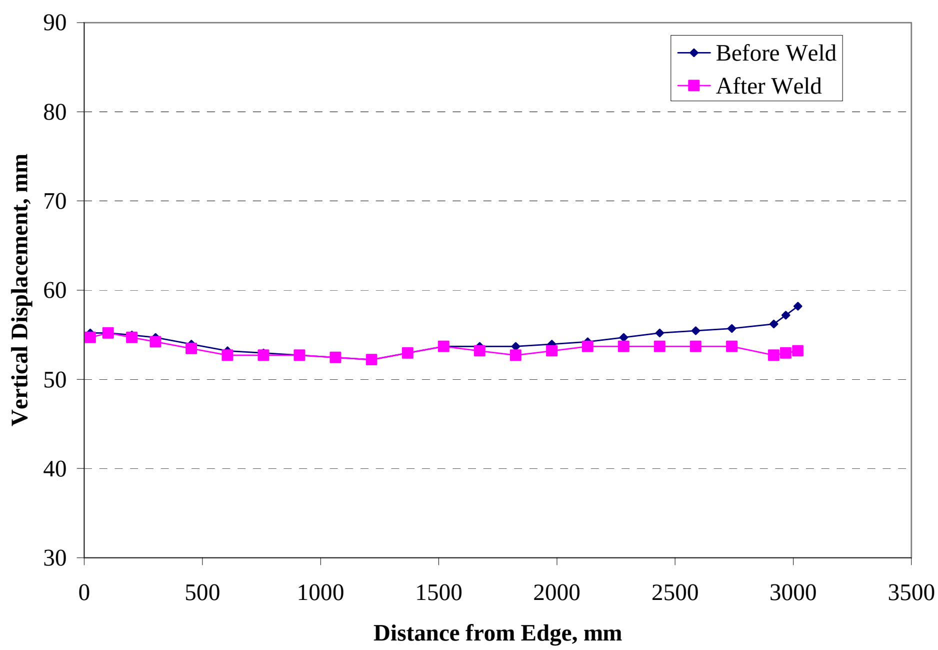


Figure 6.24: Net Displacement along Longitudinal Section T for Benchmark Assembly4 (Repeat)

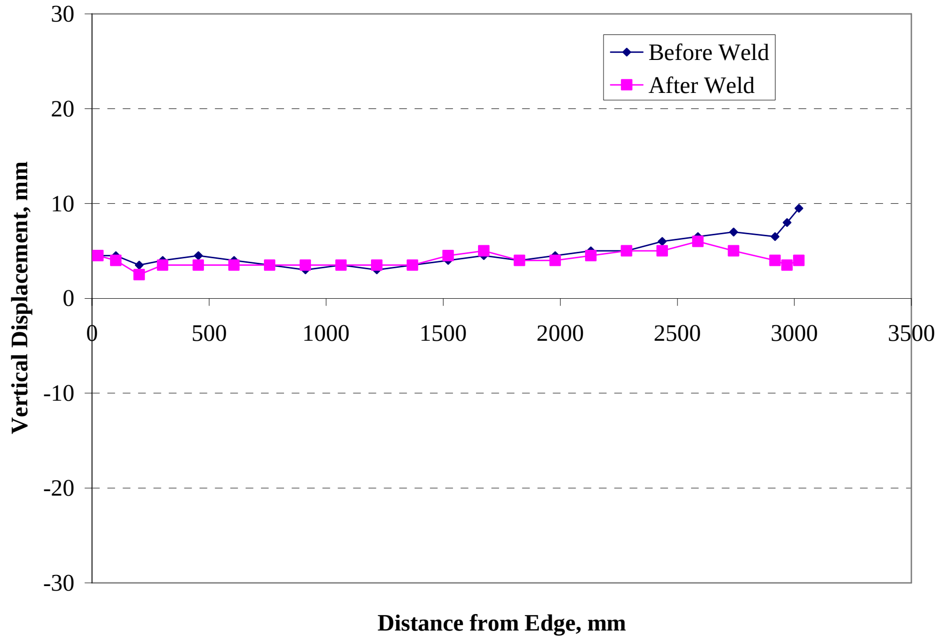


Figure 6.25: Net Displacement along Longitudinal Section C for Benchmark Assembly4 (Repeat)

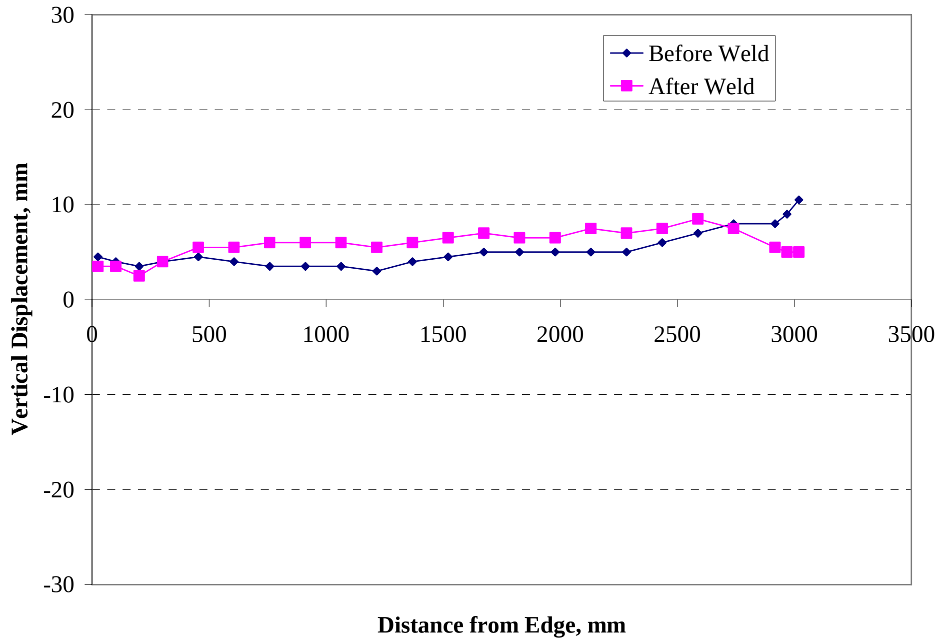


Figure 6.26: Net Displacement along Longitudinal Section B for Benchmark Assembly4 (Repeat)

Figures 6.27 through 6.30 illustrate the net displacements for benchmark stiffener assembly 5 at edge locations A, T, C and B respectively.

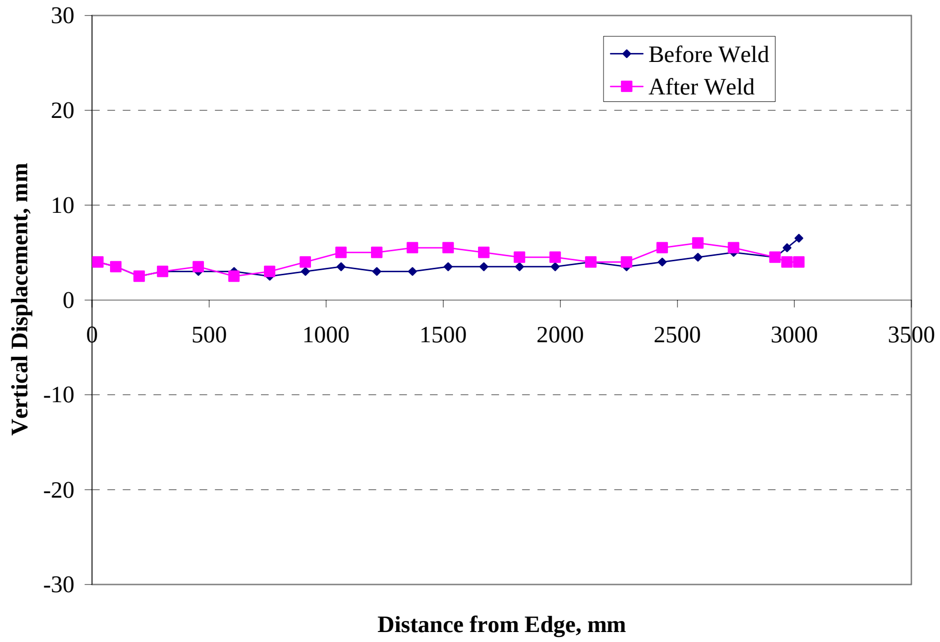


Figure 6.27: Net Displacement along Longitudinal Section A for Benchmark Assembly5

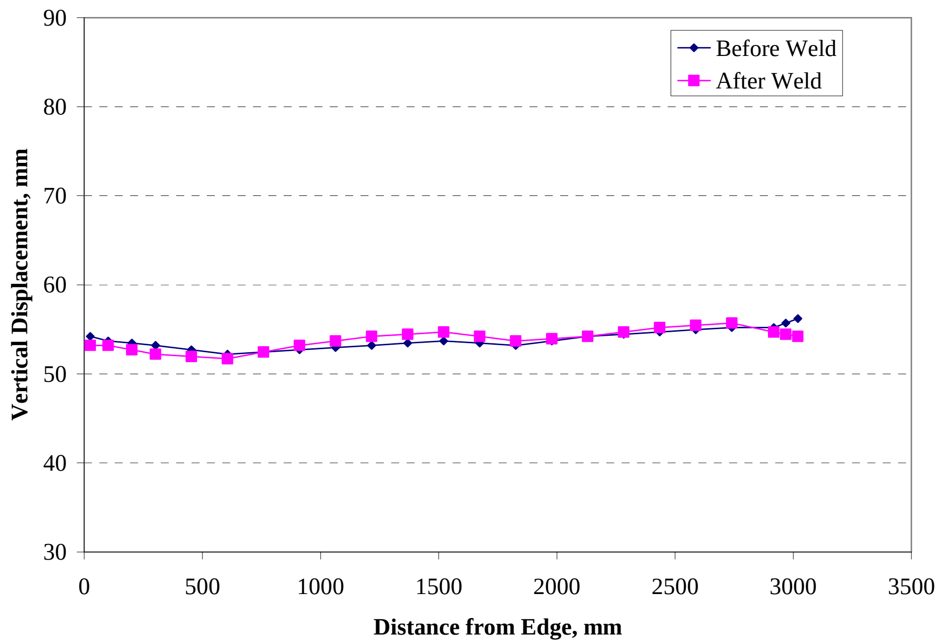


Figure 6.28: Net Displacement along Longitudinal Section T for Benchmark Assembly5

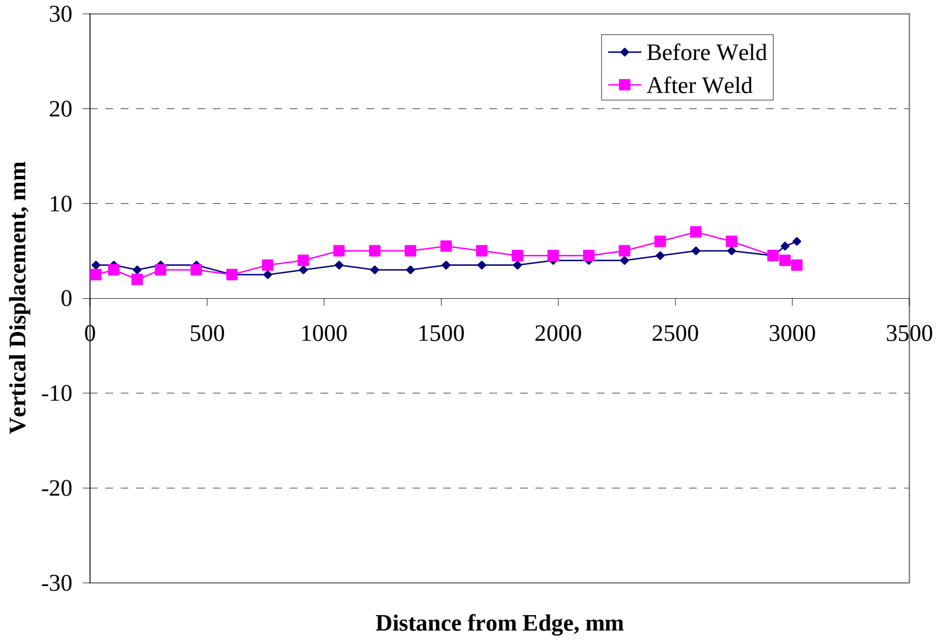


Figure 6.29: Net Displacement along Longitudinal Section C for Benchmark Assembly5

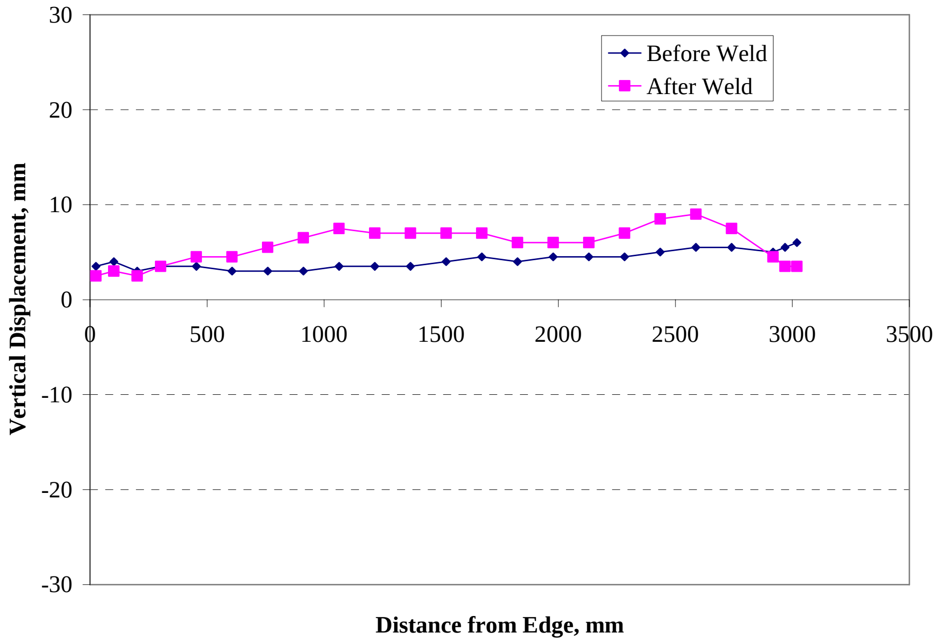


Figure 6.30: Net Displacement along Longitudinal Section B for Benchmark Assembly5

Figures 6.31 through 6.34 illustrate the net displacements for stiffener assembly 6 at edge locations A, T, C and B respectively.

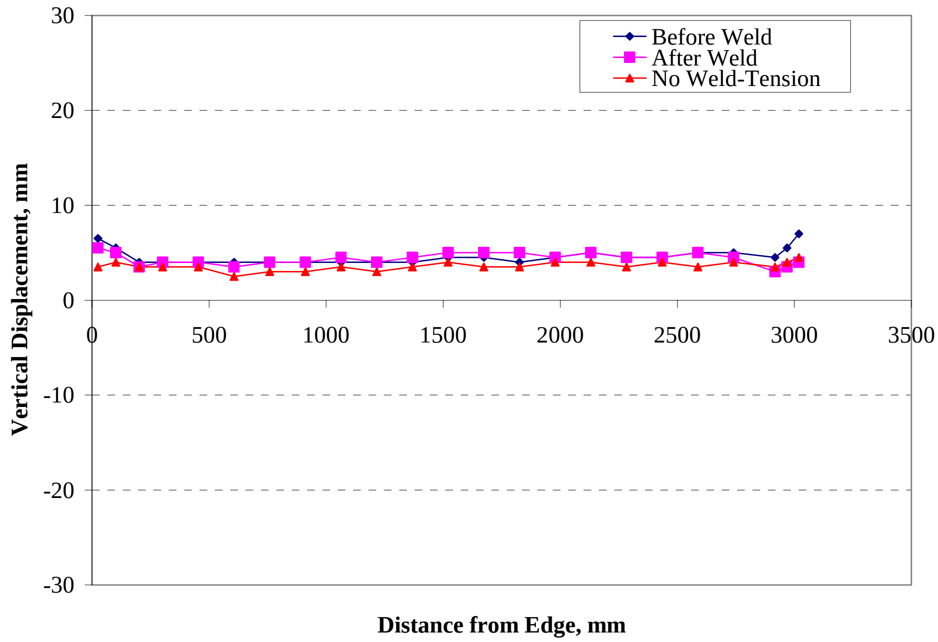


Figure 6.31: Net Displacement along Longitudinal Section A for Assembly6

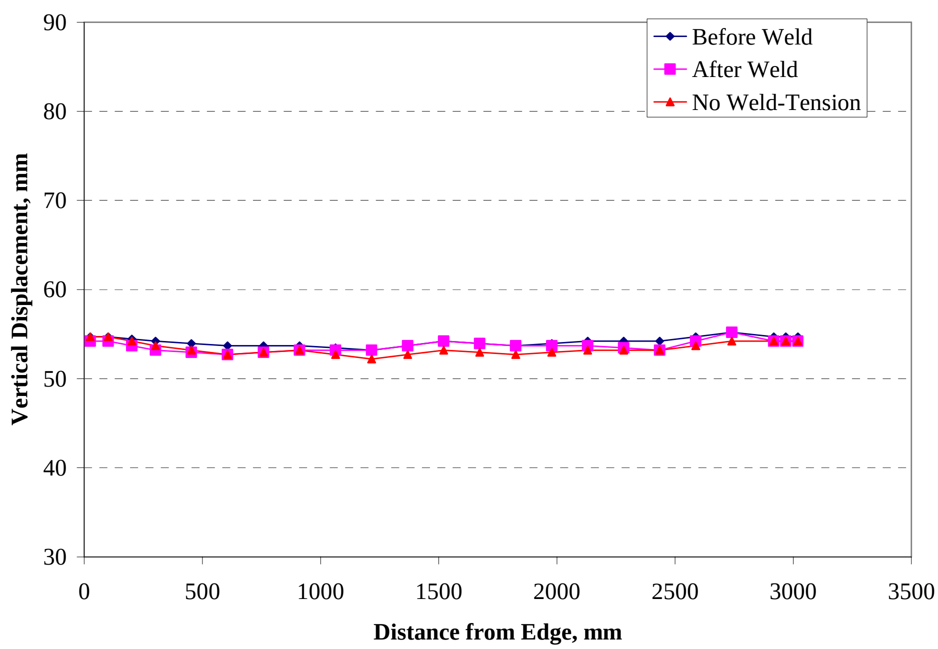


Figure 6.32: Net Displacement along Longitudinal Section T for Assembly6

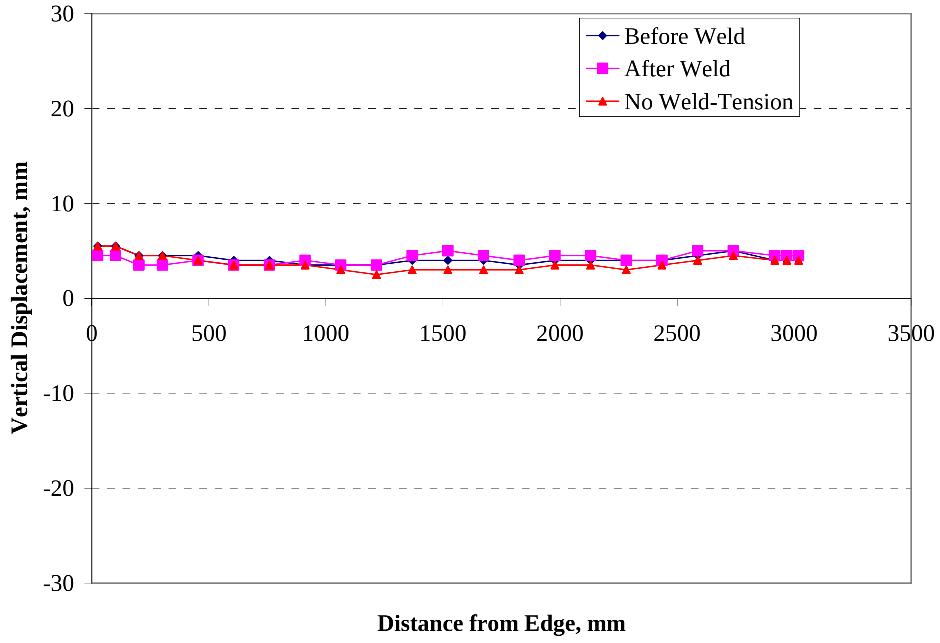


Figure 6.33: Net Displacement along Longitudinal Section C for Assembly6

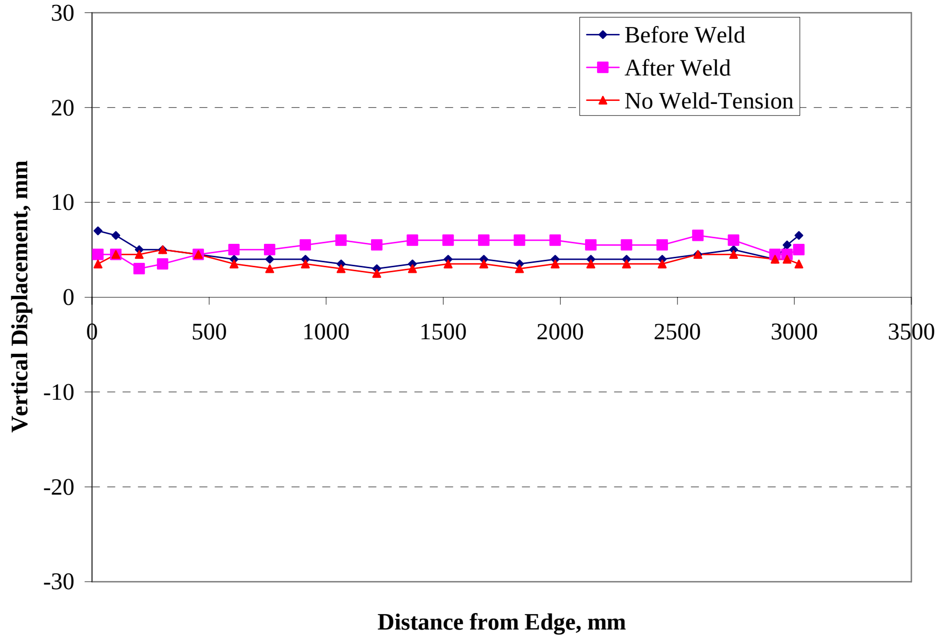


Figure 6.34: Net Displacement along Longitudinal Section B for Assembly6

6.5 Comparing Benchmark Aluminum Welding Processes

Figures 6.35 through 6.37 compare the net effectiveness of each of the welding processes in terms of the net displacement along the longitudinal section of each marked point on the assembly (Figure 6.4) with respect to corresponding point on the test frame before and after welding.

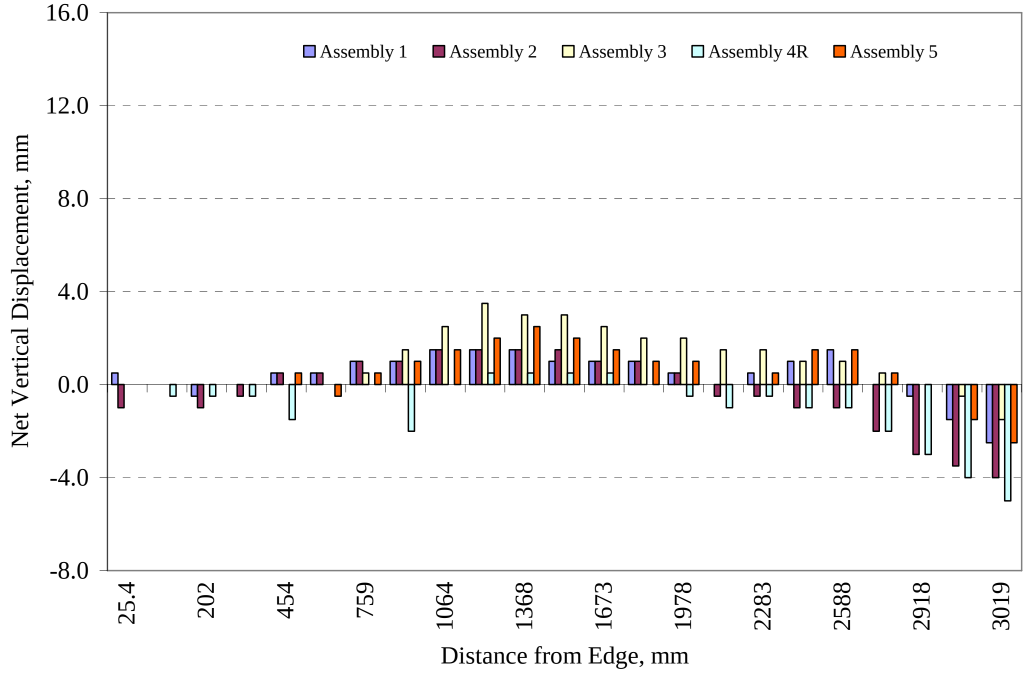


Figure 6.35: Net Displacement along Longitudinal Section A

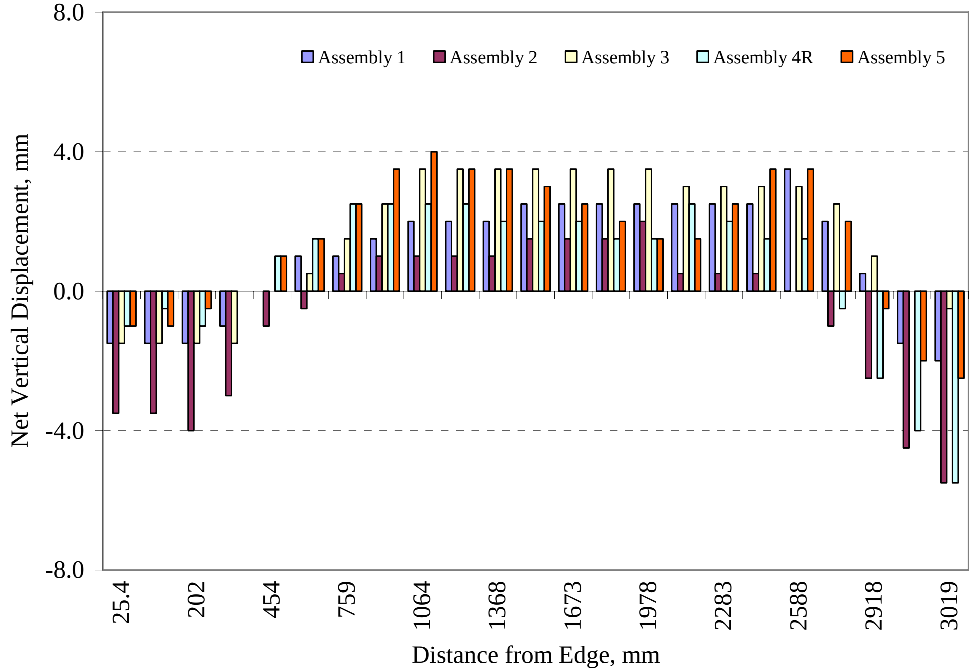


Figure 6.36: Net Displacement along Longitudinal Section B

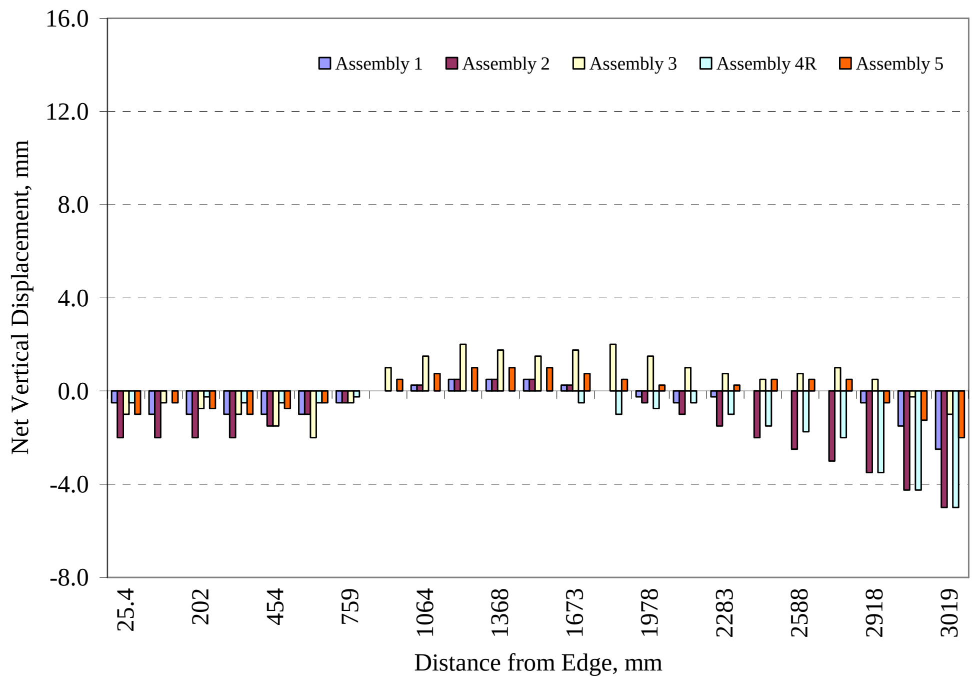


Figure 6.37: Net Displacement along Longitudinal Section T

Figures 6.38 through 6.40 compare the net improvement of test assembly 6 welded with 6000lb tension load with respect to benchmark assembly 3 after welding. The welding process for benchmark assembly 3 and test assembly 6 were the same (GMAW Superpulse Pulse on Spray). Benchmark assembly 3 was chosen to be reproduced under tension because this was determined to be the worst case scenario for vertical displacement (distortion).

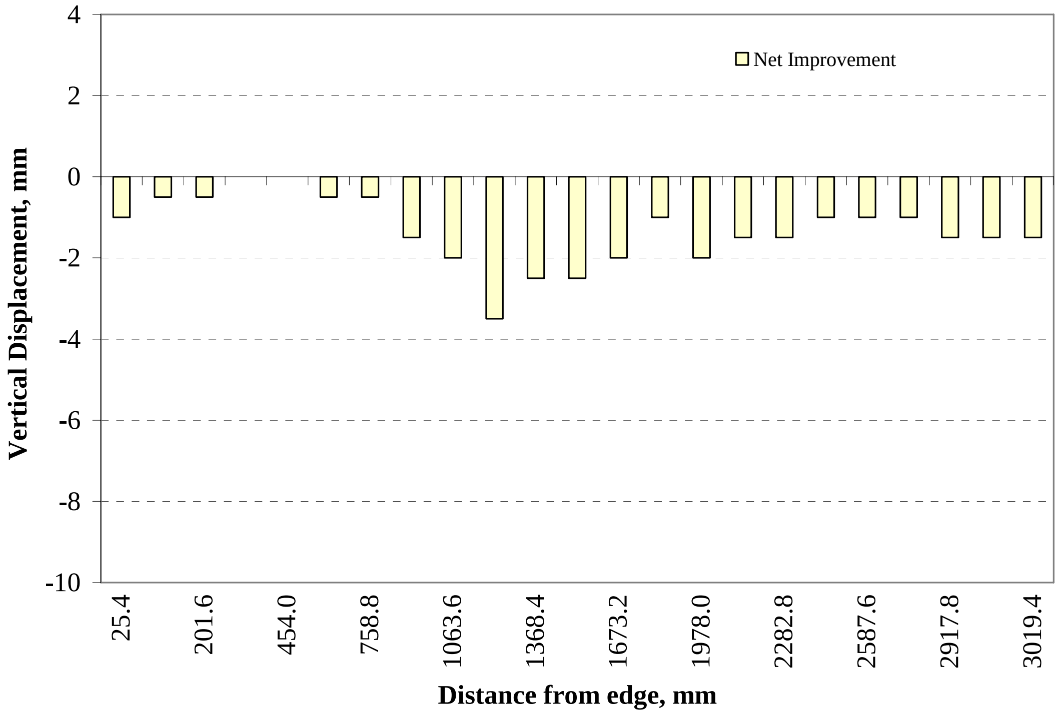


Figure 6.38: Net Improvement along Longitudinal Section A

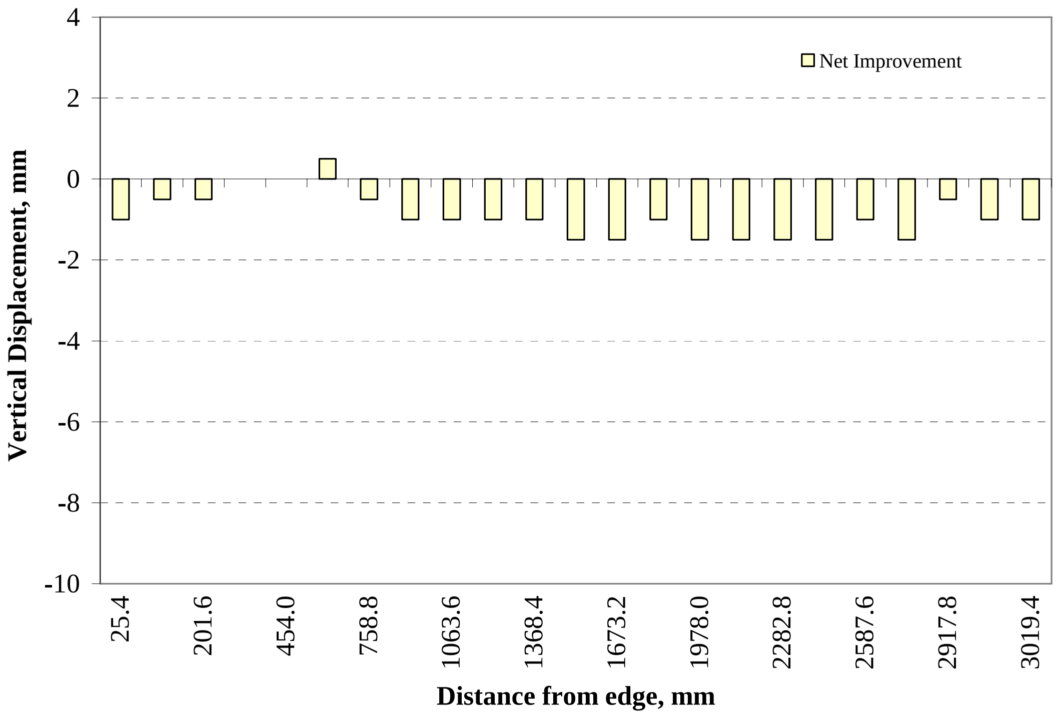


Figure 6.39: Net Improvement along Longitudinal Section B

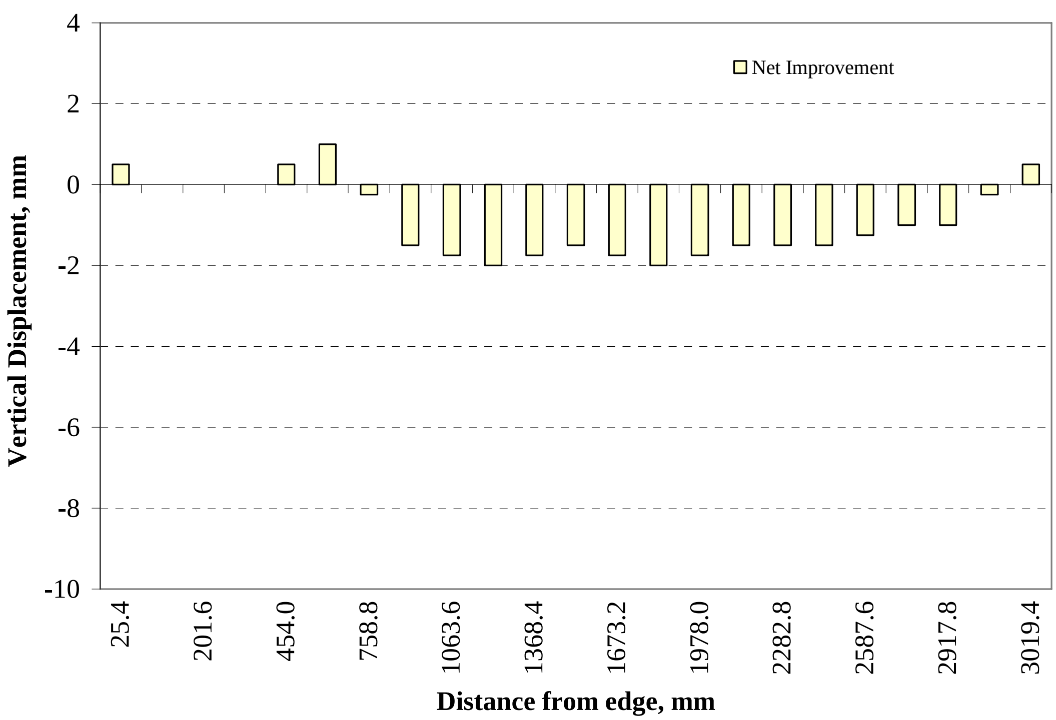


Figure 6.40: Net Improvement along Longitudinal Section T

Figures 6.41 through 6.45 show the appearance of the weld beads with the five different processes. As seen in the photos, the superpulse technology produces a very consistent bead profile.

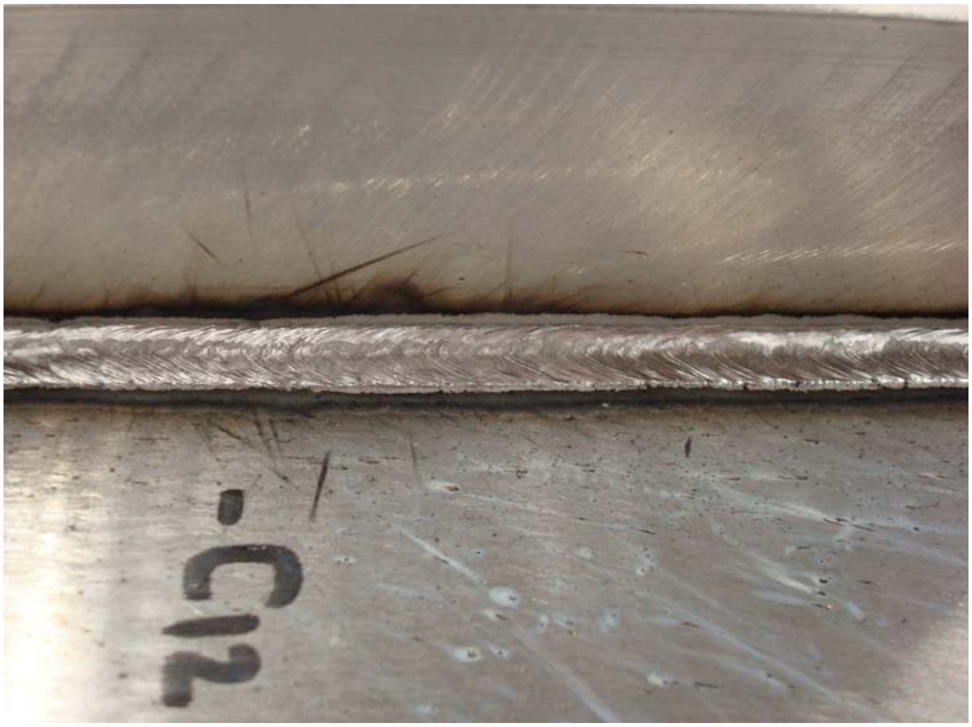


Figure 6.41: Weld Profile, Benchmark Assembly 1 (Conventional CV)

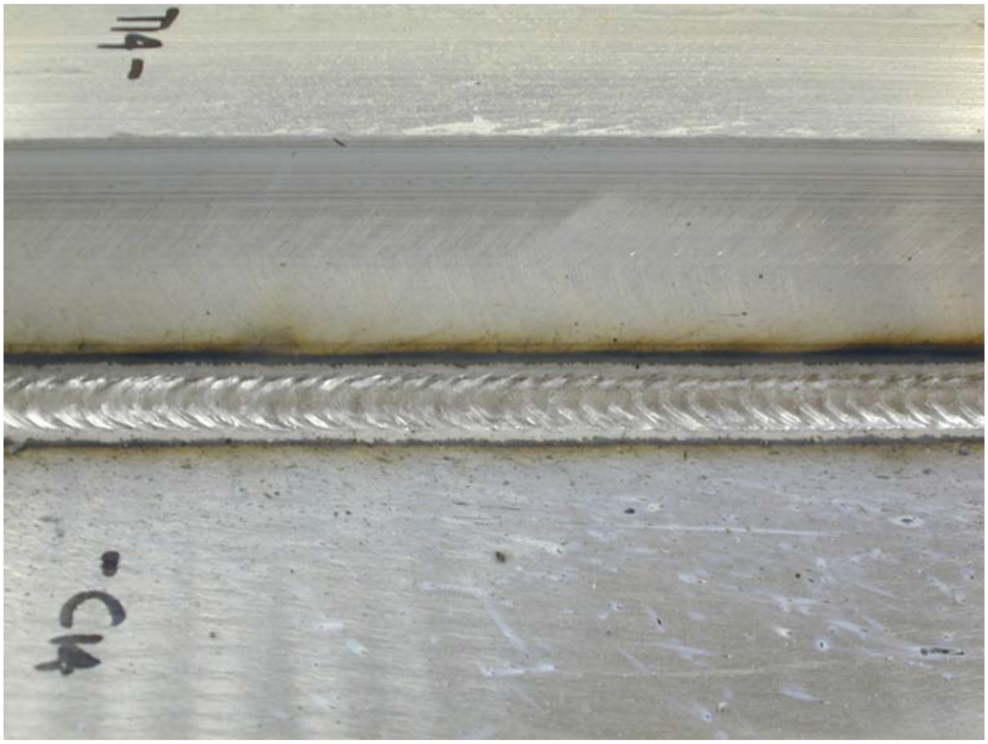


Figure 6.42: Weld Profile, Benchmark Assembly 2 (Pulse on Pulse)

Figure 6.43: Weld Profile, Benchmark Assembly 3 (Pulse on Short)

Figure 6.44: Weld Profile, Benchmark Assembly 4 (Pulse on Spray)

Figure 6.45: Weld Profile, Benchmark Assembly 5 (Pulse)

Figures 6.46 through 6.50 show the cross-section of the assembly with an etched surface demonstrating the penetration profiles of the four benchmark welds. These etched samples were taken from procedure development trials before the actual benchmark test assemblies were welded. The actual benchmark assemblies will remain intact for future reference. The penetration is acceptable for all five welds.

Figure 6.46: Cross-section Showing Penetration Profile of Benchmark Assembly1

Figure 6.47: Cross-section Showing Penetration Profile of Benchmark Assembly2

Figure 6.48: Cross-section Showing Penetration Profile of Benchmark Assembly3

Figure 6.49: Cross-section Showing Penetration Profile of Benchmark Assembly4

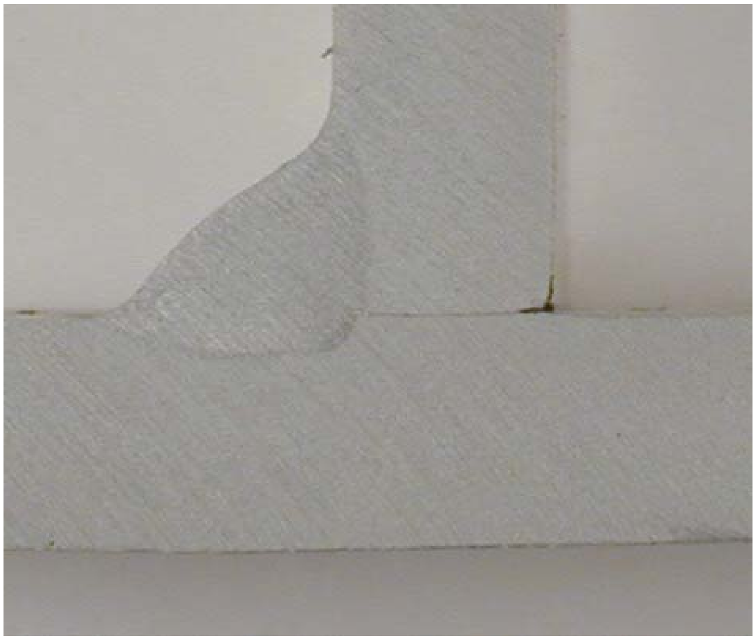


Figure 6.50: Cross-section Showing Penetration Profile of Assembly5

Tables 6.9 through 6.12 show comparisons of weld sizes obtained, travel speeds, resulting heat inputs, and displacement values. Weld size values followed by a + symbol indicate that the weld size is larger than the size indicated, and smaller than the next weld size to a 1/16”. Heat input values are calculated using average amperage and voltage values. Displacement values are obtained from Tables 6.4 through 6.8. The “Sum Torsion” column refers to the displacement relationship between points A and B after welding compared to points A and B before welding. The value shown in the table is the sum of the absolute difference between locations A and B for points 1 to 23 after welding subtracted by before welding values. A high positive value indicates increased torsion, twisting or uneven lifting of the plate edges. The “Sum Net Displacement” column refers to the sum of the net displacement values from locations A and B for all 23 points. A high positive value indicates increased vertical displacement over the length of the test assembly. A negative value represents less vertical displacement than the original test assembly which is an improvement over the original plate.

Table 6.9: Resulting Weld Sizes

Test Assembly	Weld Size (in.)
Benchmark Assembly 1 (CV)	3/16+
Benchmark Assembly 2 (Pulse/Pulse)	¼
Benchmark Assembly 3 (Pulse/Spray)	3/16+
Benchmark Assembly 4 (Pulse/Short)	¼
Benchmark Assembly 5 (Pulse)	3/16+

Table 6.10: Travel Speeds

Test Assembly	Travel Speed (IPM)
Benchmark Assembly 1 (CV)	50
Benchmark Assembly 2 (Pulse/Pulse)	30
Benchmark Assembly 3 (Pulse/Spray)	35
Benchmark Assembly 4 (Pulse/Short)	25
Benchmark Assembly 5 (Pulse)	46

Table 6.11: Heat Input

Test Assembly	Heat Input (KJ/IN)
Benchmark Assembly 1 (CV)	6.2
Benchmark Assembly 2 (Pulse/Pulse)	9.1
Benchmark Assembly 3 (Pulse/Spray)	7.9
Benchmark Assembly 4 (Pulse/Short)	7.3
Benchmark Assembly 5 (Pulse)	7.2

Table 6.12: Displacement Values

Test Assembly	Torsion (mm)	Sum Net Displacement (mm)
Benchmark Assembly 1 (CV)	+17.5	+33.5
Benchmark Assembly 2 (Pulse/Pulse)	+16.0	-23.0
Benchmark Assembly 3 (Pulse/Spray)	+13.0	+62.0
Benchmark Assembly 4 (Pulse/Short)	+40.0	+157.0
Benchmark Assembly 4 Repeat (Pulse/Short)	+35.0	-7.0
Benchmark Assembly 5 (Pulse)	+25.0	+47
Assembly 6 (6000lbs Tension, Pulse/Spray)	+13.5	+10.5

6.6 Summary of Results for Advanced Aluminum Welding Process

From the data presented, it can be concluded that the superpulse-pulse on pulse process results in less distortion than the other four benchmark processes. Based on the process comparison and data presented above, the following ranking lists the processes in order from best to worst with respect to resulting distortion (vertical displacement):

1. Superpulse, Pulse on Pulse
2. Conventional CV
3. Superpulse. Pulse on Short
4. Pulse
5. Superpulse, Pulse on Spray

This ranking is subjective because some assemblies such as benchmark assembly 4 repeat (pulse/short) demonstrated an improvement over the length of the plate; however it demonstrated more torsion (differences in displacement values between points A and B for a given location). For better visualization of torsion, refer to Tables 6.2 through 6.8 where color red indicates higher distortion compared to color yellow and light green indicates no change. In all cases, the trend for the longitudinal plots was for increased distortion at section B compared to section A, C, and T. Section B is along the edge on the same side as the weld deposit. When comparing Net Displacement Longitudinal Plots of section B for benchmark assembly 1 and benchmark assembly 2 (Figure 5.64 and Figure 5.68), it is clear that benchmark assembly 2 resulted in less distortion than benchmark assembly 1.

Benchmark assembly 3 (pulse/spray) was repeated under tension as assembly 6 because the vertical displacement values were the highest of the five processes with a "Sum Net Displacement" at +62. The objective of using mechanical tensioning during the welding of the assembly was to reduce vertical displacement without significant increases in torsion. Assembly 6 was welded using a tension load of 6000lbs and a significant reduction in distortion was observed compared to benchmark assembly 3. Assembly 6 was similar to benchmark assembly 3 for torsion. The "sum net displacement" improves from +62mm to +10.5mm, an improvement of 51.5mm or **490%** using mechanical tensioning vs. an unrestrained condition. It is also useful to compare Net Displacement Longitudinal Plots from Figure 6.11 to Figure 6.14 for benchmark 3 and Figure 6.31 to 6.34 for assembly 6. Net Improvement Longitudinal Plots from Figure 6.38 to 6.40 highlight the improvement in distortion from benchmark assembly 3 to assembly 6 performed under tension.

The results for benchmark assembly 4 (pulse/short) were compromised due to tacks breaking during welding at the 2200mm location on the assembly. Benchmark assembly 4 was repeated to rule out the possibility of additional distortion occurring in this location due to the broken tacks. Benchmark assembly 4 (repeat) confirmed that there was indeed an increase in distortion due to the broken tacks. The "Sum Net Displacement" was improved from +157mm to -7.0mm, an improvement of 164mm. During welding of assembly 6 under tension, a tack broke as well. With the aid of the mechanical tensioning, there were no adverse effects with respect to distortion from the broken tack on this assembly.

There appears to be no correlation between heat input and resulting distortion as superpulse-pulse on pulse has the highest heat input, and lowest distortion of the four processes. The conventional CV process was able to achieve the greatest travel speed at 50IPM which is a benefit for productivity. The pulse process was very close in travel speed at 46IPM; however, distortion was greater with pulse than with conventional CV.

The superpulse technology is limited in travel speed due to the switching between primary and secondary phases. Reducing the second phase time can assist in traveling faster; however, this is counteractive to the benefits of the superpulse technology as the process becomes more similar to standard pulse transfer. Traveling too fast with the superpulse processes results in less desirable weld profile and erratic arc characteristics. The weld size of ¼" for Benchmark Assembly 2 and Benchmark Assembly 4 was larger than initially desired; however, the parameters were necessary to maintain acceptable penetration and fusion profiles. Benchmark Assembly 2 (Pulse on Pulse) achieves the greatest amount of straightening at the two ends of the plate as seen in Figures 6.35, 6.36 and 6.37. Negative values indicate that the plate has reduced in vertical displacement after welding compared to the plate position before welding. Benchmark Assembly 4 (repeat) resulted in a similar effect as well as benchmark assembly 1.

There appears to be no correlation between penetration profile and resulting distortion. The most desirable weld profiles resulted from the superpulse and pulse processes with flat bead shapes. The conventional CV process resulted in a slightly convex bead shape. Depth of penetration is acceptable for all five processes with the least penetration being achieved with superpulse, pulse on short as seen in Figure 2.103.

Welding procedure data sheets for the five process variations (Standard CV, Standard Pulse, Superpulse Pulse on Pulse, Superpulse Pulse on Spray, and Superpulse Pulse on Short) are shown in **Appendix D.**

Follow on work to this project could include investigating the tolerance of superpulse technology when dealing with inconsistent fit-up (root gaps) compared to conventional CV. This work could be performed in both non-restrained and tensioned state. It is believed that the cooling effect of the secondary phase with superpulse technology would allow for larger deviations in fit-up. It is also believed, based on the effectiveness of the mechanical tensioning with breaking tacks, that there would be a more significant advantage of using mechanical tensioning in cases where fit up is less than optimal.

7. TASK 5: TANDEM MCAW (T-MCAW) OF STIFFENER ASSEMBLIES RESULTS

Welding of stiffener assemblies with the FCAW process, tension and no-tension cases, was discussed earlier. The same stiffener panel assembly configuration was repeated using the T-MCAW process, tension and no-tension cases, to compare with the FCAW results. Different shielding gases were also experimented with to determine the optimal gas for achieving high speed fillet welds with desired surface and penetration profile characteristics. The base plates used for this work were 10" wide, 5mm thick CSA G40.21 300W uncoated steel.

Once the results were complete and the optimal parameters, shielding gas and tension load was determined, final weldments were produced on larger scale 4' x 10' primed HSLA 80 panels. Parameters were fine tuned to achieve desirable fillet welds welding over primer. The FCAW benchmark procedure was repeated for tension and no-tension cases for comparison to the T-MCAW when welding over primer on HSLA 80 Steel.

7.1 Stiffened Panel Assembly (10" wide base plate)

All the stiffened panels (5mm thick) to be welded were marked up as illustrated in Figure 7.1. Panel distortion (vertical) measurements are recorded for points A, B and T along the width and T1 to T23 along the length, using a laser level. For all plates to be welded under mechanical tension, the distortion data is recorded at all three stages:

1. Before welding
2. Before welding under tension
3. After welding

For benchmark stiffener assembly in absence of tension, data is recorded before and after completion of welding. In addition, a similar measurement grid was setup for the test support frame upon which the stiffener assembly to be welded was supported.

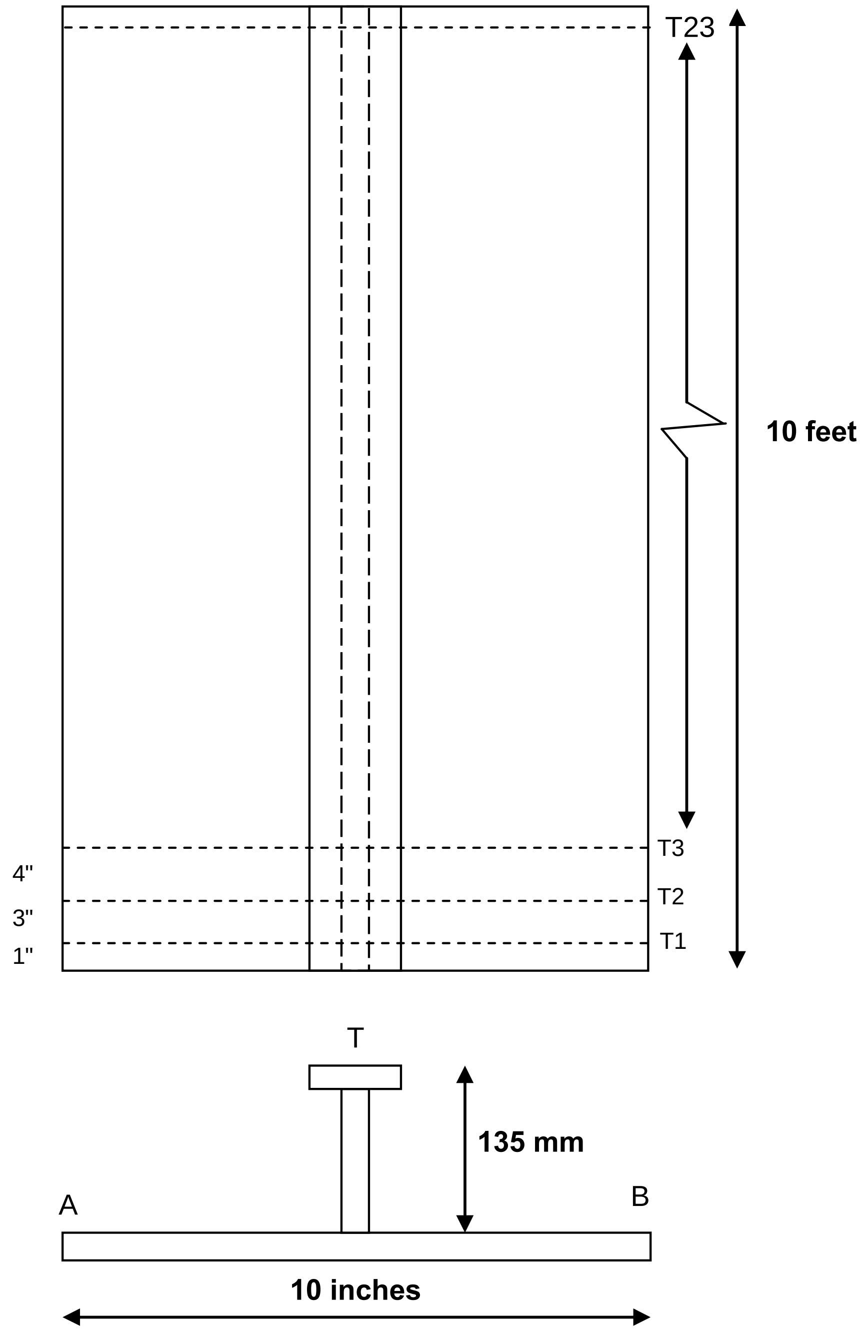


Figure 7.1: Stiffened Panel Distortion Measurement Grid

T-MCAW process was used for all welded stiffener assemblies. Table 7.1 summarizes the test cases that were analyzed. Tables 7.2 through 7.5 summarize the measured distortion data for stiffener assemblies at locations A and B. The data is color-coded red and yellow to help better visualize the assembly distortion (torsion). The color red indicates a higher distortion compared to color yellow, whereas light green indicates no change in displacement.

Table 7.1: Test Summary

Stiffener Assembly	Applied Tension (lbs)
T-MCAW_Stiff_1_Benchmark 92Ar/8C02	0
T-MCAW_Stiff_2 92Ar/8C02	10,000
T-MCAW_Stiff_3 85Ar/15C02	10,000
T-MCAW_Stiff_4 75Ar/25C02	10,000

Table 7.2: T-MCAW_Stiff_1_Benchmark Distortion Data

	Before Weld					After Weld			
	Displacement w.r.t to Frame, mm					Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff		A	T	B	Abs Diff
1	9	58.5	10	1	1	5.5	55.5	5.5	0
2	8	58	9	1	2	5.5	55	5.5	0
3	6.5	56.75	7.5	1	3	4.5	54	4.5	0
4	6	55.5	6.5	0.5	4	4	53	4.5	0.5
5	4.5	54	5	0.5	5	3.5	52	3.5	0
6	3.5	52.5	3	0.5	6	2	51	2.5	0.5
7	2.5	51.75	2.5	0	7	1.5	50.5	2	0.5
8	1.5	51	1.5	0	8	1	50	1	0
9	1	50.5	1	0	9	1	49.5	0.5	0.5
10	0.5	50	0.5	0	10	0.5	49	0.5	0
11	1	50.5	0.5	0.5	11	1	49.5	0.5	0.5
12	1	51	1	0	12	1.5	50	1.5	0
13	1.5	51	1	0.5	13	1.5	50.25	1.5	0
14	1	51	1	0	14	1	50.5	1	0
15	2	51.75	1	1	15	2	51	1.5	0.5
16	3	52.5	1.5	1.5	16	3	51.5	2	1
17	4	53.25	2	2	17	3.5	52.5	2	1.5
18	5.5	54	3	2.5	18	4.5	53.5	3.5	1
19	7	55.5	4.5	2.5	19	4	54.5	4.5	0.5
20	8.5	57	6	2.5	20	7.5	55.5	5	2.5
21	10.5	59	7.5	3	21	8.5	57	5.5	3
22	11	59.5	7.5	3.5	22	9.5	57.5	6	3.5
23	11.5	60	9.5	2	23	10	58	6.5	3.5

Table 7.3: T-MCAW_Stiff_2_92Ar/8C02 Distortion Data

	Before Weld			
	Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff
1	11.5	60	11.5	0
2	11.5	59.5	11.5	0
3	10.5	58	11	0.5
4	10	56.5	10	0
5	8	55	8.5	0.5
6	6.5	53.5	6.5	0
7	5.5	52.5	4.5	1
8	4.5	51.5	4	0.5
9	3.5	50.25	3	0.5
10	3	49	2	1
11	3	49.5	2	1
12	3	50	2.5	0.5
13	3.5	49.75	2.5	1
14	3	49.5	2	1
15	3	50	2.5	0.5
16	4	50.5	3.5	0.5
17	4	51.25	4	0
18	4.5	52	4.5	0
19	5.5	52.75	5	0.5
20	6.5	53.5	6.5	0
21	7.5	55	8	0.5
22	7.5	55.25	8	0.5
23	7.5	55.5	8	0.5

	Tension No Weld			
	Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff
1	6.5	55	6.5	0
2	6.5	54.5	6.5	0
3	5	53.5	5	0
4	5.5	52.5	5.5	0
5	4.5	51.5	4.5	0
6	3	50.5	3	0
7	2	49.5	2	0
8	1.5	48.5	1.5	0
9	1	47.75	1	0
10	0.5	47	0	0.5
11	1	47.25	0.5	0.5
12	1.5	47.5	1	0.5
13	1.5	47.5	1	0.5
14	1	47.5	0.5	0.5
15	1	47.75	0.5	0.5
16	1.5	48	1	0.5
17	1	48.25	0.5	0.5
18	1.5	48.5	1.5	0
19	2	49.25	1.5	0.5
20	3.5	50	2.5	1
21	3.5	51	2	1.5
22	3.5	51.75	2	1.5
23	3.5	52.5	2	1.5

	After Weld			
	Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff
1	6.5	55	7	0.5
2	6.5	54.5	7	0.5
3	5.5	53.5	6	0.5
4	6	52.5	7	1
5	5	51	6.5	1.5
6	3.5	49.5	5	1.5
7	2.5	49	4	1.5
8	2	48.5	3.5	1.5
9	2	48	3	1
10	1.5	47.5	2.5	1
11	2	48	2.5	0.5
12	2	48.5	2.5	0.5
13	2	48.5	3	1
14	2	48.5	2.5	0.5
15	2	49	2.5	0.5
16	2.5	49.5	3	0.5
17	2.5	49.5	2.5	0
18	3	49.5	3.5	0.5
19	3	50.25	3.5	0.5
20	4	51	4	0
21	4	52	4	0
22	4	52.75	4	0
23	4	53.5	4	0

Table 7.4: T-MCAW_Stiff_3_85Ar/15C02 Distortion Data

	Before Weld			
	Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff
1	9.5	52.5	10.5	1
2	9.5	52	10.5	1
3	8.5	50.75	9.5	1
4	8	49.5	8.5	0.5
5	6.5	47.75	7	0.5
6	5	46	5	0
7	4	45.25	4.5	0.5
8	2.5	44.5	3	0.5
9	2	43.75	2	0
10	1.5	43	1	0.5
11	1.5	43.5	1	0.5
12	2	44	1.5	0.5
13	2	44	2	0
14	2	44	2	0
15	2.5	44.75	2	0.5
16	3	45.5	3	0
17	3.5	46.5	3.5	0
18	5	47.5	5	0
19	6	49	6	0
20	7.5	50.5	7.5	0
21	9	52	9	0
22	9	52.75	9	0
23	9	53.5	9	0

	Tension No Weld			
	Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff
1	5.5	49	6.5	1
2	5.5	48.5	6.5	1
3	4.5	47.5	5.5	1
4	5	46.5	5.5	0.5
5	4	45.25	5	1
6	2.5	44	3.5	1
7	1.5	43.5	2.5	1
8	1	43	1.5	0.5
9	1	42.5	1	0
10	0.5	42	0.5	0
11	1	42.5	1	0
12	1.5	43	1	0.5
13	1.5	43	1.5	0
14	1	43	1	0
15	1	43.25	1	0
16	1.5	43.5	1.5	0
17	1.5	44.25	2	0.5
18	2	45	3	1
19	3	46	4	1
20	4	47	5.5	1.5
21	3	48.5	5	2
22	3	49.25	5	2
23	3	50	5	2

	After Weld			
	Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff
1	6	48.5	7.5	1.5
2	6	48	7.5	1.5
3	5	47	6.5	1.5
4	5.5	46	7.5	2
5	4	45.25	7.5	3.5
6	3	44.5	6.5	3.5
7	2.5	44	6.5	4
8	1.5	43.5	5.5	4
9	2	43	5	3
10	1	42.5	4	3
11	1.5	43.25	4.5	3
12	2	44	5	3
13	2.5	43.75	5.5	3
14	2	43.5	5	3
15	2.5	44.25	5.5	3
16	2.5	45	5.5	3
17	3	45.5	6	3
18	4	46	7	3
19	4.5	47.25	7.5	3
20	5	48.5	7.5	2.5
21	4.5	49	6.5	2
22	4.5	49.75	5.5	1
23	4	50.5	5.5	1.5

Table 7.5: T-MCAW_Stiff_4_75Ar/25C02 Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	9.5	68	10	0.5
2	9.5	67.5	10	0.5
3	8.5	66	9	0.5
4	7.5	64.5	8	0.5
5	6	62.75	6.5	0.5
6	4.5	61	4.5	0
7	3	60	3	0
8	2.5	59	2.5	0
9	2	58.25	2	0
10	1.5	57.5	1	0.5
11	2	58	1	1
12	2	58.5	1.5	0.5
13	2	58.5	1.5	0.5
14	2	58.5	1	1
15	2.5	59.25	1.5	1
16	4	60	3	1
17	4.5	61	3	1.5
18	6	62	4	2
19	7.5	63.75	6	1.5
20	9.5	65.5	7.5	2
21	11.5	68	9.5	2
22	11.5	68.5	9.5	2
23	11.5	69	9.5	2

Tension No Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	6	65	4	2
2	6	64.5	4	2
3	5	63.25	3	2
4	6	62	4	2
5	5	60.5	3.5	1.5
6	3	59	2	1
7	2	58.25	1.5	0.5
8	1.5	57.5	1	0.5
9	1	57	1	0
10	0.5	56.5	0.5	0
11	1	57	0.5	0.5
12	1	57.5	1	0
13	1.5	57.5	1	0.5
14	1	57.5	1	0
15	1.5	58	1	0.5
16	2	58.5	1	1
17	2	58.75	1.5	0.5
18	2.5	59	2.5	0
19	3	60.25	3.5	0.5
20	4.5	61.5	5	0.5
21	4	63	5	1
22	4	63.75	5	1
23	4	64.5	5	1

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	5	63.5	4.5	0.5
2	5	63.5	4.5	0.5
3	4	62.25	3.5	0.5
4	5	61	5	0
5	4	59.5	5	1
6	2.5	58	4	1.5
7	2	57.5	3.5	1.5
8	1.5	57	3	1.5
9	1.5	56.75	2.5	1
10	1	56.5	1.5	0.5
11	1.5	57.25	2.5	1
12	2	58	2.5	0.5
13	2	57.75	2.5	0.5
14	2	57.5	2	0
15	2.5	57.5	2.5	0
16	3	57.5	3	0
17	3	58.5	3	0
18	3.5	59.5	3.5	0
19	5	60.5	3.5	1.5
20	6	61.5	4	2
21	6.5	63	3.5	3
22	6.5	63.5	3.5	3
23	6.5	64	3.5	3

Figures 7.2 through 7.4 illustrate the net displacements for the T-MCAW benchmark stiffener assembly.

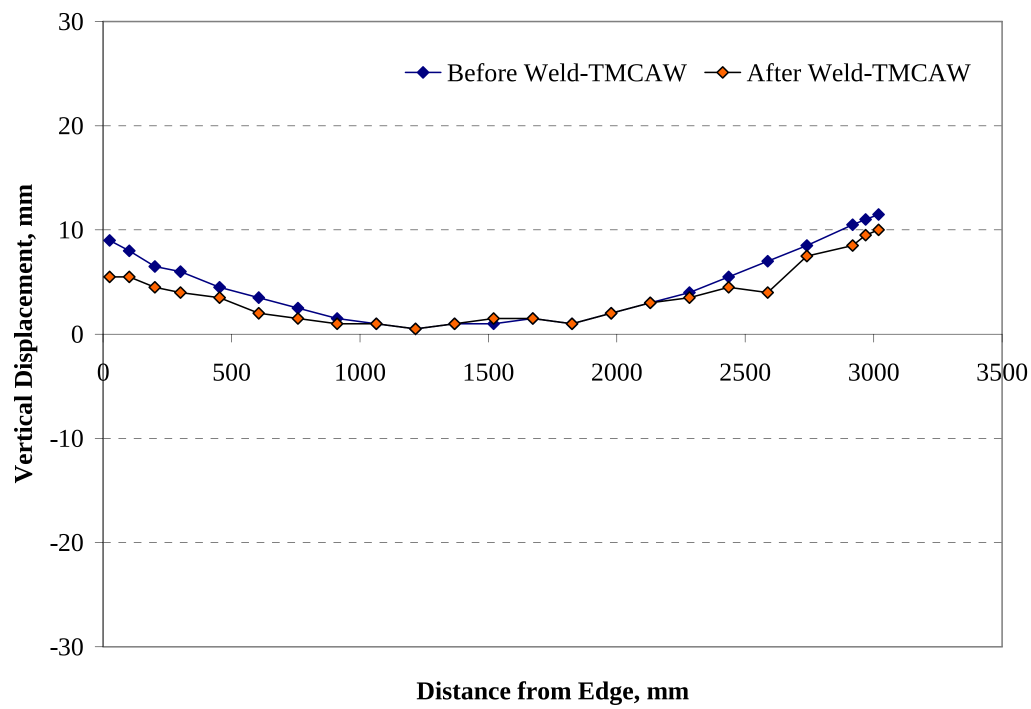


Figure 7.2: Net Displacement along Longitudinal Section A for T-MCAW Stiffener Benchmark Assembly

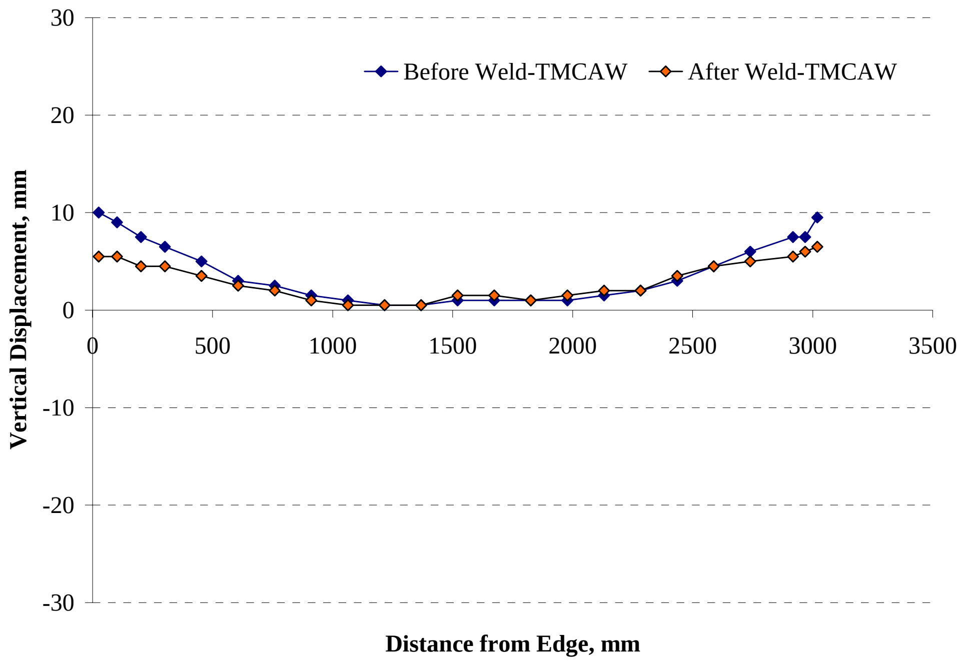


Figure 7.3: Net Displacement along Longitudinal Section B for T-MCAW Stiffener Benchmark Assembly

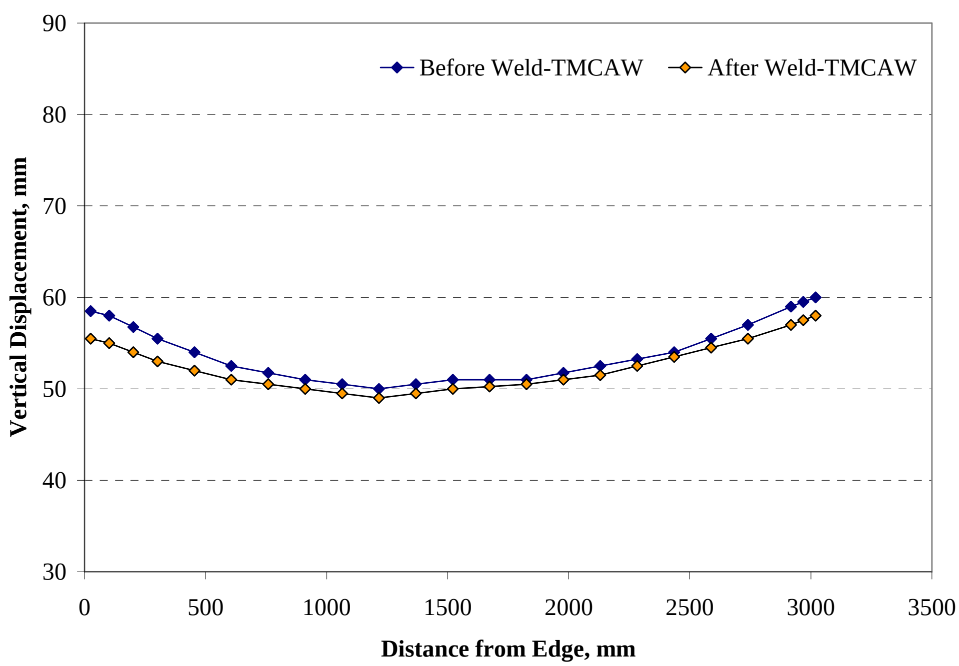
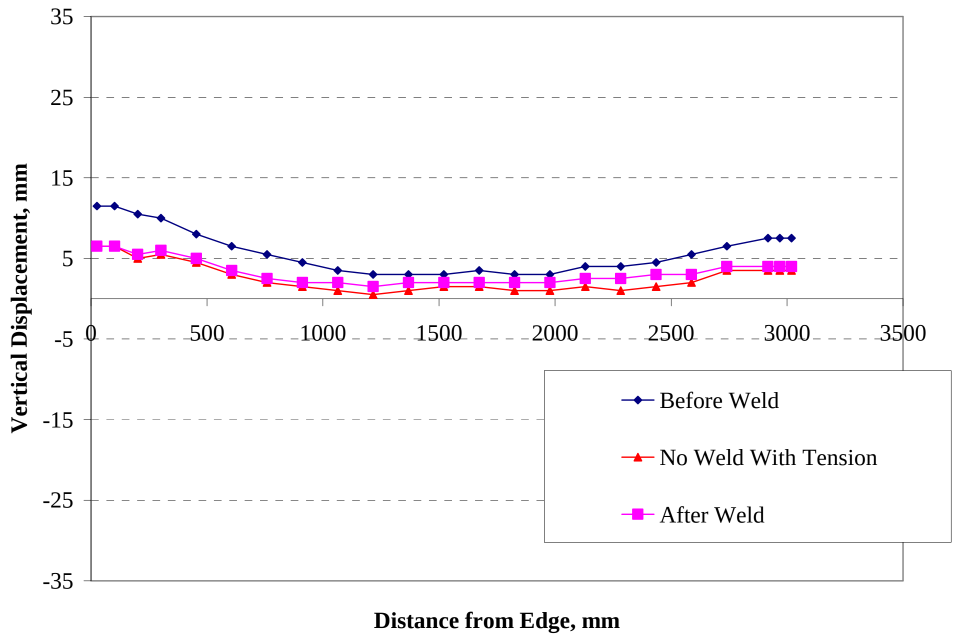


Figure 7.4: Net Displacement along Longitudinal Section T for T-MCAW Stiffener Benchmark Assembly

In order to measure the effectiveness of mechanical tensioning approach, the net displacement of each marked point on the assembly (Figure 6.39) with respect to the corresponding point on the test frame is compared at each of the stages. Figures 7.5 and 7.6 compare the net displacement along the longitudinal sections A and B for T-MCAW Stiffener Assembly subjected to a tension load of 10,000 lbs. using 92Ar/8C02 shielding gas. Additional plots are provided in **Appendix A.**



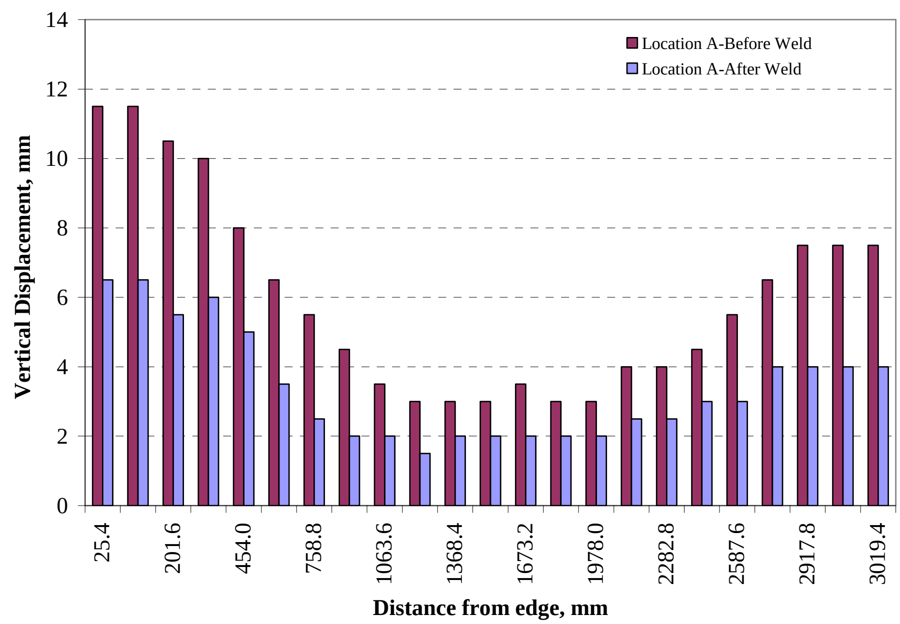


Figure 7.5: Net Displacement along Longitudinal Section A for T-MCAW Stiffener Assembly 2

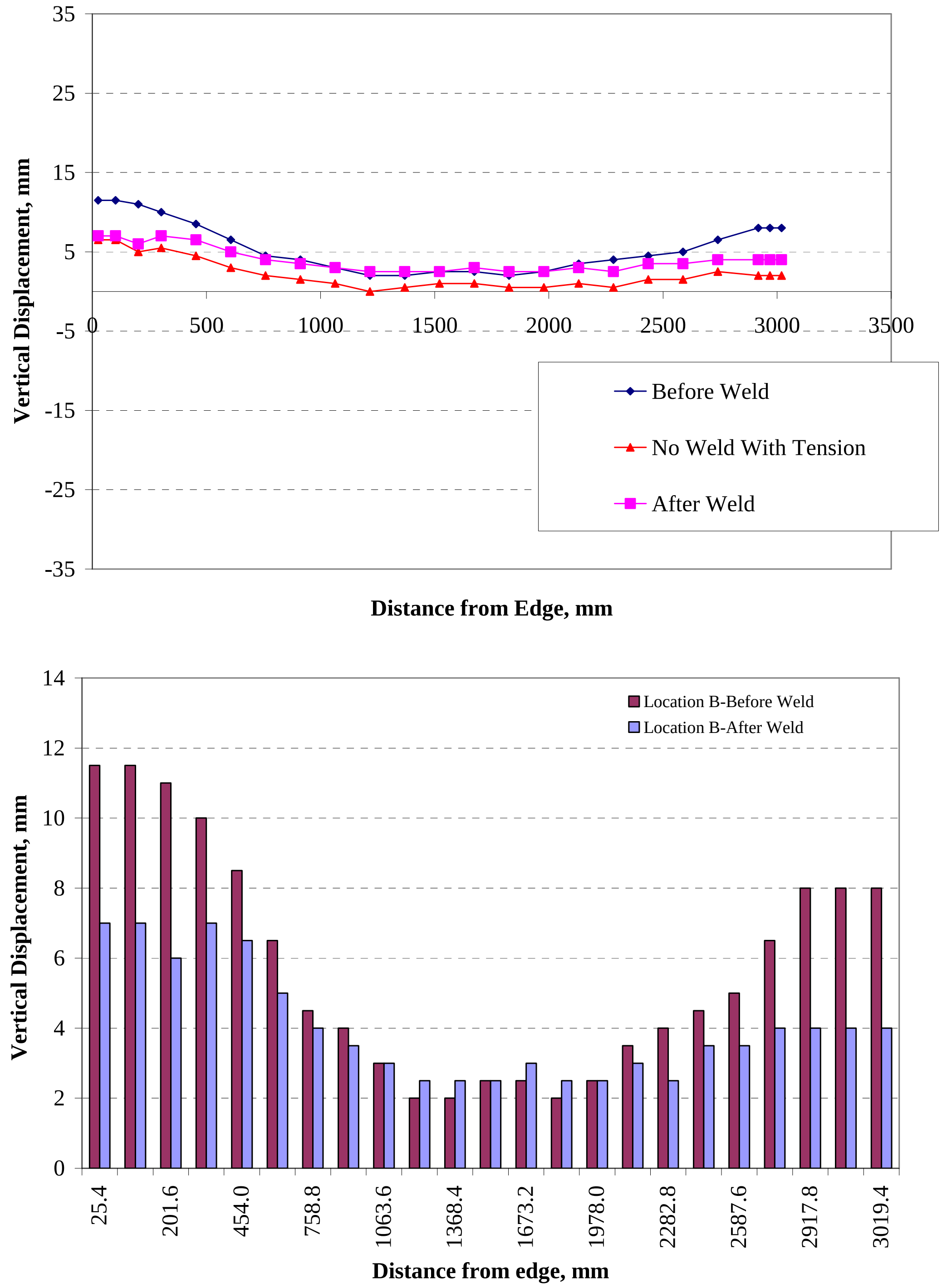


Figure 7.6: Net Displacement along Longitudinal Section B for T-MCAW Stiffener Assembly 2

7.1.1 Net Improvement

The distortion data in Table 7.6 and Figures 7.7 through 7.9 compare the overall net improvement achieved in controlling distortion under applied tension with respect to benchmark assembly. The negative values, color coded light blue indicates location where tensioning has been effective to counter distortion due to welding. Also cells color coded green indicate no change in distortion and yellow indicates an increase in distortion. Additional plots are provided in **Appendix F.**

Table 7.6: T-MCAW_Stiff_2 Net Displacement

Net Displacement, mm Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	-5	-5	-4.5	0.5
2	-5	-5	-4.5	0.5
3	-5	-4.5	-5	0
4	-4	-4	-3	1
5	-3	-4	-2	1
6	-3	-4	-1.5	1.5
7	-3	-3.5	-0.5	2.5
8	-2.5	-3	-0.5	2
9	-1.5	-2.25	0	1.5
10	-1.5	-1.5	0.5	2
11	-1	-1.5	0.5	1.5
12	-1	-1.5	0	1
13	-1.5	-1.25	0.5	2
14	-1	-1	0.5	1.5
15	-1	-1	0	1
16	-1.5	-1	-0.5	1
17	-1.5	-1.75	-1.5	0
18	-1.5	-2.5	-1	0.5
19	-2.5	-2.5	-1.5	1
20	-2.5	-2.5	-2.5	0
21	-3.5	-3	-4	0.5
22	-3.5	-2.5	-4	0.5
23	-3.5	-2	-4	0.5

Net Displacement, mm Benchmark				
	A	T	B	Abs Diff
1	-3.5	-3	-4.5	1
2	-2.5	-3	-3.5	1
3	-2	-2.75	-3	1
4	-2	-2.5	-2	0
5	-1	-2	-1.5	0.5
6	-1.5	-1.5	-0.5	1
7	-1	-1.25	-0.5	0.5
8	-0.5	-1	-0.5	0
9	0	-1	-0.5	0.5
10	0	-1	0	0
11	0	-1	0	0
12	0.5	-1	0.5	0
13	0	-0.75	0.5	0.5
14	0	-0.5	0	0
15	0	-0.75	0.5	0.5
16	0	-1	0.5	0.5
17	-0.5	-0.75	0	0.5
18	-1	-0.5	0.5	1.5
19	-3	-1	0	3
20	-1	-1.5	-1	0
21	-2	-2	-2	0
22	-1.5	-2	-1.5	0
23	-1.5	-2	-3	1.5

Net Improvement, mm Benchmark		
-1.5	-2	0
-2.5	-2	-1
-3	-1.75	-2
-2	-1.5	-1
-2	-2	-0.5
-1.5	-2.5	-1
-2	-2.25	0
-2	-2	0
-1.5	-1.25	0.5
-1.5	-0.5	0.5
-1	-0.5	0.5
-1.5	-0.5	-0.5
-1.5	-0.5	0
-1	-0.5	0.5
-1	-0.25	-0.5
-1.5	0	-1
-1	-1	-1.5
-0.5	-2	-1.5
0.5	-1.5	-1.5
-1.5	-1	-1.5
-1.5	-1	-2
-2	-0.5	-2.5
-2	0	-1

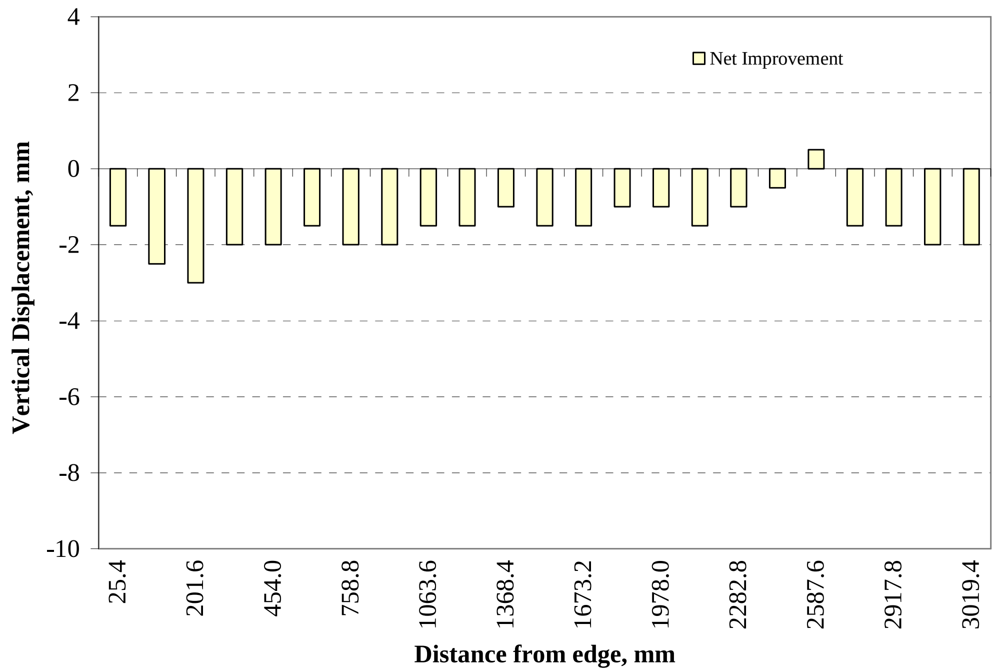


Figure 7.7: T-MCAW_Stiff_2 -Net Improvement at Location A.

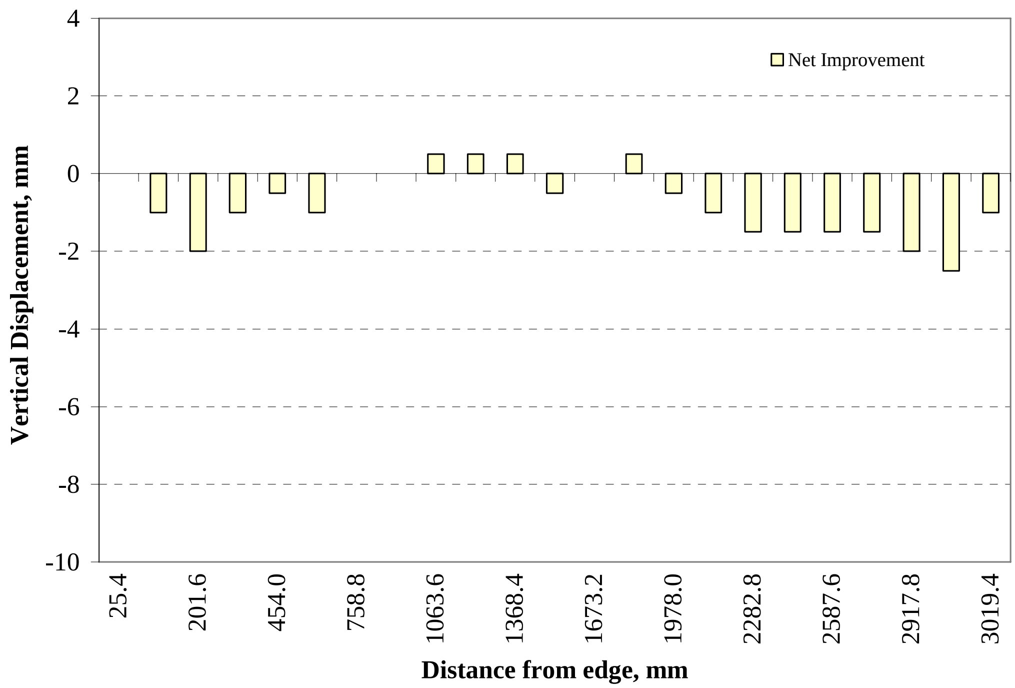


Figure 7.8: T-MCAW_Stiff_2 -Net Improvement at Location B

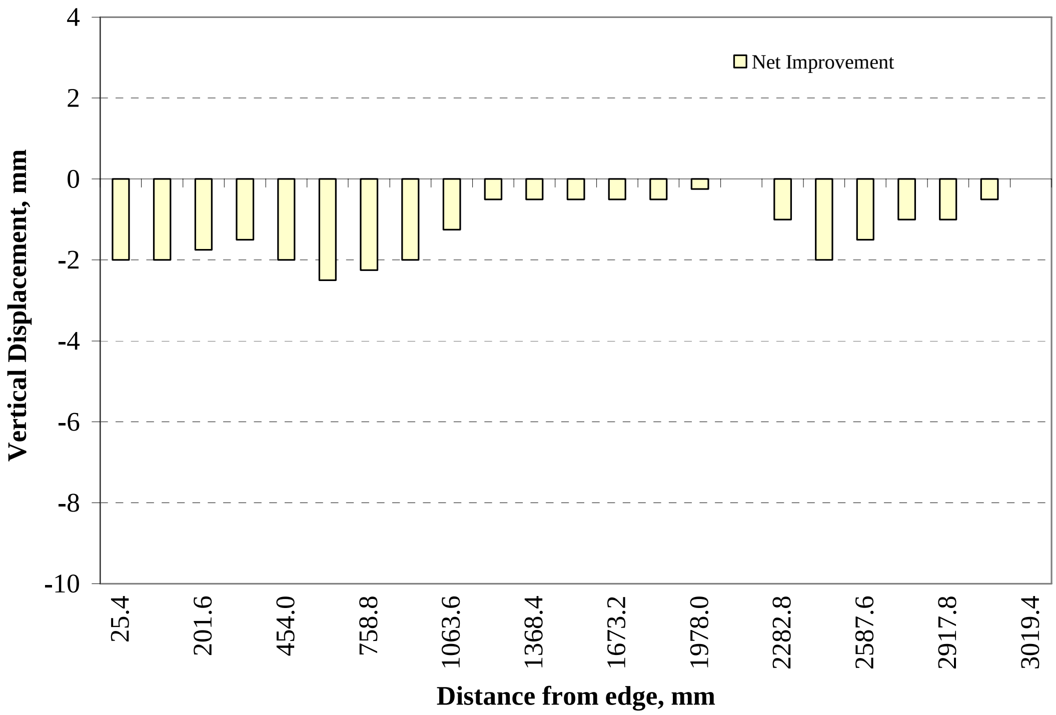


Figure 7.9: T-MCAW_Stiff_2 -Net Improvement at Location T

As mentioned previously, the FCAW process, with and without tension, was presented in earlier in this report. Displacements are plotted on Figures 7.10 through 7.12 for locations A, B, and T to compare the non-tension cases. Net-Improvement comparisons are shown on Figures 7.13 through 7.15 for 10 000lbs tension cases. Additional distortion plots are shown in **Appendix E.**

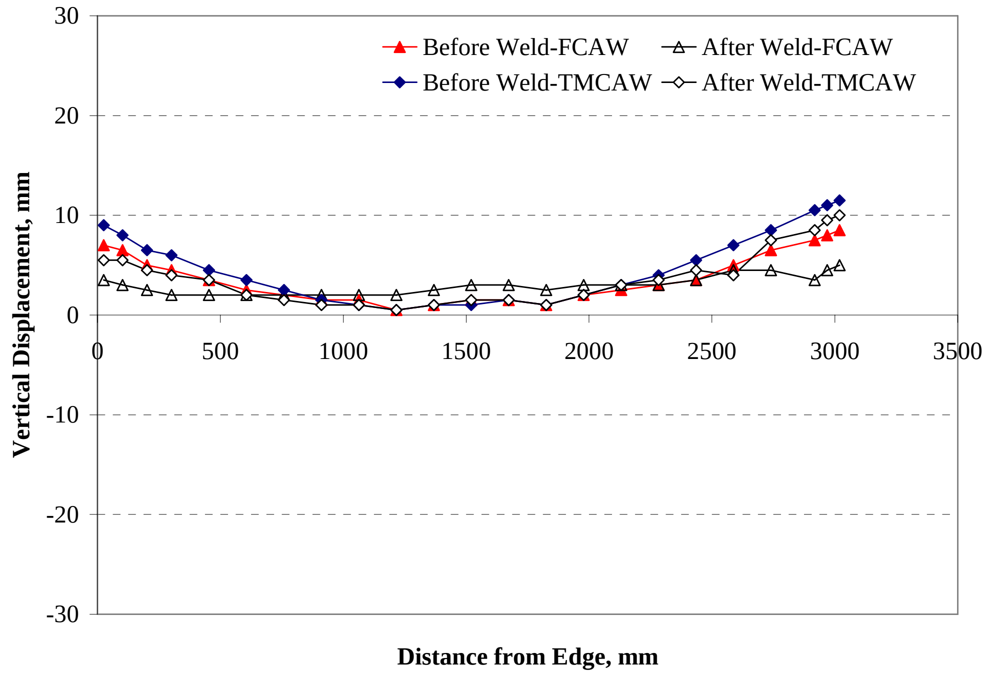


Figure 7.10: Net Displacement along Longitudinal Section A for Benchmark T-MCAW Stiffener Assembly vs. Benchmark FCAW Stiffener Assembly

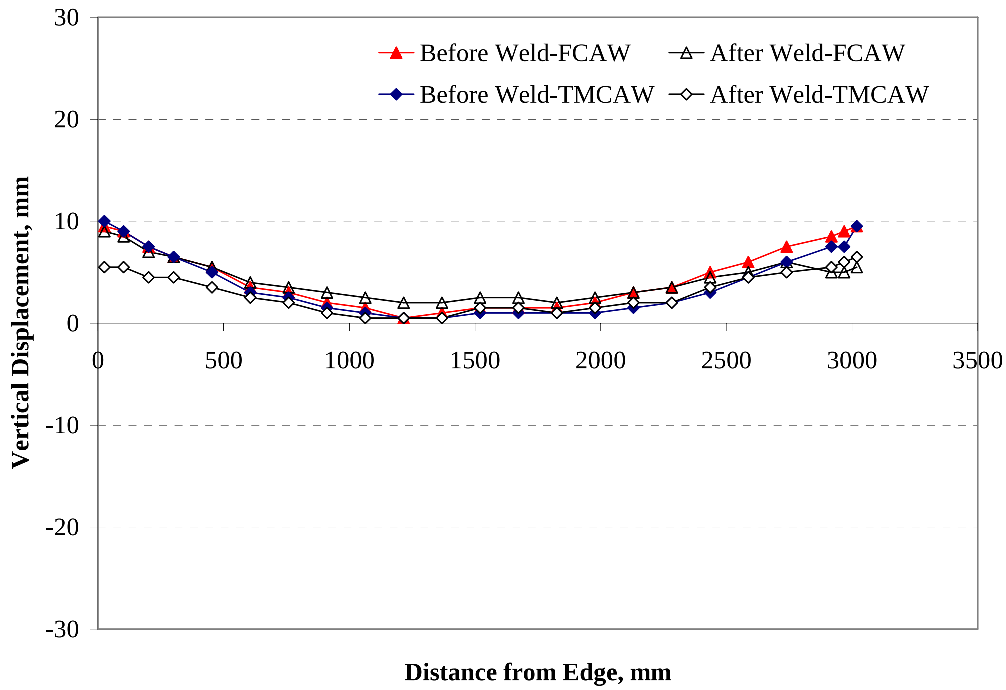


Figure 7.11: Net Displacement along Longitudinal Section B for Benchmark T-MCAW Stiffener Assembly vs. Benchmark FCAW Stiffener Assembly

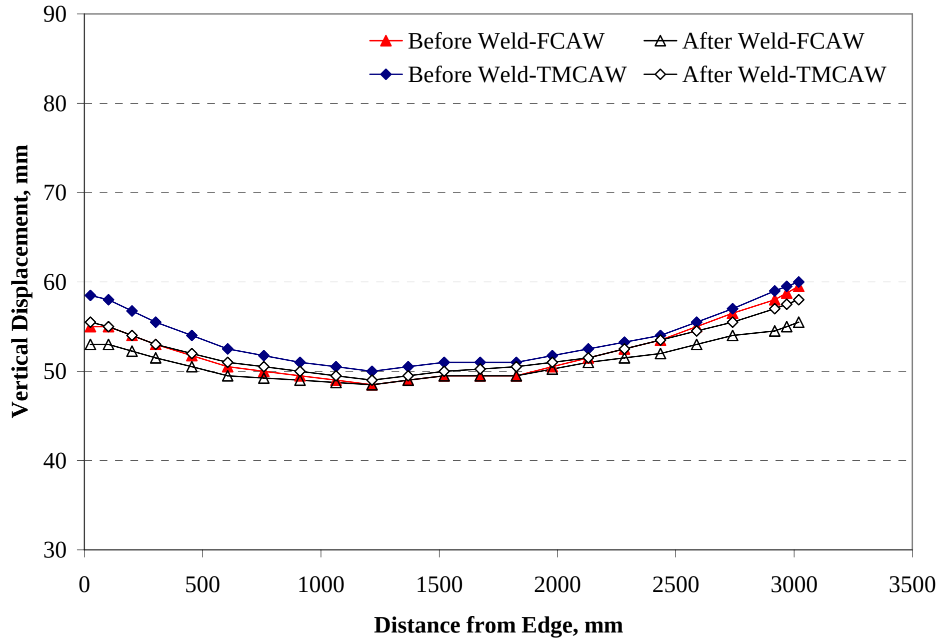


Figure 7.12: Net Displacement along Longitudinal Section T for Benchmark T-MCAW Stiffener Assembly vs. Benchmark FCAW Stiffener Assembly

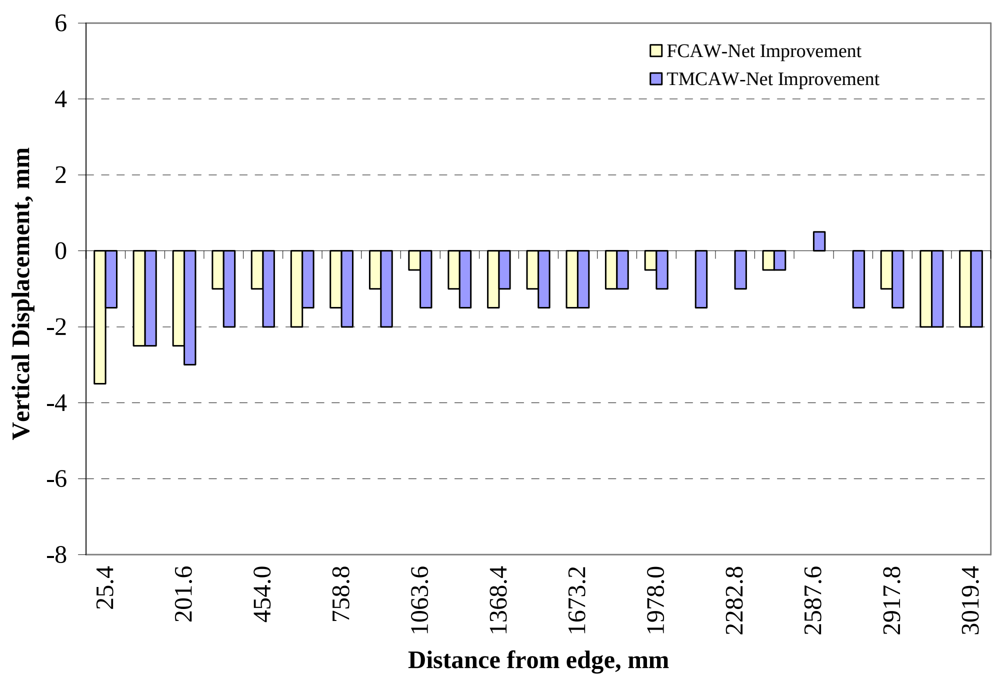


Figure 7.13: Net Improvement along Longitudinal Section A for T-MCAW Stiffener Assembly vs. FCAW Stiffener Assembly with 10 000lbs Tension

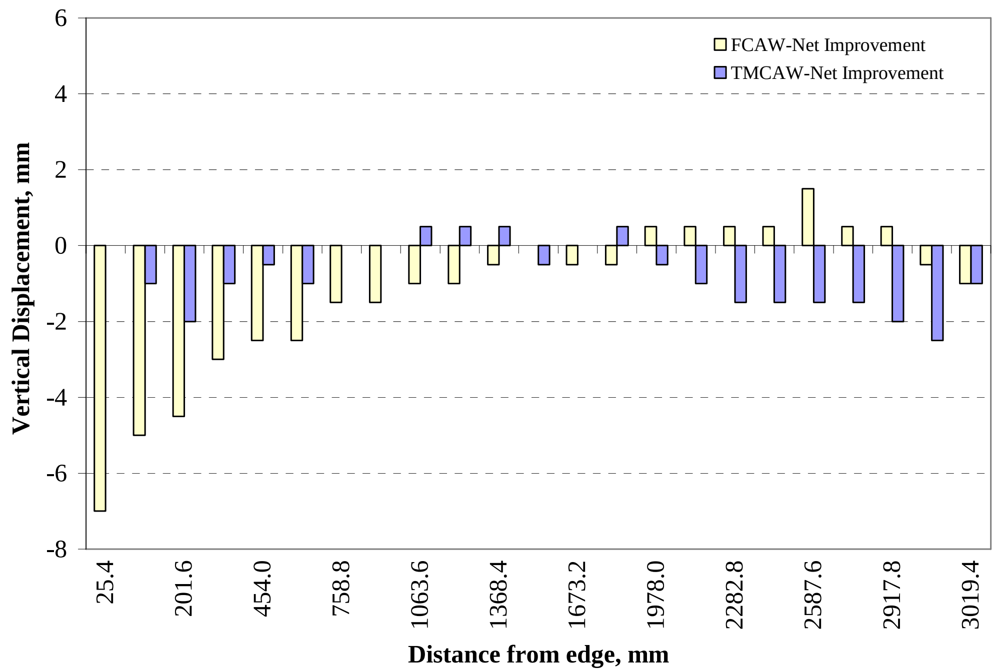


Figure 7.14: Net Improvement along Longitudinal Section B for T-MCAW Stiffener Assembly vs. FCAW Stiffener Assembly with 10 000lbs Tension

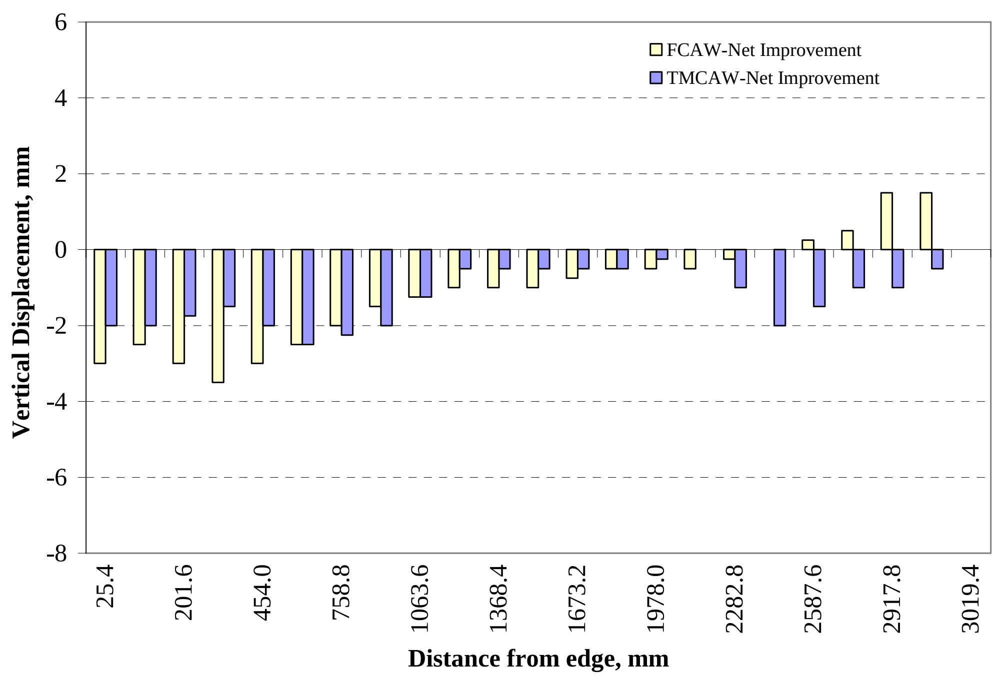


Figure 7.15: Net Improvement along Longitudinal Section T for T-MCAW Stiffener Assembly vs. FCAW Stiffener Assembly with 10 000lbs Tension

From the data presented it can be concluded that the mechanical tensioning approach as applied to fillet welding of stiffener assemblies does provide an advantage to counter distortion. The best weldability, profile, and distortion results were with the use of 92Ar/8C02 shielding gas. Penetration profile and weld profile are shown in Figure 7.16 and 7.17**.** Second best results were achieved with the use of 85Ar/15C02, see Figure 7.18 for weld profile.

The data presented also shows that use of the T-MCAW process results in a similar reduction in distortion compared with the FCAW process. The advantage is that with the T-MCAW process, welding speeds are 90IPM compared to 28IPM with the FCAW Process representing a 221% improvement in travel speed. The productivity of the stiffener welding operations would be greatly increased by using the T-MCAW process.

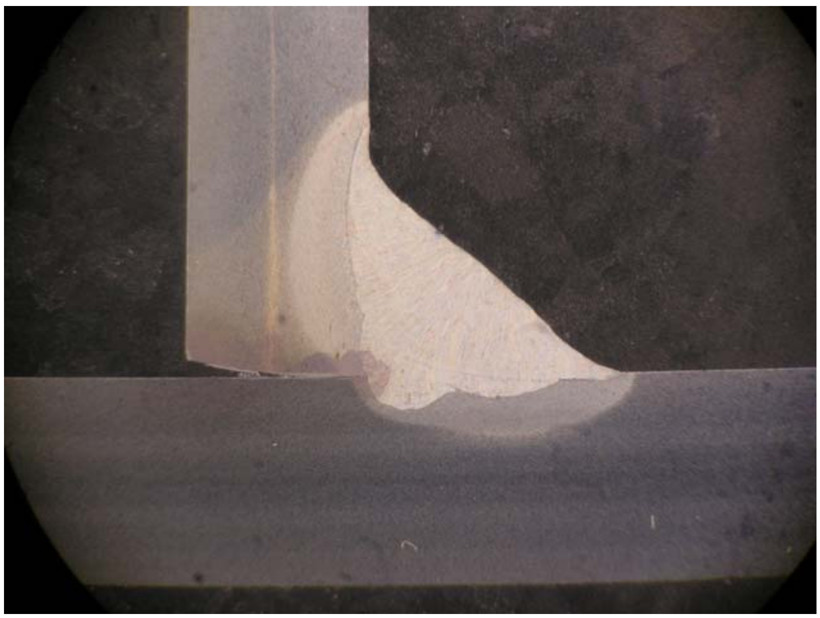


Figure 7.16: T-MCAW Weld Profile

Figure 7.17: T-MCAW Weld Profile with 92Ar/8C02

Figure 7.18: T-MCAW Weld Profile with 85Ar/15C02

The above results are with material that has primer and mill scale removed. Common practice in the shipyards is to weld the stiffeners to the plate material over the primer. Parameters were tweaked for both FCAW and T-MCAW process for welding over primer. The test assemblies welded over primer used larger HSLA 80 sheets, approximately 4' x 10' in size. A new distortion matrix was created to adequately capture change in vertical displacement of the larger assemblies. Preliminary welds were produced and it was determined that the use of 85Ar/15C02 shielding gas was better suited to welding over primer compared to 92Ar/8C02 shielding gas.

7.2 Stiffened Panel Assembly (4' x 10' HSLA 80 Base Plate)

All the stiffened panels (5mm thick) to be welded were marked up as illustrated in Figure 7.19. Panel distortion (vertical) measurements are recorded for points A through K along the width and T1 to T23 along the length, using a laser level. For all plates to be welded under mechanical tension, the distortion data is recorded at all three stages:

1. Before welding
2. Before welding under tension
3. After welding

For benchmark stiffener assembly in absence of tension, data is recorded before and after completion of welding. In addition, a similar measurement grid was setup for the test support frame upon which the stiffener assembly to be welded are supported.

Additional readings included coating thickness measurements which were taken every 4" along the length of the plate (weld zone) and stiffener edge to determine if there is any correlation between porosity and primer thickness. Tables 7.7 and 7.8 show the coating thickness readings for stiffener and plate 7.

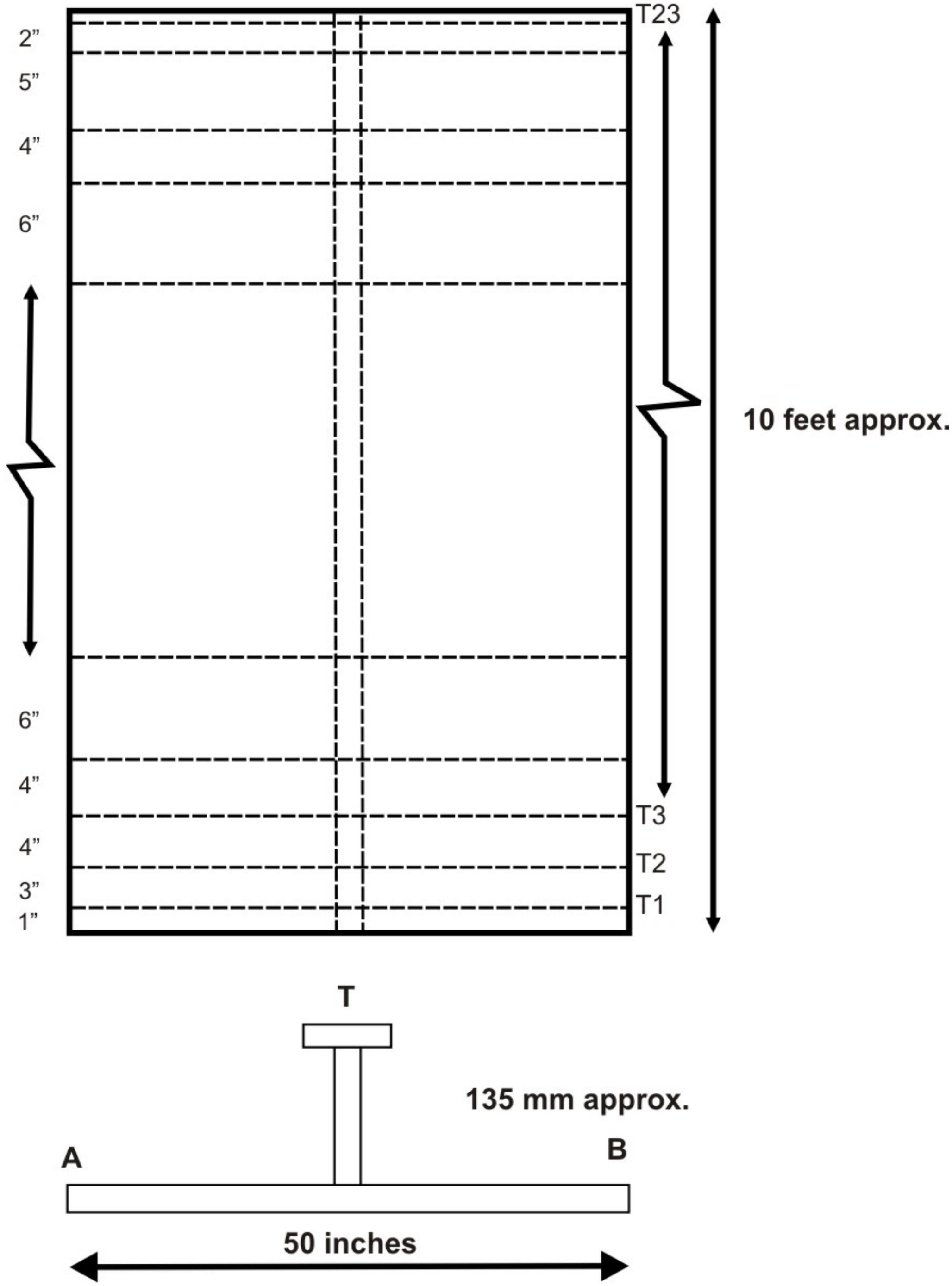


Figure 7.19: Stiffened Panel Distortion Measurement Grid

Table 7.7: Coating Thickness Readings for Stiffener 7

Distance (mm) From Stiffener End	Thickness Reading (mil)
25	1.74
125	1.99
225	1.27
325	1.21
425	1.83
525	1.56
625	1.38
725	1.67
825	1.90
925	1.71
1025	1.64
1125	1.95
1225	1.94
1325	1.72
1425	2.07
1525	1.83
1625	1.32
1725	1.71
1825	1.98
1925	1.73
2025	1.80
2125	1.85
2225	1.29
2325	1.61
2425	1.69
2525	1.62
2625	1.58
2725	1.77
2825	1.34
2925	1.83
3125	1.66
Average	**1.68**

Table 7.8: Coating Thickness Readings for Plate 7

Distance (mm) From Plate End	Thickness Reading (mil)
25	0.94
125	1.10
225	1.16
325	1.15
425	1.33
525	1.51
625	1.47
725	1.16
825	1.14
925	1.44
1025	1.89
1125	0.84
1225	0.84
1325	1.22
1425	1.02
1525	0.82
1625	1.22
1725	0.90
1825	0.73
1925	0.89
2025	1.37
2125	0.80
2225	1.01
2325	1.38
2425	1.00
2525	1.36
2625	1.24
2725	1.01
2825	0.78
2925	1.39
3125	1.39
Average	**1.15**

Rows highlighted in red indicate readings above 1.5mil. As seen in Table 7.7, many of the reading are above 1.5mil making stiffener 7 the stiffener with the thickest application of primer with an average thickness reading of 1.68mil. Base plate 7 had a thinner application of primer with an average thickness reading of 1.15mil.

Tables 7.9 and 7.10 show the coating thickness readings for stiffener and plate 3.

Table 7.9: Coating Thickness Readings for Stiffener 3

Distance (mm) From Stiffener End	Thickness Reading (mil)
25	1.53
125	1.31
225	1.35
325	1.09
425	1.07
525	1.18
625	1.09
725	1.36
825	1.23
925	1.13
1025	1.11
1125	1.28
1225	0.93
1325	0.93
1425	0.93
1525	1.22
1625	1.51
1725	1.18
1825	1.24
1925	1.13
2025	1.17
2125	0.74
2225	1.08
2325	1.13
2425	1.13
2525	1.51
2625	1.75
2725	1.23
2825	1.39
2925	1.26
3125	1.20
Average	**1.21**

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Table 7.10: Coating Thickness Readings for Plate 3

Distance (mm) From Plate End	Thickness Reading (mil)
25	0.98
125	1.15
225	0.61
325	0.96
425	1.06
525	1.32
625	0.62
725	0.90
825	1.32
925	0.78
1025	1.21
1125	0.98
1225	1.02
1325	1.08
1425	1.05
1525	0.79
1625	1.12
1725	0.88
1825	0.98
1925	1.49
2025	0.83
2125	1.22
2225	0.80
2325	0.63
2425	0.85
2525	1.11
2625	0.63
2725	0.86
2825	0.90
2925	0.92
3125	1.15
Average	**0.97**

Stiffener and base plate 3 had an application of primer significantly less than 1.5mil with an average thickness reading of 1.21mil and 0.97mil. Because of the significant differences in average coating thickness between stiffener 7 and 3, test assembly 7 and test assembly 3 will be compared for porosity counts to determine if primer thickness plays a role in the amount of porosity generated for the FCAW process.

Tables 7.11 and 7.12 show the coating thickness readings for stiffener and plate 8.

Table 7.11: Coating Thickness Readings for Stiffener 8

Distance (mm) From Stiffener End	Thickness Reading (mil)
25	2.04
125	1.57
225	1.16
325	1.17
425	0.99
525	1.10
625	0.87
725	1.33
825	1.03
925	0.85
1025	1.03
1125	2.11
1225	1.01
1325	0.93
1425	1.28
1525	2.31
1625	1.69
1725	2.31
1825	1.08
1925	1.29
2025	1.52
2125	1.39
2225	1.78
2325	1.58
2425	1.41
2525	4.73
2625	0.77
2725	3.16
2825	0.71
2925	2.15
3125	1.09
Average	**1.53**

Table 7.12: Coating Thickness Readings for Plate 8

Distance (mm) From Plate End	Thickness Reading (mil)
25	0.95
125	1.44
225	0.93
325	0.93
425	1.52
525	1.39
625	1.22
725	0.91
825	1.31
925	1.60
1025	0.97
1125	1.06
1225	1.59
1325	1.87
1425	1.45
1525	1.29
1625	0.79
1725	1.04
1825	1.11
1925	1.58
2025	0.99
2125	1.05
2225	1.25
2325	1.51
2425	1.39
2525	1.17
2625	1.00
2725	1.65
2825	1.07
2925	0.85
3125	1.09
Average	**1.22**

Stiffener 8 had an application of primer that was greater than 1.5mil. Not only was it greater than 1.5mil, it exhibited regions (due to inconsistencies in the profile of the cut surface of the stiffener) where the coating thickness was as great as 4.73mil. Plate 8 had a typical coating thickness that was uniform throughout the length of the plate.

Tables 7.13 and 7.14 show the coating thickness readings for stiffener and plate 9.

Table 7.13: Coating Thickness Readings for Stiffener 9

Distance (mm) From Stiffener End	Thickness Reading (mil)
25	1.23
125	1.08
225	1.54
325	1.36
425	1.22
525	1.42
625	0.98
725	0.81
825	1.35
925	1.35
1025	1.29
1125	1.74
1225	1.28
1325	1.86
1425	0.96
1525	1.36
1625	1.37
1725	1.45
1825	1.16
1925	0.86
2025	1.31
2125	1.09
2225	1.12
2325	1.04
2425	0.92
2525	1.02
2625	1.15
2725	0.94
2825	1.02
2925	0.93
3125	1.22
Average	**1.21**

Table 7.14: Coating Thickness Readings for Plate 9

Distance (mm) From Plate End	Thickness Reading (mil)
25	1.03
125	0.96
225	0.95
325	0.89
425	0.84
525	1.36
625	0.77
725	1.59
825	1.66
925	0.94
1025	1.74
1125	1.11
1225	1.24
1325	0.94
1425	1.03
1525	1.35
1625	1.12
1725	1.80
1825	1.18
1925	1.27
2025	1.09
2125	0.94
2225	0.94
2325	1.08
2425	1.17
2525	1.38
2625	1.41
2725	0.95
2825	1.52
2925	1.61
3125	1.52
Average	**1.21**

Stiffener and base plate 9 had an application of primer that averaged 1.21mil. The coating thickness of stiffener 9 was much more consistent compared to that of stiffener 8. Assembly 8 and assembly 9 will be compared for porosity counts to determine if primer thickness plays a role in the amount of porosity generated for the T-MCAW process.

It was decided that since the large 4' x 10' plates are distorted to begin with, a distortion matrix consisting of 11 points down the length of the plates and three point (center and the two extremities) across the width of the plates was used to measure distortion of the base plates for the purpose of matching up base plates with similar distortion profiles. This was done for better accuracy in comparison of the benchmark and tension cases. A total of ten plates were selected with each of these ten plates marked with a distortion matrix and measured for distortion. Distortion plots were produced and used to compare between the ten plates. Figures 7.20 through 7.22 show the displacement plots of the base plates. Figures 7.23 through 7.25 show the similarity between plates 7 and 3 used for the FCAW benchmark and tension case. Figures 7.26 through 7.28 show the similarity between plates 8 and 9.

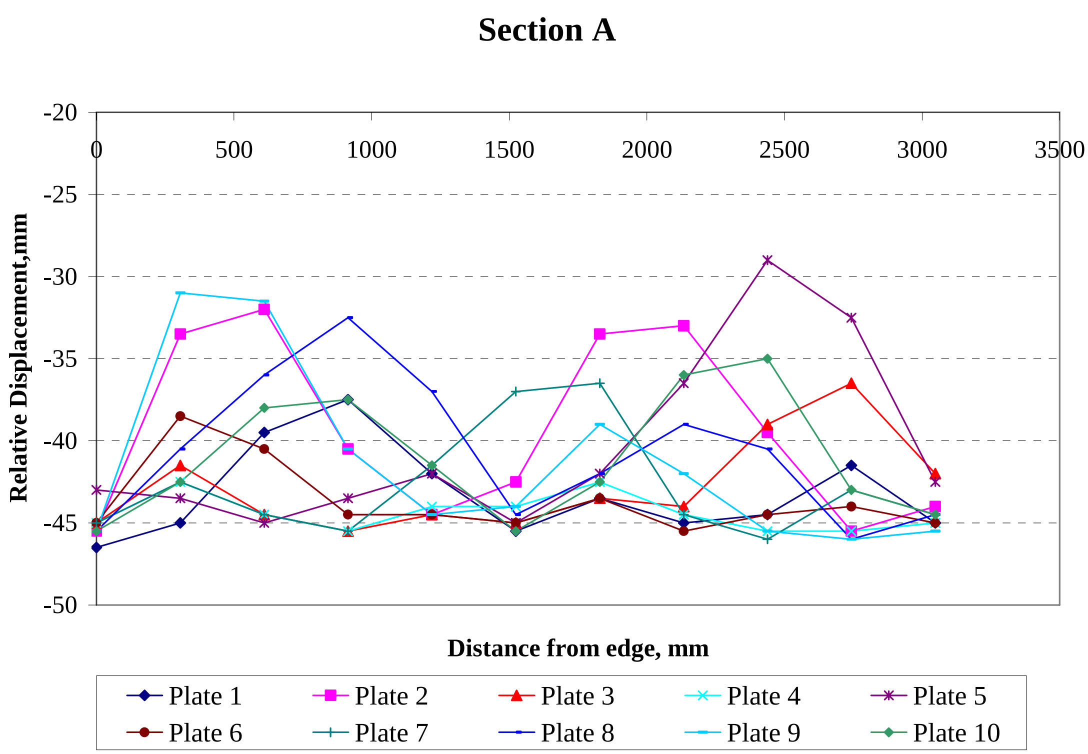


Figure 7.20: Vertical Displacement of Ten Base Plates for Location A

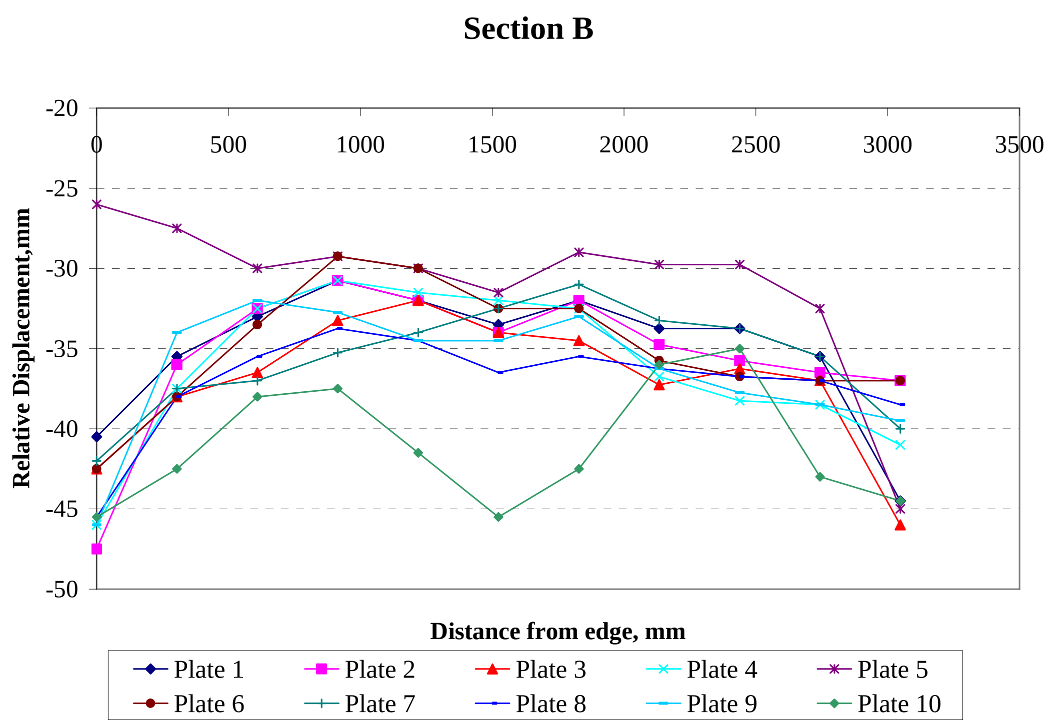


Figure 7.21: Vertical Displacement of Ten Base Plates for Location B

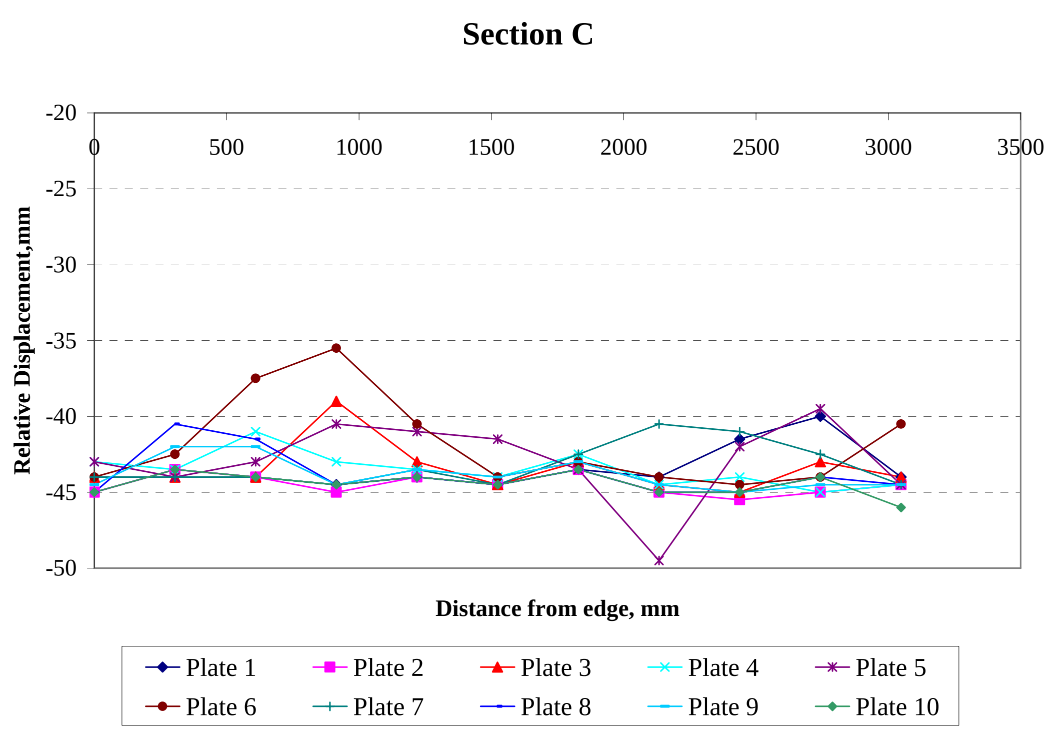


Figure 7.22: Vertical Displacement of Ten Base Plates for Location C

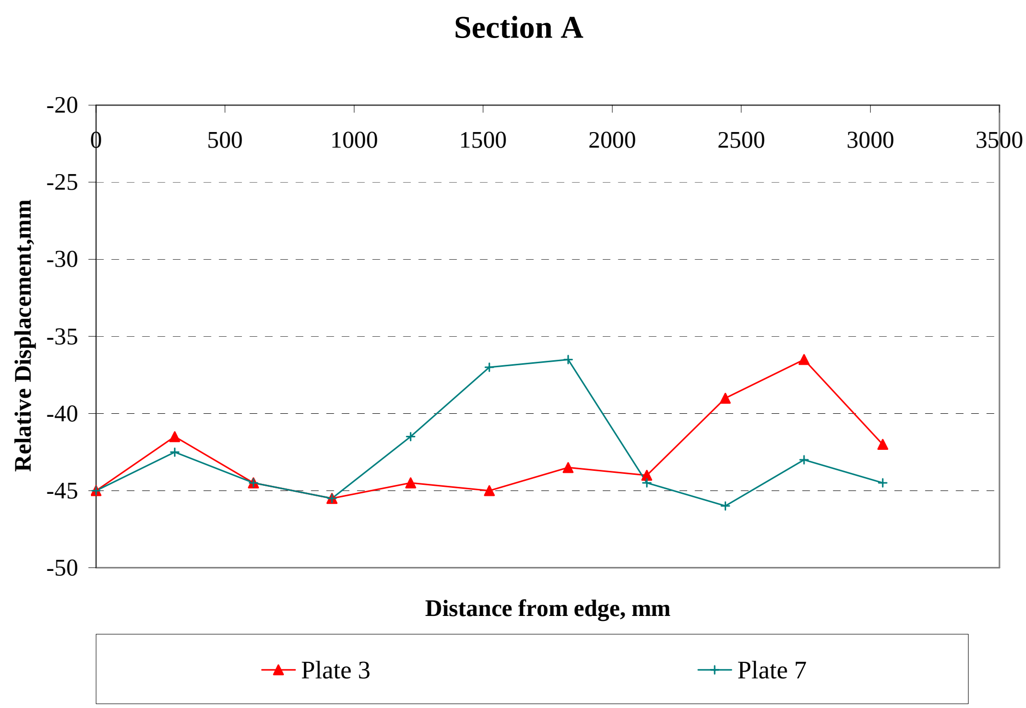


Figure 7.23: Vertical Displacement Comparison of Plate 3 and Plate 7 for Location A

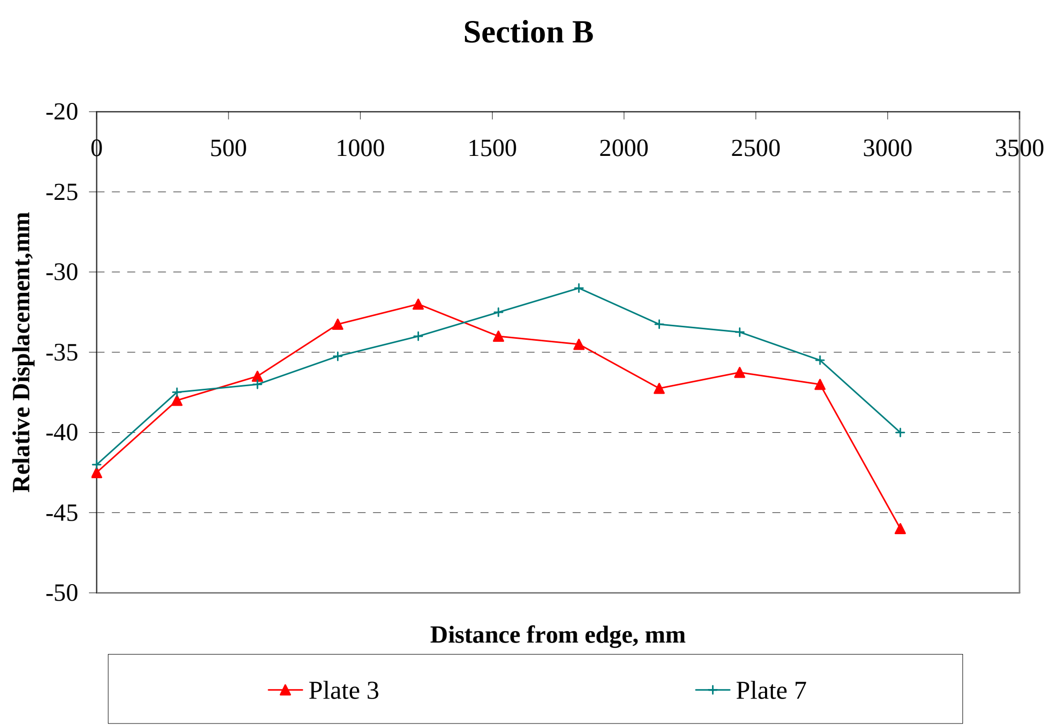


Figure 7.24: Vertical Displacement Comparison of Plate 3 and Plate 7 for Location B

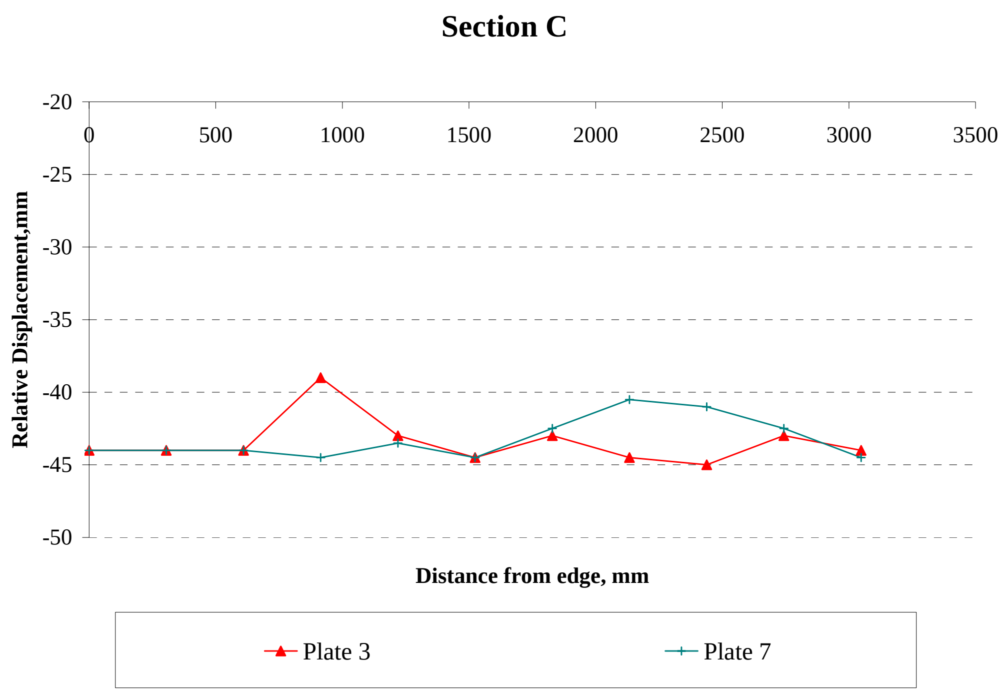


Figure 7.25: Vertical Displacement Comparison of Plate 3 and Plate 7 for Location C

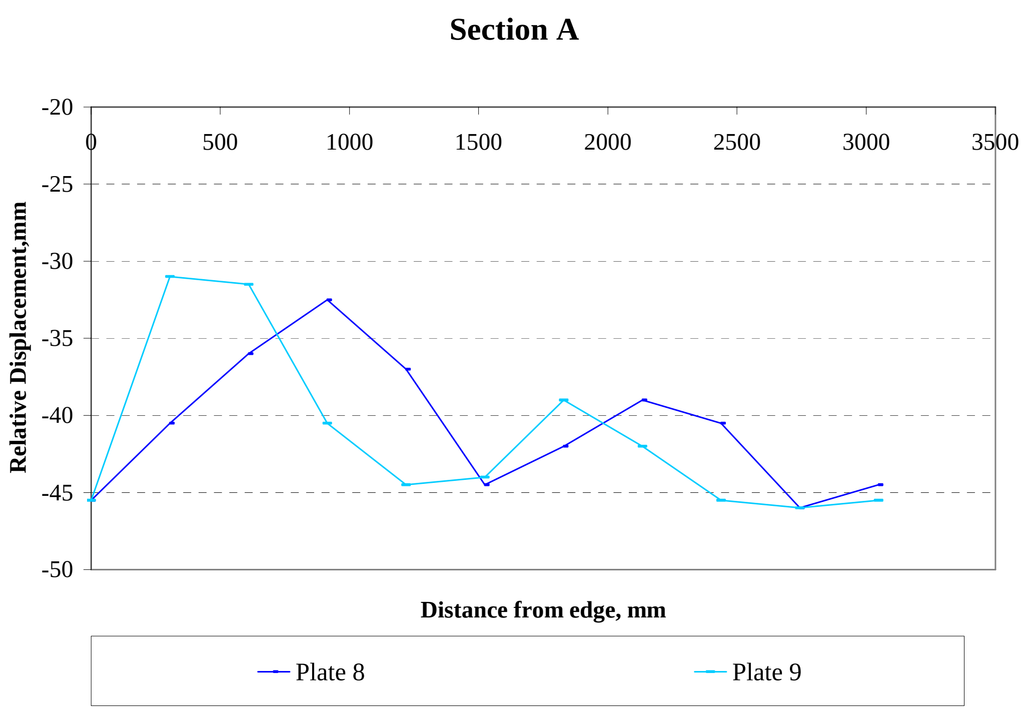


Figure 7.26: Vertical Displacement Comparison of Plate 8 and Plate 9 for Location A

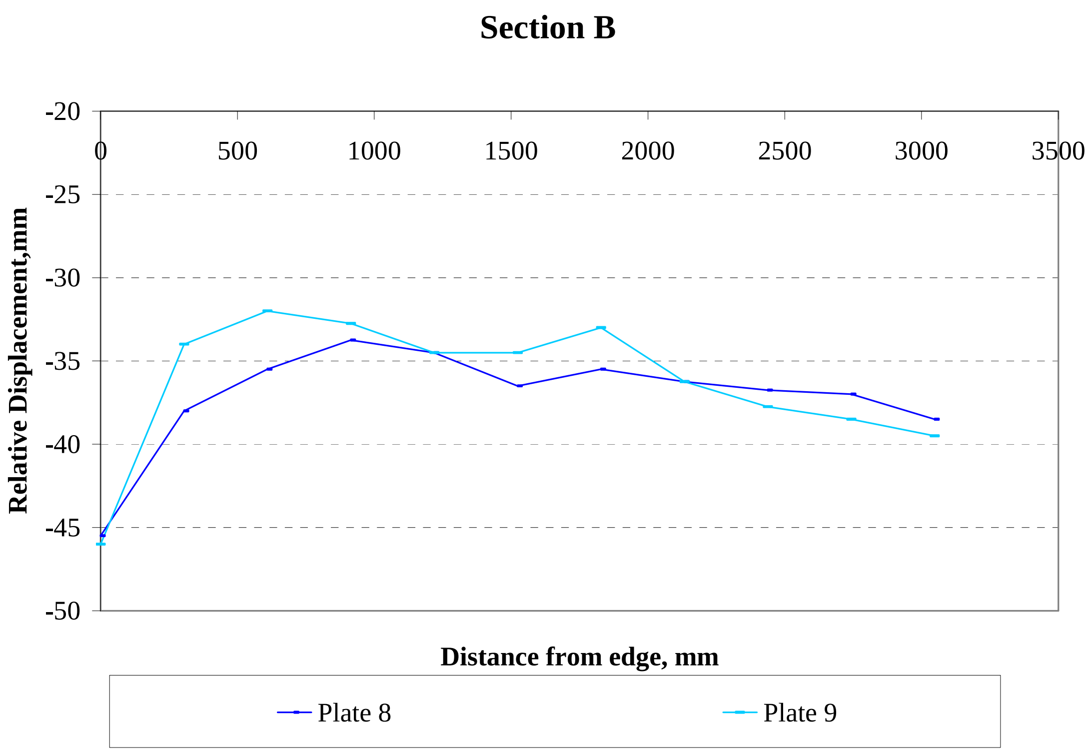


Figure 7.27: Vertical Displacement Comparison of Plate 8 and Plate 9 for Location B

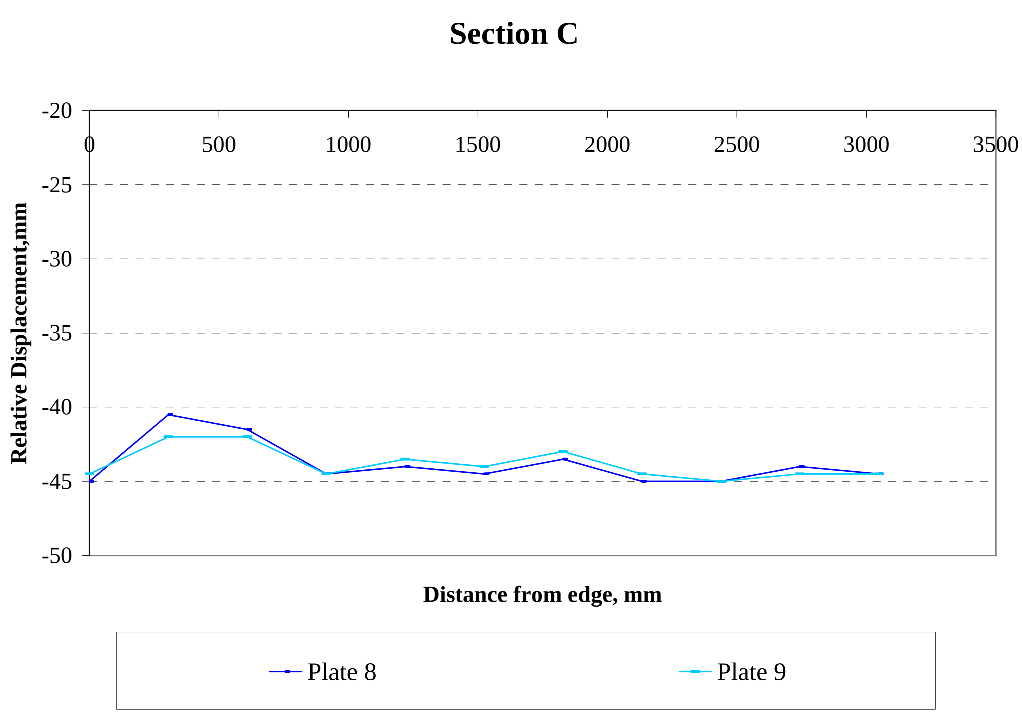


Figure 7.28: Vertical displacement Comparison of Plate 8 and Plate 9 for Location C

The FCAW and T-MCAW processes were used for the welded stiffener assemblies. Table 7.15 summarizes the test cases that were analyzed. Tables 7.16 through 7.25 summarize the measured distortion data for stiffener assemblies at locations A through K. The data is color-coded red and yellow to help better visualize the assembly distortion (torsion). The color red indicates a higher distortion compared to color yellow, whereas light green indicates no change in displacement. Additional net-displacement plots are shown in **Appendix G** and **Appendix J**.

Table 7.15: Test Summary

Stiffener Assembly	Applied Tension (lbs)
FCAW, Benchmark Plate 7	0
T-MCAW, Benchmark Plate 8	0
FCAW, Plate 3	10,000
T-MCAW, Plate 9	10,000

Table 7.16: FCAW Benchmark Plate 7 Distortion Data before Welding

Before Weld - Plate 7											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	22	26	27.5	27.5	28.5	160	28	26.5	25	24	21
2	23.5	28	29	28.5	29.5	160	28	27	26.5	24	20
3	24	28	29	28.5	28.5	159.5	28	26	25	23.5	19
4	23.5	27	28.5	29.5	29.5	159	27.5	26	25	23.5	19.5
5	21	24.5	26	26	27	159	27	26	25	23.5	20.5
6	18.5	22.5	24	25.5	25.5	158.5	26.5	25.5	25	23	21
7	16.5	21	24	25	25.5	158	25.5	25	24	23	20.5
8	16	21	24	24	25.5	159	26	25.5	24	23.5	20.5
9	16.5	21	23	25	25	159	25.5	25	24	23	21
10	17.5	22.5	23.5	25	26.5	159	25	24.5	23.5	23	21
11	20	24	24.5	26	25.5	159.5	24.5	24	23	23	20.5
12	21.5	25	26	27	26.5	160	25	24.5	23	23	20.5
13	21.5	26	26.5	28	28	161	26	25	23.5	22	20.5
14	17.5	22	23.5	25	24.5	160	24	23.5	22.5	20.5	20
15	16	21	23	24.5	25	161	25	24.5	24	22	20
16	15	25	23	24.5	25	162.5	26.5	26	24.5	23	20
17	14.5	19.5	22	24.5	25	161.5	25.5	25.5	24.5	22.5	20.5
18	15	19.5	23	24.5	26	162	24.5	24.5	23.5	22	21
19	19	23	25.5	26.5	27.5	163	25	24.5	23.5	22	21
20	21.5	25	26.5	28.5	29	164.5	24.5	24.5	23.5	22	19.5
21	23	27.5	29	29.5	30.5	165.5	25.5	25	23.5	21.5	19
22	23.5	27.5	29	29.5	31.5	166.5	26	25	22.5	20.5	17
23	22.5	26.5	28.5	29.5	31	167	26	25	22.5	20	17

Table 7.17: FCAW Benchmark Plate 7 Distortion Data after Welding

After Weld - Plate 7											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	24.5	27	26.5	27	25	155	20	19	19	19	16.5
2	26	28	27.5	28	26	155	20.5	20	20	20	17.5
3	25.5	28	27.5	28	25	154.5	21	20	20.5	20.5	18.5
4	24	26.5	26.5	28.5	26.5	154	21.5	21	22	22	19.5
5	20	23	23	24.5	23	154	22	22.5	23.5	23.5	22.5
6	16.5	19	20.5	23	21.5	153.5	22.5	23.5	25.5	26	25
7	13.5	17	19	22	21.5	153	22.5	24.5	26	26.5	26
8	12.5	16.5	18.5	20.5	21.5	153.5	23	24.5	26.5	27	26
9	13.5	17.5	18	21.5	21	154	22.5	24.5	25	26.5	25
10	16.5	20	20	22.5	23	154.5	22	23	23.5	23.5	23
11	21	24.5	23	24.5	22.5	154	20.5	21.5	21.5	22	20.5
12	25.5	27.5	26	26.5	24.5	155	21	21.5	21.5	21.5	19.5
13	27.5	29	27.5	27.5	25.5	156	22	22	22.5	21.5	20
14	23	25	24	24	21.5	154.5	20.5	21.5	22	22.5	22
15	19.5	22.5	22.5	23	21.5	156	22	23.5	25	25	24.5
16	17	20	21	22	21.5	157	23.5	25	26.5	27	27.5
17	15.5	18.5	19.5	22	21	156.5	21.5	25	26	26.5	28
18	15.5	18.5	20	21.5	22	157	20.5	23	24	25.5	26
19	18.5	21.5	22.5	23	22.5	158	21	22	22.5	23.5	24.5
20	21	24	24.5	24.5	24	159	19.5	20.5	21	21.5	20.5
21	22	25	25.5	25.5	25	159.5	20.5	20	20	19.5	18.5
22	22	24.5	25	25.5	25.5	160.5	20	19	18.5	17	15
23	21	24	24.5	24.5	25.5	161	20	19	17.5	16.5	14

Table 7.18: T-MCAW Benchmark Plate 8 Distortion Data before Welding

Before Weld - Plate 8											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	13.5	17	19	20.5	23	151	22.5	21	19.5	17.5	13
2	15	18.5	20.5	22	24	151	23	21.5	20	18.5	14
3	16	19.5	21.5	22.5	23	150	23	21.5	19.5	19	15
4	17	20	22.5	24	24.5	149.5	22.5	21	20.5	19.5	15
5	17	20.5	22.5	22.5	23	149.5	21.5	20.5	19.5	19	16
6	18.5	22	23.5	23.5	22.5	149	20.5	19.5	18	17.5	14.5
7	21	24	25	24.5	23	148.5	19	18	16.5	15	12
8	22.5	25.5	26	25	24	149	20	18	16.5	14.5	11.5
9	22	25	24.5	25	23.5	149	20	18.5	16.5	15.5	12.5
10	19.5	22.5	22.5	23.5	23.5	149	20.5	19	18	16.5	14
11	17	20.5	20.5	21.5	22.5	149	20.5	20	19	18.5	16.5
12	17	19.5	19	21	22.5	150	21	20.5	19.5	19	16.5
13	18	20.5	20	21.5	23	150.5	22	21	20	19	17
14	17	19.5	19.5	20	21	150	20	19	18	16.5	14.5
15	19	22.5	22	22.5	22.5	150	21	19.5	18.5	16.5	15.5
16	21.5	24.5	24.5	24	23.5	151	21	20.5	18.5	17	14.5
17	20.5	23.5	24	24.5	23.5	150.5	20.5	20	18.5	17	15
18	18.5	21.5	23	24	24.5	150.5	21	21	19	17.5	17
19	17	20.5	22	23.5	25	152	21.5	22	20.5	20	19.5
20	16.5	20	22	24.5	26.5	153	23	22.5	21.5	21	18
21	17	21	23	25	26.5	154	24	23.5	22.5	21.5	18.5
22	19.5	22.5	24.5	27	28.5	155	25	24	22.5	20.5	17
23	20	23	25.5	27.5	29	155.5	25.5	24.5	24	20.5	17

Table 7.19: T-MCAW Benchmark Plate 8 Distortion Data after Welding

After Weld No Tension - Plate 8

Displacement w.r.t to Frame, mm

	A	B	C	D	E	F	G	H	I	J	K
1	11	13	14.5	16	15.5	145	16.5	17	17	17	13
2	13.5	15.5	17	17.5	16.5	145	17	17.5	17.5	17.5	14
3	16.5	18	19	19	16.5	144.5	16.5	17.5	17	17.5	14.5
4	18.5	20.5	21.5	21.5	18.5	144	16.5	17.5	18	18	14.5
5	21.5	23.5	23.5	21.5	18	143.5	16	16.5	16.5	16.5	14
6	26	27	26.5	24	18	143	15	15	14.5	14	11
7	31	31	29.5	26.5	20	143	13.5	12.5	11.5	11	7
8	33	33	31.5	27	20.5	143	13.5	12.5	11	10	6.5
9	31.5	32	29.5	27.5	20	143	14	13.5	11.5	11.5	7.5
10	26	27	25.5	24	20.5	143	15	14.5	13.5	13.5	9.5
11	20.5	22	20.5	20	18.5	143	15	16.5	16.5	16.5	15
12	17.5	19	17.5	18	17	144	16	17.5	18.5	18	17
13	18.5	19.5	18	18.5	18	144.5	16.5	18.5	18.5	19.5	18
14	19	19.5	18.5	18	16.5	142.5	15	16	17	17	15.5
15	24	24.5	23	21.5	18.5	143.5	15.5	16.5	17	16	15
16	28.5	28.5	26.5	24	19.5	144.5	16	16.5	17	16.5	15
17	27.5	28	25.5	24	20	144	15	16	16.5	16	15
18	23.5	24	23.5	22	20	144	15	16	16.5	16.5	17
19	20	20.5	20.5	20	19.5	145	15.5	17	17	17.5	18.5
20	16.5	18.5	18.5	19.5	19.5	145.5	16	17	17	17.5	17
21	16.5	18.5	18.5	19.5	20.5	146.5	17	17.5	17.5	17.5	16.5
22	16.5	18.5	19.5	21	21.5	147	17	17	17	16.5	15
23	17	19	20.5	21.5	21.5	147.5	17.5	17.5	17	16	14.5

Table 7.20: FCAW Plate 3 Distortion Data, No-Tension before Welding

Before Weld - Plate 3

Displacement w.r.t to Frame, mm

	A	B	C	D	E	F	G	H	I	J	K
1	24	27	27	28.5	30	164	30.5	29.5	25	22	17
2	24.5	27.5	28	28.5	30.5	163.5	31	30	26.5	24	19
3	24.5	27	27	27.5	28.5	162	31	30	27	23.5	19.5
4	23.5	26	27	28.5	30	161	30	30	27.5	24.5	20
5	20.5	23.5	24.5	25	27.5	159.5	29.5	29.5	27.5	25	21
6	17	21	23	24	25	158.5	28	29	26.5	25	21
7	15	19.5	22	24	25	157	27	28	26	23.5	20.5
8	15	19.5	22	23	25	156.5	26.5	27.5	25.5	23.5	20
9	16	19	20.5	23	23.5	156	26	26.5	25	24	19.5
10	16.5	19	19.5	21.5	24	155.5	25	26	25	23.5	20.5
11	18	19.5	19	20.5	21.5	154	23.5	25.5	25.5	24	20.5
12	19.5	20.5	19.5	20.5	21.5	154	23.5	26	25.5	24	21
13	20	21	19.5	21	22	154	24.5	26	25.5	23.5	21
14	17	17.5	17	18	19	151.5	22	23.5	23.5	22	20
15	15.5	17	16.5	17.5	19	151.5	22	23.5	23.5	22	19
16	15.5	17.5	17	18	19	151.5	22	23	22.5	21.5	19
17	15	16.5	16.5	18.5	19	150	21	21.5	21.5	20	19.5
18	15.5	17	17.5	18.5	19.5	149.5	19.5	21	20	20.5	20
19	17	18	18.5	19	20	149.5	20	21	21.5	21.5	21
20	18.5	18.5	19	19.5	20.5	149.5	19.5	21.5	21.5	22	20.5
21	17	17.5	18.5	19.5	21	150	19.5	20.5	21	20	20
22	13.5	14.5	16	18.5	20	150.5	18	18	17.5	17	17
23	10.5	12	14	17	19.5	150.5	17	16.5	15.5	15	15

Table 7.21: FCAW Plate 3 Distortion Data, Tension before Welding

Tension No Weld - Plate 3											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	18	19.5	19	18.5	20	154.5	19	19	17.5	15.5	13.5
2	20	21	20	20	21	154	21	21.5	19.5	18	15
3	20	22.5	20	20	20.5	153	21.5	21.5	21	19	17.5
4	20.5	22	22	21.5	22.5	152.5	21.5	22.5	21.5	21.5	18
5	20	21.5	20.5	19	21	151.5	22	22.5	22.5	22	19
6	18	19.5	20	19.5	19.5	151	21.5	22	21.5	21.5	19
7	16	18.5	19.5	19.5	19.5	150	20	20.5	20.5	20	17.5
8	16	18.5	19.5	19	20	150	20	21	21	20	17.5
9	16.5	19	18.5	19.5	19.5	150	19	20.5	20.5	19.5	17
10	17	19	18.5	19.5	20	149.5	19	20.5	20.5	20	18
11	18	19	17.5	18.5	18.5	149	18.5	20.5	20.5	20.5	19.5
12	19.5	20.5	18.5	19	19.5	149.5	19	21	21.5	20.5	19
13	20	21	19	19.5	20	149.5	20	22	22	21	19
14	17	18	16.5	16.5	17	147.5	17.5	19.5	21	19.5	18
15	17	18	17	17.5	17.5	148	18.5	20	20	19.5	17.5
16	17.5	18.5	17.5	17.5	17.5	148.5	18.5	20	20	19	17
17	16.5	17.5	17	18.5	17.5	147.5	17.5	19.5	19.5	18	17.5
18	16.5	18	17.5	17.5	18	147.5	17	19	19	18	18.5
19	17.5	18	18	18.5	19	147.5	18	19.5	19	19	20
20	18	18	18	18.5	19	148	18	19	19.5	19	18.5
21	17.5	17	17.5	18.5	19	149.5	18.5	19	18.5	18	18
22	13.5	14	15.5	17.5	18.5	149.5	16	16.5	15.5	14.5	14
23	10	12	13.5	16.5	18	149.5	14.5	14	13	13	12

Table 7.22: FCAW Plate 3 Distortion Data, Tension after Welding

After Weld - Plate 3											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	25	25.5	23.5	21.5	21	154	18.5	18.5	17	16.5	13.5
2	26	26.5	24	22.5	22	153.5	20.5	21	20	19	16
3	26	26.5	24	22.5	21	152.5	21.5	22	21.5	21	18.5
4	25.5	26	24.5	24.5	23	152	22	24	22.5	23.5	20
5	21.5	23	22.5	21.5	21	151	23	25	24	25	22
6	16.5	19.5	20	20	19.5	150.5	23	25	24	25.5	22
7	13	17	19.5	20.5	20	149.5	22	24	23.5	24	21
8	13	17	19.5	20	20.5	150	22.5	24.5	23.5	23	20.5
9	14.5	17.5	18.5	20.5	20	150	22	24	23.5	23	19
10	16	18	18.5	19.5	21	150	22	24	24	23	20
11	18.5	19.5	18.5	19	19	149.5	21.5	25	25.5	24.5	22
12	20	20.5	19	21	20	150	23	25.5	27.5	27	25
13	20.5	21	19.5	20	21	150.5	24	27.5	29.5	29.5	28
14	17	18	17	17	17.5	148.5	22.5	25.5	28.5	29	30
15	16.5	18	17	17.5	18	149	22.5	26	28.5	29.5	30
16	17.5	19.5	18.5	19	19	150	22.5	25	27	27.5	27.5
17	19	20	19.5	20.5	20	149.5	21	23.5	25	24.5	24
18	21	21.5	21.5	21.5	21	149.5	20	22	22.5	22.5	22
19	23.5	23.5	23	22.5	21.5	150.5	20.5	21.5	22	22	22
20	24	23.5	23	23	22.5	151	20.5	20.5	21.5	21.5	20
21	22.5	22	22	23	23	151.5	20.5	20.5	20.5	20.5	19.5
22	18.5	19	19.5	21	22	152.5	18	18	18	17	16
23	16.5	16.5	17.5	19.5	21	153	16	16	15	14.5	14

Table 7.23: T-MCAW Plate 9 Distortion Data, No-Tension before Welding

Before Weld - Plate 9											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	6	12.5	17	19.5	23	157.5	25	24	19.5	18	13
2	10.5	17.5	20.5	22.5	25.5	157.5	25.5	25	20.5	19	14
3	15.5	26.5	23.5	25.5	26.5	157	26	24.5	20.5	19	14
4	19	25	26.5	28.5	29	156.5	26	23	21.5	19.5	15
5	20.5	26	26.5	26.5	27	156	25	22.5	21	19.5	15.5
6	19.5	25	26	26.5	26	155.5	25.5	22	20.5	19	15.5
7	17.5	22.5	25	26	25.5	154.5	24.5	21	18.5	17	13.5
8	16	21	24	24.5	25.5	154.5	24.5	21	19	17	14
9	14.5	19.5	22	24	24	153.5	24.5	21	19.5	17	14
10	14.5	19.5	21	23.5	25	153	24.5	21.5	19.5	17.5	15.5
11	16.5	20.5	21.5	22.5	24.5	152	24	26	19.5	18.5	17
12	18.5	23	24	25	25.5	152.5	23.5	21	20	19	17
13	21	25	25.5	26.5	26	153.5	23	21	19.5	18.5	17
14	20	23	24.5	24.5	23.5	151.5	21	18.5	17.5	16.5	15
15	20	23.5	24.5	25	24	152.5	21.5	19	18	16.5	14.5
16	19.5	23	24.5	24.5	24.5	153	22.5	19.5	18.5	17	15.5
17	16.5	20.5	22	23.5	23.5	152.5	21.5	19.5	18.5	17.5	16
18	15.5	19	21.5	22.5	24	152.5	21.5	20	19	17.5	18
19	16.5	19.5	22	23.5	24.5	154	22.5	21	19.5	19	19
20	17.5	21.5	24	25	25.5	154.5	22.5	21	20.5	19	18
21	18.5	22.5	25	26.5	26.5	155	22.5	21.5	20.5	19.5	17
22	19	23	25.5	26.5	27	156	22.5	21.5	20	18.5	16.5
23	18	22.5	25.5	26.5	27	156.5	22.5	21.5	20	18.5	16.5

Table 7.24: T-MCAW Plate 9 Distortion Data, Tension before Welding

Tension No Weld - Plate 9											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	4.5	9	11	13	16	150	13.5	14	13.5	14.5	9
2	9.5	13	15	16	18	150	15	15.5	15	16	10
3	14	17.5	18.5	18.5	19	149.5	16.5	16	16.5	16.5	12.5
4	17	20.5	21	21.5	21.5	149	17	17	17	17	13
5	18	21	20.5	19.5	20	148.5	16	17	17.5	17	14
6	17	19.5	20	19.5	18	148	16	16.5	16.5	16.5	14
7	14.5	18.5	19	19	18	146.5	15.5	15.5	15.5	15	11.5
8	13.5	16.5	18.5	18	18	146.5	15.5	15.5	15.5	14.5	11.5
9	12.5	15.5	16.5	17.5	16.5	146	15.5	15.5	15.5	15	12.5
10	13	15.5	16	17	17.5	145.5	16	15.5	16	15.5	14
11	15	17	16	17	17	145	15	15.5	16	16	15
12	17	18.5	18	18	18	145	15.5	16	16.5	16.5	15.5
13	18	20	19.5	19.5	18.5	145.5	15.5	16	16	16.5	15.5
14	16	18	18	17.5	16	143.5	13.5	13.5	14	14.5	13.5
15	16	18.5	18.5	18	16.5	143.5	13.5	14	14	14.5	13
16	16	18.5	18.5	18	17	145.5	14.5	15	15	14.5	13.5
17	14.5	16.5	16.5	17	16.5	145	14	14.5	15	15	15
18	14	15	16.5	16.5	17	145	14	15	15.5	16	17
19	15	16	17	17	17.5	146	15	16	16.5	16.5	18
20	15.5	17.5	18.5	19	18.5	147	15.5	16	16.5	17	16.5
21	16.5	18.5	19.5	19.5	19.5	148.5	16	16.5	16.5	17	16
22	16	18	19.5	19.5	20	149	15.5	16	16	16	15
23	15	17.5	19	19	19.5	149.5	15.5	15.5	16	16	15

Table 7.25: T-MCAW Plate 9 Distortion Data, Tension after Welding

After Weld No Tension - Plate 9											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	8	12	13.5	14.5	17	150	15	15	14	10.5	8
2	13.5	17	18	18	19.5	150	17	17	16	13.5	10.5
3	19	22.5	22.5	21	20.5	149.5	18	17.5	17	15.5	12.5
4	23	26	25.5	25	23.5	149	19	19.5	19.5	17	14
5	25.5	27.5	26	24	22	148.5	20	21	21.5	19.5	17
6	23.5	25.5	25	24	21	148	20.5	21.5	23	21.5	20.5
7	19.5	22	22.5	22	20	147	20.5	22.5	24	23.5	23
8	16	18.5	19.5	19	19.5	146.5	21.5	24	26	26	26.5
9	13	16	16.5	18	18	146	21.5	24.5	27	27	26.5
10	13	15.5	15.5	17.5	18	145.5	21.5	24	26	26	26.5
11	16	18	17	18	18	145	20	22.5	24	23.5	24
12	20.5	22.5	21.5	21.5	20	145.5	19	21	21.5	20.5	20
13	25.5	27	25.5	24	21.5	146	18.5	19	18.5	17	16
14	26.5	27.5	26	23	19	144.5	15.5	15.5	15	13	12.5
15	27	27.5	26	23.5	19.5	145	16	15.5	14.5	12.5	10.5
16	25	26	25	23	19.5	146	16.5	16.5	15.5	13.5	12
17	20	21.5	21	21	19	146	16.5	17	16	14.5	14.5
18	16.5	18	19	18.5	18.5	146	16	17	16.5	16	17
19	15.5	17.5	18.5	18.5	18.5	147	16.5	17.5	17.5	17.5	18.5
20	16	17.5	19	19.5	19	148	16.5	16.5	17	17.5	17.5
21	16.5	18.5	20	20	20	148.5	16.5	17	16.5	17	17
22	15.5	18	19.5	19.5	19.5	149.5	15.5	16	16	16	15
23	15	17.5	19	19	19	150	15	15.5	16	16	14.5

Figures 7.29 through 7.31 illustrate the net displacements for the FCAW benchmark stiffener assembly welding over primer. Lines are plotted representing the average for each set of readings for comparison purposes. Plots were prepared for points A through K as shown in **Appendix G**. Points E, F (stiffener), and G are shown below.

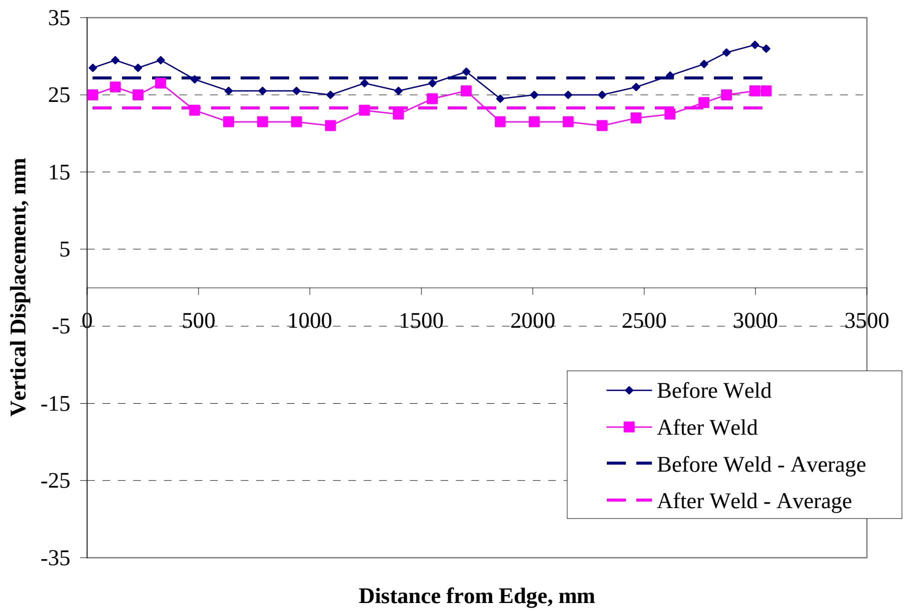


Figure 7.29: Net Displacement along Longitudinal Section E for FCAW Benchmark Assembly Plate 7

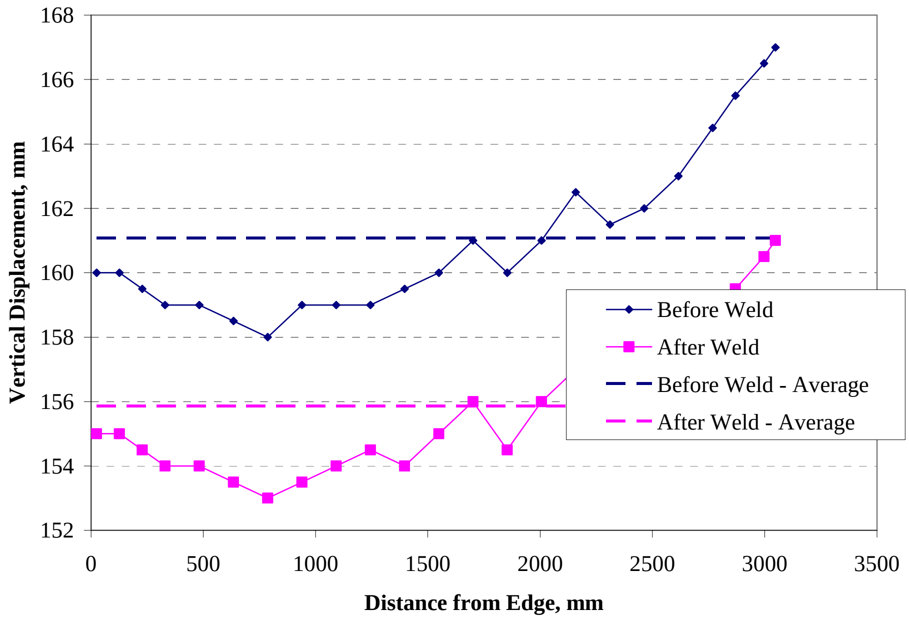


Figure 7.30: Net Displacement along Longitudinal Section F (Stiffener) for FCAW Benchmark Assembly Plate 7

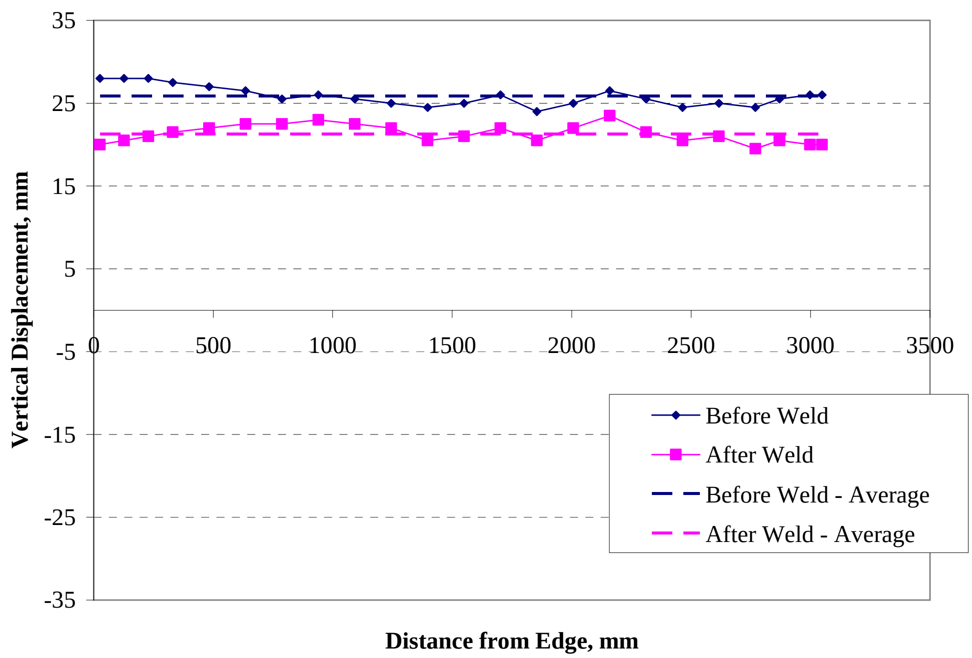


Figure 7.31: Net Displacement along Longitudinal Section G for FCAW Benchmark Assembly Plate 7

Figures 7.32 through 7.34 illustrate the net displacements for the T-MCAW benchmark stiffener assembly welding over primer. Lines are plotted representing the average for each set of readings for comparison purposes. Plots were prepared for points A through K as shown in **Appendix G**. Points E, F (stiffener), and G are shown below.

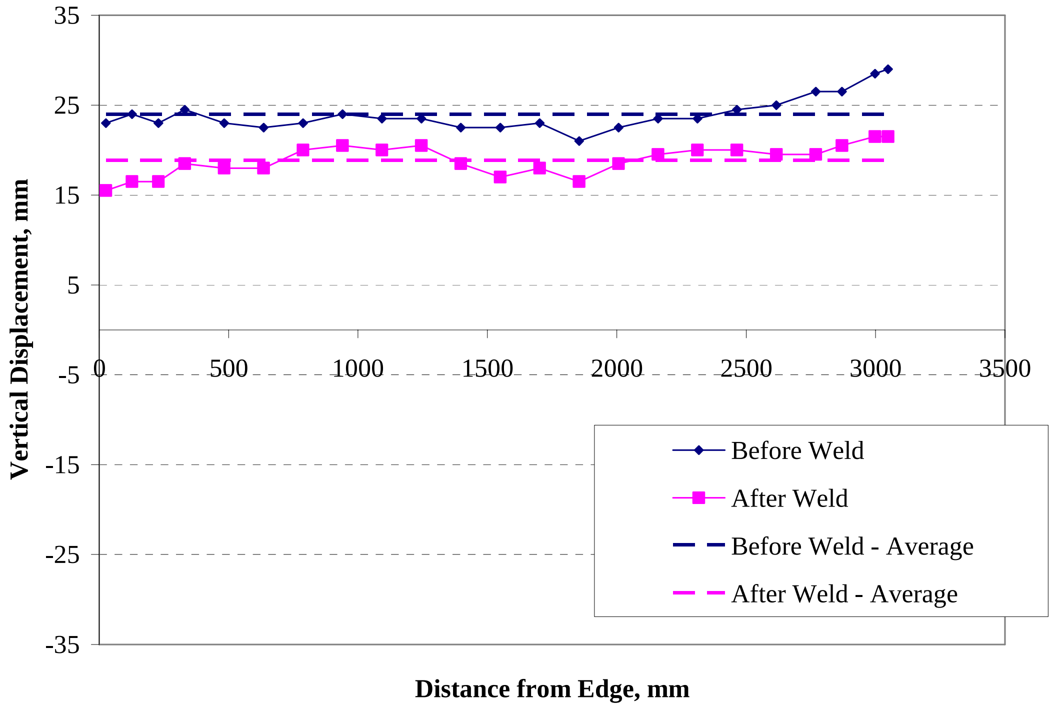


Figure 7.32: Net Displacement along Longitudinal Section E for T-MCAW Benchmark Assembly Plate 8

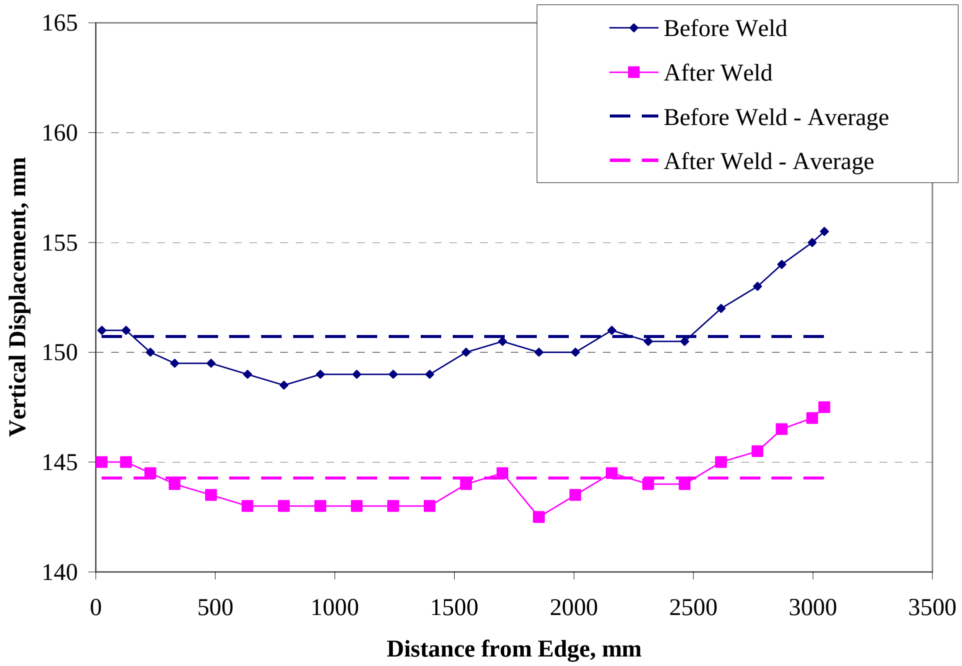


Figure 7.33: Net Displacement along Longitudinal Section F (Stiffener) for T-MCAW Benchmark Assembly Plate 8

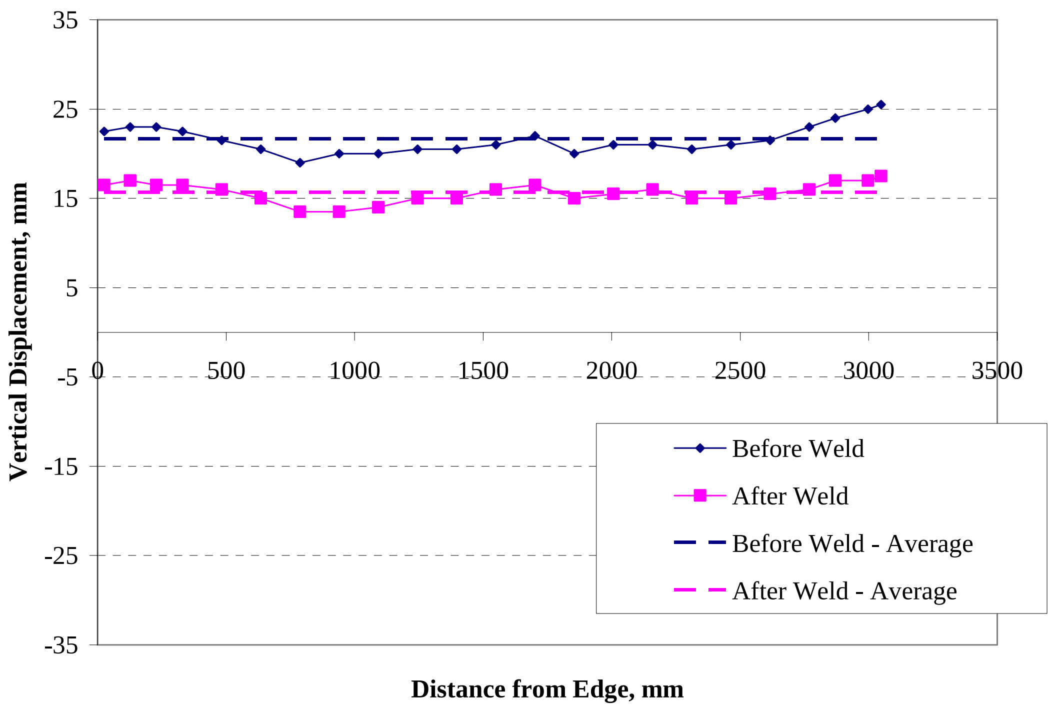


Figure 7.34: Net Displacement along Longitudinal Section G for T-MCAW Benchmark Assembly Plate 8

Figures 7.35 through 7.37 illustrate the net displacements for the FCAW stiffener assembly welded using 10 000lbs tension (welding over primer). Lines are plotted representing the average for each set of readings for comparison purposes. Plots were prepared for points A through K as shown in **Appendix G**. Points E, F (stiffener), and G are shown below.

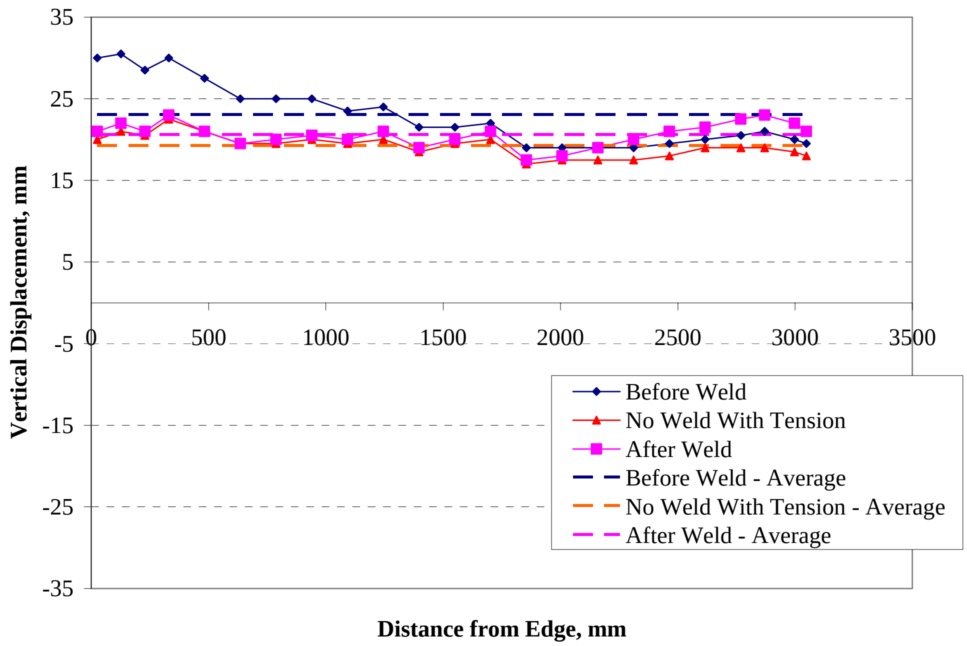


Figure 7.35: Net Displacement along Longitudinal Section E for FCAW 10 000lbs Tension Assembly Plate 3

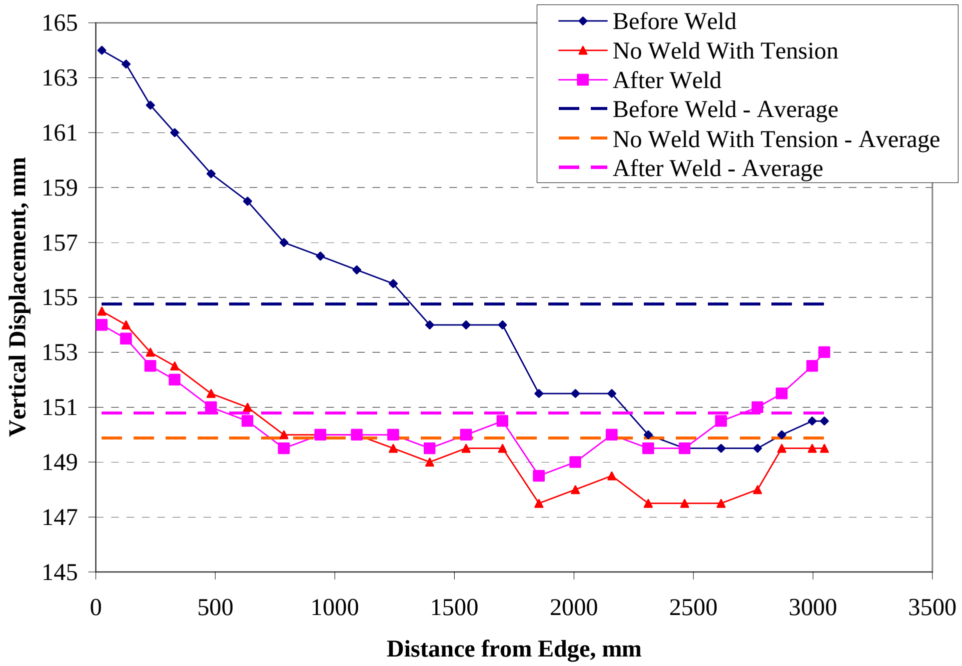


Figure 7.36: Net Displacement along Longitudinal Section F (Stiffener) for FCAW 10 000lbs Tension Assembly Plate 3

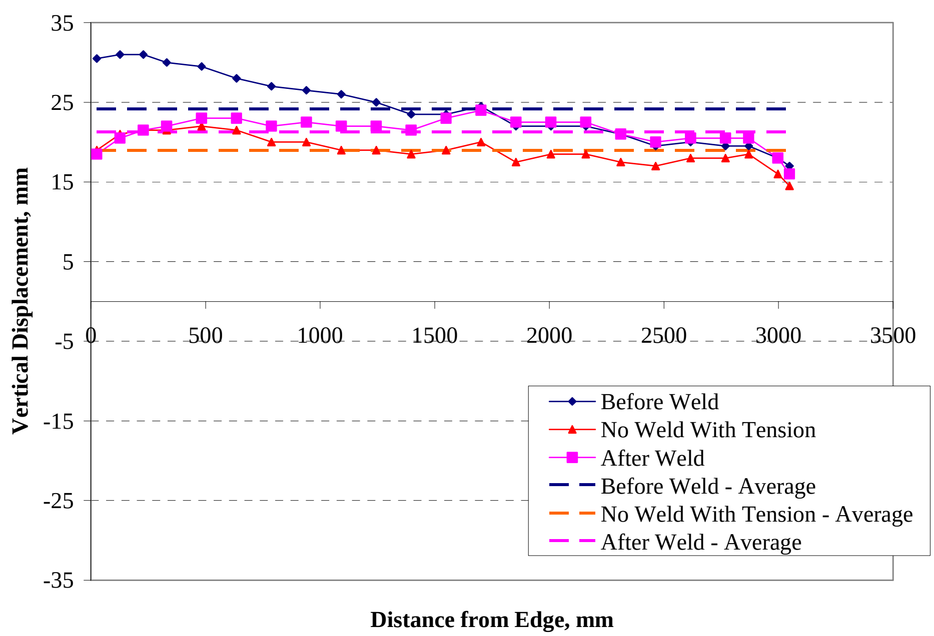


Figure 7.37: Net Displacement along Longitudinal Section G for FCAW 10 000lbs Tension Assembly Plate 3

Figures 7.38 through 7.40 illustrate the net displacements for the T-MCAW stiffener assembly welded using 10 000lbs tension (welding over primer). Lines are plotted representing the average for each set of readings for comparison purposes. Plots were prepared for points A through K as shown in **Appendix G**. Points E, F (stiffener), and G are shown below.

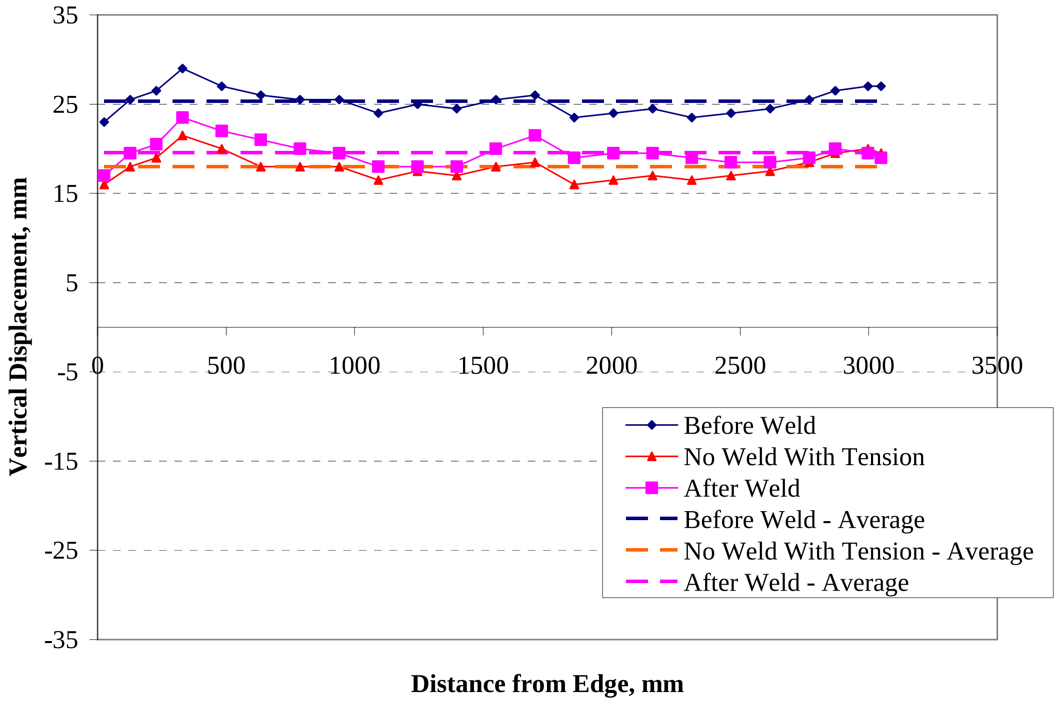


Figure 7.38: Net Displacement along Longitudinal Section E for T-MCAW 10 000lbs Tension Assembly Plate 9

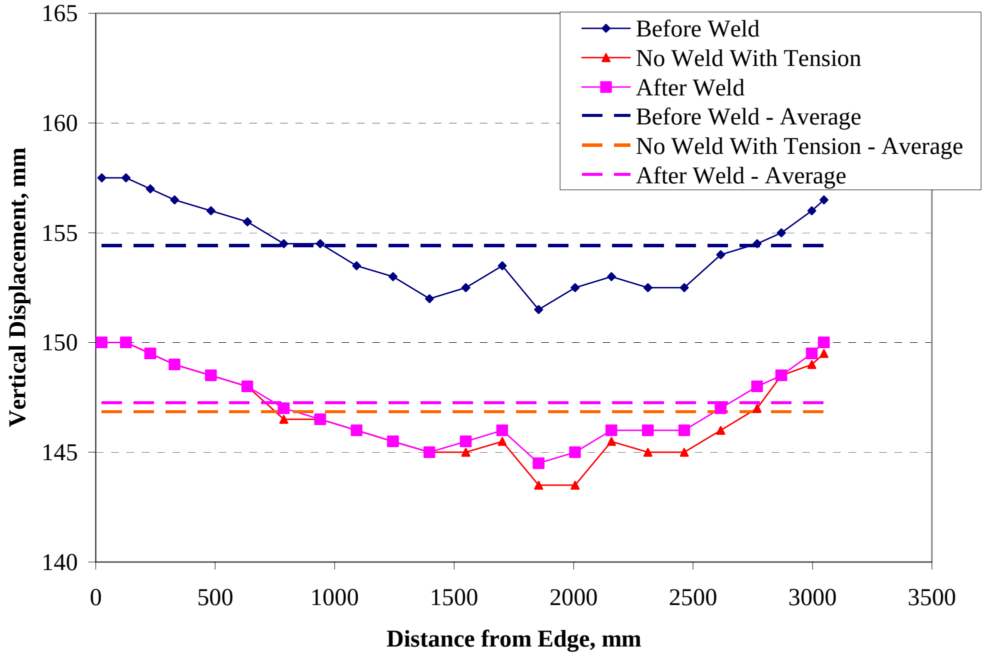


Figure 7.39: Net Displacement along Longitudinal Section F (Stiffener) for T-MCAW 10 000lbs Tension Assembly Plate 9

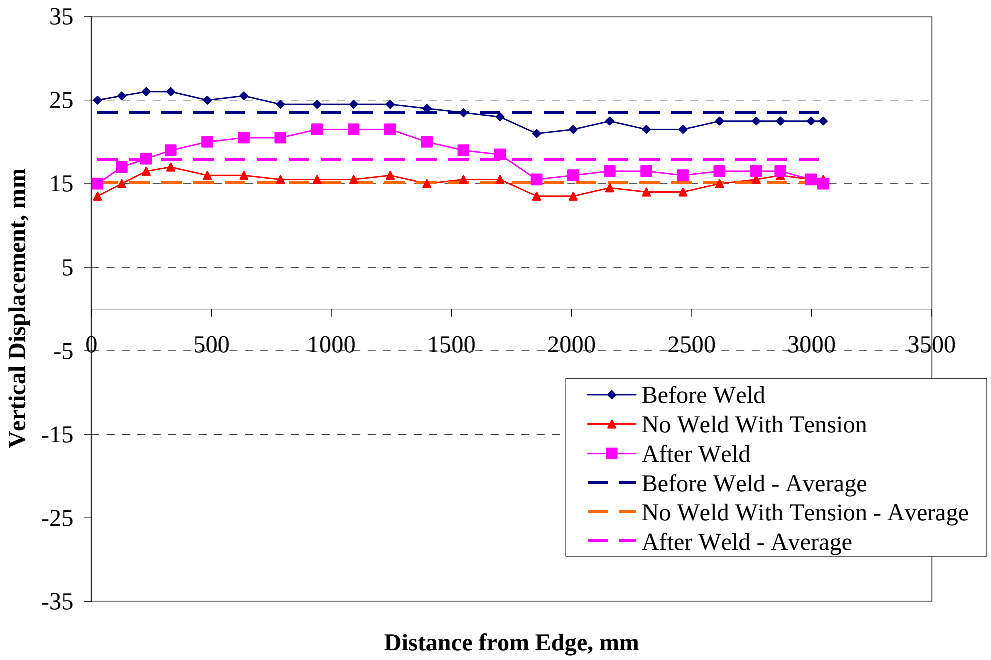


Figure 7.40: Net Displacement along Longitudinal Section G for T-MCAW 10 000lbs Tension Assembly Plate 9

7.2.1 Net Improvement

The distortion data in Table 7.26 and Figures 7.41 through 7.43 compare the overall net improvement achieved in controlling distortion with the use of the T-MCAW (benchmark assembly) with respect to FCAW (benchmark assembly). The negative values, color coded light blue indicates location where tensioning has been effective to counter distortion due to welding. Also cells color coded green indicate no change in distortion and yellow indicates an increases in distortion. Additional plots and tables are provided in **Appendix H.**

Table 7.26: Net Improvement, T-MCAW Plate 8 vs. FCAW Plate 7 (No Tension)

Net Improvement, mm										
Benchmark										
A	B	C	D	E	F	G	H	I	J	K
-5	-5	-3.5	-4	-4	-1	2	3.5	3.5	4.5	4.5
-4	-3	-2	-4	-4	-1	1.5	3	4	3	2.5
-1	-1.5	-1	-3	-3	-0.5	0.5	2	2	1.5	0
1	1	1	-1.5	-3	-0.5	0	1.5	0.5	0	-0.5
5.5	4.5	4	0.5	-1	-1	-0.5	-0.5	-1.5	-2.5	-4
9.5	8.5	6.5	3	-0.5	-1	-1.5	-2.5	-4	-6.5	-7.5
13	11	9.5	5	1	-0.5	-2.5	-5	-7	-7.5	-10.5
14	12	11	5.5	0.5	-0.5	-3.5	-4.5	-8	-8	-10.5
12.5	10.5	10	6	0.5	-1	-3	-4.5	-6	-7.5	-9
7.5	7	6.5	3	0.5	-1.5	-2.5	-3	-4.5	-3.5	-6.5
2.5	1	1.5	0	-1	-0.5	-1.5	-1	-1	-1	-1.5
-3.5	-3	-1.5	-2.5	-3.5	-1	-1	0	0.5	0.5	1.5
-5.5	-4	-3	-2.5	-2.5	-1	-1.5	0.5	-0.5	1	1.5
-3.5	-3	-1.5	-1	-1.5	-2	-1.5	-1	-0.5	-1.5	-1
1.5	0.5	1.5	0.5	-0.5	-1.5	-2.5	-2	-2.5	-3.5	-5
5	9	4	2.5	-0.5	-1	-2	-3	-3.5	-4.5	-7
6	5.5	4	2	0.5	-1.5	-1.5	-3.5	-3.5	-5	-7.5
4.5	3.5	3.5	1	-0.5	-1.5	-2	-3.5	-3	-4.5	-5
3.5	1.5	1.5	0	-0.5	-2	-2	-2.5	-2.5	-4	-4.5
0.5	-0.5	-1.5	-1	-2	-2	-2	-1.5	-2	-3	-2
0.5	0	-1	-1.5	-0.5	-1.5	-2	-1	-1.5	-2	-1.5
-1.5	-1	-1	-2	-1	-2	-2	-1	-1.5	-0.5	0
-1.5	-1.5	-1	-1	-2	-2	-2	-1	-2	-1	0.5

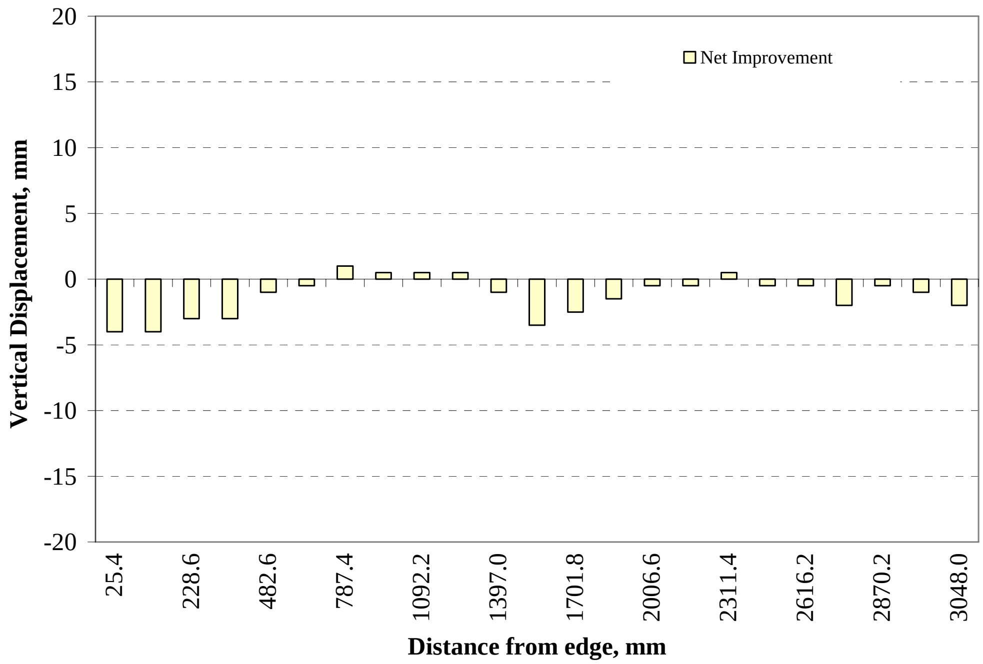


Figure 7.41: Net Improvement along Longitudinal Section E for T-MCAW Plate 8 vs. FCAW Plate 7 (No Tension)

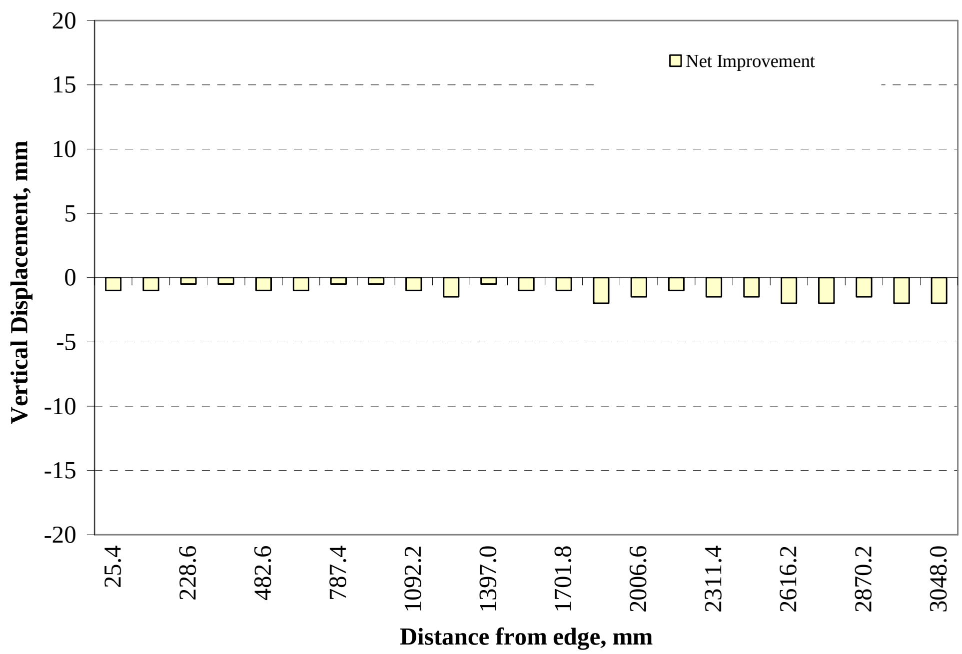


Figure 7.42: Net Improvement along Longitudinal Section F (Stiffener) for T-MCAW Plate 8 vs. FCAW Plate 7 (No Tension)

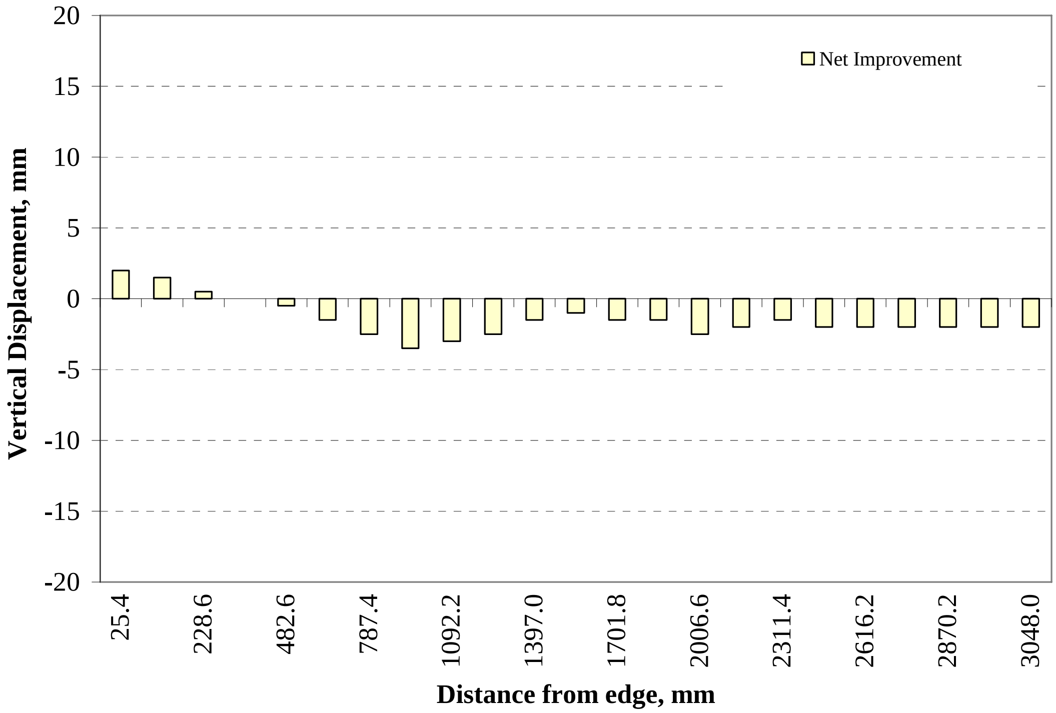


Figure 7.43: Net Improvement along Longitudinal Section G for T-MCAW Plate 8 vs. FCAW Plate 7 (No Tension)

The T-MCAW process results in a reduction in vertical displacement (distortion) compared to the FCAW process for the benchmark assemblies with no applied mechanical tension.

The distortion data in Table 7.27 and Figures 7.44 through 7.46 compare the overall net improvement achieved in controlling distortion with the use of the T-MCAW (10 000lbs tension) with respect to FCAW (benchmark assembly). The negative values, color coded light blue indicates location where tensioning has been effective to counter distortion due to welding. Also cells color coded green indicate no change in distortion and yellow indicates an increases in distortion. Additional plots and tables are provided in **Appendix H.**

Table 7.27: Net Improvement, T-MCAW Plate 9 vs. FCAW Plate 7 (No Tension)

Net Improvement, mm										
Benchmark										
A	B	C	D	E	F	G	H	I	J	K
-0.5	-1.5	-2.5	-4.5	-2.5	-2.5	-2	-1.5	0.5	-2.5	-0.5
0.5	-0.5	-1	-4	-2.5	-2.5	-1	-1	2	-1.5	-1
2	-4	0.5	-4	-2.5	-2.5	-1	-1	1	-0.5	-1
3.5	1.5	1	-2.5	-2.5	-2.5	-1	1.5	1	-1	-1
6	3	2.5	-1	-1	-2.5	0	2	2	0	-0.5
6	4	2.5	0	-1	-2.5	-1	1.5	2	-0.5	1
5	3.5	2.5	-1	-1.5	-2.5	-1	2	3.5	3	4
3.5	2	1	-2	-2	-2.5	0	4	4.5	5.5	7
1.5	0	-0.5	-2.5	-2	-2.5	0	4	6.5	6.5	8.5
-0.5	-1.5	-2	-3.5	-3.5	-3	0	4	6.5	8	9
-1.5	-3	-3	-3	-3.5	-1.5	0	-1	6	6	7
-2	-3	-2.5	-3	-3.5	-2	-0.5	3	3	3	4
-1.5	-1	-1	-2	-2	-2.5	-0.5	1	0	-1	-0.5
1	1.5	1	-0.5	-1.5	-1.5	-2	-1	-2	-5.5	-4.5
3.5	2.5	2	0	-1	-2.5	-2.5	-2.5	-4.5	-7	-8.5
3.5	8	2.5	1	-1.5	-1.5	-3	-2	-5	-7.5	-11
2.5	2	1.5	0	-0.5	-1.5	-1	-2	-4	-7	-9
0.5	0	0.5	-1	-1.5	-1.5	-1.5	-1.5	-3	-5	-6
-0.5	-0.5	-0.5	-1.5	-1	-2	-2	-1	-1	-3	-4
-1	-3	-3	-1.5	-1.5	-1	-1	-0.5	-1	-1	-1.5
-1	-1.5	-1.5	-2.5	-1	-0.5	-1	0.5	-0.5	-0.5	0.5
-2	-2	-2	-3	-1.5	-0.5	-1	0.5	0	1	0.5
-1.5	-2.5	-2.5	-2.5	-2.5	-0.5	-1.5	0	1	1	1

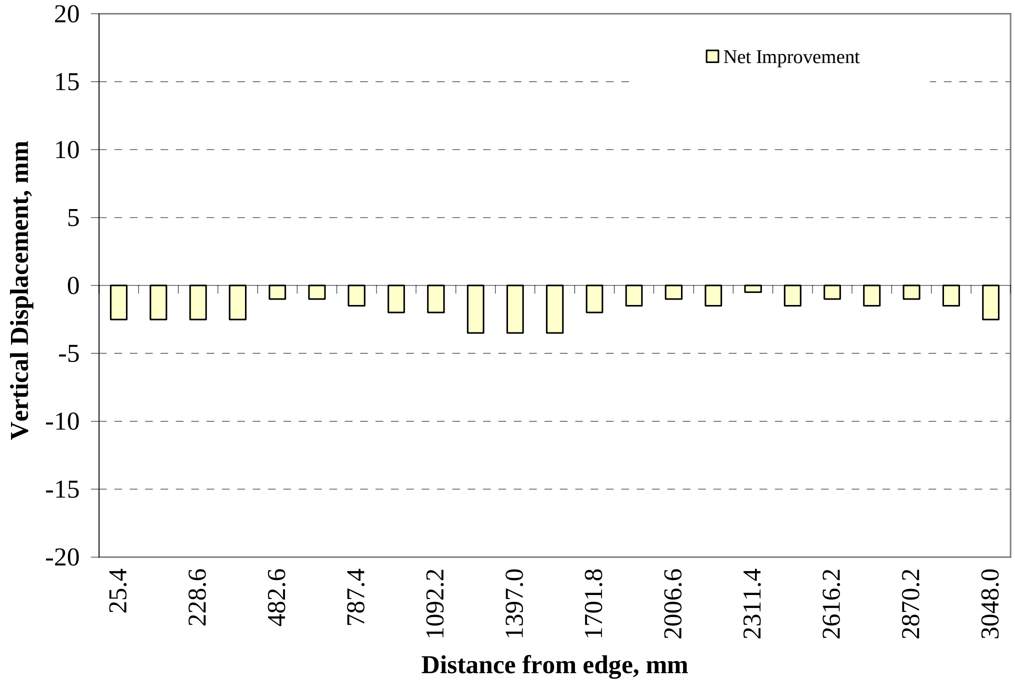


Figure 7.44: Net Improvement along Longitudinal Section E for T-MCAW Plate 9 (10 000lbs tension) vs. FCAW Plate 7 (No Tension)

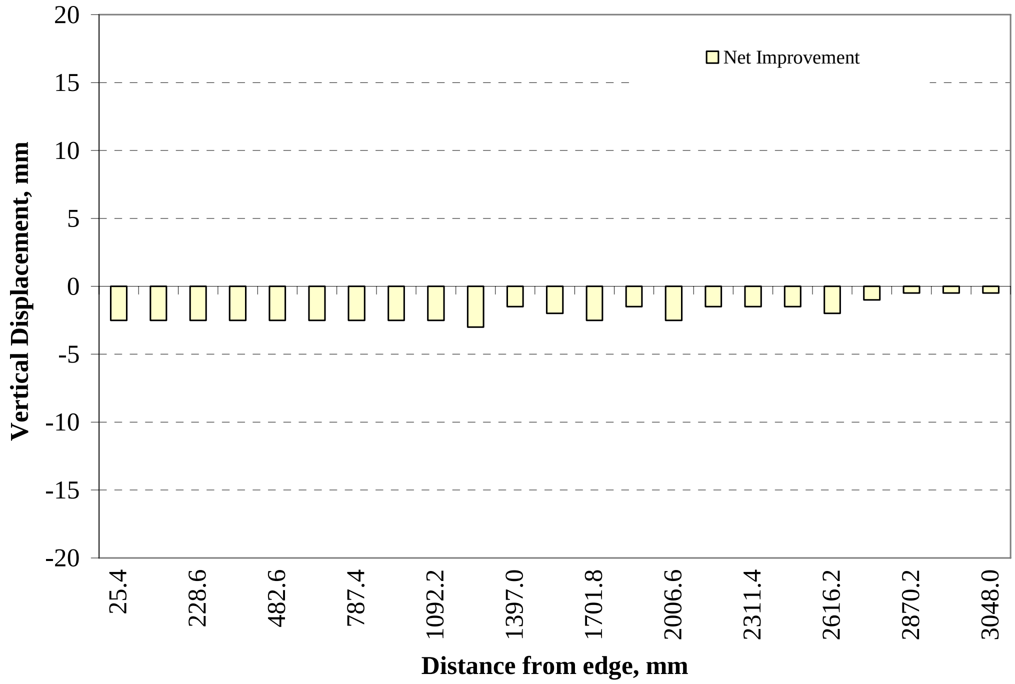


Figure 7.45: Net Improvement along Longitudinal Section F (Stiffener) for T-MCAW Plate 9 (10 000lbs tension) vs. FCAW Plate 7 (No Tension)

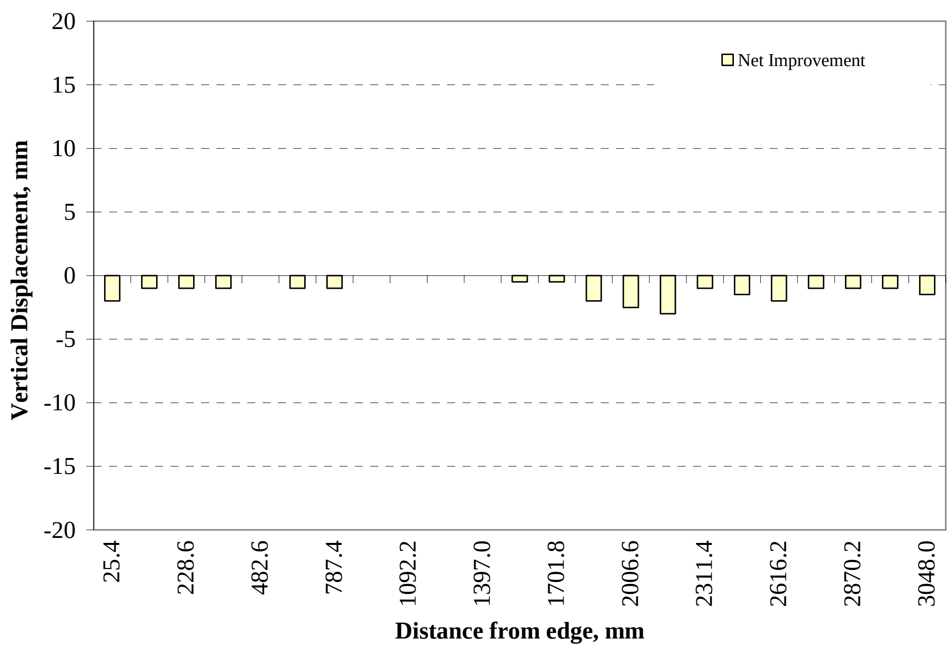


Figure 7.46: Net Improvement along Longitudinal Section G for T-MCAW Plate 9 (10 000lbs tension) vs. FCAW Plate 7 (No Tension)

From the data presented, it can be concluded that the T-MCAW process, as applied to fillet welding of high strength steel stiffener assemblies does provide some advantage to counter distortion without the use of tension. It can also be concluded that the mechanical tensioning approach as applied to fillet welding of high strength steel stiffener assemblies also provides some advantage to counter distortion.

All the distortion comparisons to this point have been with respect to vertical displacement, assuming that a negative displacement is good and a positive displacement is bad. A negative displacement represents the plate lowering with respect to the frame and a positive displacement represents the plate rising with respect to the frame.

7.3 Difference between Average and Displacement Values

Another approach was used to compare distortion. This approach requires that an average of the displacements for points 1 to 23 for each location (A through K) is calculated and represented as a straight line on the displacement plots (see Figures 7.29-7.40). Figures 7.47 and 7.48 show the displacement values with respect to the average including before welding, before welding with tension (if applicable), and after welding. The difference between the average and the positive or negative displacement was plotted to visualize how much deviation there was from the straight line average. With this methodology, positive and negative values both represent unwanted displacement. Tables 7.28 and 7.29 display values (deviation from the average) showing all values as positive so that they could be added to come up with a number to compare between the plates. Additional plots are shown in **Appendix K.**

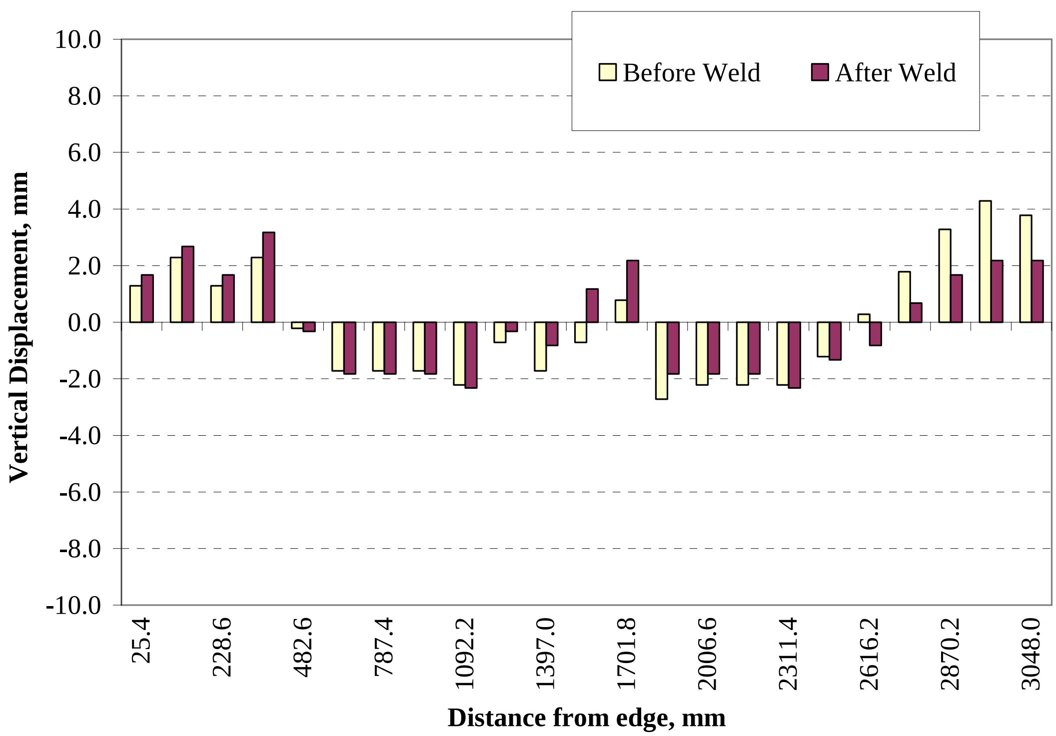


Figure 7.47: Vertical Displacement with Respect to Average along Longitudinal Section E for FCAW Plate 7 (No Tension)

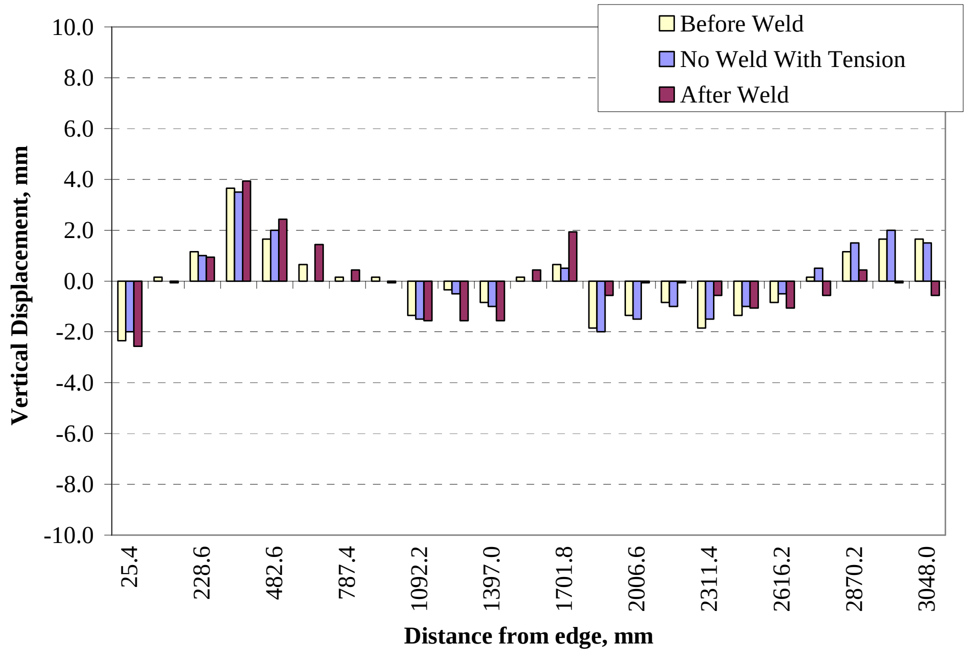


Figure 7.48: Vertical Displacement with Respect to Average along Longitudinal Section E for T-MCAW Plate 9 (10 000lbs Tension

Table 7.28: Vertical Displacement with Respect to Average for FCAW Plate 7 (No Tension)

Difference Btw. Avg and Disp - After Weld - Plate 7												
Displacement w.r.t to Frame, mm												
	A	B	C	D	E	F	G	H	I	J	K	
1	4.4	4.1	3.3	2.7	1.7	0.9	1.3	3.0	3.6	3.8	5.2	28.8
2	5.9	5.1	4.3	3.7	2.7	0.9	0.8	2.0	2.6	2.8	4.2	30.8
3	5.4	5.1	4.3	3.7	1.7	1.4	0.3	2.0	2.1	2.3	3.2	28.3
4	3.9	3.6	3.3	4.2	3.2	1.9	0.2	1.0	0.6	0.8	2.2	22.7
5	0.1	0.1	0.2	0.2	0.3	1.9	0.7	0.5	0.9	0.7	0.8	5.5
6	3.6	3.9	2.7	1.3	1.8	2.4	1.2	1.5	2.9	3.2	3.3	24.5
7	6.6	5.9	4.2	2.3	1.8	2.9	1.2	2.5	3.4	3.7	4.3	34.5
8	7.6	6.4	4.7	3.8	1.8	2.4	1.7	2.5	3.9	4.2	4.3	39.0
9	6.6	5.4	5.2	2.8	2.3	1.9	1.2	2.5	2.4	3.7	3.3	34.0
10	3.6	2.9	3.2	1.8	0.3	1.4	0.7	1.0	0.9	0.7	1.3	16.5
11	0.9	1.6	0.2	0.2	0.8	1.9	0.8	0.5	1.1	0.8	1.2	8.7
12	5.4	4.6	2.8	2.2	1.2	0.9	0.3	0.5	1.1	1.3	2.2	20.3
13	7.4	6.1	4.3	3.2	2.2	0.1	0.7	0.0	0.1	1.3	1.7	25.4
14	2.9	2.1	0.8	0.3	1.8	1.4	0.8	0.5	0.6	0.3	0.3	11.6
15	0.6	0.4	0.7	1.3	1.8	0.1	0.7	1.5	2.4	2.2	2.8	11.7
16	3.1	2.9	2.2	2.3	1.8	1.1	2.2	3.0	3.9	4.2	5.8	26.7
17	4.6	4.4	3.7	2.3	2.3	0.6	0.2	3.0	3.4	3.7	6.3	28.2
18	4.6	4.4	3.2	2.8	1.3	1.1	0.8	1.0	1.4	2.7	4.3	23.3
19	1.6	1.4	0.7	1.3	0.8	2.1	0.3	0.0	0.1	0.7	2.8	9.0
20	0.9	1.1	1.3	0.2	0.7	3.1	1.8	1.5	1.6	1.3	1.2	13.5
21	1.9	2.1	2.3	1.2	1.7	3.6	0.8	2.0	2.6	3.3	3.2	21.5
22	1.9	1.6	1.8	1.2	2.2	4.6	1.3	3.0	4.1	5.8	6.7	27.5
23	0.9	1.1	1.3	0.2	2.2	5.1	1.3	3.0	5.1	6.3	7.7	26.5
	84.4	**76.3**	**60.7**	**45.2**	**38.5**	**43.6**	**21.3**	**38.0**	**50.8**	**59.8**	**78.3**	**518.5**

Table 7.29: Vertical Displacement with Respect to Average for T-MCAW Plate 9 (10 000lbs Tension)

Difference Btw. Avg and Disp - After Weld - Plate 9												
Displacement w.r.t to Frame, mm												
	A	B	C	D	E	F	G	H	I	J	K	
1	11.0	9.3	6.6	5.2	2.3	3.1	1.4	2.4	0.1	0.2	2.7	41.6
2	6.5	4.3	3.1	2.2	0.2	3.1	1.9	3.4	0.9	0.8	1.7	26.4
3	1.5	4.7	0.1	0.8	1.2	2.6	2.4	2.9	0.9	0.8	1.7	17.9
4	2.0	3.2	2.9	3.8	3.7	2.1	2.4	1.4	1.9	1.3	0.7	24.7
5	3.5	4.2	2.4	1.8	1.7	1.6	1.4	0.9	1.4	1.3	0.2	20.2
6	2.5	3.2	2.4	1.8	0.7	1.1	1.9	0.4	0.9	0.8	0.2	15.7
7	0.5	0.7	1.4	1.3	0.2	0.1	0.9	0.6	1.1	1.2	2.2	8.0
8	1.0	0.8	0.4	0.2	0.2	0.1	0.9	0.6	0.6	1.2	1.7	6.0
9	2.5	2.3	1.6	0.7	1.3	0.9	0.9	0.6	0.1	1.2	1.7	12.1
10	2.5	2.3	2.6	1.2	0.3	1.4	0.9	0.1	0.1	0.7	0.2	12.1
11	0.5	1.3	2.1	2.2	0.8	2.4	0.4	4.4	0.1	0.3	1.3	14.5
12	1.5	1.2	0.4	0.3	0.2	1.9	0.1	0.6	0.4	0.8	1.3	7.4
13	4.0	3.2	1.9	1.8	0.7	0.9	0.6	0.6	0.1	0.3	1.3	14.1
14	3.0	1.2	0.9	0.2	1.8	2.9	2.6	3.1	2.1	1.7	0.7	19.5
15	3.0	1.7	0.9	0.3	1.3	1.9	2.1	2.6	1.6	1.7	1.2	17.1
16	2.5	1.2	0.9	0.2	0.8	1.4	1.1	2.1	1.1	1.2	0.2	12.5
17	0.5	1.3	1.6	1.2	1.8	1.9	2.1	2.1	1.1	0.7	0.3	14.3
18	1.5	2.8	2.1	2.2	1.3	1.9	2.1	1.6	0.6	0.7	2.3	16.8
19	0.5	2.3	1.6	1.2	0.8	0.4	1.1	0.6	0.1	0.8	3.3	9.4
20	0.5	0.3	0.4	0.3	0.2	0.1	1.1	0.6	0.9	0.8	2.3	5.2
21	1.5	0.7	1.4	1.8	1.2	0.6	1.1	0.1	0.9	1.3	1.3	10.6
22	2.0	1.2	1.9	1.8	1.7	1.6	1.1	0.1	0.4	0.3	0.8	12.1
23	1.0	0.7	1.9	1.8	1.7	2.1	1.1	0.1	0.4	0.3	0.8	11.1
	55.5	**54.1**	**41.5**	**34.3**	**26.1**	**36.1**	**31.6**	**31.9**	**17.8**	**20.4**	**30.1**	**349.3**

The sum of all vertical displacement with respect to the average for the benchmark FCAW plate 7 was 518.5 compared to 349.3 for the T-MCAW plate welded with 10 000lbs tension. This indicates that the stiffener plate assembly welded with T-MCAW using 10 000lbs of tension exhibited **48%** less distortion overall compared to the benchmark FCAW stiffener test assembly.

7.4 Porosity Results

FCAW plates 7, 3 and MCAW plates 8, 9 (primed plates) were evaluated for porosity indications by method of visual examination of fractured weld surface as per the requirements of MIL-ST-248C. A total length of 36” was required for testing from each test assembly. A 12” section was taken from the start, center, and end locations of the large test assemblies to investigate possible patterns related to amount of porosity and location of porosity on the plate. The 12” sections were then cut into 6” sections to facilitate fracturing for examination. The first side weld was removed by grinding and tabs were welded to the top and bottom of the specimen for loading in the load cell where tension was applied until fracture occurred. Measurements of porosity indications were taken from the fractured weld surface and evaluation was performed to MIL-STD-248C. See Tables 7.30 through 7.33 for porosity results.

Table 7.30: Porosity Counts for Plate 7

Porosity Counts for Plate 7			
Weld Location	**Location (Ruler)**	**# Defects at 3/32" min.**	**Special Notes**
Start 1	0-1"	1	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
Start 2	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
Center 1	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	**Fail: More than 5 indications larger than 1/16" were found within**
	5-6"	0	**1 inch of weld exceeding maximum as stated in MIL-STD-248C**
Center 2	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
End 1	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
End 2	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	

Plate 7 was relatively free of porosity in the fractured weld with only one region in the center of the plate exhibiting an accumulation of more than 5 porosity indications greater than 1/16" within 1 inch of weld. For this reason plate 7 fails to meet the requirements of MIL-STD-248C. Photographs of all fracture specimens for plate 7 are shown in **Appendix M**.

Table 7.31: Porosity Counts for Plate 3

Porosity Counts for Plate 3			
Weld Location	**Location (Ruler)**	**# Defects at 3/32" min.**	**Special notes**
Start 1	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
Start 2	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
Center 1	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
Center 2	0-1"	1	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
End 1	0-1"	6	3/32" defect to surface at 7/8" mark.
	1-2"	3	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**
End 2	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	

Plate 3 was also relatively free of porosity in the fractured weld with only one region in the end of the plate exhibiting a porosity indication greater than 3/32." For this reason plate 3 fails to meet the requirements of MIL-STD-248C. Photographs of all fracture specimens for plate 3 are shown in **Appendix L**.

The stiffener used for Plate 7 had a thicker layer of primer (1.68 mil average) compared to the stiffener used for Plate 3 (1.21 mil average). The base plate used for Plate 7 also had a thicker layer of primer (1.15 mil average) compared to the base plate used for Plate 3 (0.97 mil). It appears that the primer thickness does not have a bearing (under 2 mil in thickness) on the resulting porosity indications using the FCAW process. This is most likely explained by the slower welding speeds and longer degasification times associated with the FCAW process when welding over primers.

Table 7.32: Porosity Counts for Plate 8

Porosity Counts for Plate 8			
Weld Location	**Location (Ruler)**	**# Defects at 3/32" min.**	**Special notes**
Start 1	0-1"	2	3/32" defect to surface at 1-7/8"" mark.
	1-2"	2	
	2-3"	4	
	3-4"	2	
	4-5"	0	
	5-6"	0	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**
Start 2	0-1"	2	
	1-2"	2	
	2-3"	3	
	3-4"	3	
	4-5"	3	**Fail: More than 5 indications larger than 1/16" were found within**
	5-6"	3	**1 inch of weld exceeding maximum as stated in MIL-STD-248C**
Center 1	0-1"	2	
	1-2"	4	
	2-3"	3	3/32" defect to surface at 2-1/4" mark.
	3-4"	1	
	4-5"	2	
	5-6"	4	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**
Center 2	0-1"	2	
	1-2"	1	
	2-3"	1	
	3-4"	1	
	4-5"	0	
	5-6"	4	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**
End 1	0-1"	1	
	1-2"	2	
	2-3"	1	
	3-4"	2	
	4-5"	2	
	5-6"	1	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**
End 2	0-1"	2	
	1-2"	2	
	2-3"	3	
	3-4"	2	
	4-5"	4	
	5-6"	3	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**

Plate 8 exhibited the greatest amount of porosity with many indications exceeding 3/32” throughout the start, center, and end locations. For this reason plate 8 fails to meet the requirements of MIL-STD-248C. Photographs of all fracture specimens for plate 8 are shown in **Appendix N**.

Table 7.33: Porosity Counts for Plate 9

Porosity Counts for Plate 9			
Weld Location	**Location (Ruler)**	**# Defects at 3/32" min.**	**Special Notes**
Start 1	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	2	
	5-6"	0	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**
Start 2	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
Center 1	0-1"	2	
	1-2"	1	
	2-3"	2	
	3-4"	2	
	4-5"	0	
	5-6"	0	
Center 2	0-1"	1	
	1-2"	2	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**
End 1	0-1"	0	
	1-2"	0	
	2-3"	0	
	3-4"	0	
	4-5"	0	
	5-6"	0	
End 2	0-1"	1	
	1-2"	1	
	2-3"	3	
	3-4"	1	
	4-5"	0	
	5-6"	0	**Fail: Indication exceeding 3/32" as stated in MIL-STD-248C**

Plate 9 exhibited significantly less porosity compared to plate 8. A total of three indications exceeding 3/32" in the start, center, and end locations were observed. For this reason plate 9 fails to meet the requirements of MIL-STD-248C. Photographs of all fracture specimens for plate 9 are shown in **Appendix O**.

The stiffener used for Plate 8 had a thicker layer of primer (1.53 mil average) compared to the stiffener used for Plate 9 (1.21 mil average). The stiffener used for plate 8 also exhibited dramatic fluctuations in primer thickness from 0.71 mil to 4.73 mil due to the rough surface condition of the cut edge of the stiffener. The base plate used for Plate 8 and Plate 9 were similar in thickness at 1.22 mil and 1.21 mil. It appears that fluctuations in primer thickness have a bearing on the resulting porosity indications using the T-MCAW process.

7.5 Productivity Results

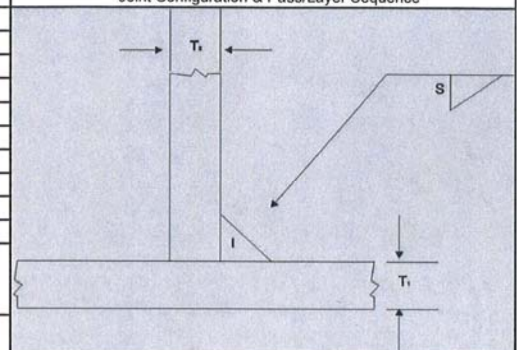
Travel speeds obtained with the T-MCAW process were much faster than with the benchmark FCAW process. The T-MCAW non-primed stiffener assemblies were welded at 90IPM travel speeds compared to 28IPM travel speeds achieved with the FCAW benchmark procedure for a **221% increase** in travel speed. The T-MCAW primed stiffener assemblies were welded at 60IPM travel speeds compared to 25IPM travel speeds achieved with the FCAW benchmark procedure for a **140%** increase in travel speed. The resulting weld size was slightly larger for the T-MCAW process (between ¼" and 3/16" leg size) compared to the resulting weld size for the FCAW process (between 1/8" and 3/16"). Figures 7.49 and 7.50 show data sheets for the FCAW and T-MCAW processes for both welding over primer and welding on clean steel.

BMT Fleet Technology — **WELDING PROCEDURE DATA SHEET**

WPDS NO.:	FCAW-2F		
DATE:	26-Jun-08	Rev.:	
Company Name:	BMT Fleet Technology	Ref. Standards:	
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8	Ref. WPS:	

Welding Processes:	1	FCAW	Pulsed: ☐ Yes ☑ No
Shielding Gas Type:		100% C02	
	2		Pulsed: ☐ Yes ☐ No
Positions:	Horizontal (2F)		
Process Mode:	☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto		
Joint Type:	☐ Butt ☑ Tee ☐ Corner ☐ Lap ☐ Edge		
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet		
Backing:	Material: N/A	Thickness: N/A	
Backgouging:	☐ Yes Method: N/A		
	☐ No Depth: N/A		
Electrode Extension:	contact tip to work distance = 19mm to 25mm		
Nozzle Diameter(s):	7/8" to 3/4"		
Flux Classification:	N/A		
Tungsten Electrode:	Type: N/A	Dia.: N/A	
Cleaning Procedures	As Required: Chipping, wire brush, wire wheel		
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only		

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	HSLA 80	3/16"	
II	HSLA 80	3/16"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
FCAW	Trimark	MIL-101TM		

Welding Parameters

Thick-ness (In.)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Burn-Off Rate ( )	Gas Flow Rate (CFH	Heat Input (kJ/in)
Base Material in Primed Condition													
3/16	3/16	1	1	FCAW	.045	350	210	30	DCEP	25	N/A	40	15
Base Material with Primer Removed													
3/16	3/16	1	1	FCAW	.045	320	205	27.5	DCEP	28	N/A	40	12

Heat treatment :				**CWB Acceptance**	**Company Authorization**
Preheat min:	Ambient	Interpasstemp.max.:	N/A		
		Interpasstemp.min.:	N/A		
					Date:

Figure 7.49: Welding Procedure Data Sheet for FCAW

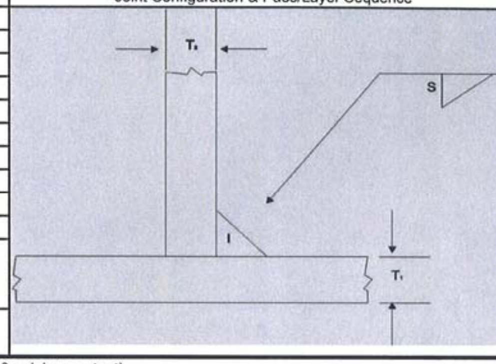
BMT Fleet Technology — **WELDING PROCEDURE DATA SHEET**

WPDS NO.: T-MCAW-2F
DATE: 26-Jun-08 Rev.:

Company Name:	BMT Fleet Technology	Ref. Standards:	
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8	Ref. WPS:	

Welding Processes:	1	T-MCAW	Pulsed: ☐ Yes ☑ No	2 — Pulsed: ☐ Yes ☐ No
Shielding Gas Type:		85Ar/15C02		
Positions:	Horizontal (2F)			
Process Mode:	☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto			
Joint Type:	☐ Butt ☑ Tee ☐ Corner ☐ Lap ☐ Edge			
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet			
Backing:	Material: N/A	Thickness: N/A		
Backgouging:	☐ Yes Method: N/A			
	☐ No Depth: N/A			
Electrode Extension:	contact tip to work distance = 19mm to 25mm			
Nozzle Diameter(s):	7/8" to 3/4"			
Flux Classification:	N/A			
Tungsten Electrode:	Type: N/A	Dia.: N/A		
Cleaning Procedures	As Required: Chipping, wire brush, wire wheel			
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only			

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	HSLA 80	3/16"	
II	HSLA 80	3/16"	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
T-MCAW	Trimark Metalloy 100	E100C-G		

Welding Parameters

Thick-ness (In.)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Burn-Off Rate ( )	Gas Flow Rate (CFH	Heat Input (kJ/in)
Base Material in Primed Condition													
		Lead Wire											
3/16	3/16	1	1	T-MCAW	.045	500	280	26	DCEP	60	N/A	45	28
		Trail Wire											
		1	1	T-MCAW	.045	350	250	27	DCEP	60	N/A	45	
Base Material with Primer Removed													
		Lead Wire											
3/16	3/16	1	1	T-MCAW	.045	500	315	23	DCEP	90	N/A	45	18
		Trail Wire											
		1	1	T-MCAW	.045	374	258	23.5	DCEP	90	N/A	45	

Heat treatment :				**CWB Acceptance**	**Company Authorization**
Preheat min:	Ambient	Interpasstemp.max.:	N/A		
		Interpasstemp.min.:	N/A		

Power Supplies: ESAB Aristomig 450
Program: MIG/MAG, DIP/SPRAY, FE Metal Cored, Ar+8%C02, 1.2mm
Lead and trail wires set at 80% Inductance with synergic mode on
Start Data: 0.1s preflow, creep start: no, hot start: yes, 0.5s time
lead wire speed: 402, trail wire speed: 303

Date:

Figure 7.50: Welding Procedure Data Sheet for T-MCAW

APPENDIX A

DISTORTION PLOTS FOR GROOVE WELDS

PLATE 1 – SIDE 1

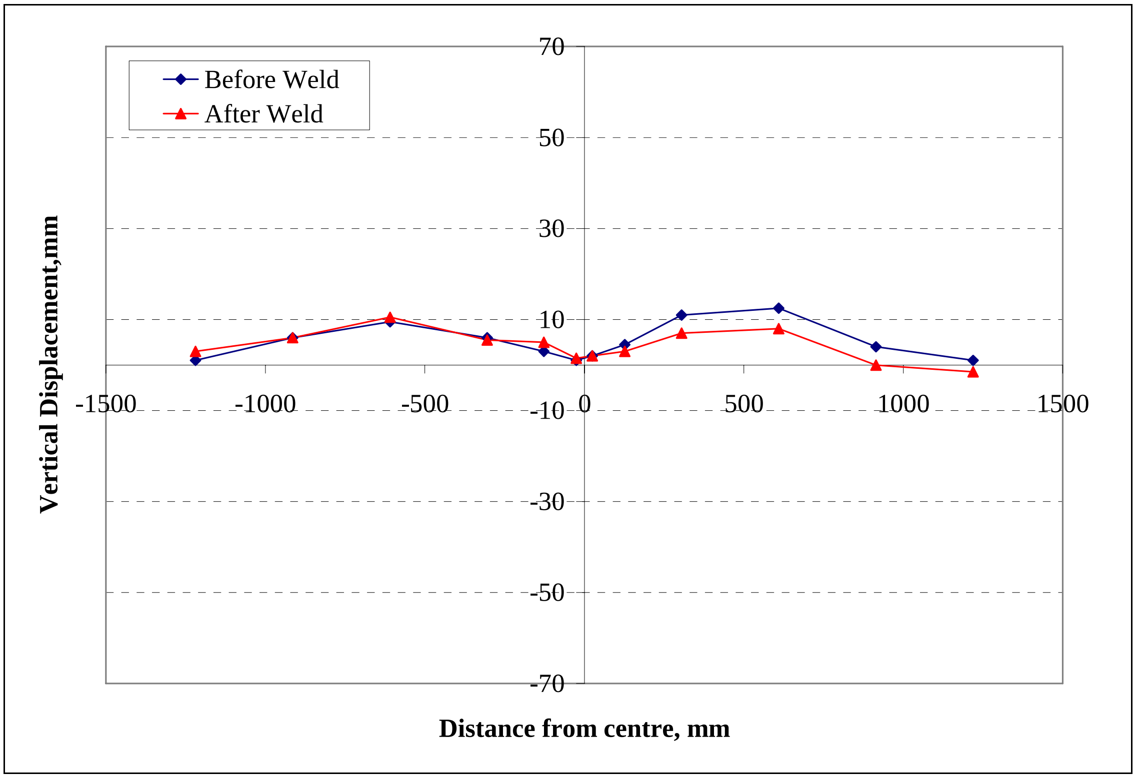


Figure 1: Transverse Section A1

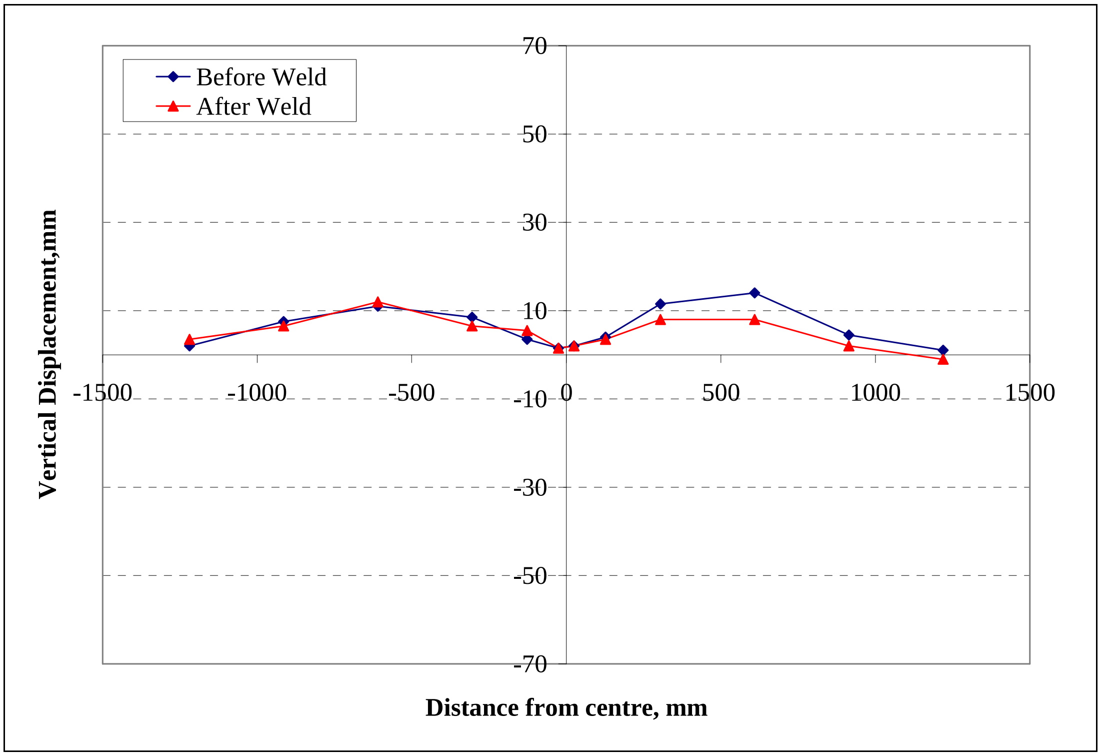


Figure 2: Transverse Section A2

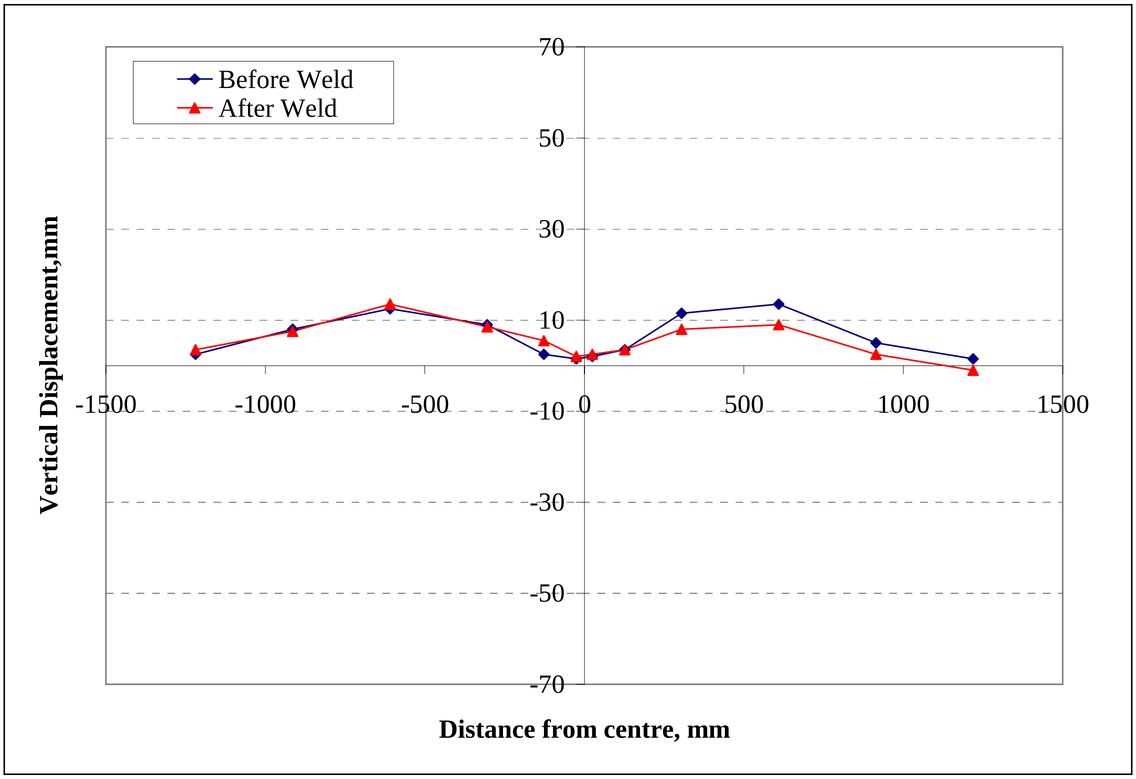


Figure 3: Transverse Section A3

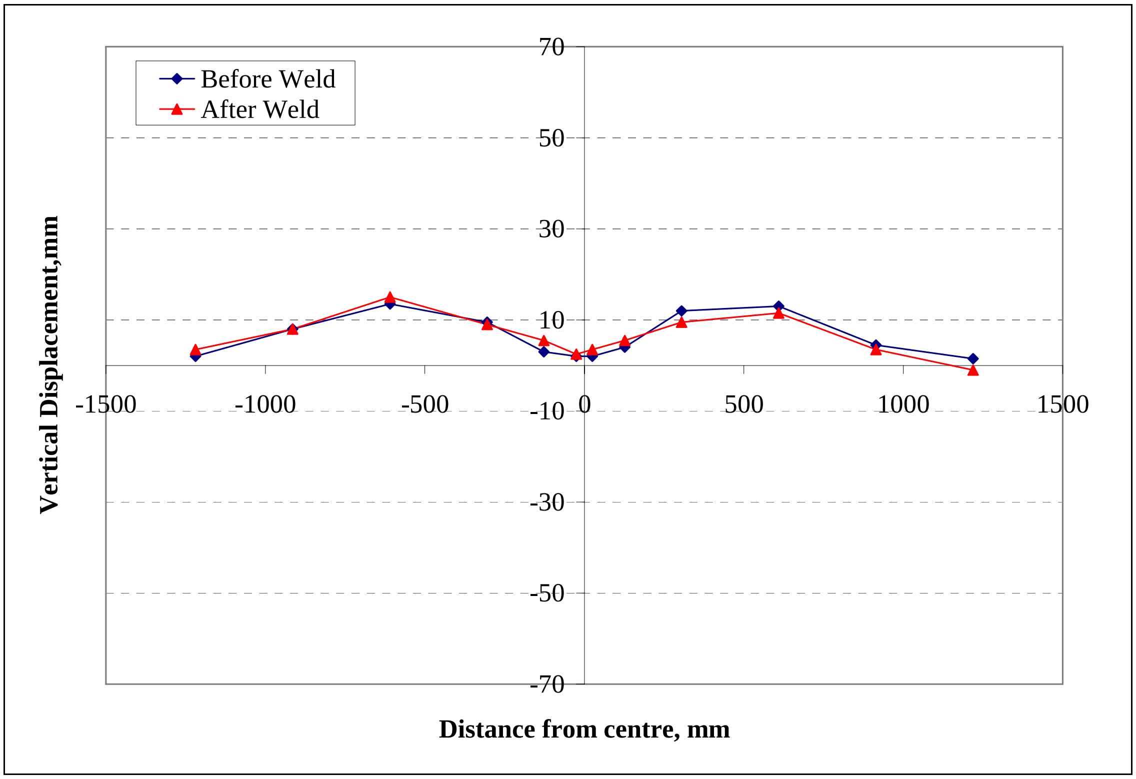


Figure 4: Transverse Section A5

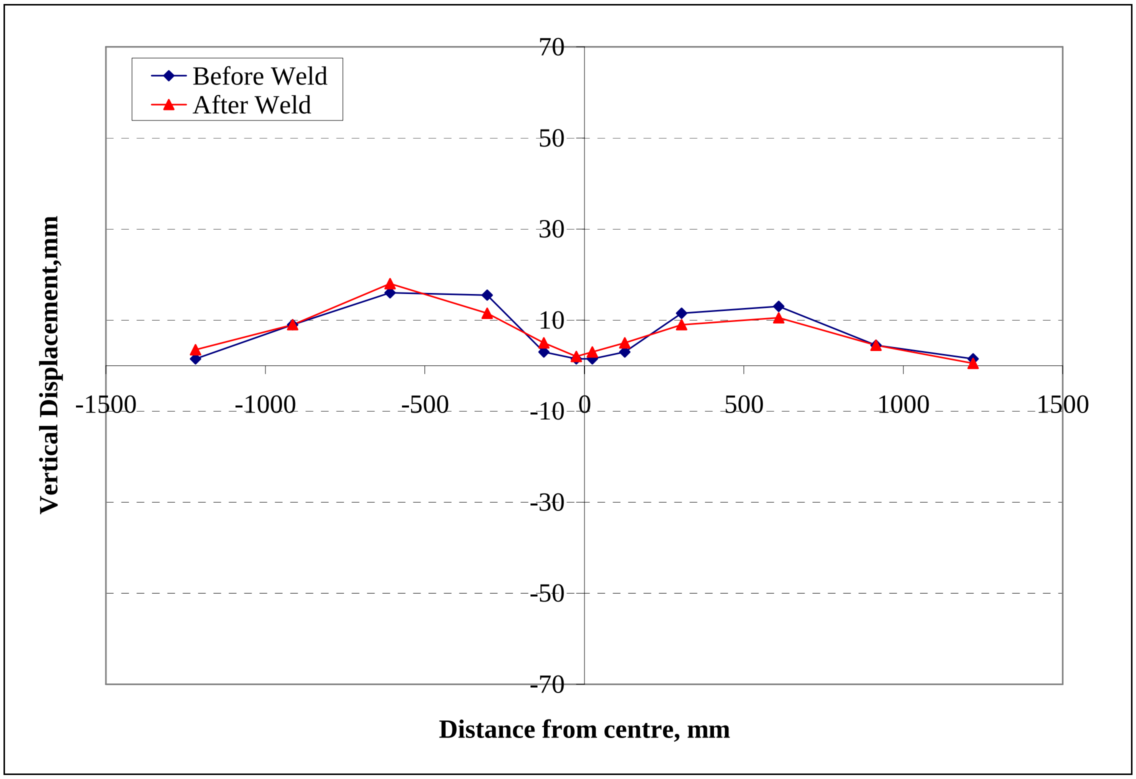


Figure 5: Transverse Section A7

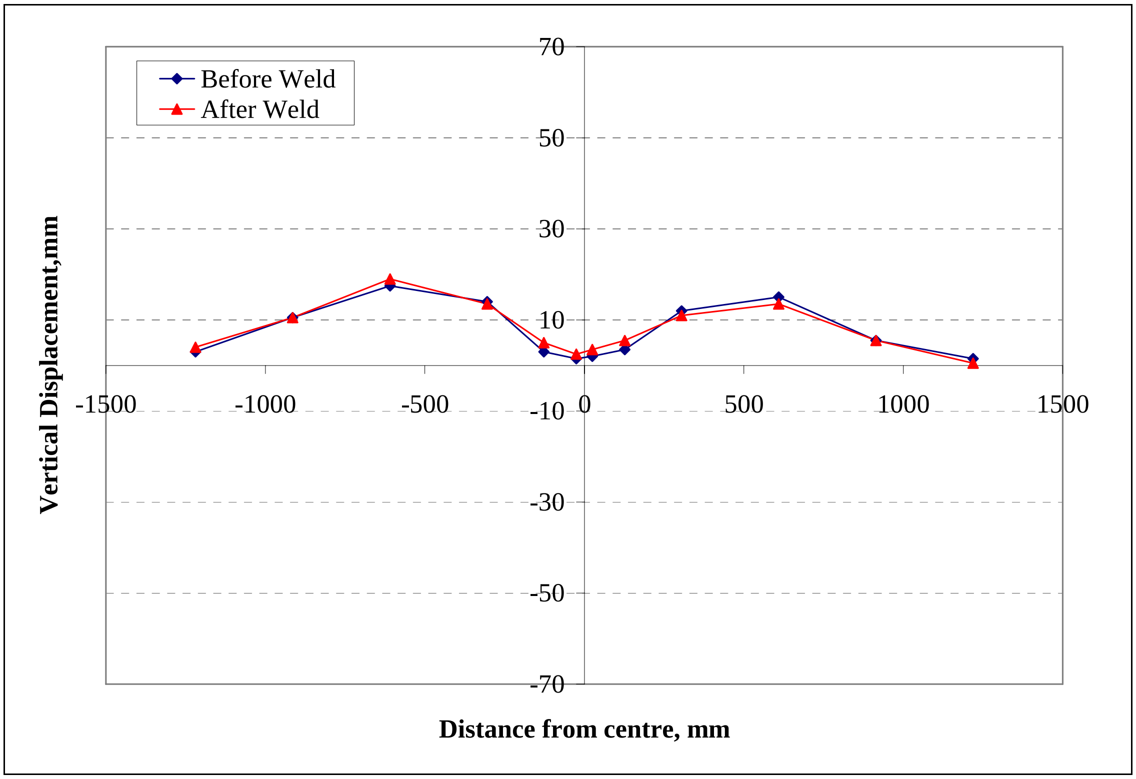


Figure 6: Transverse Section A9

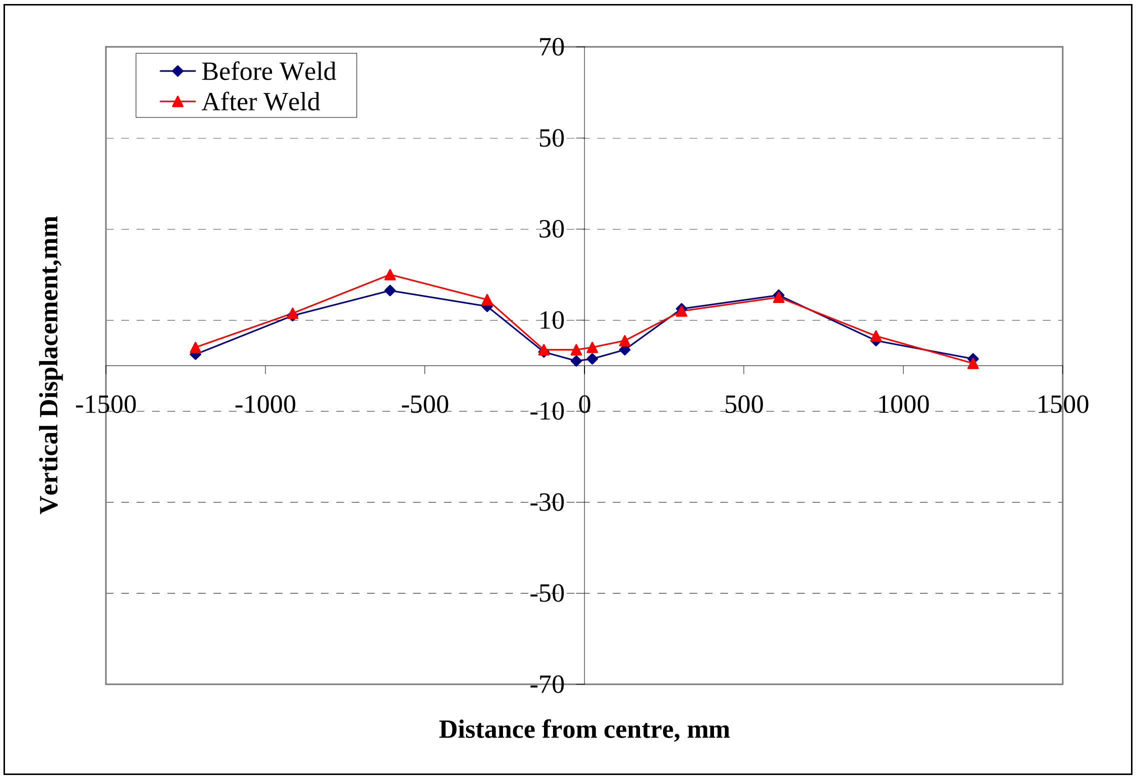


Figure 7: Transverse Section A11

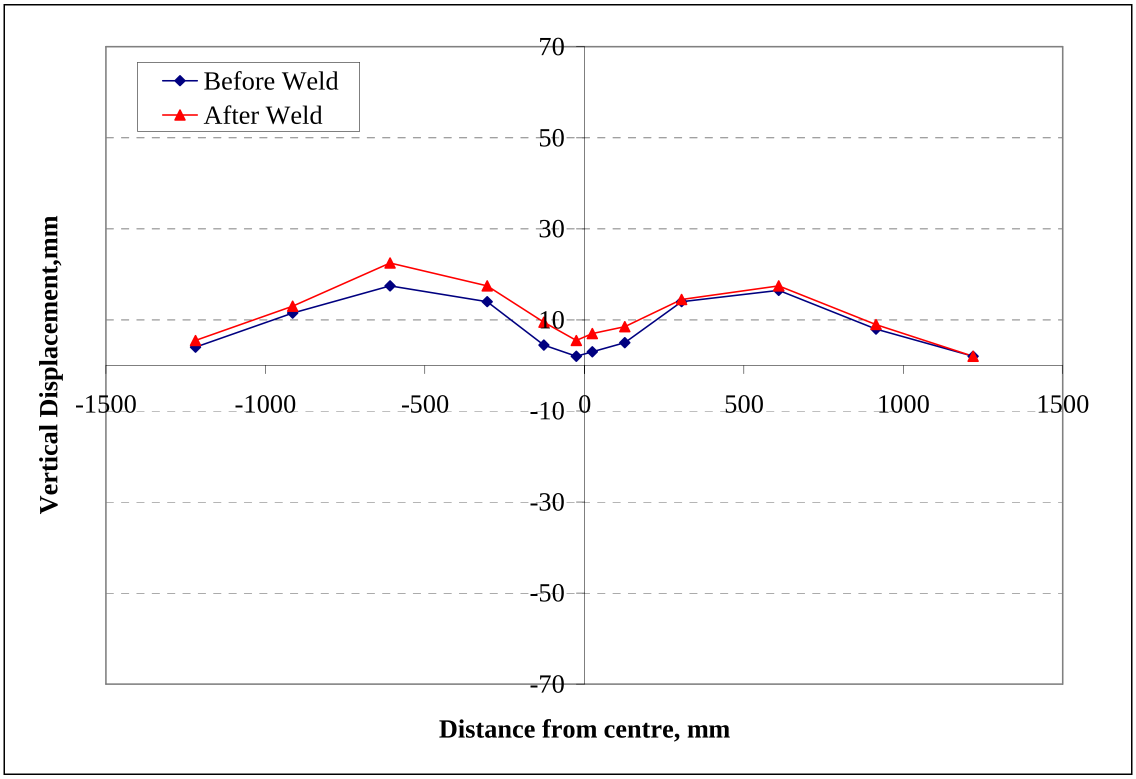


Figure 8: Transverse Section A13

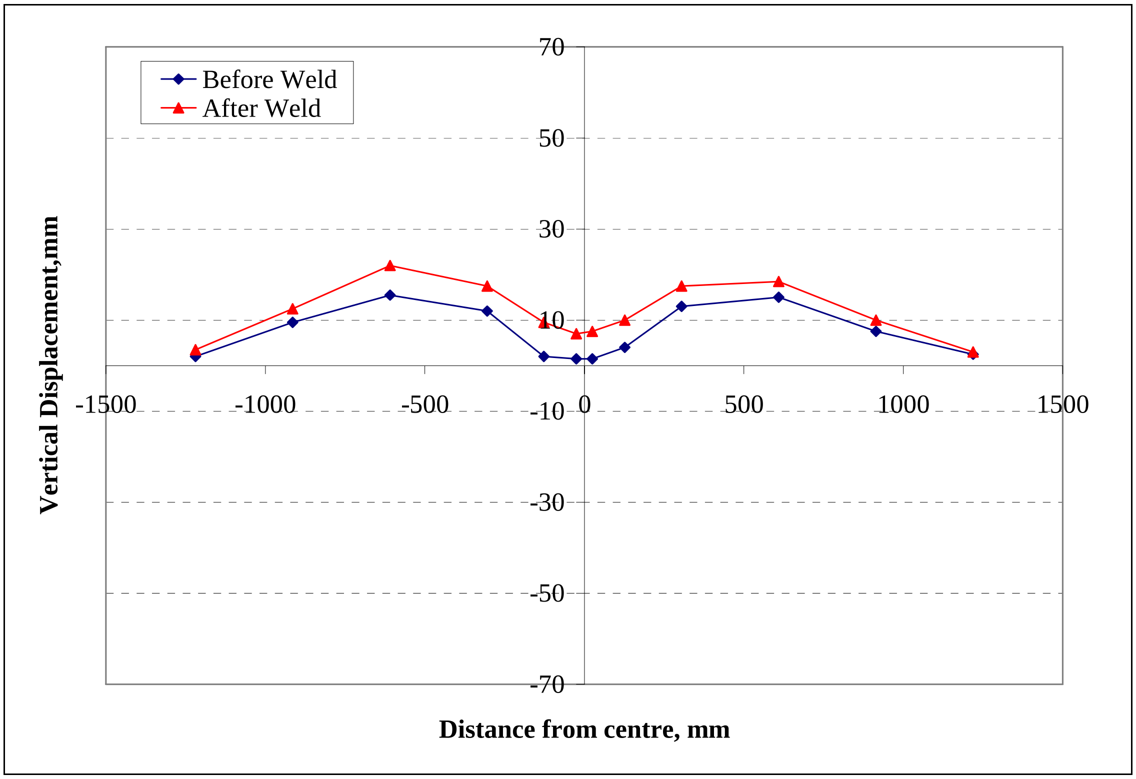


Figure 9: Transverse Section A15

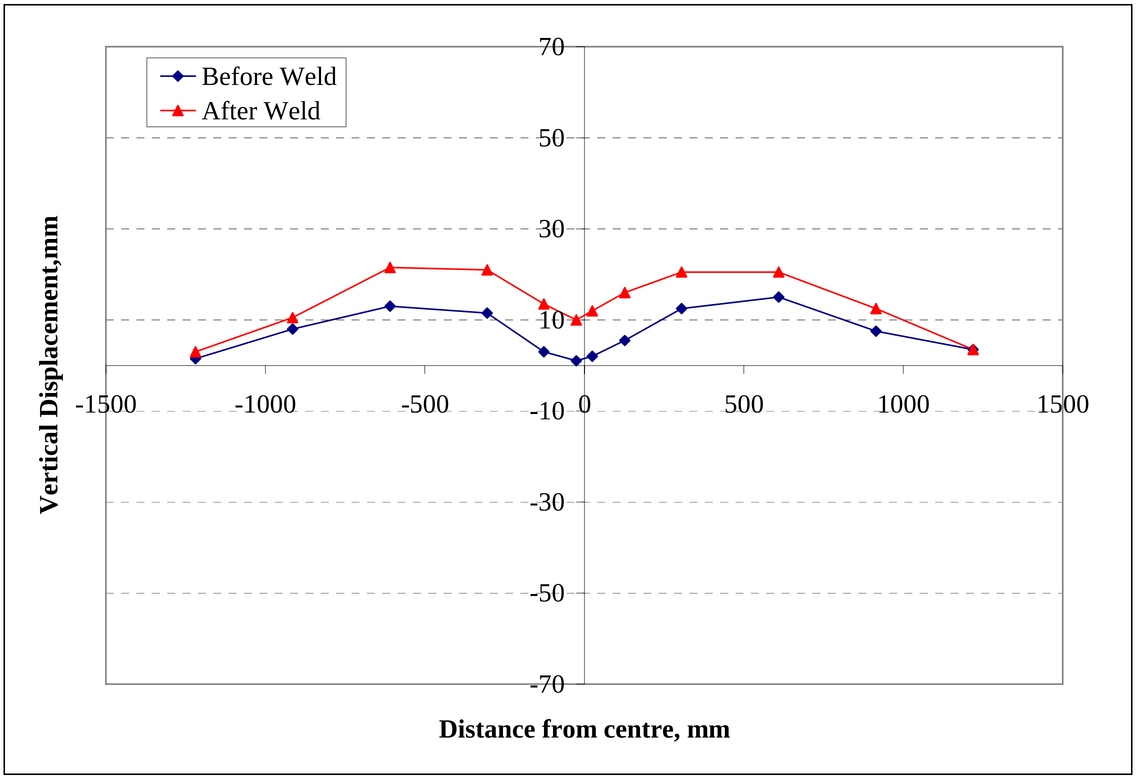


Figure 10: Transverse Section A17

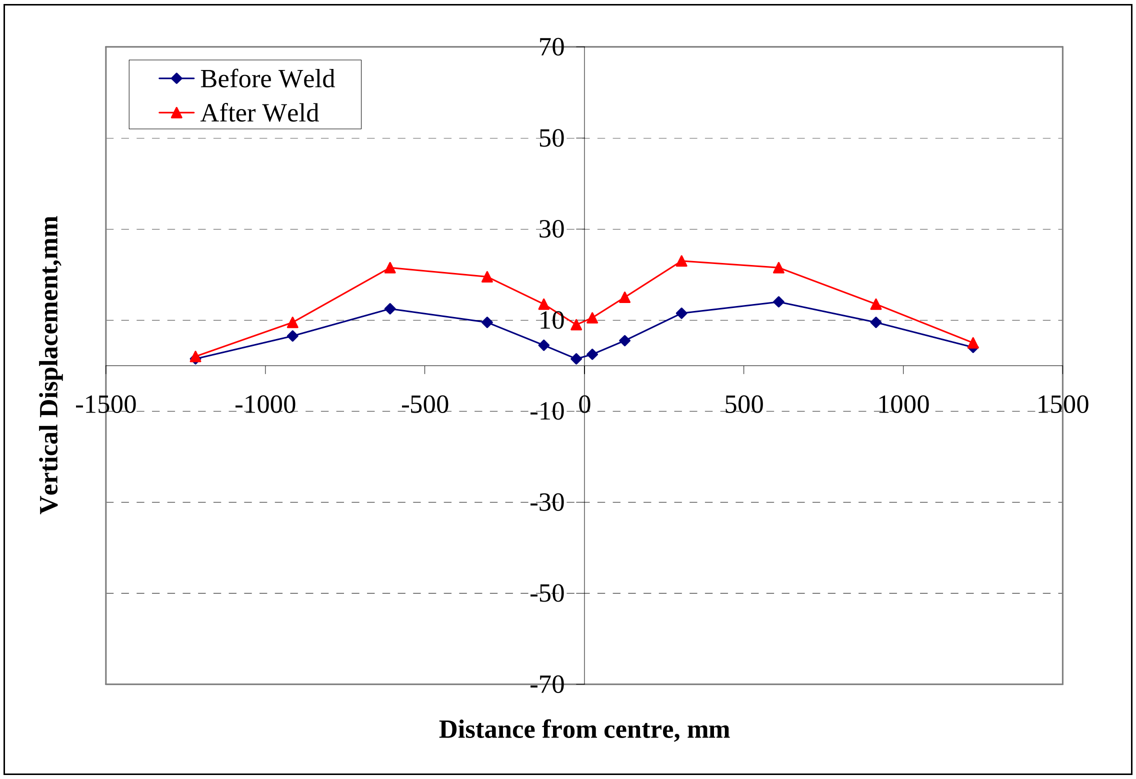


Figure 11: Transverse Section A19

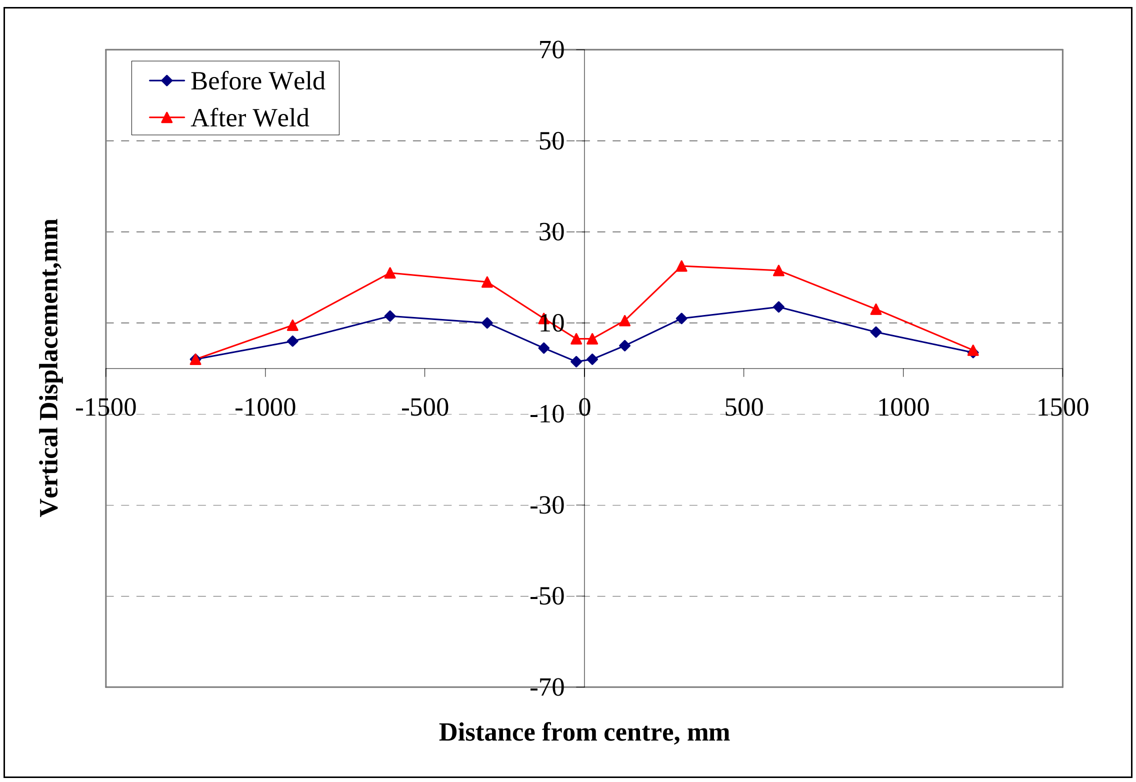


Figure 12: Transverse Section A20

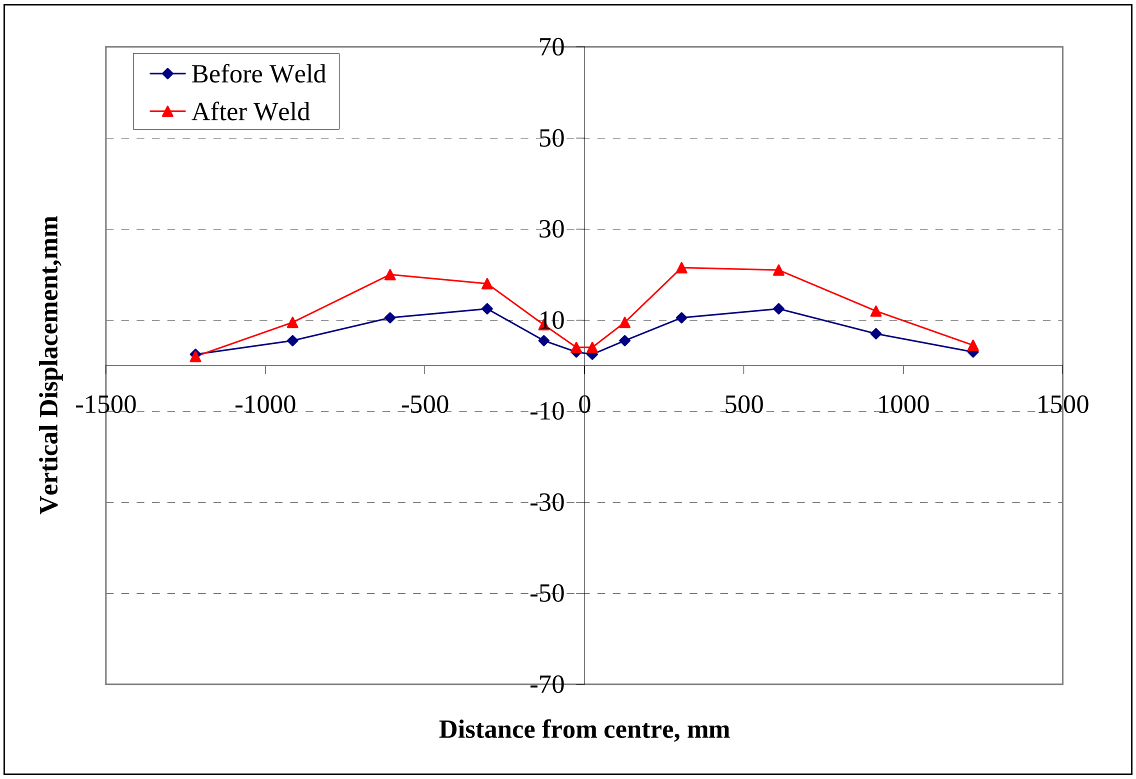


Figure 13: Transverse Section A21

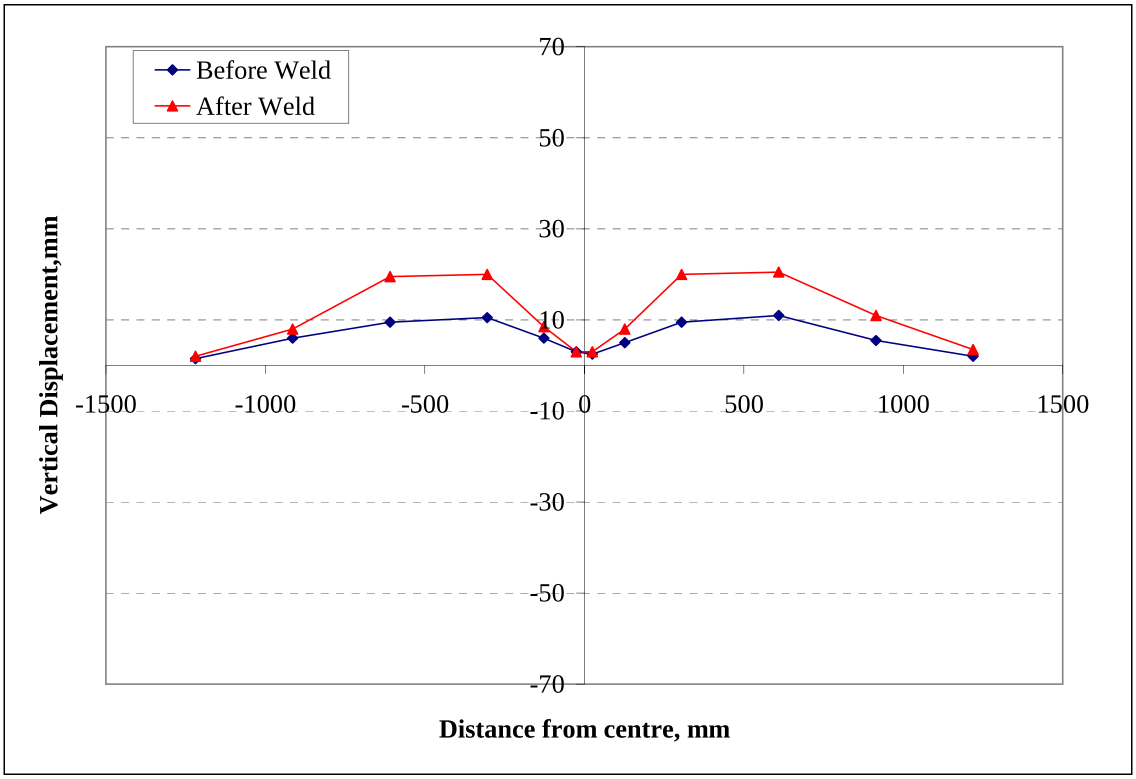


Figure 14: Transverse Section A22

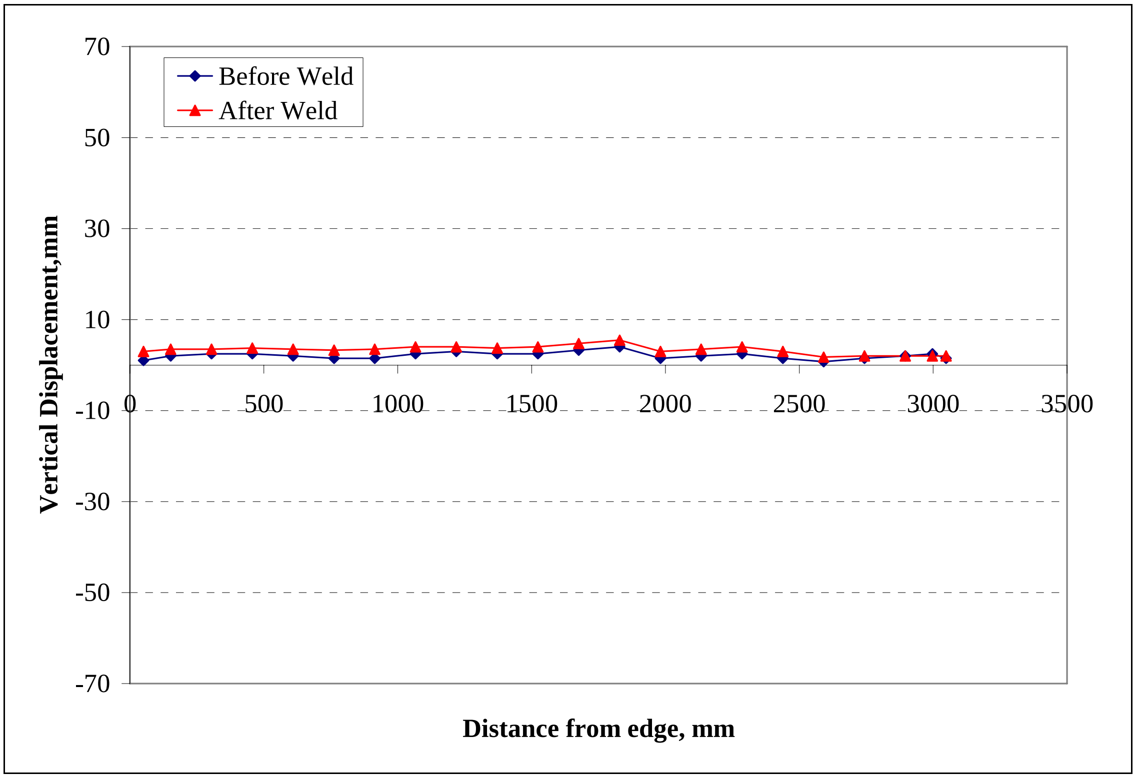


Figure 15: Longitudinal Section A

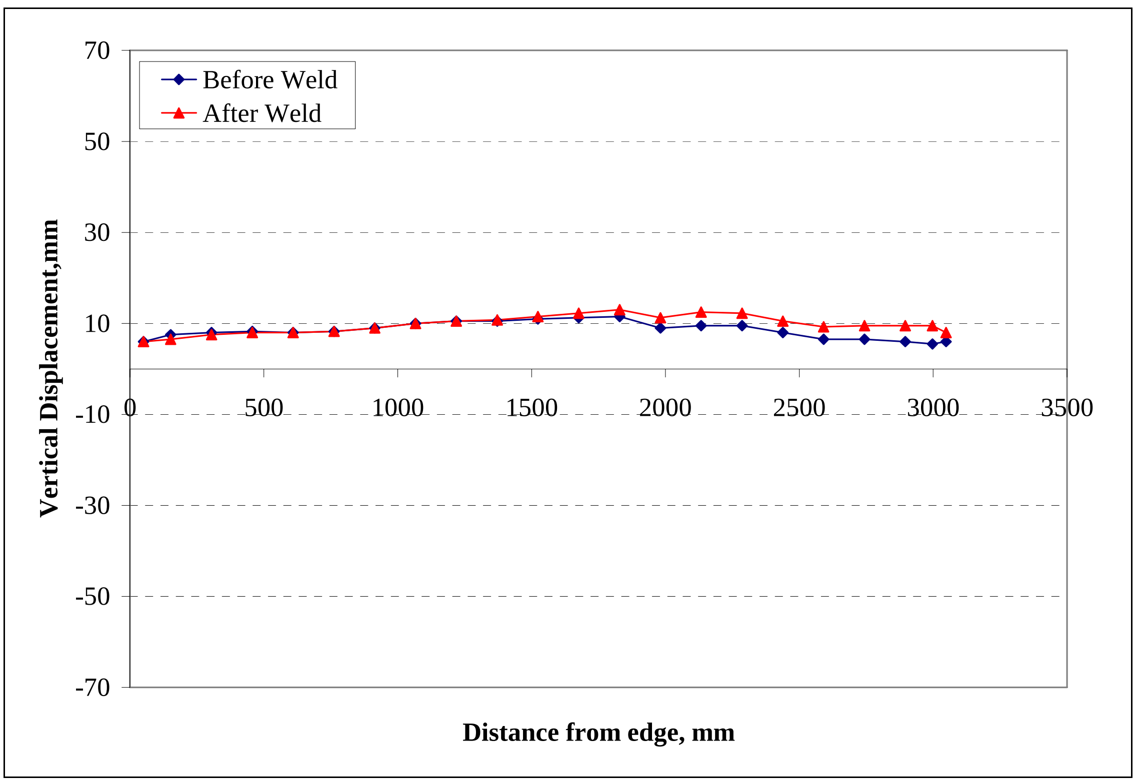


Figure 16: Longitudinal Section B

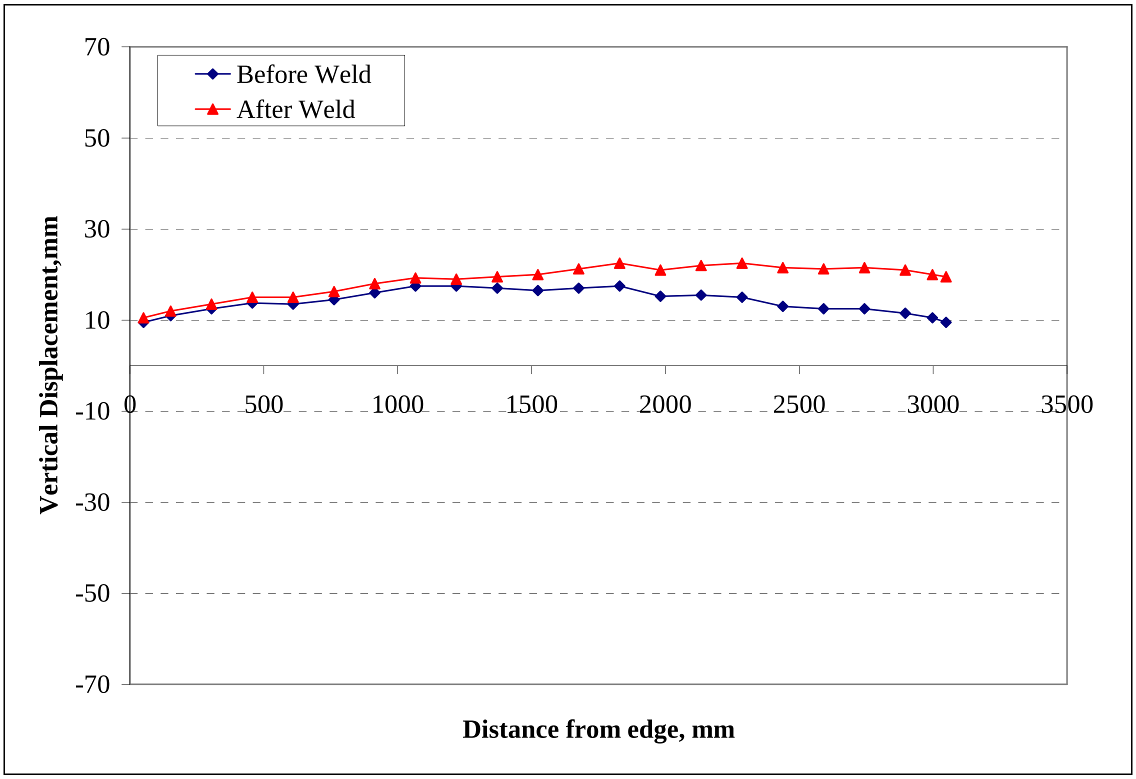


Figure 17: Longitudinal Section C

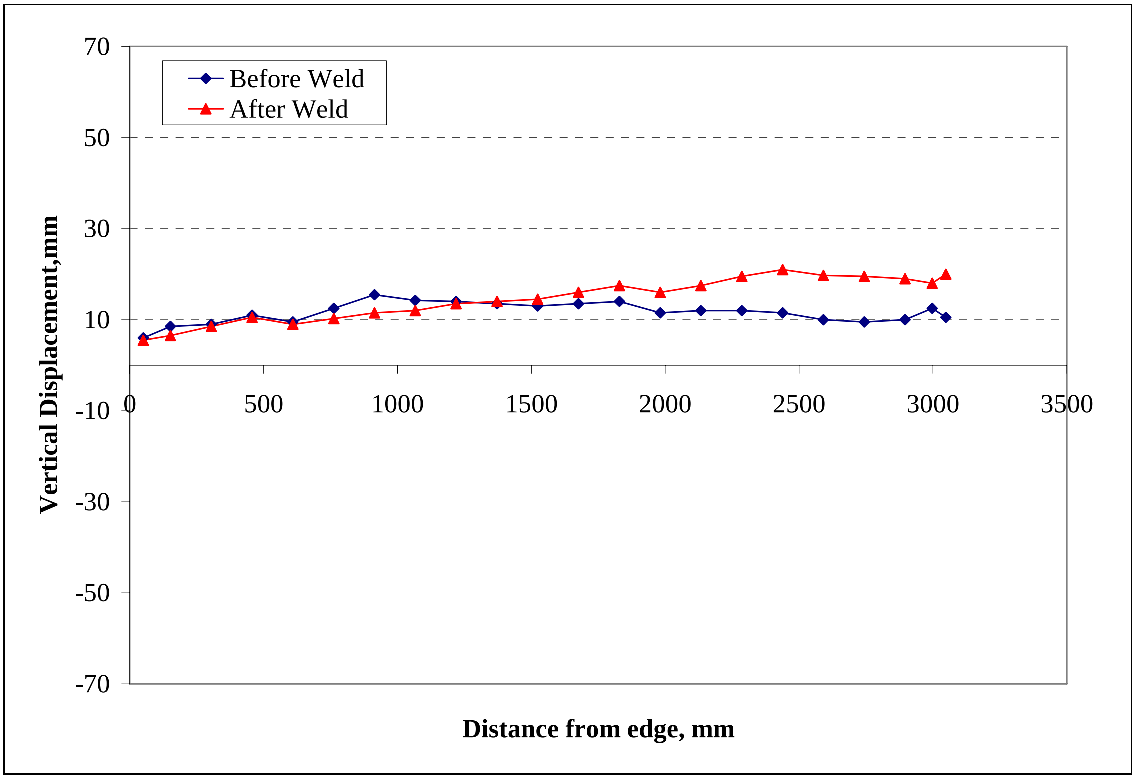


Figure 18: Longitudinal Section D

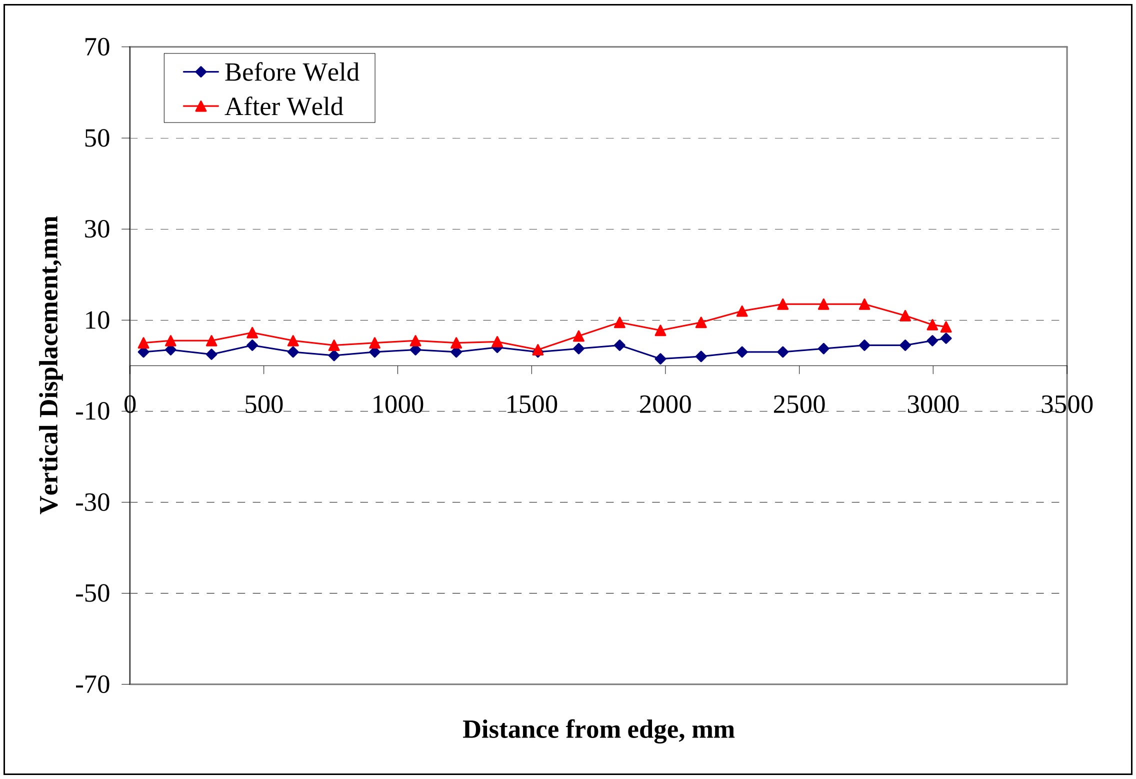


Figure 19: Longitudinal Section E

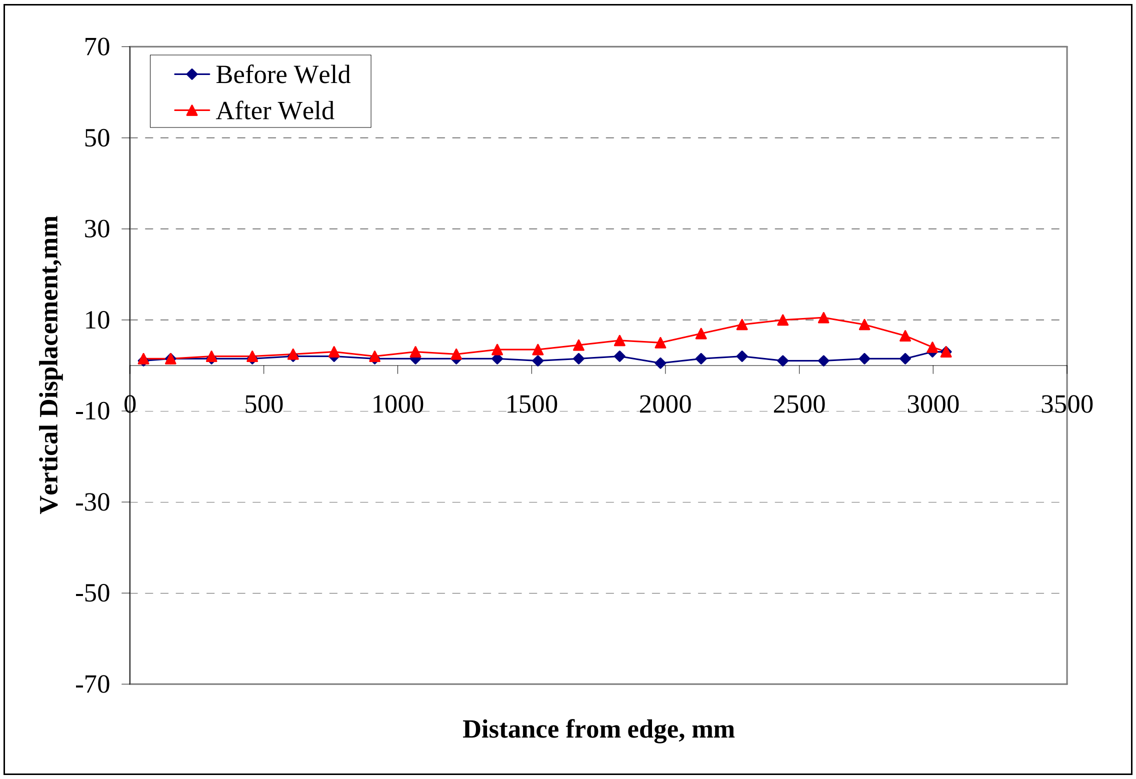


Figure 20: Longitudinal Section F

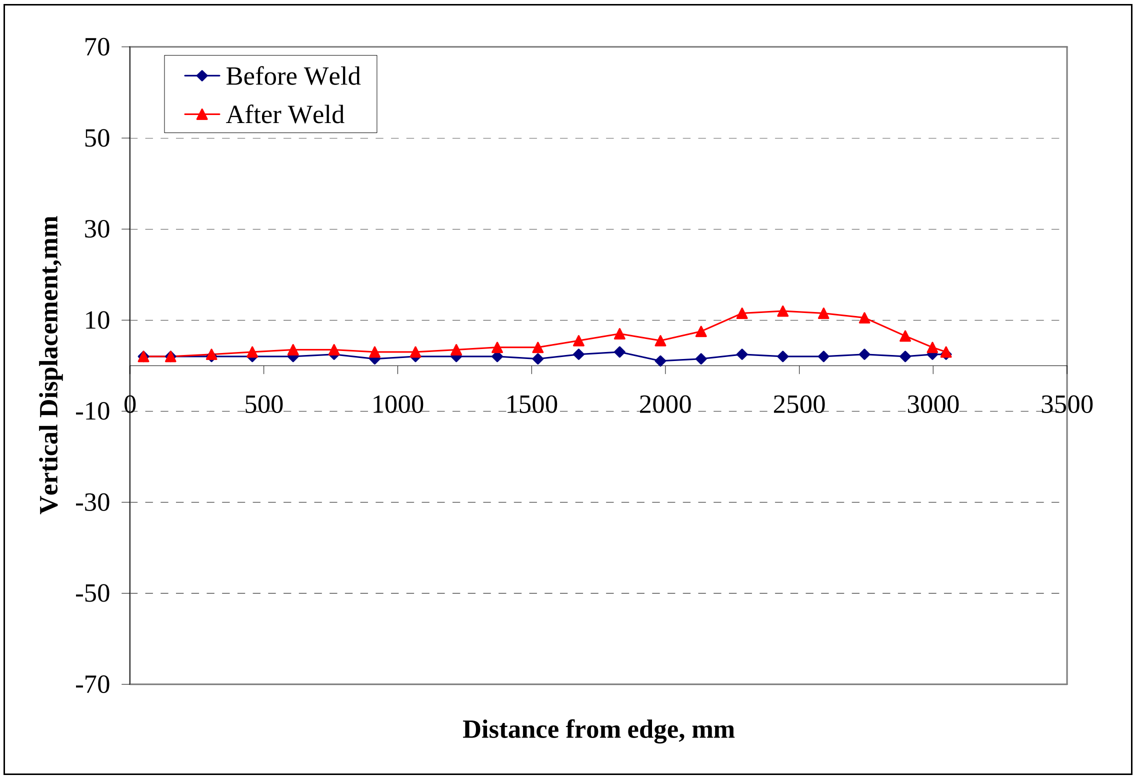


Figure 21: Longitudinal Section G

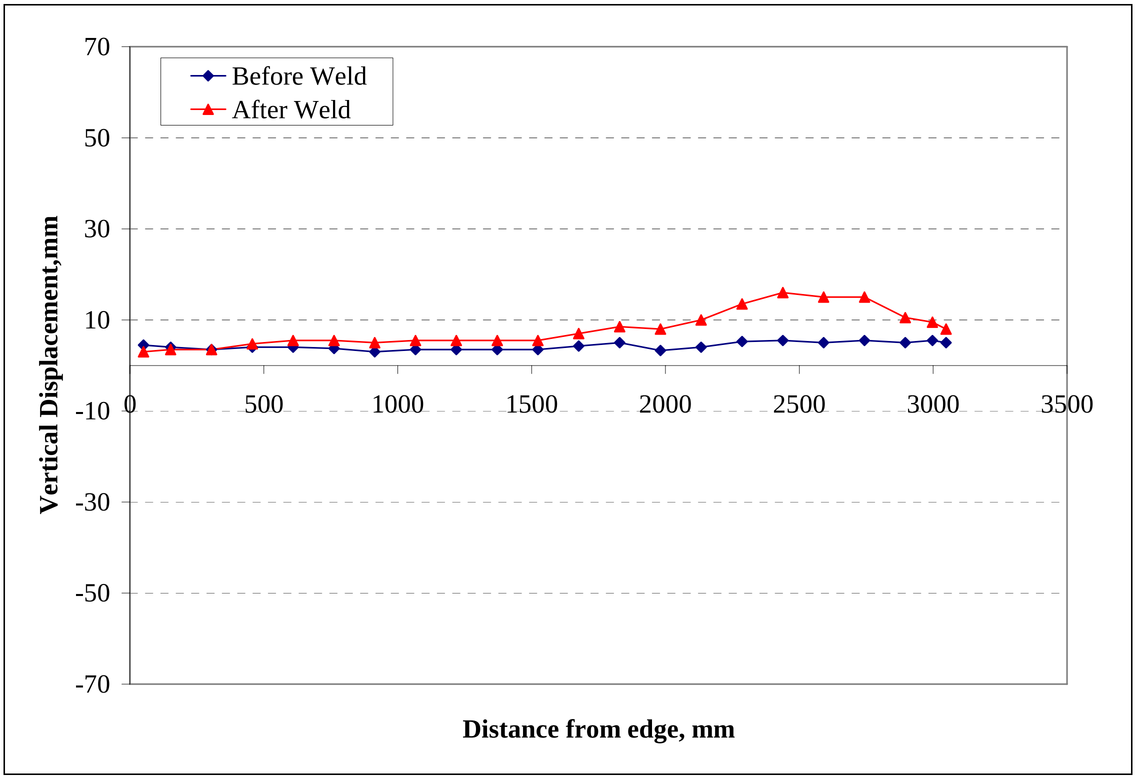


Figure 22: Longitudinal Section H

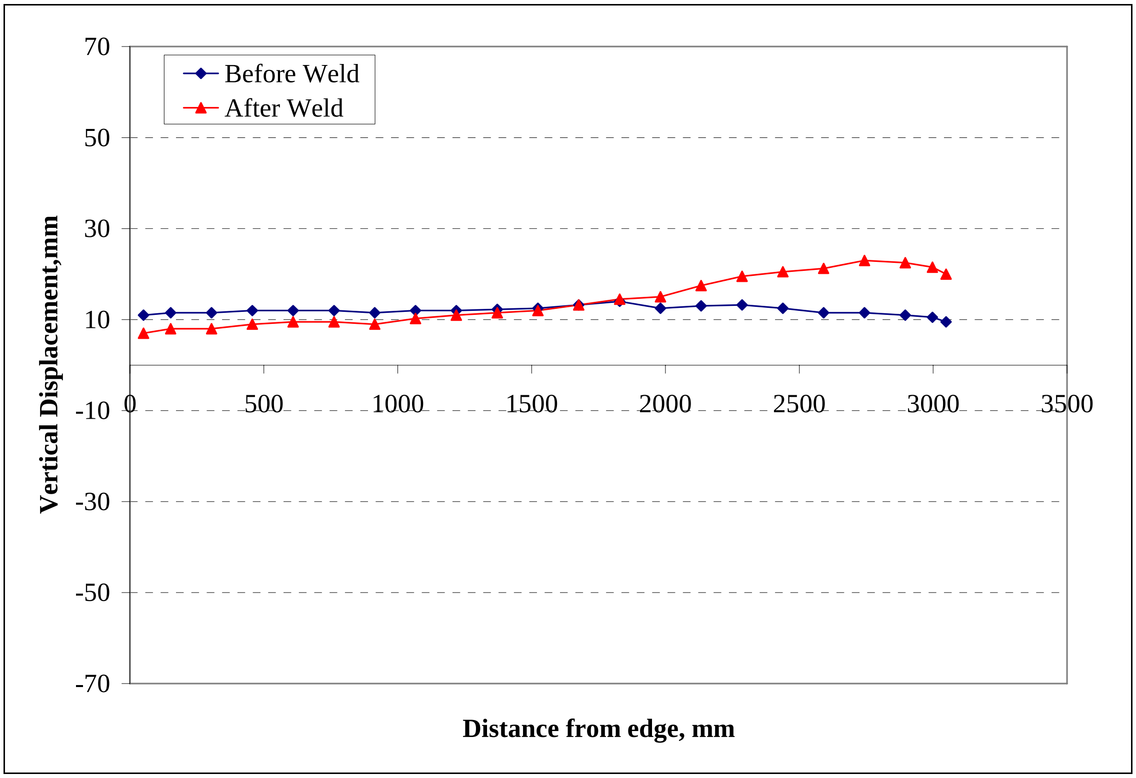


Figure 23: Longitudinal Section I

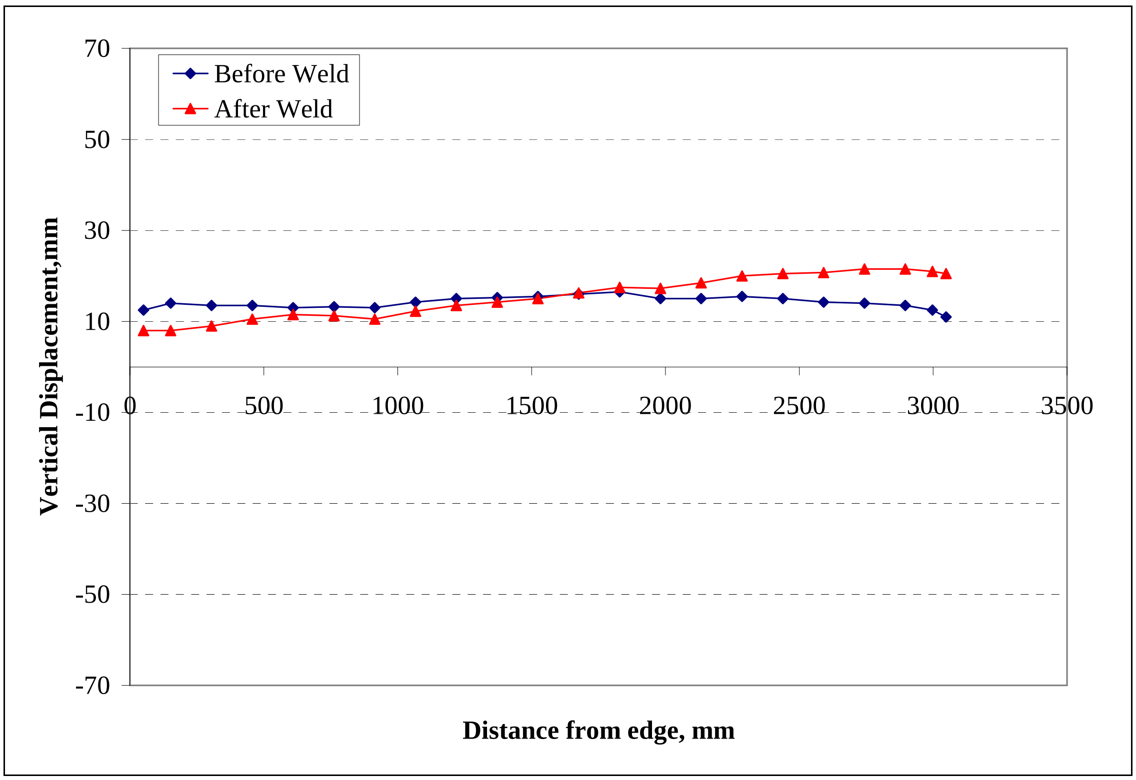


Figure 24: Longitudinal Section J

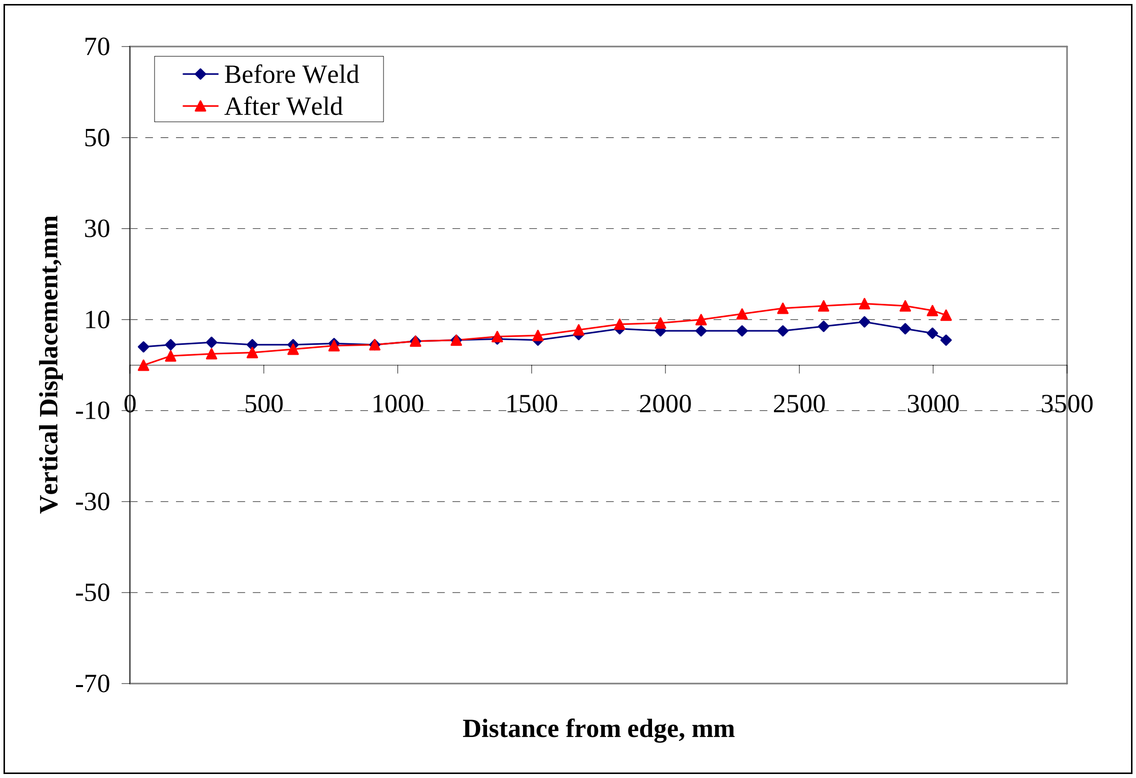


Figure 25: Longitudinal Section K

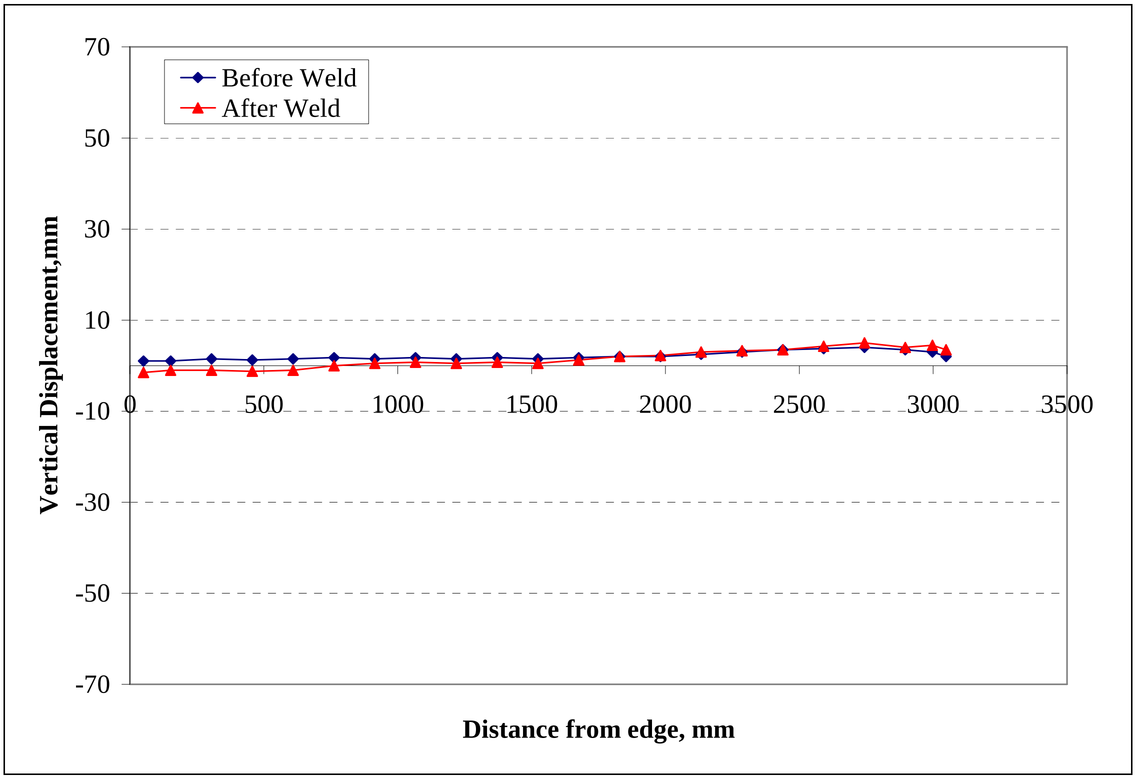


Figure 26: Longitudinal Section L

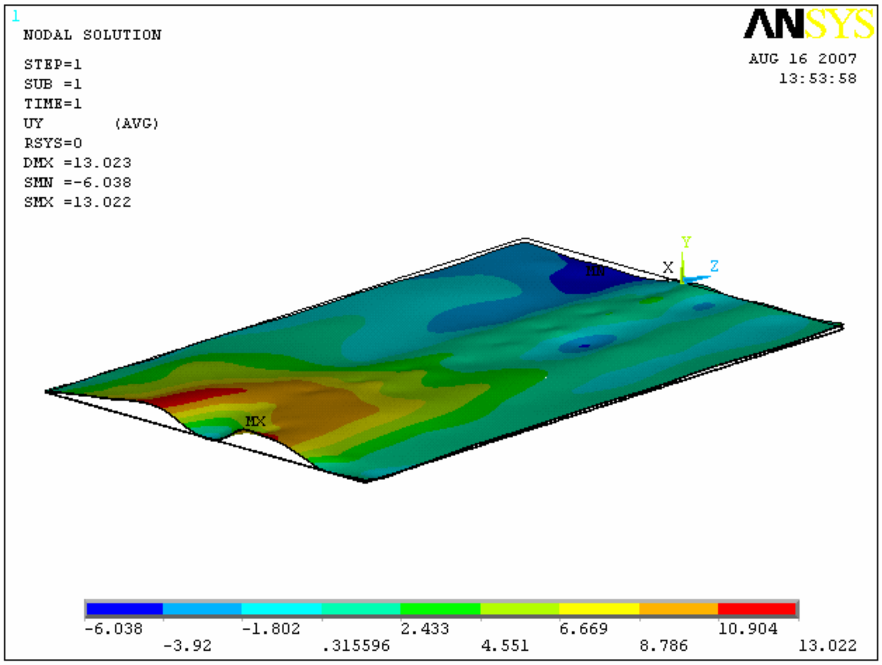


Figure 27: Net Plate Deformation after Welding

PLATE 1 – SIDE 2

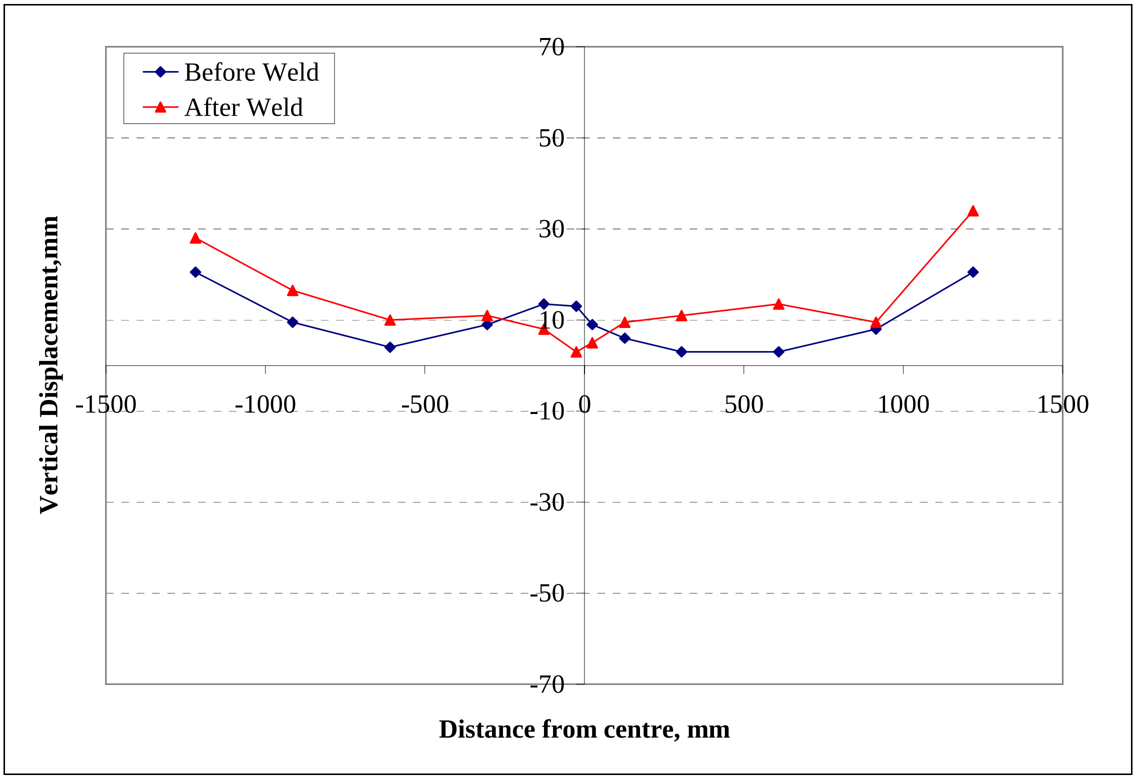


Figure 1: Transverse Section A1

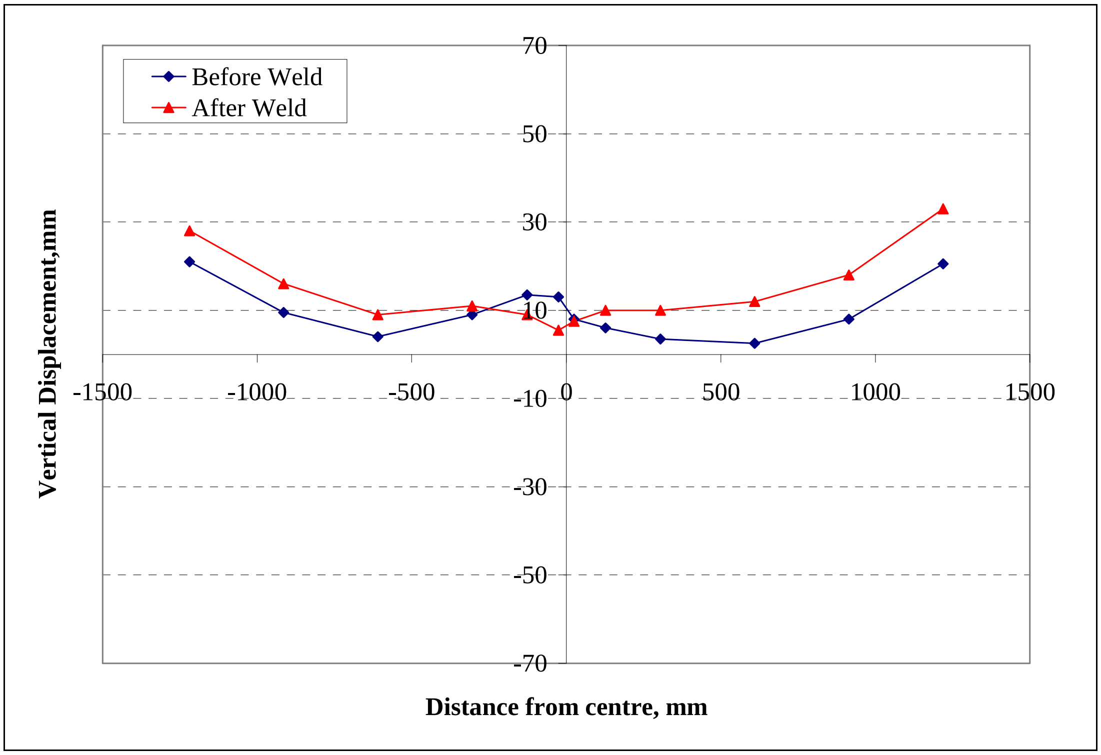


Figure 2: Transverse Section A2

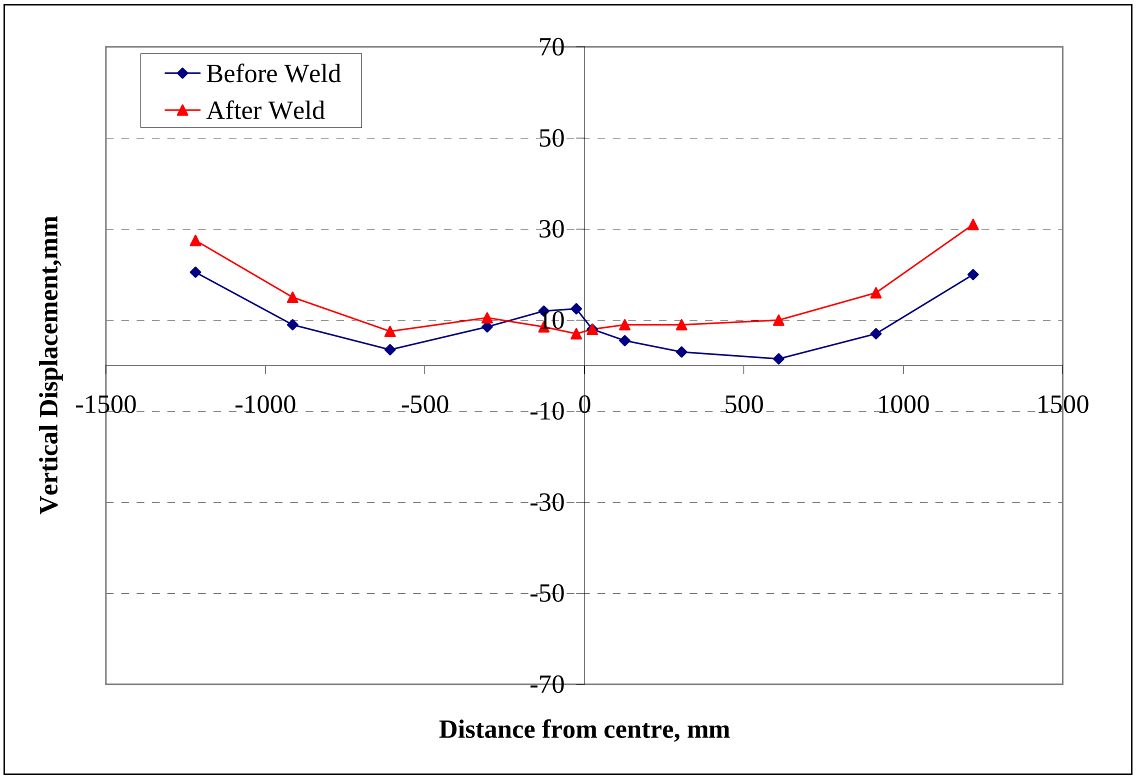


Figure 3: Transverse Section A3

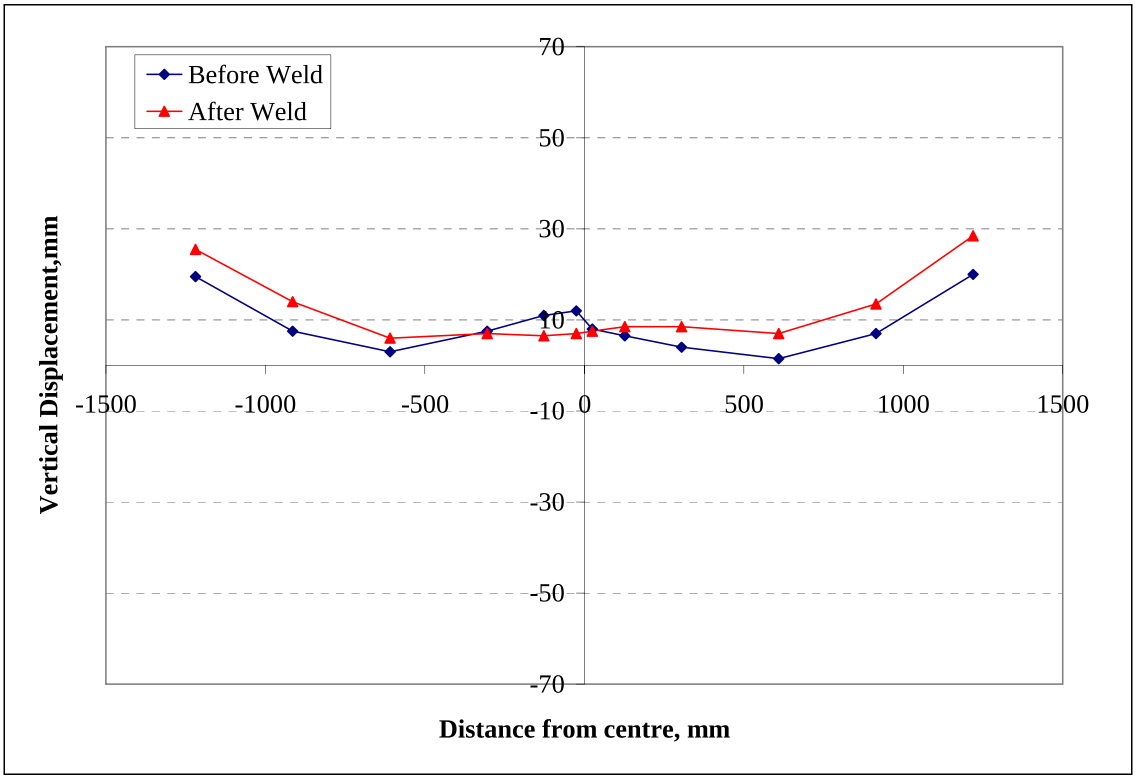


Figure 4: Transverse Section A5

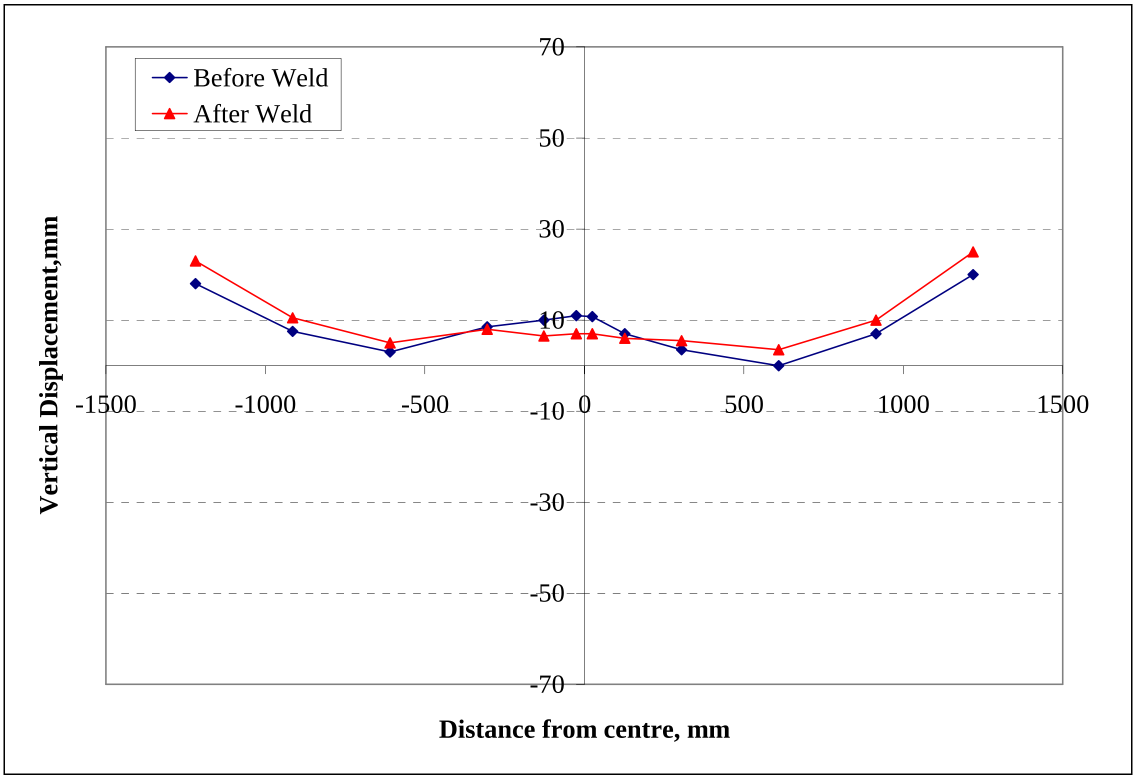


Figure 5: Transverse Section A7

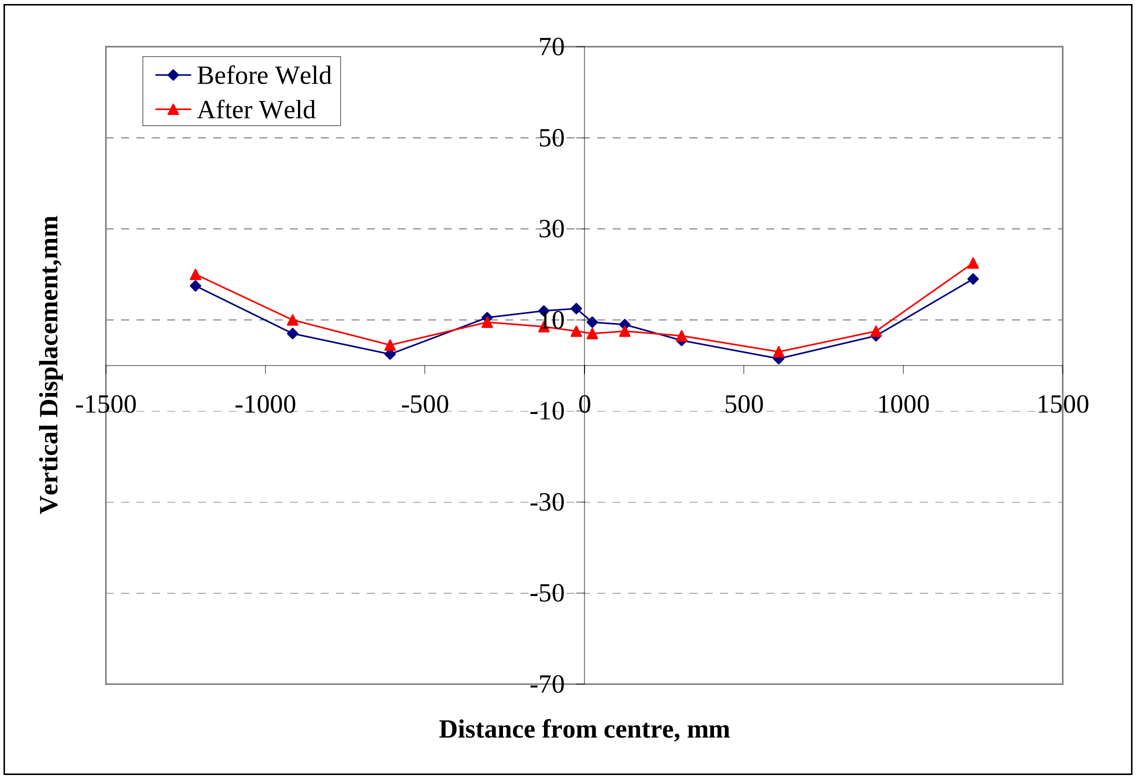


Figure 6: Transverse Section A9

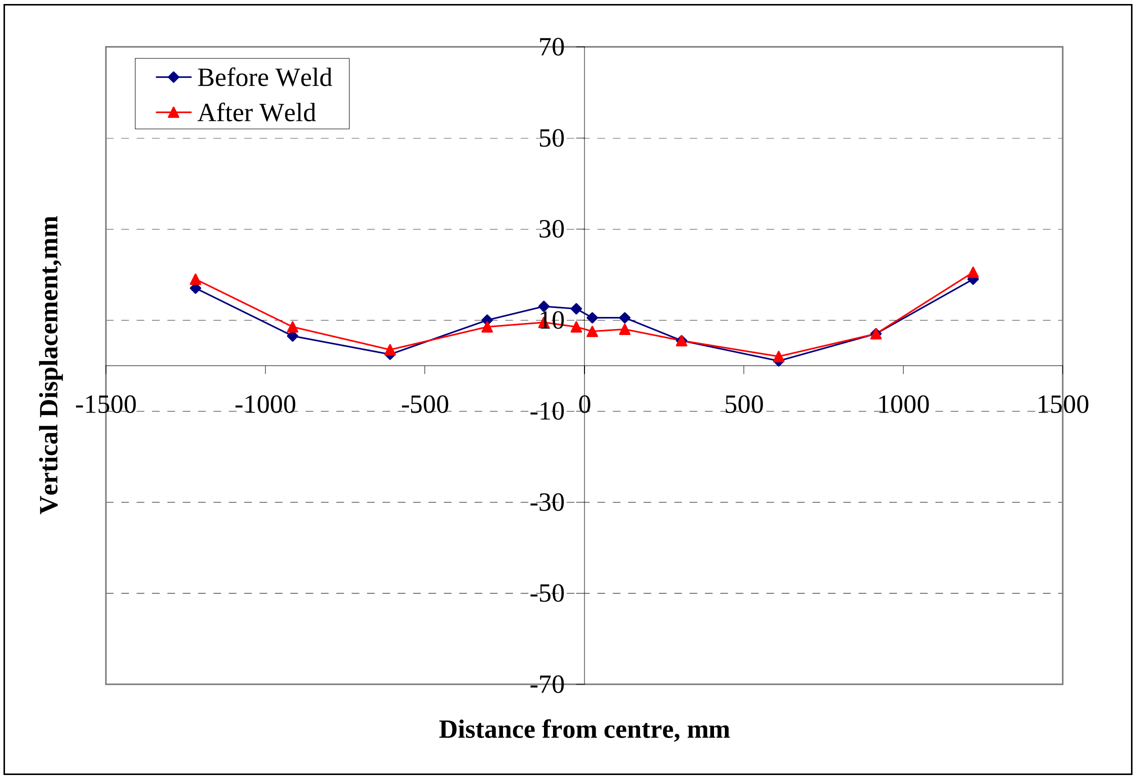


Figure 7: Transverse Section A11

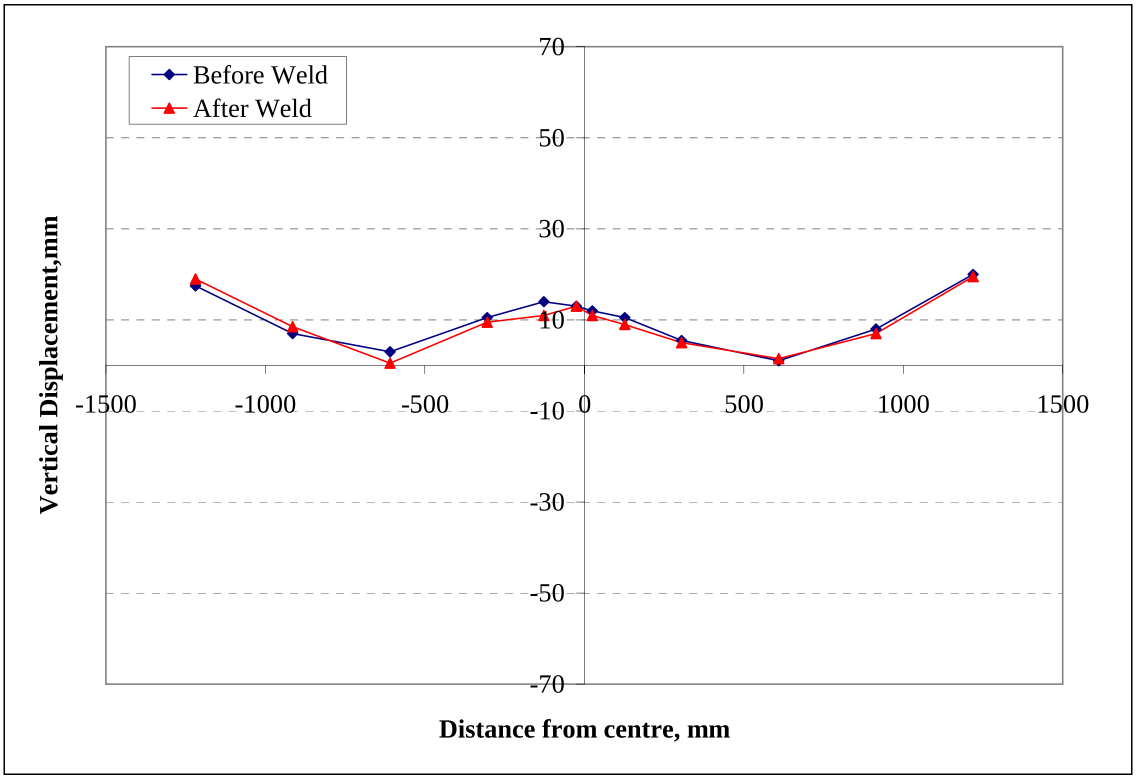


Figure 8: Transverse Section A13

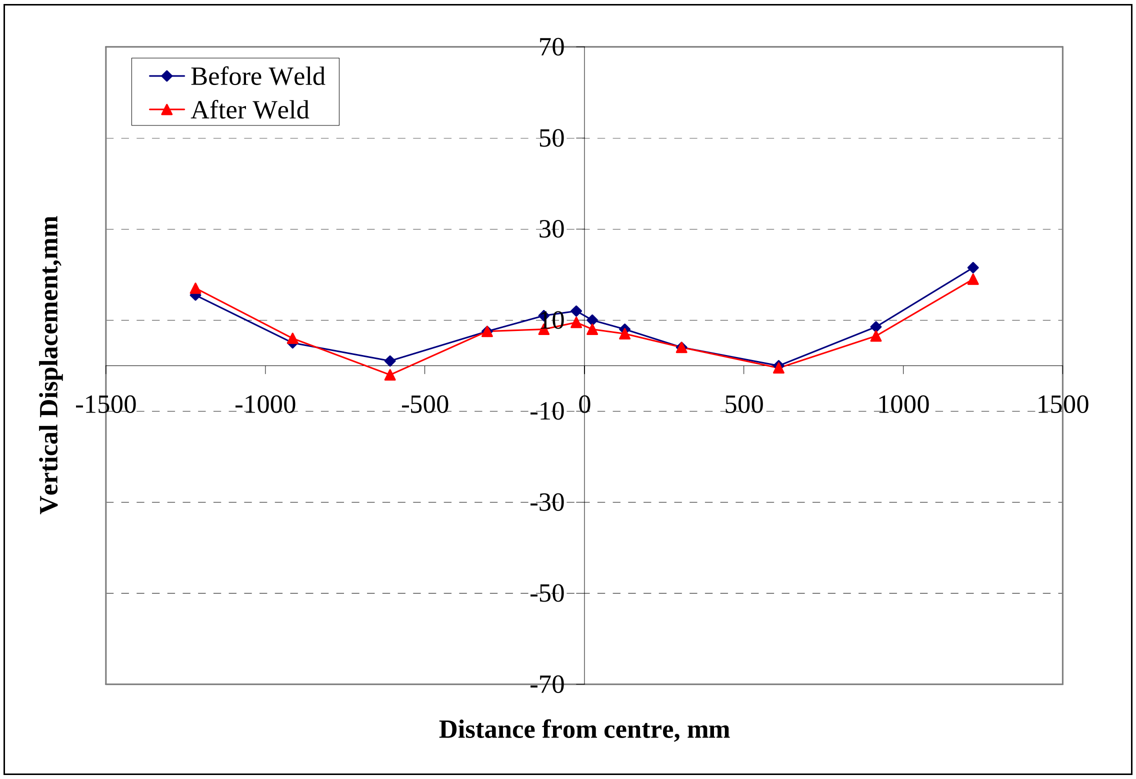


Figure 9: Transverse Section A15

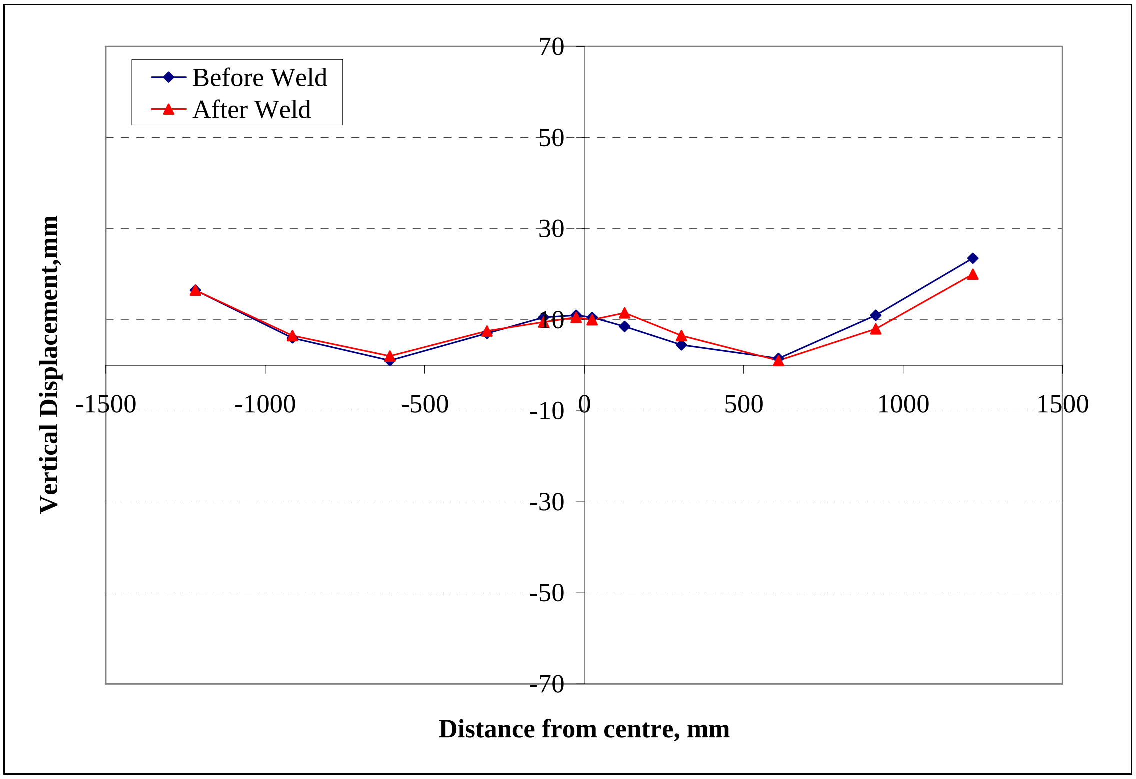


Figure 10: Transverse Section A17

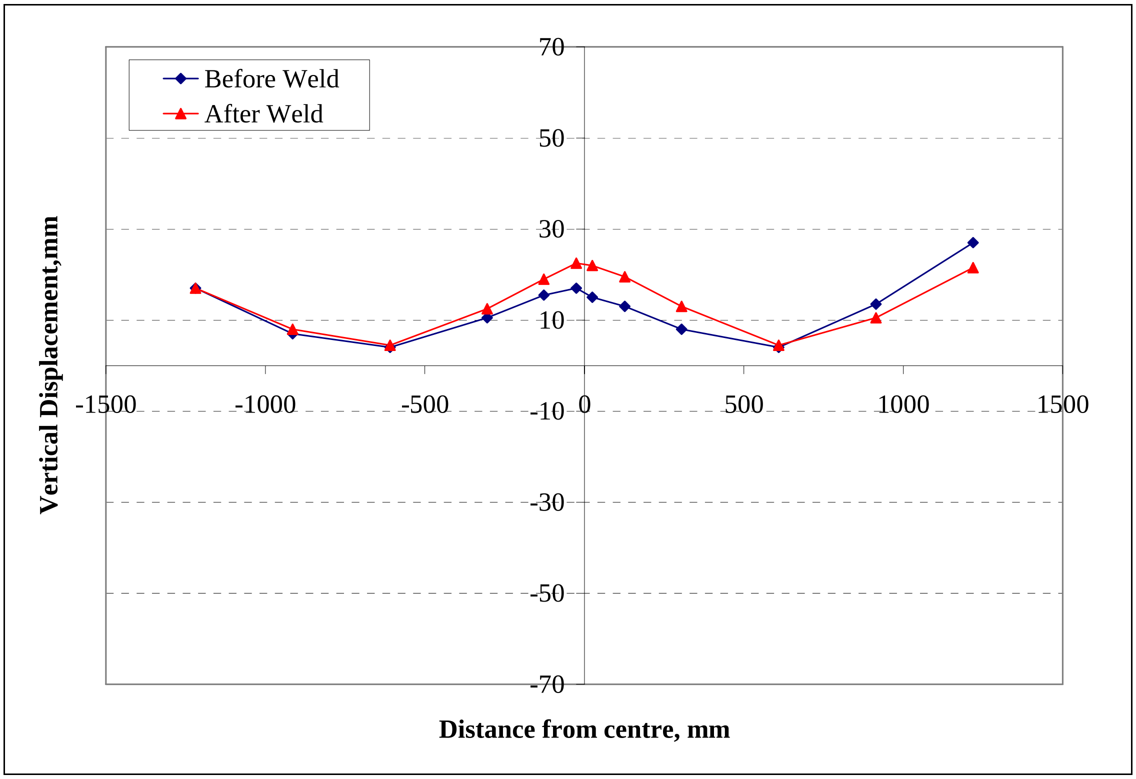


Figure 11: Transverse Section A19

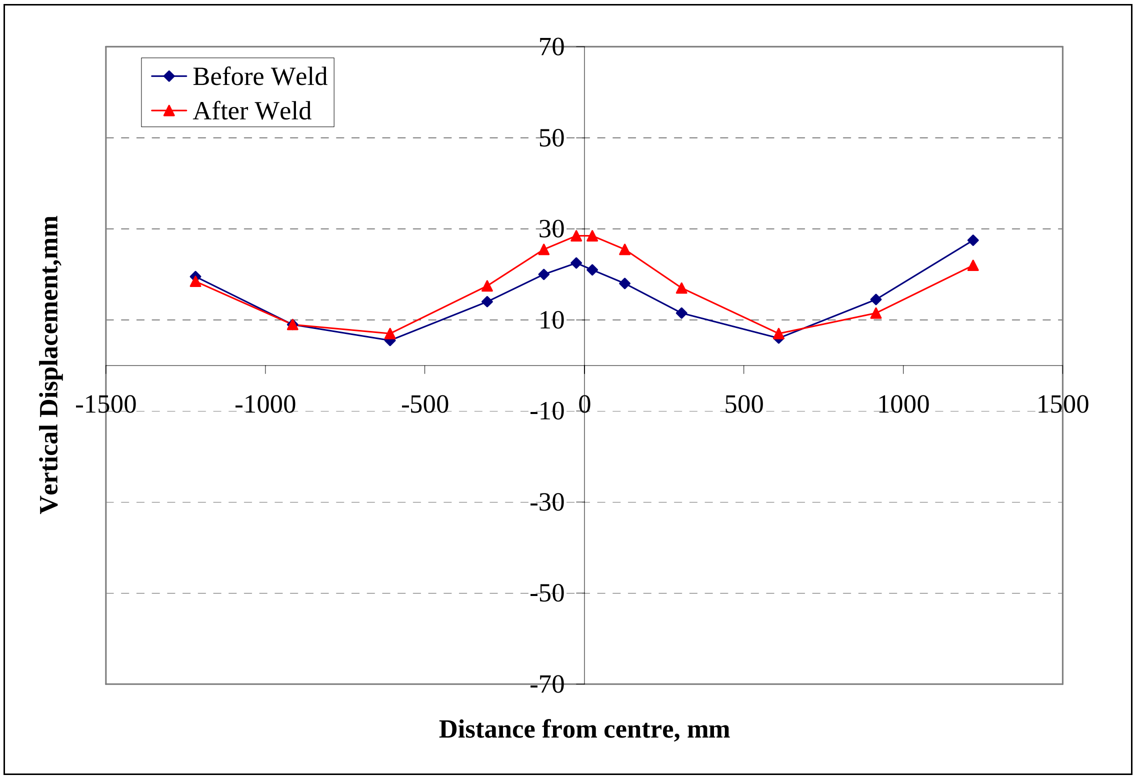


Figure 12: Transverse Section A20

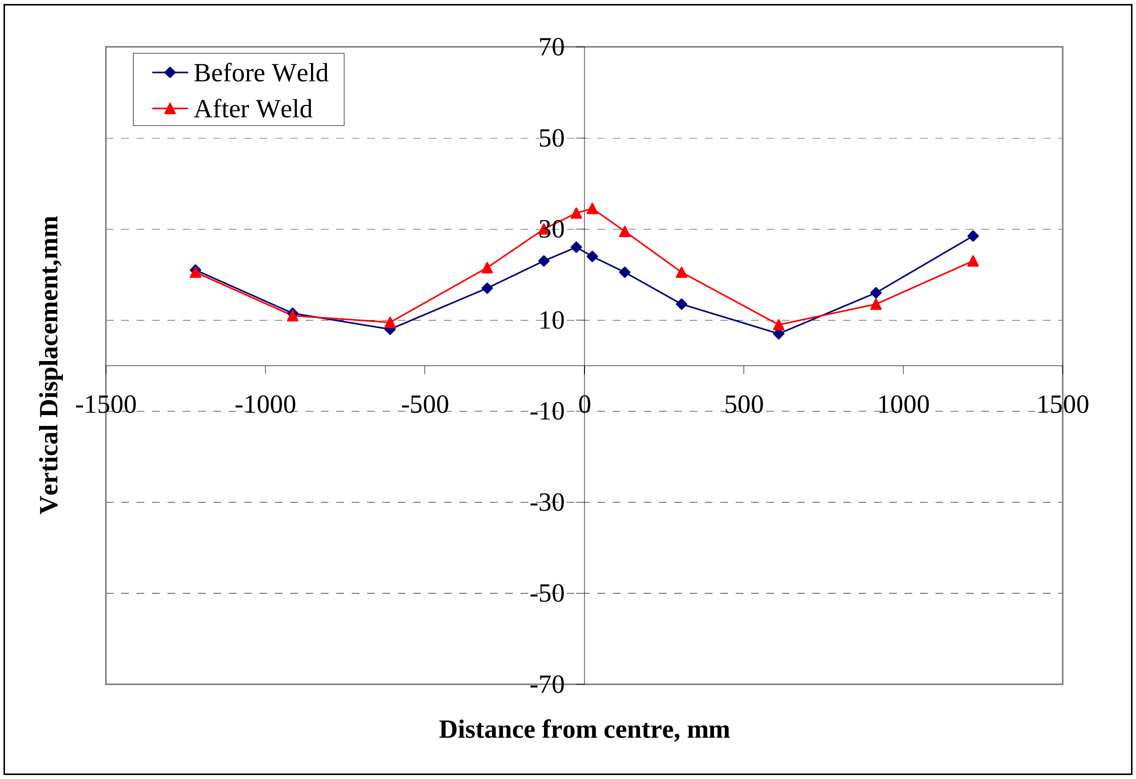


Figure 13: Transverse Section A21

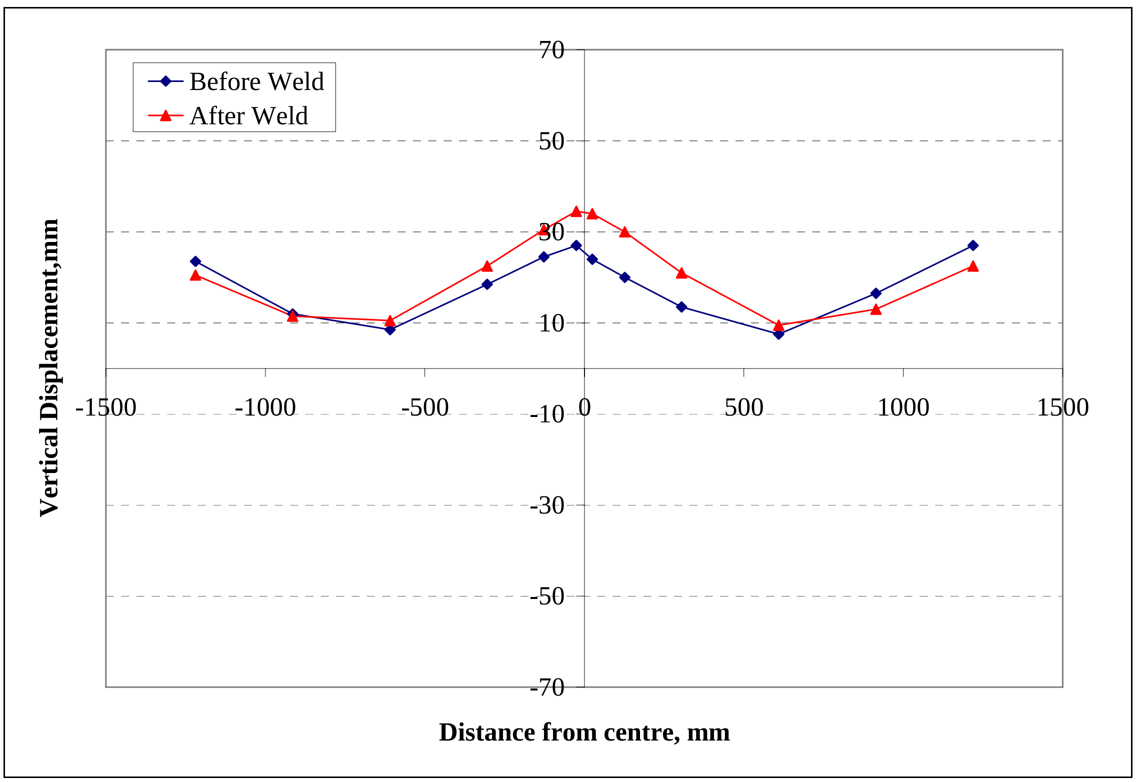


Figure 14: Transverse Section A22

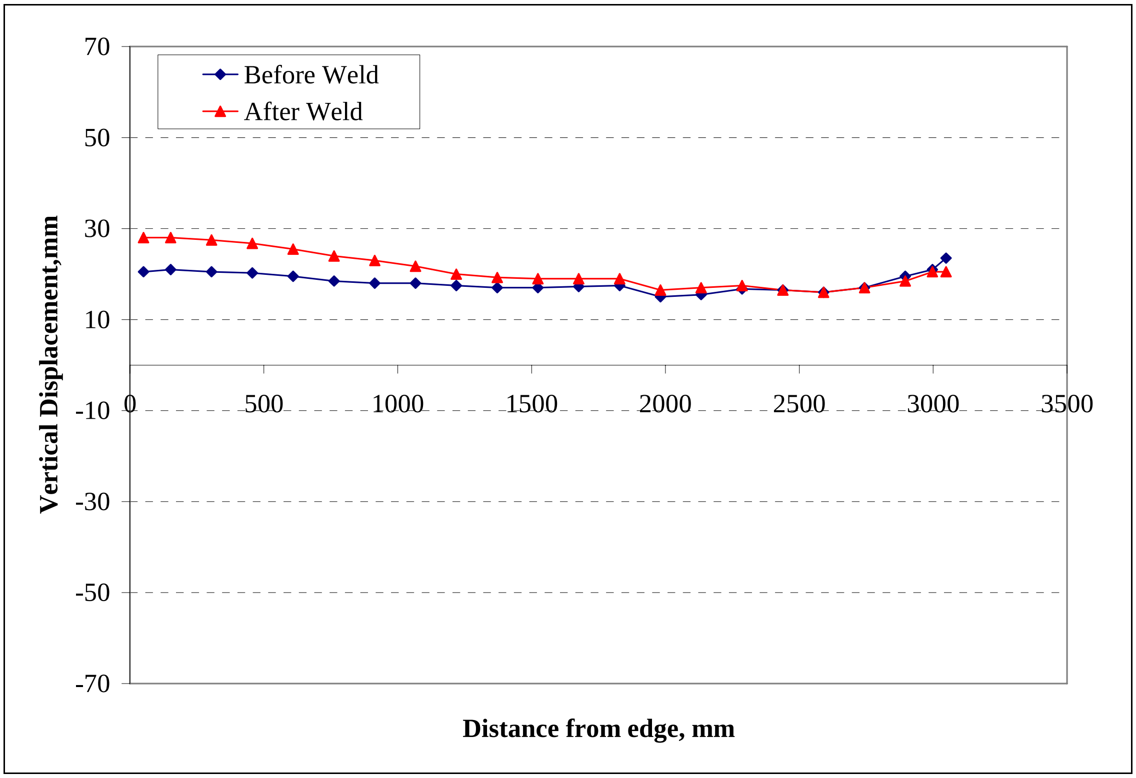


Figure 15: Longitudinal Section A

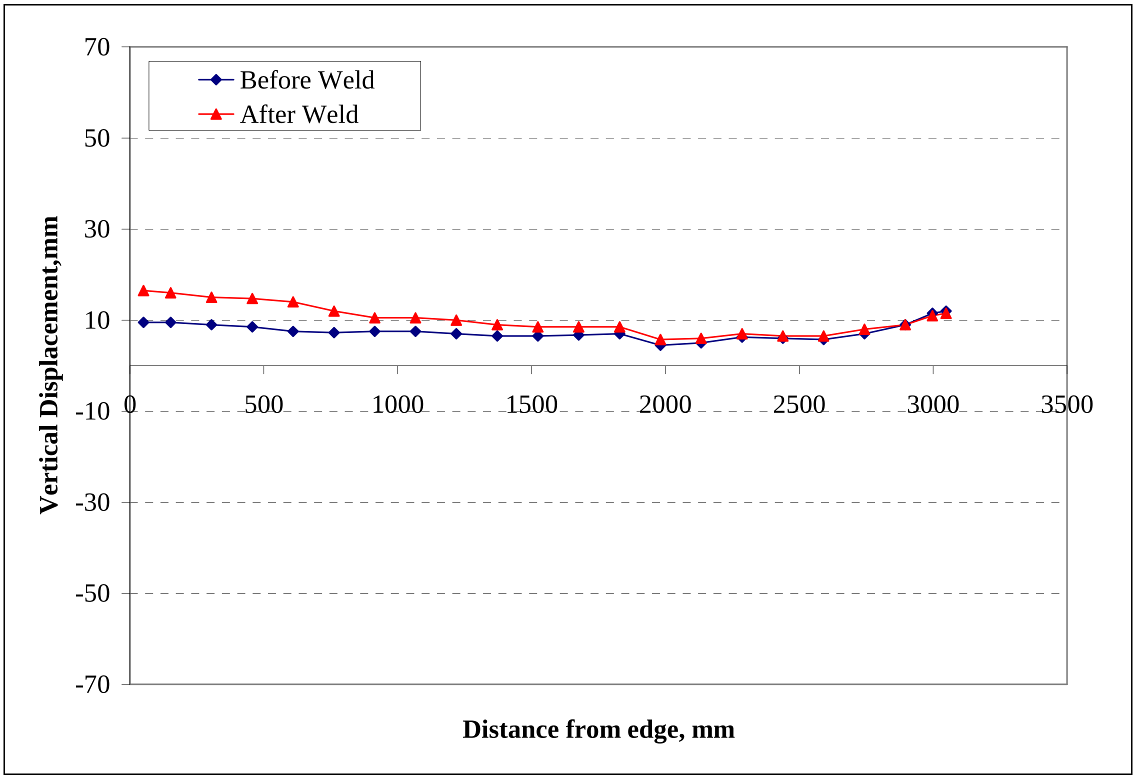


Figure 16: Longitudinal Section B

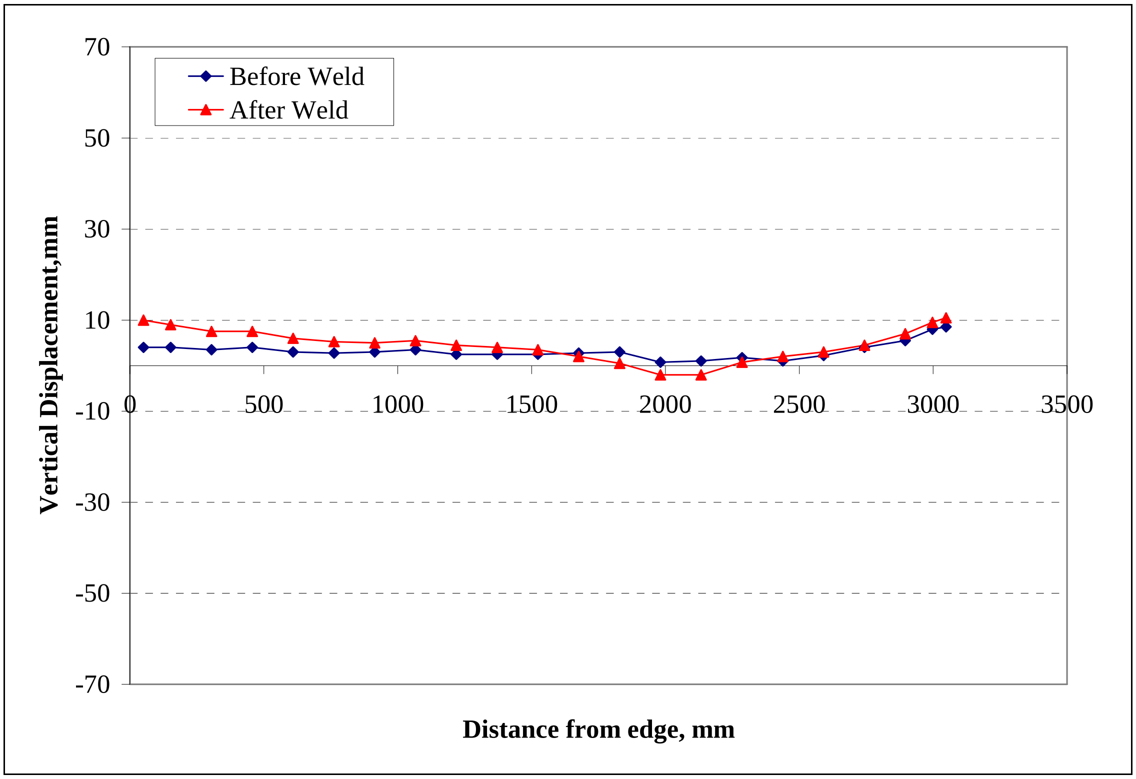


Figure 17: Longitudinal Section C

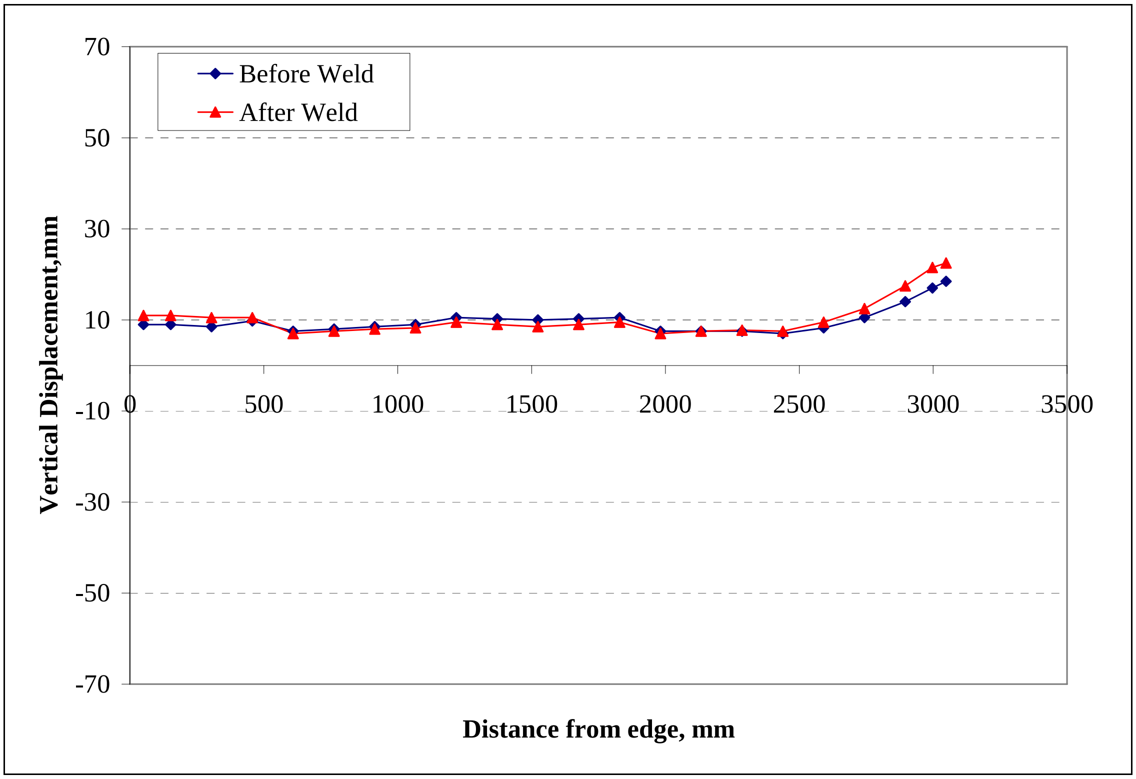


Figure 18: Longitudinal Section D

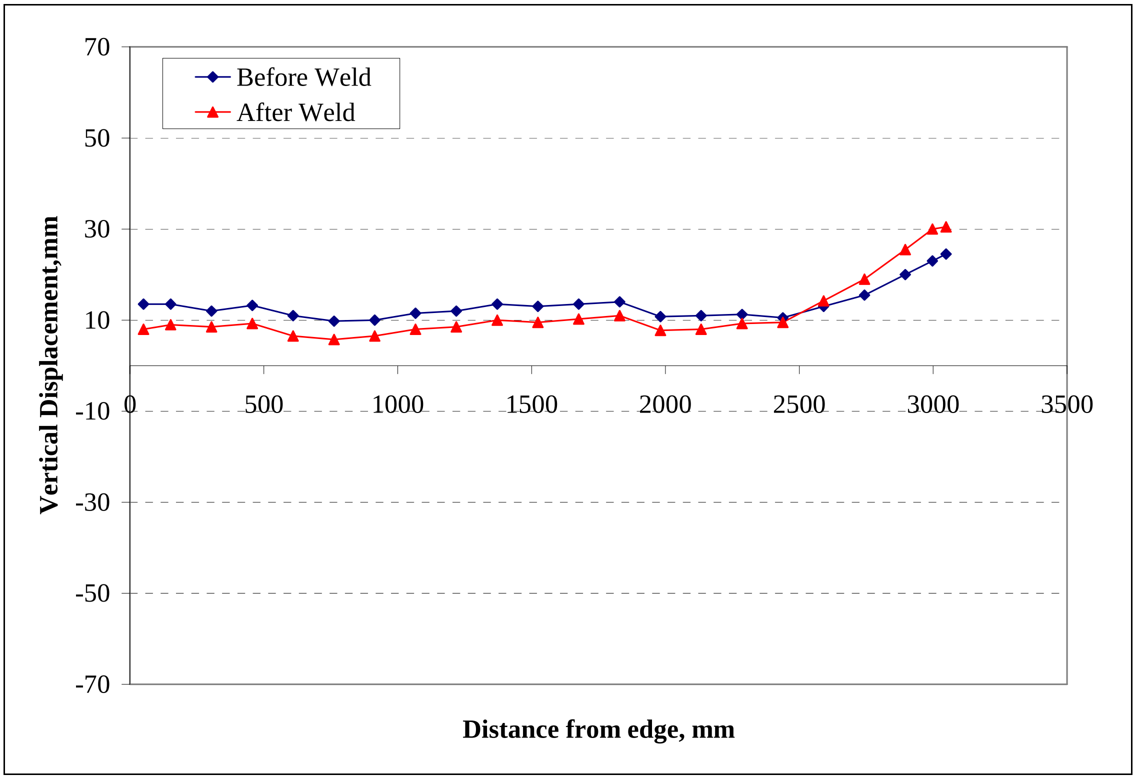


Figure 19: Longitudinal Section E

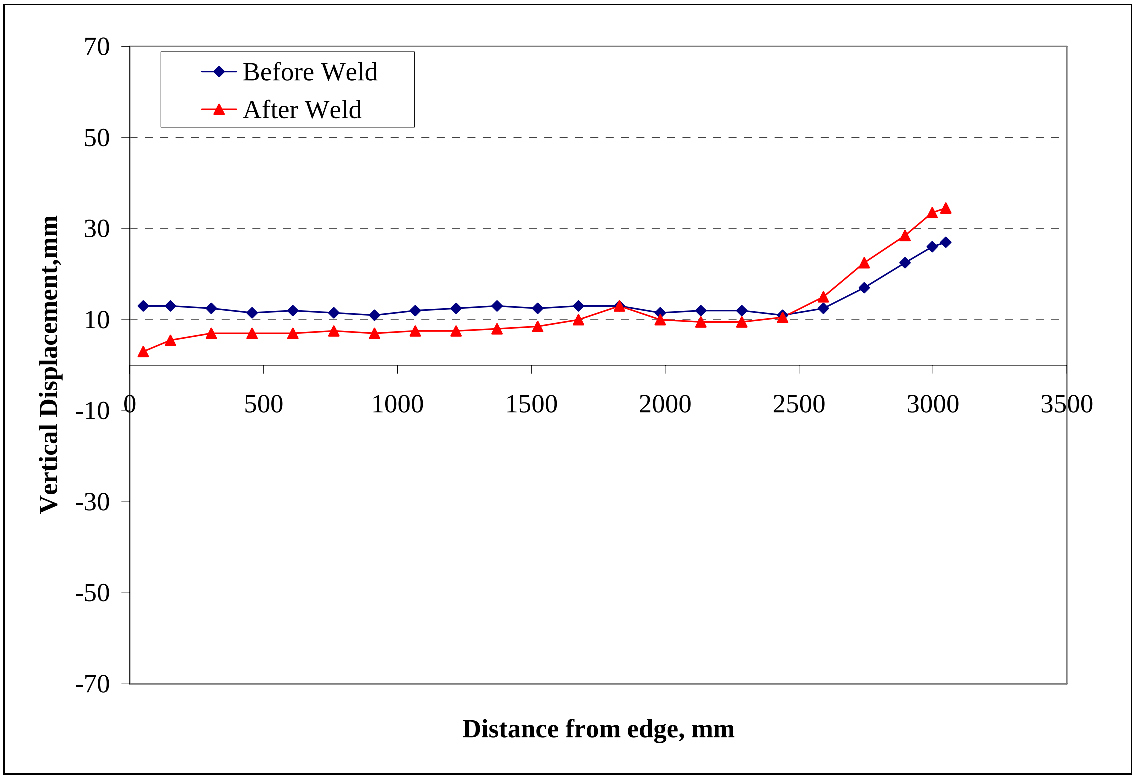


Figure 20: Longitudinal Section F

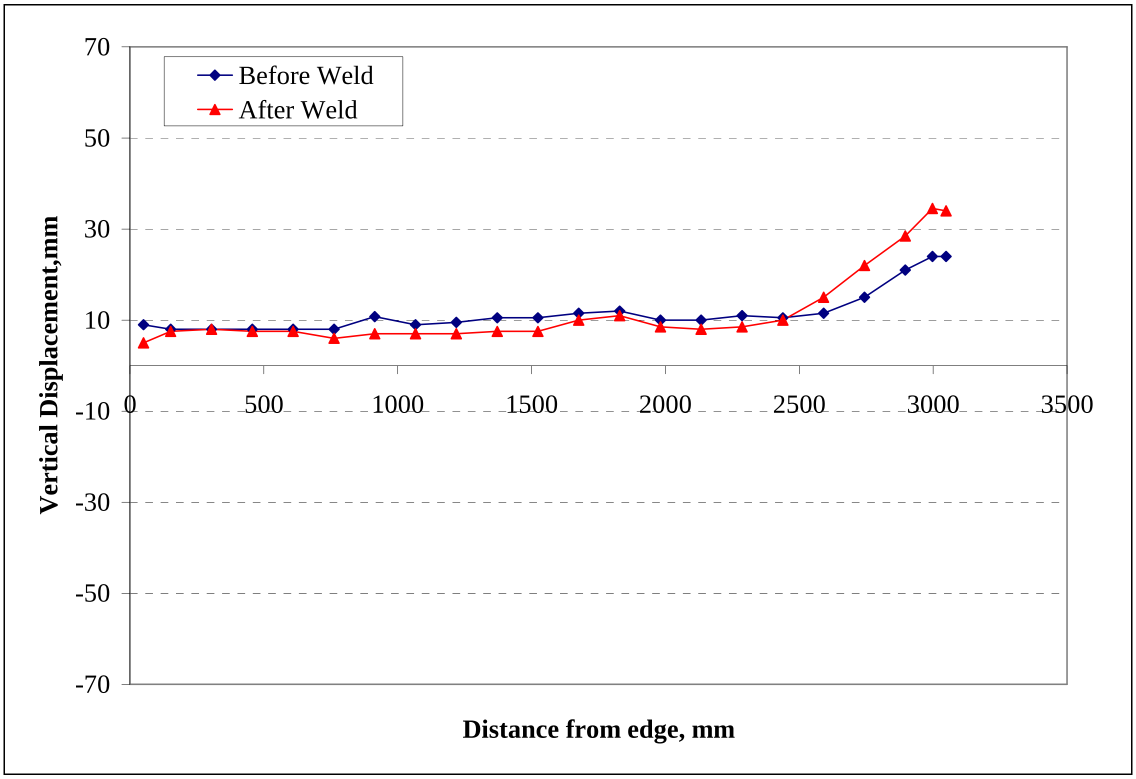


Figure 21: Longitudinal Section G

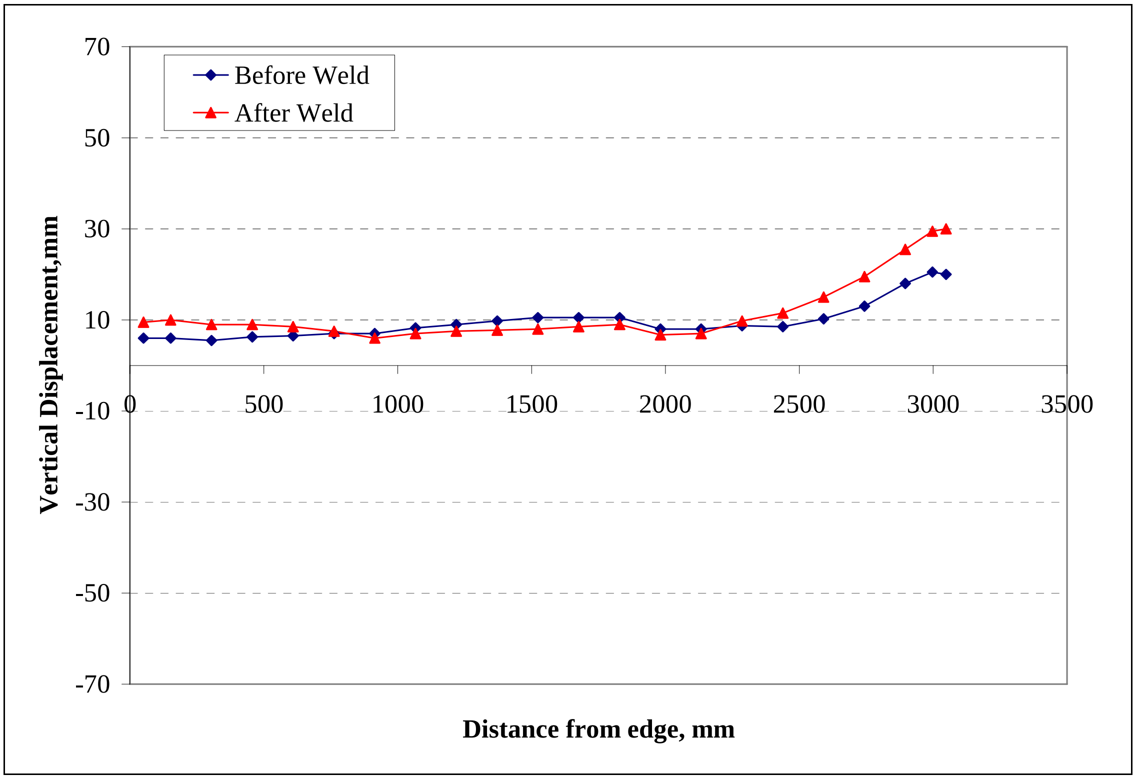


Figure 22: Longitudinal Section H

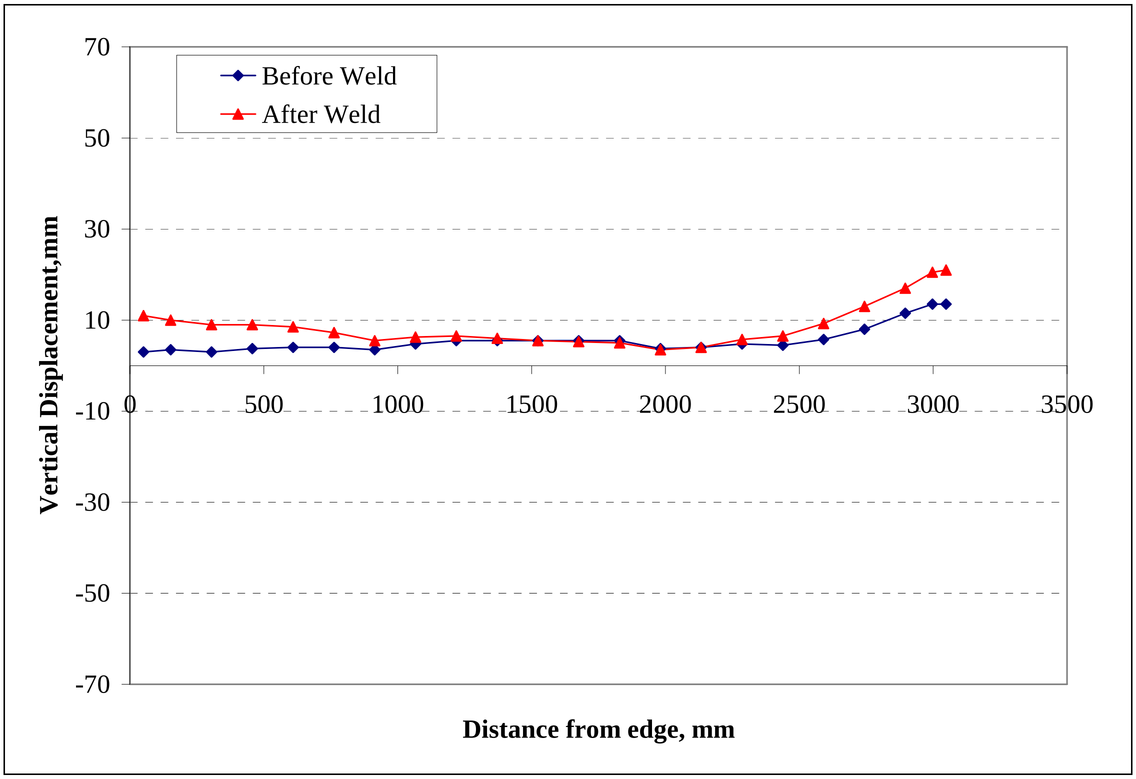


Figure 23: Longitudinal Section I

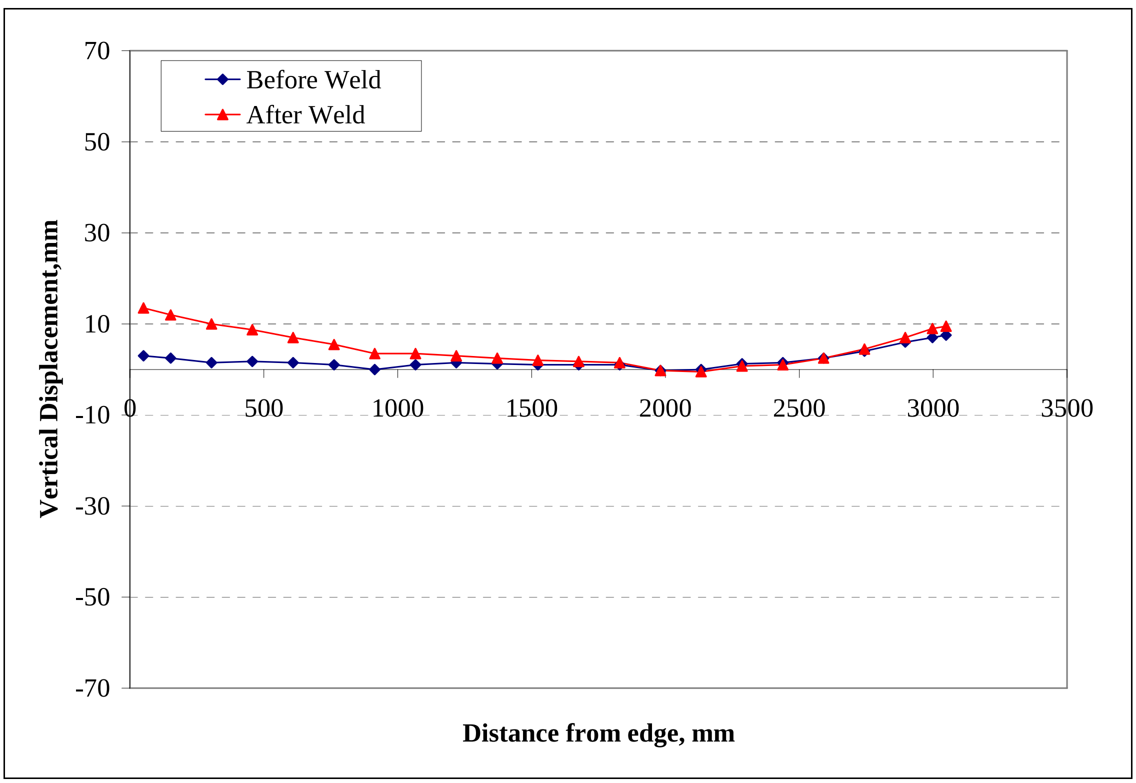


Figure 24: Longitudinal Section J

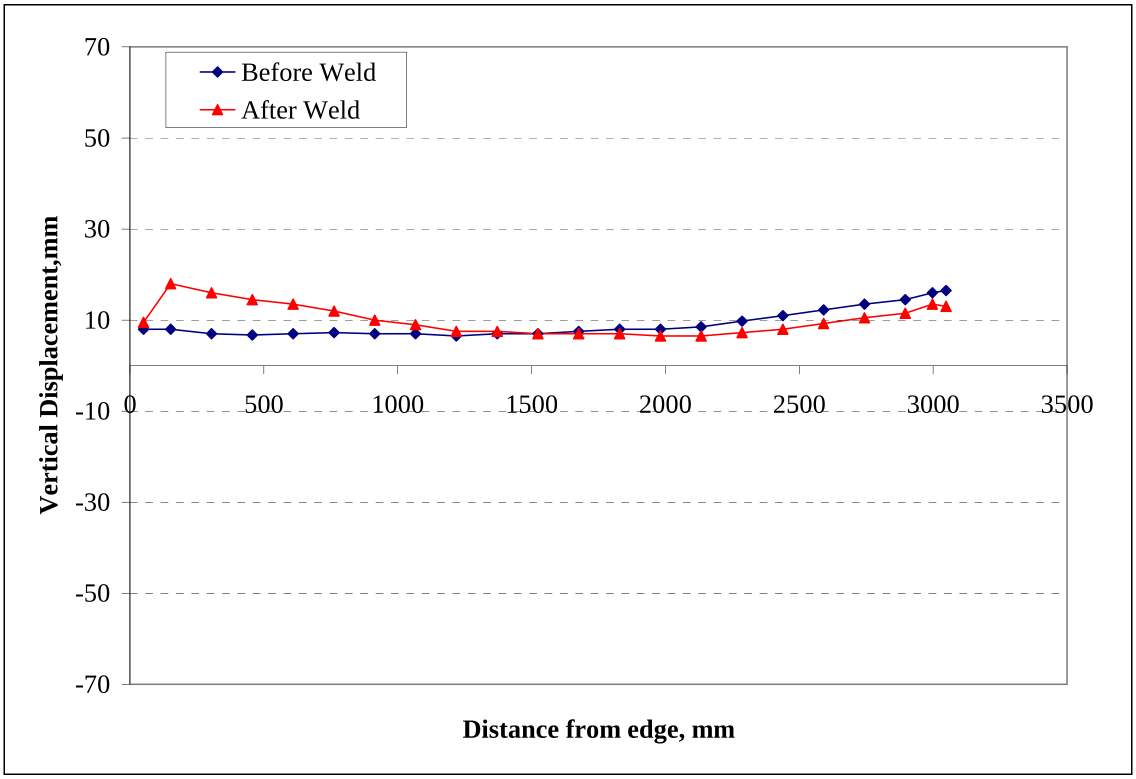


Figure 25: Longitudinal Section K

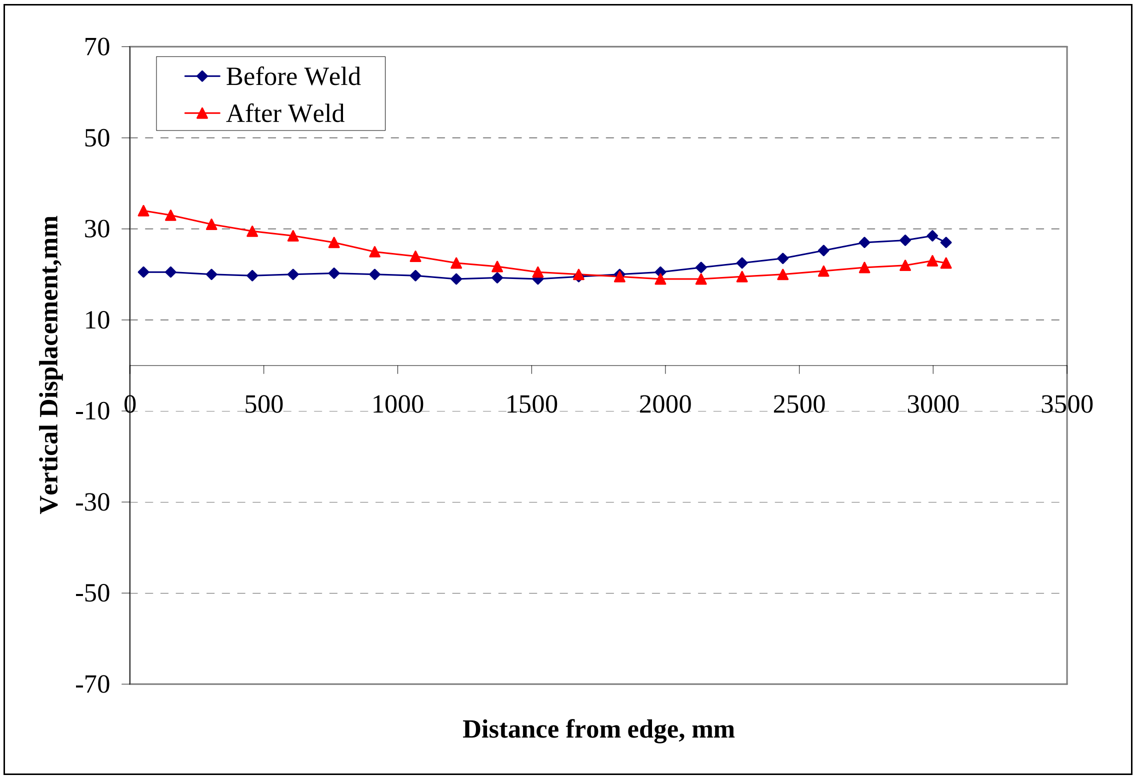


Figure 26: Longitudinal Section L

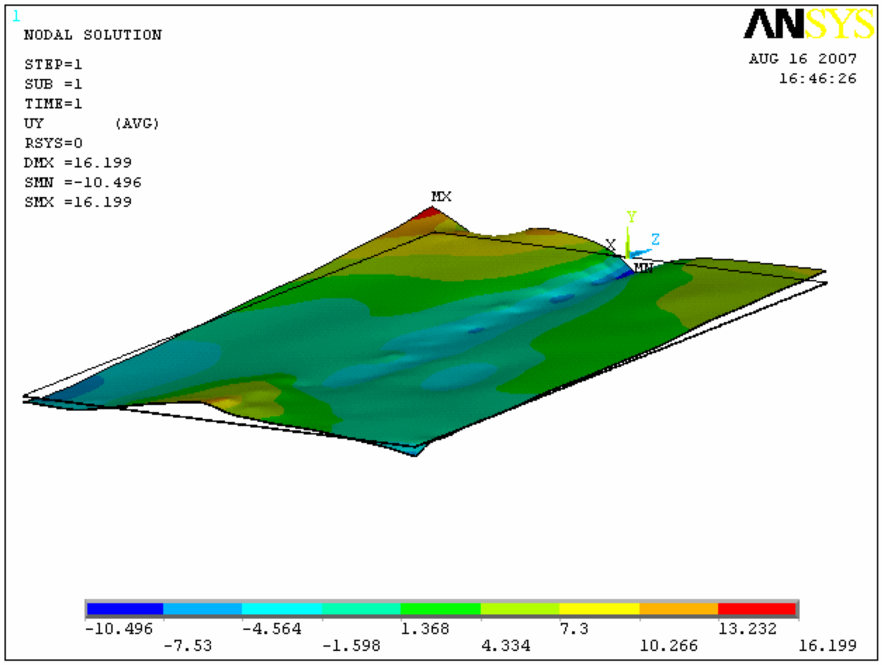


Figure 27: Net Plate Deformation after Welding

PLATE 2 – SIDE 1

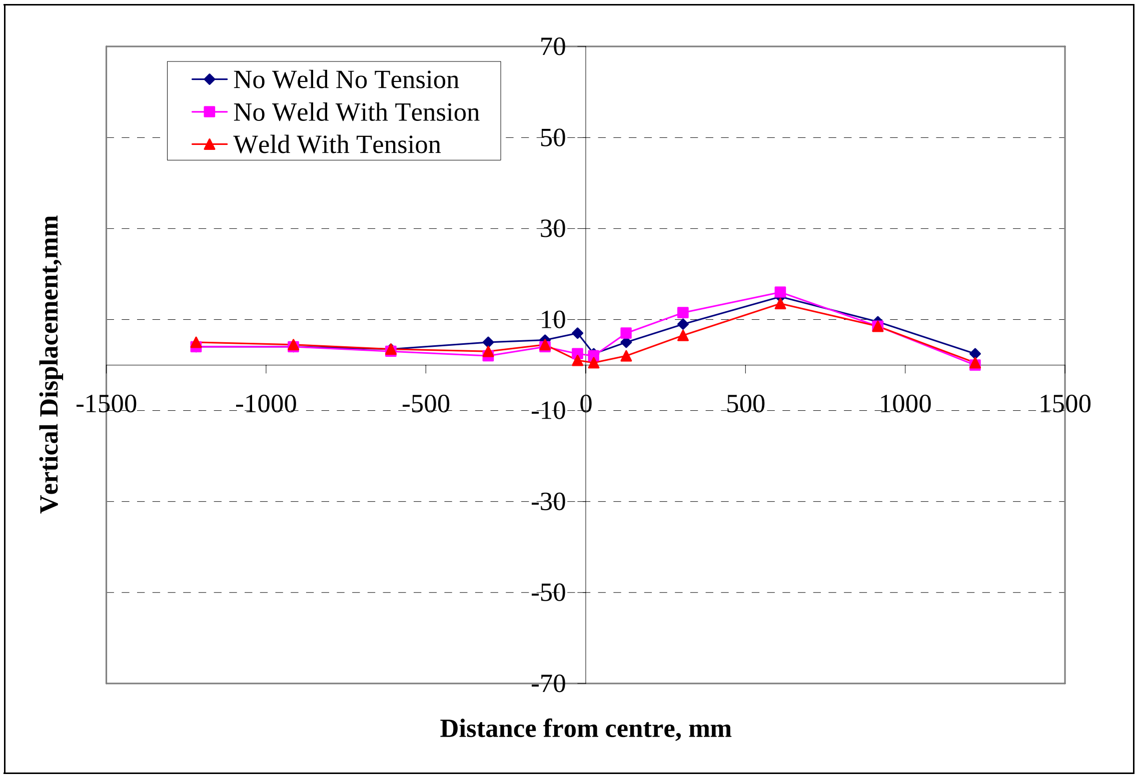


Figure 1: Transverse Section A1

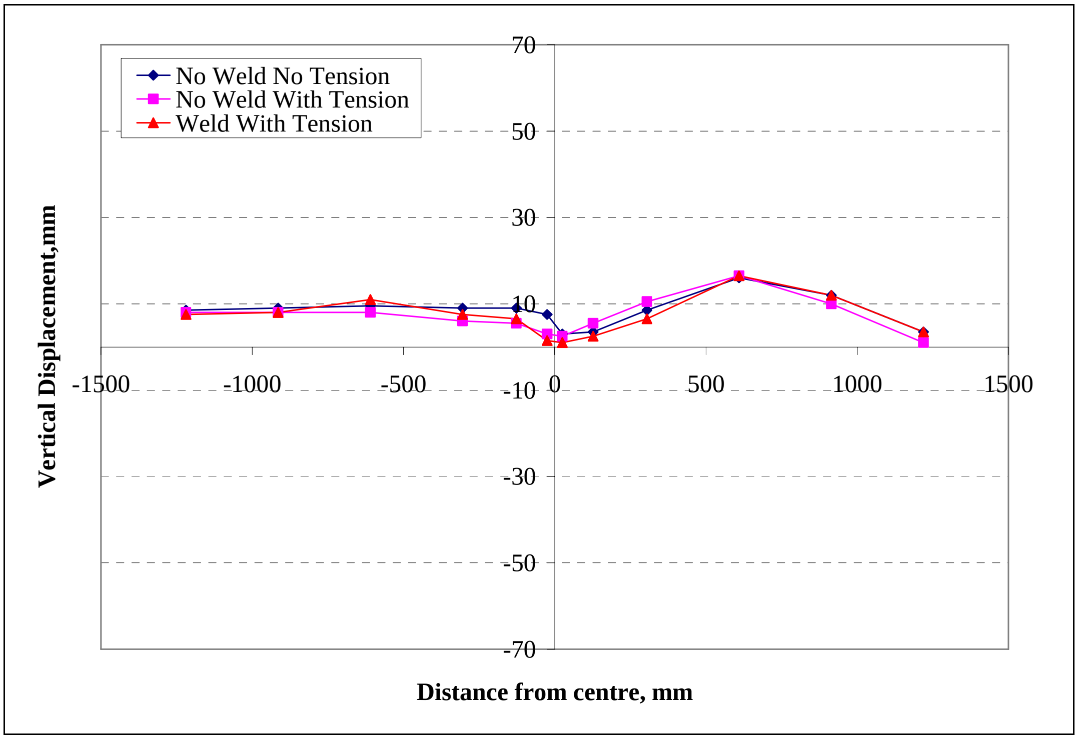


Figure 2: Transverse Section A2

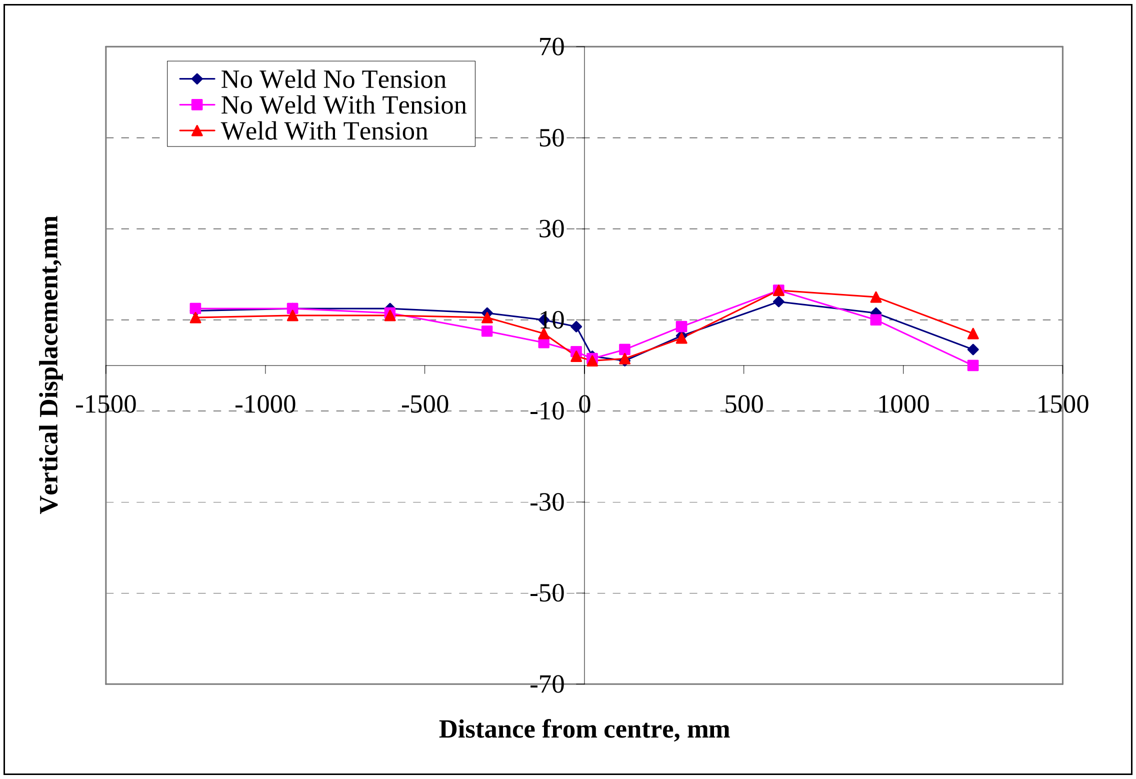


Figure 3: Transverse Section A3

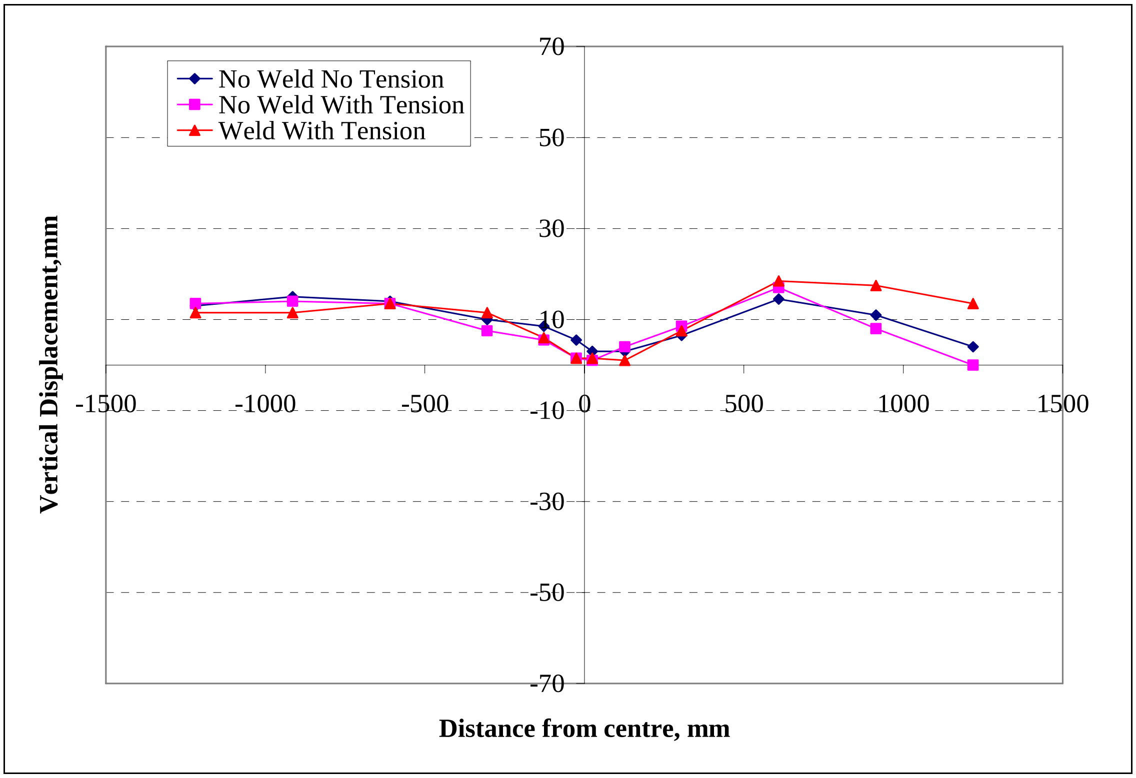


Figure 4: Transverse Section A5

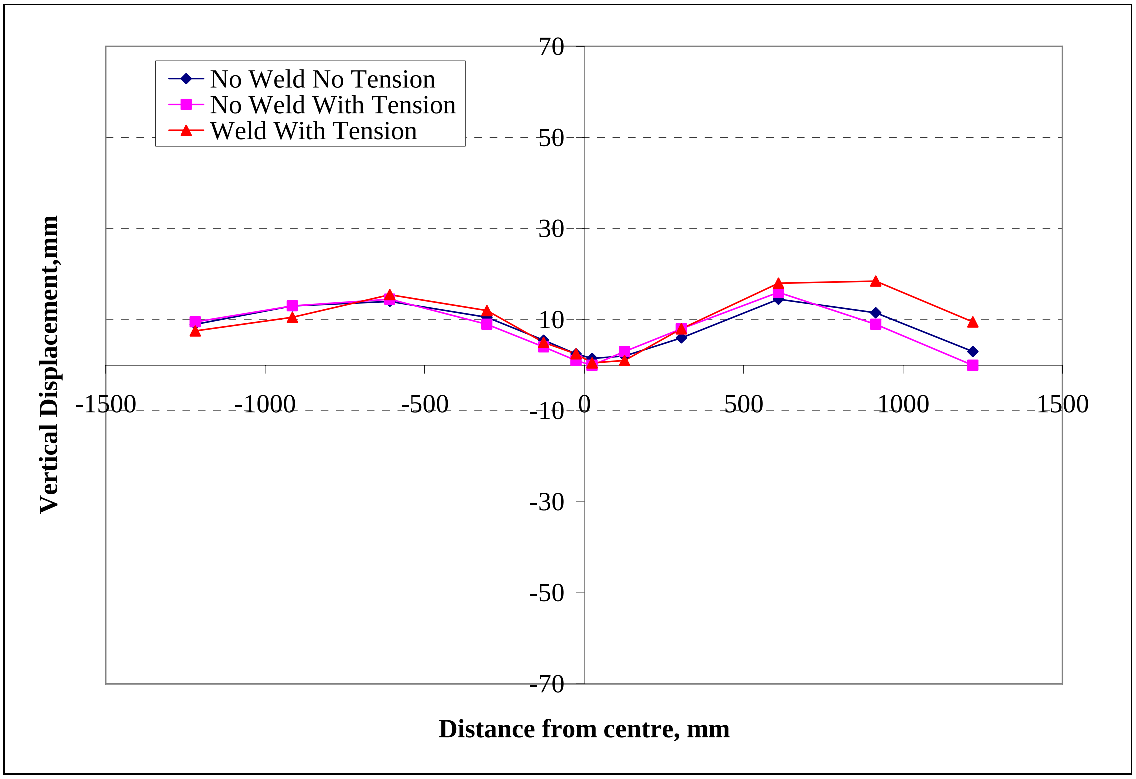


Figure 5: Transverse Section A7

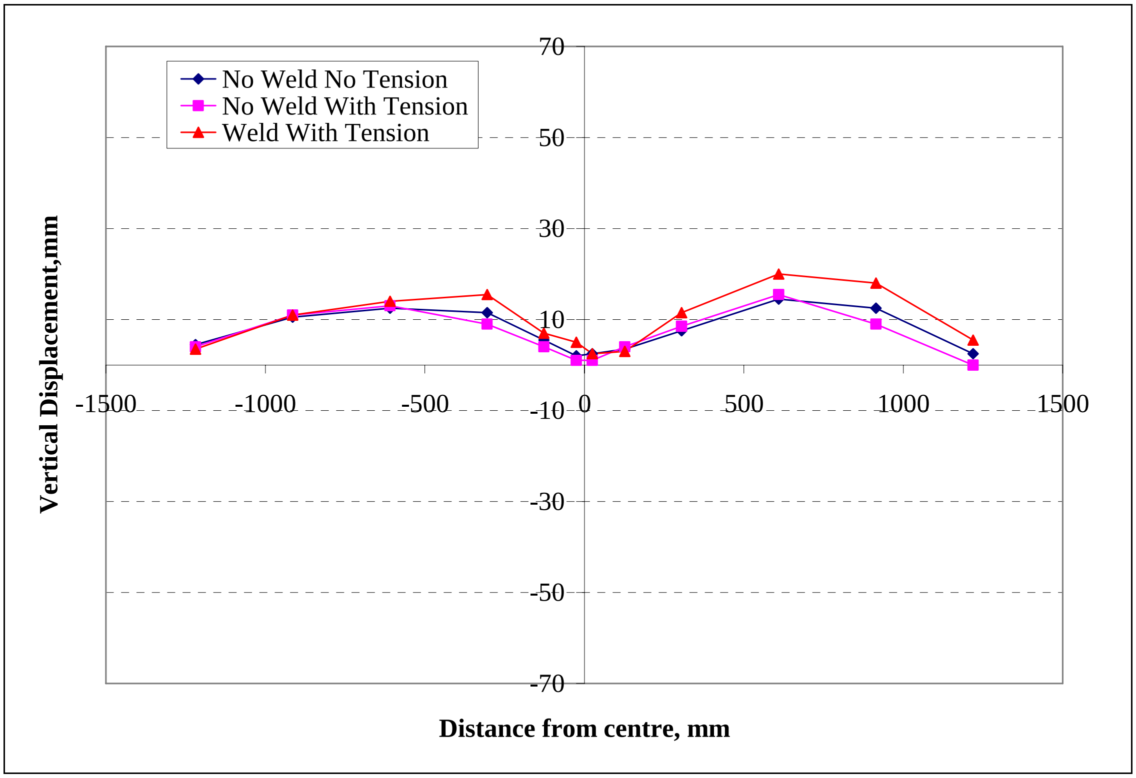


Figure 6: Transverse Section A9

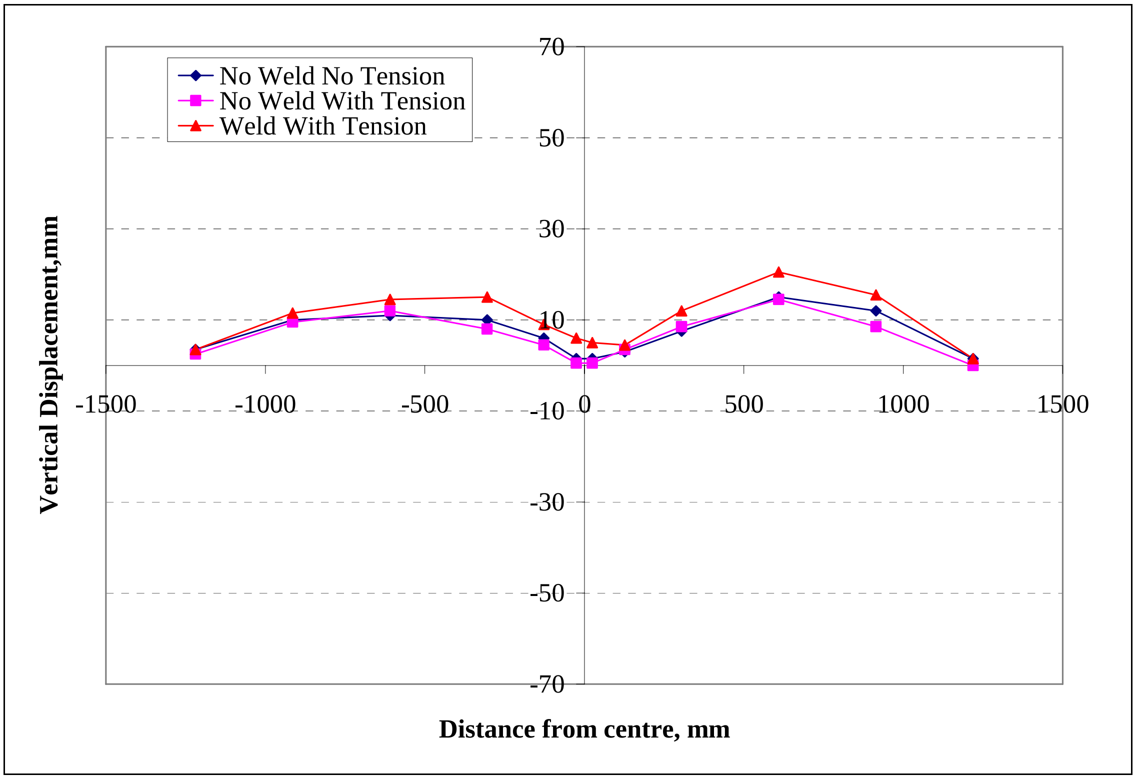


Figure 7: Transverse Section A11

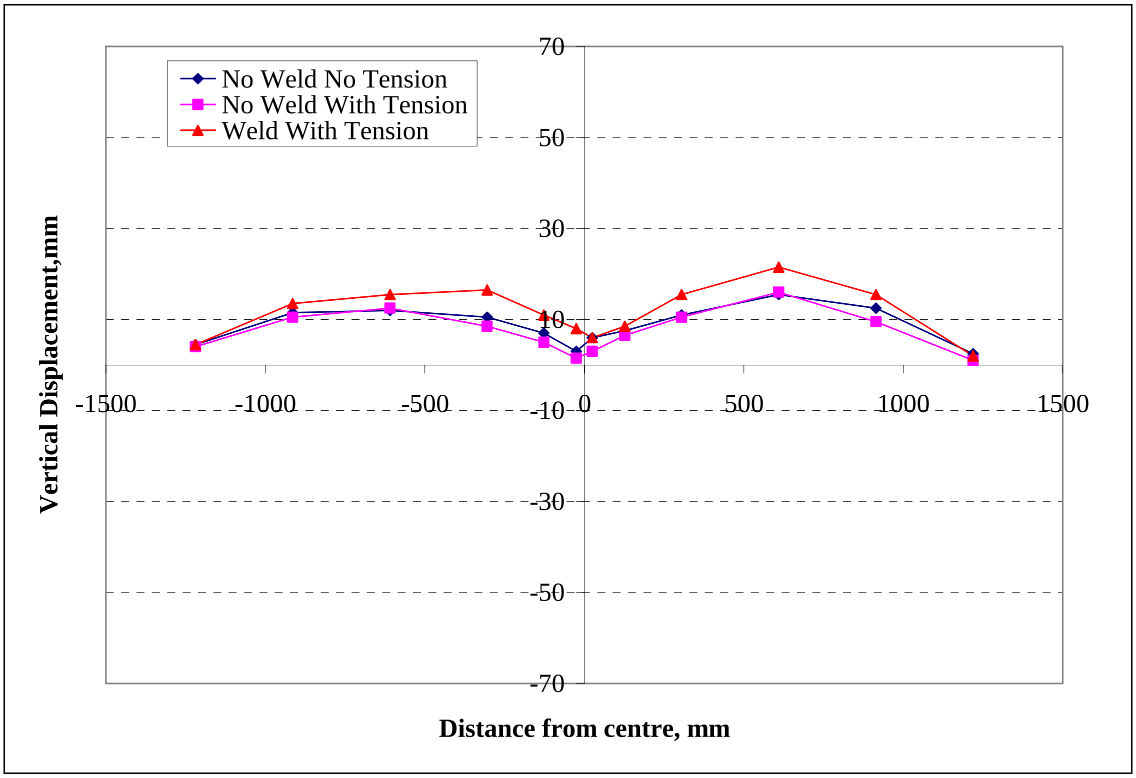


Figure 8: Transverse Section A13

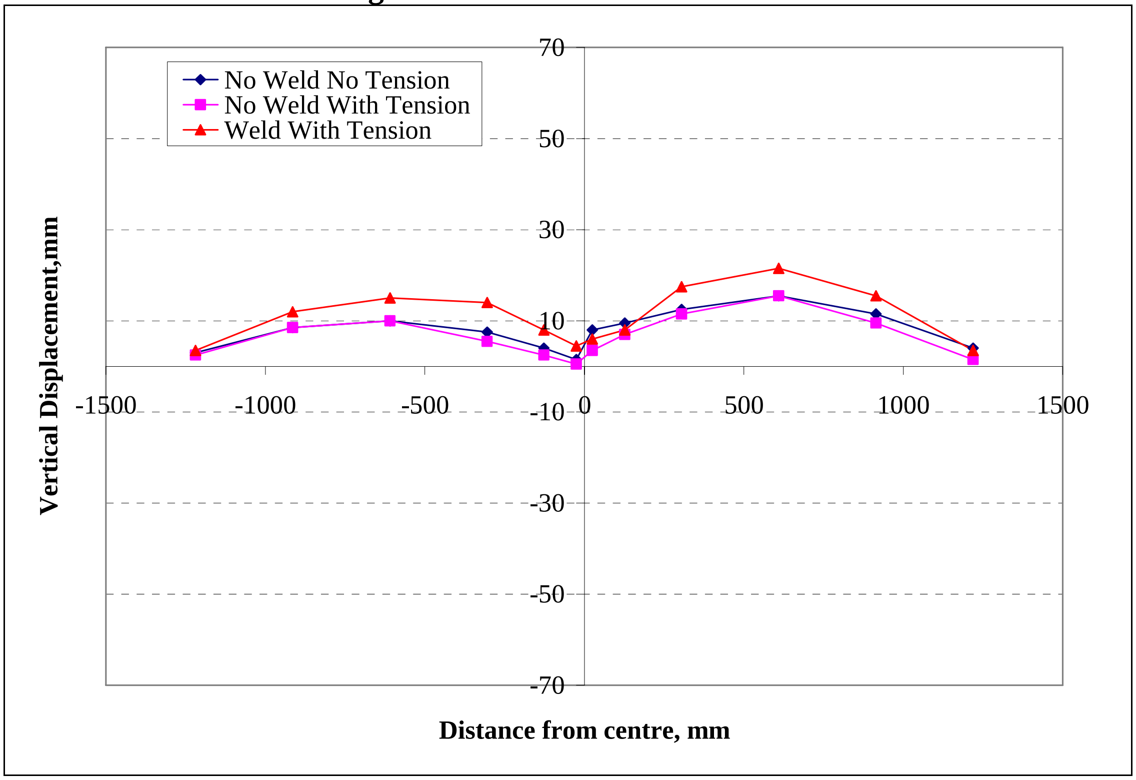


Figure 9: Transverse Section A15

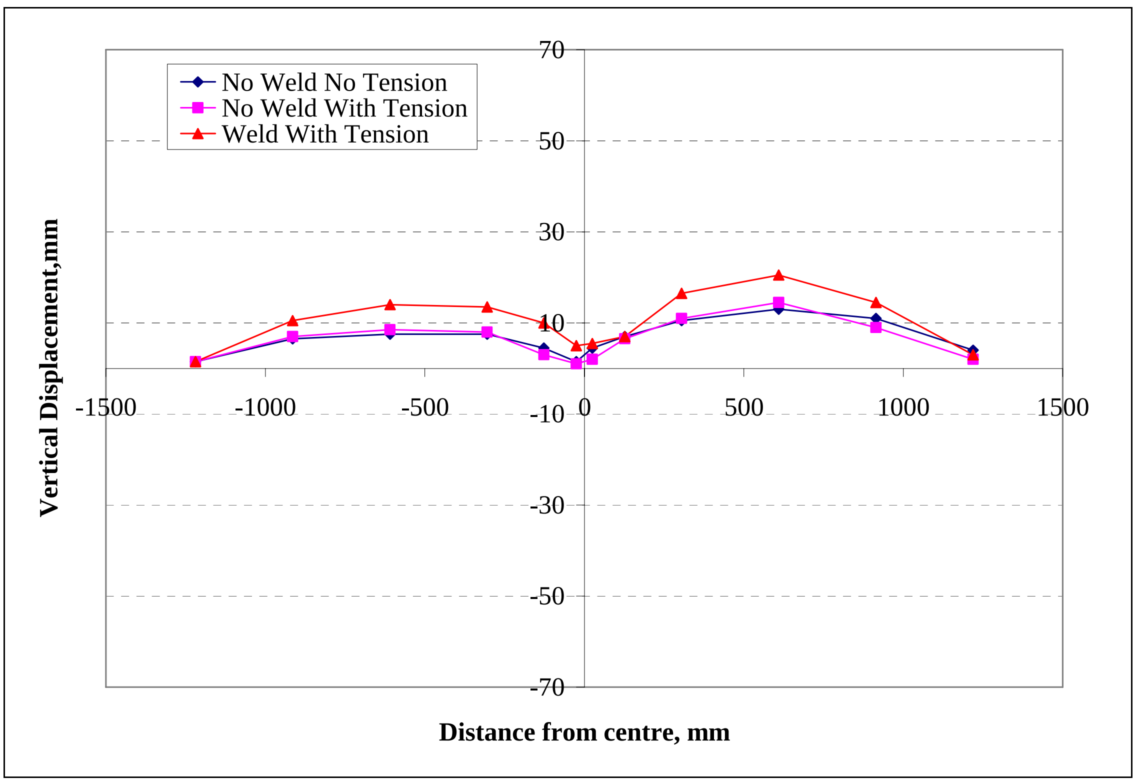


Figure 10: Transverse Section A17

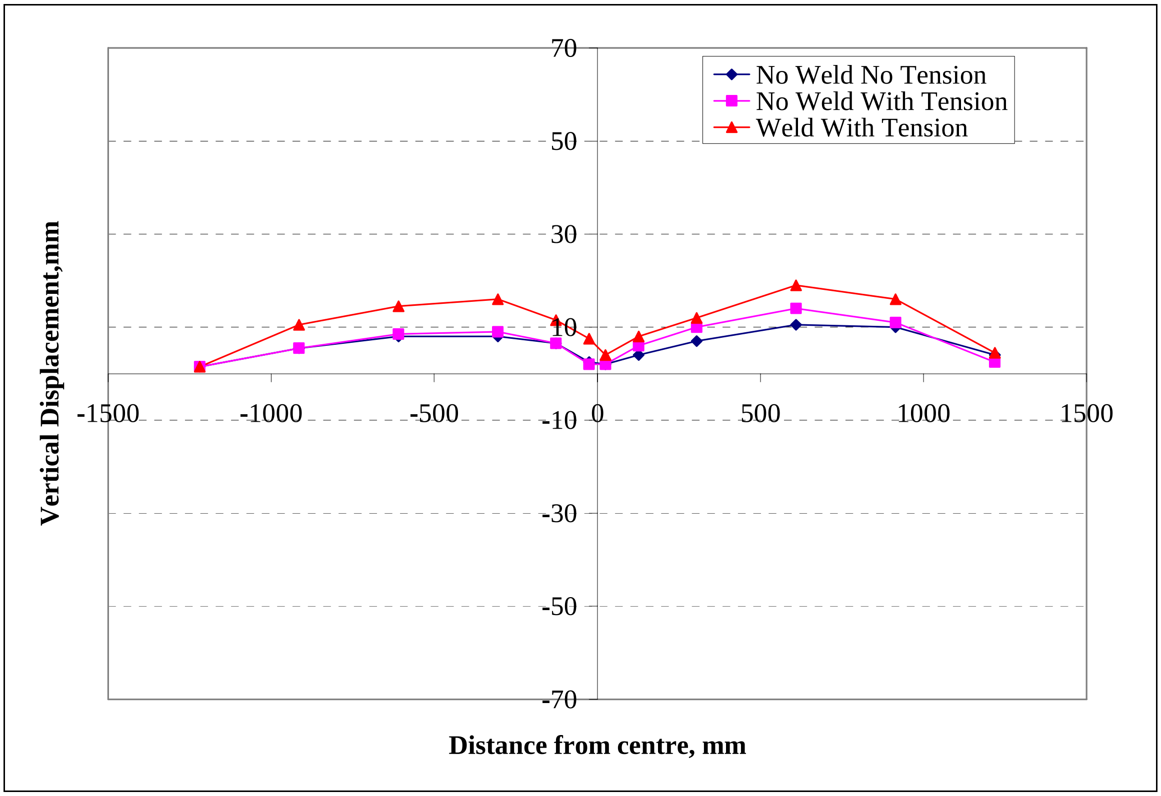


Figure 11: Transverse Section A19

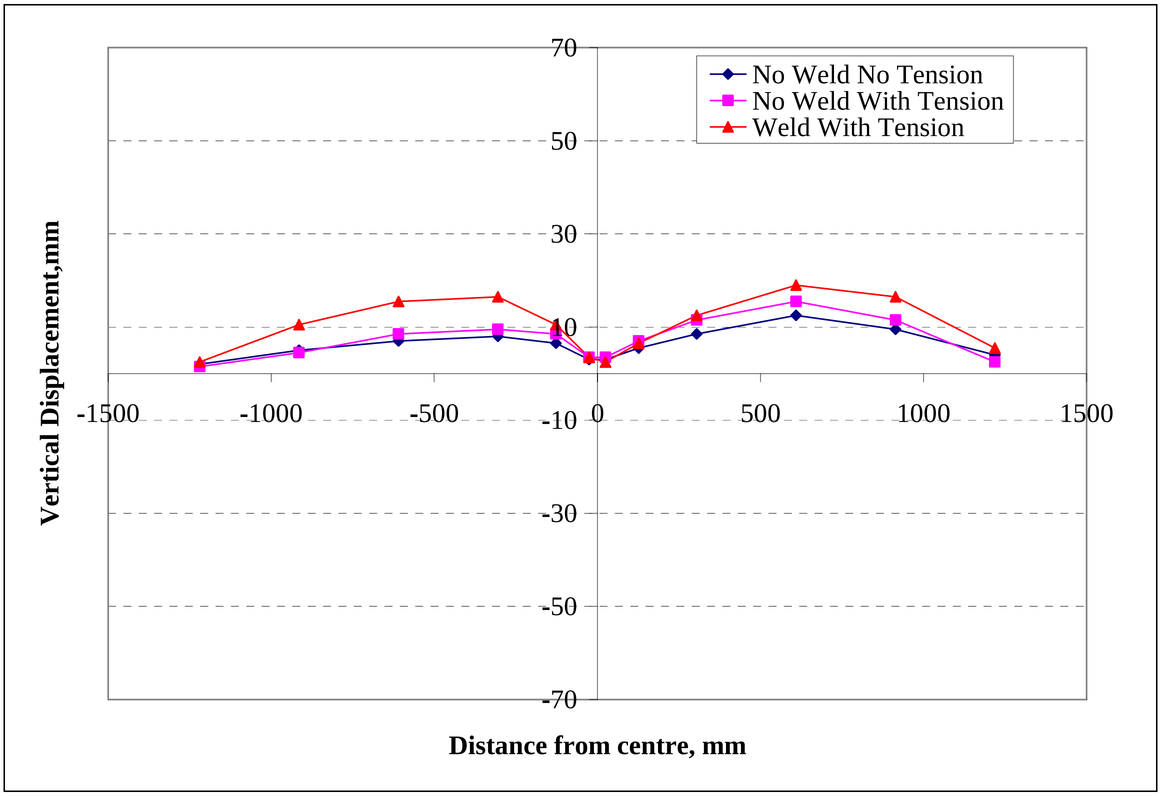


Figure 12: Transverse Section A20

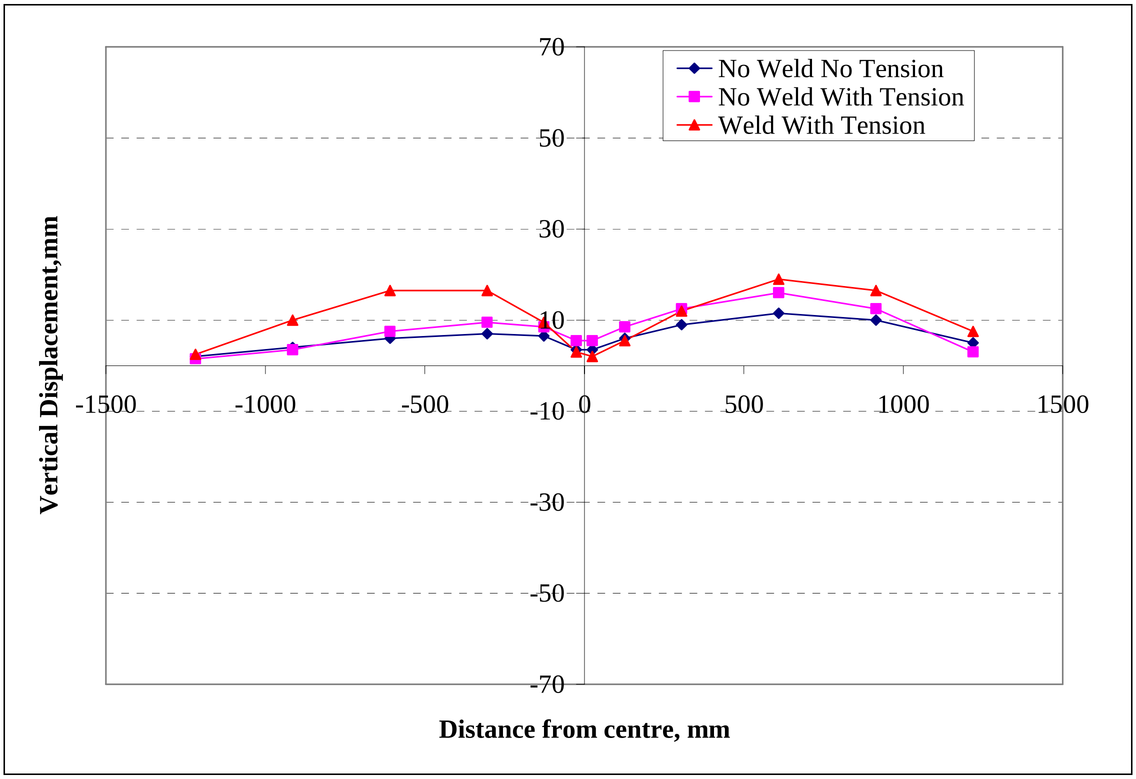


Figure 13: Transverse Section A21

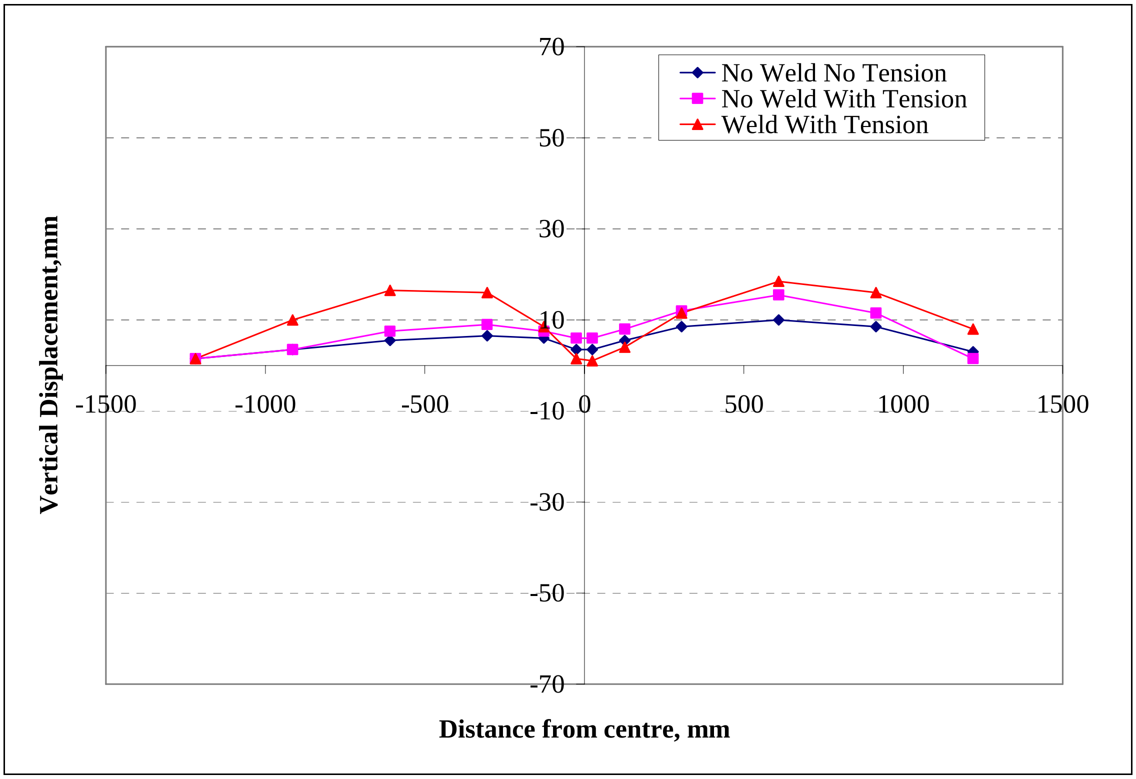


Figure 14: Transverse Section A22

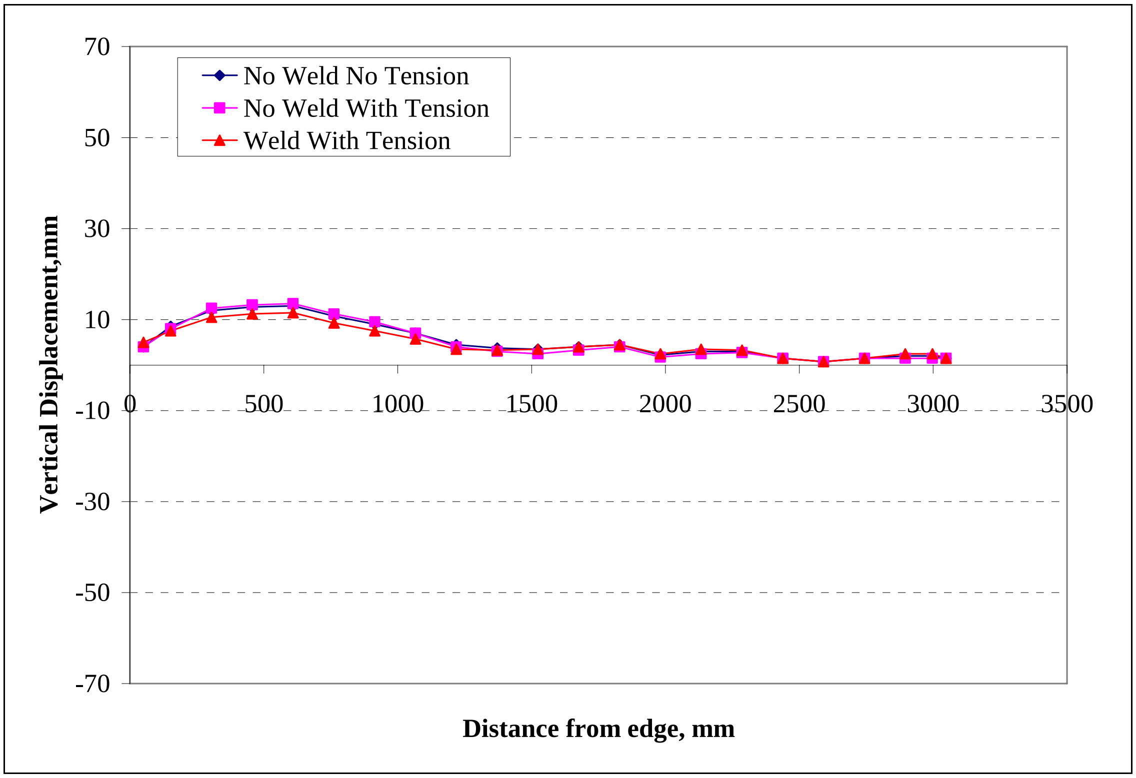


Figure 15: Longitudinal Section A

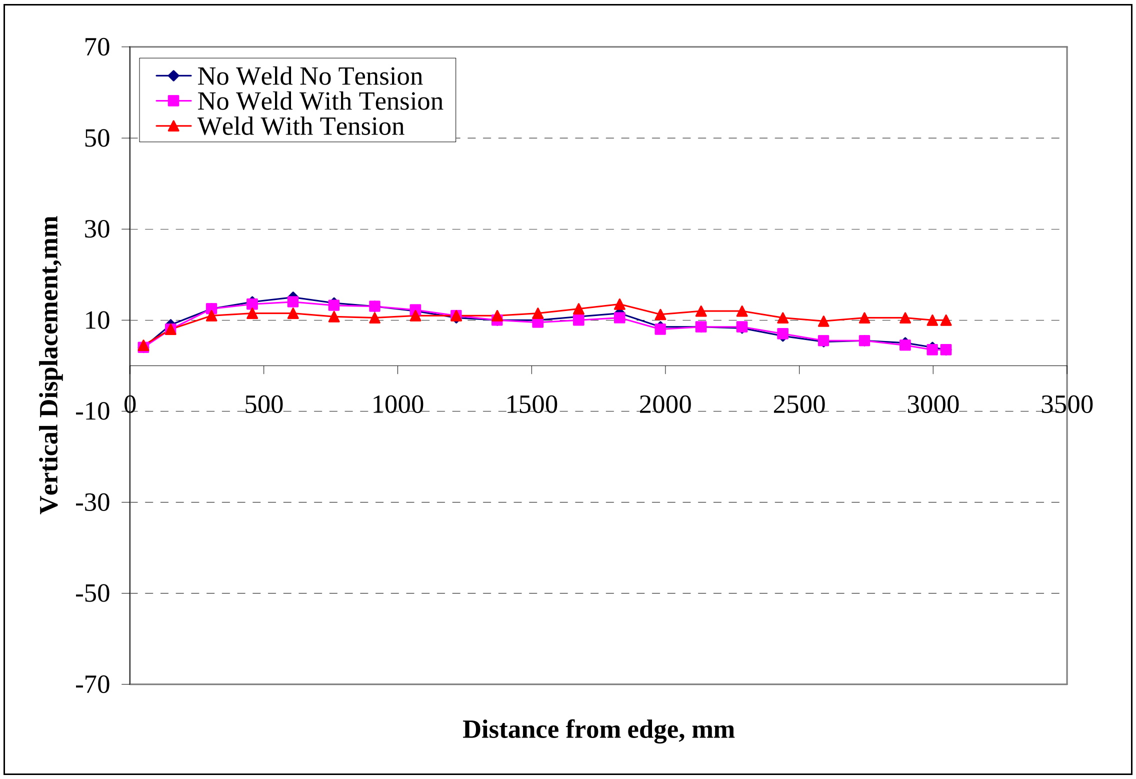


Figure 16: Longitudinal Section B

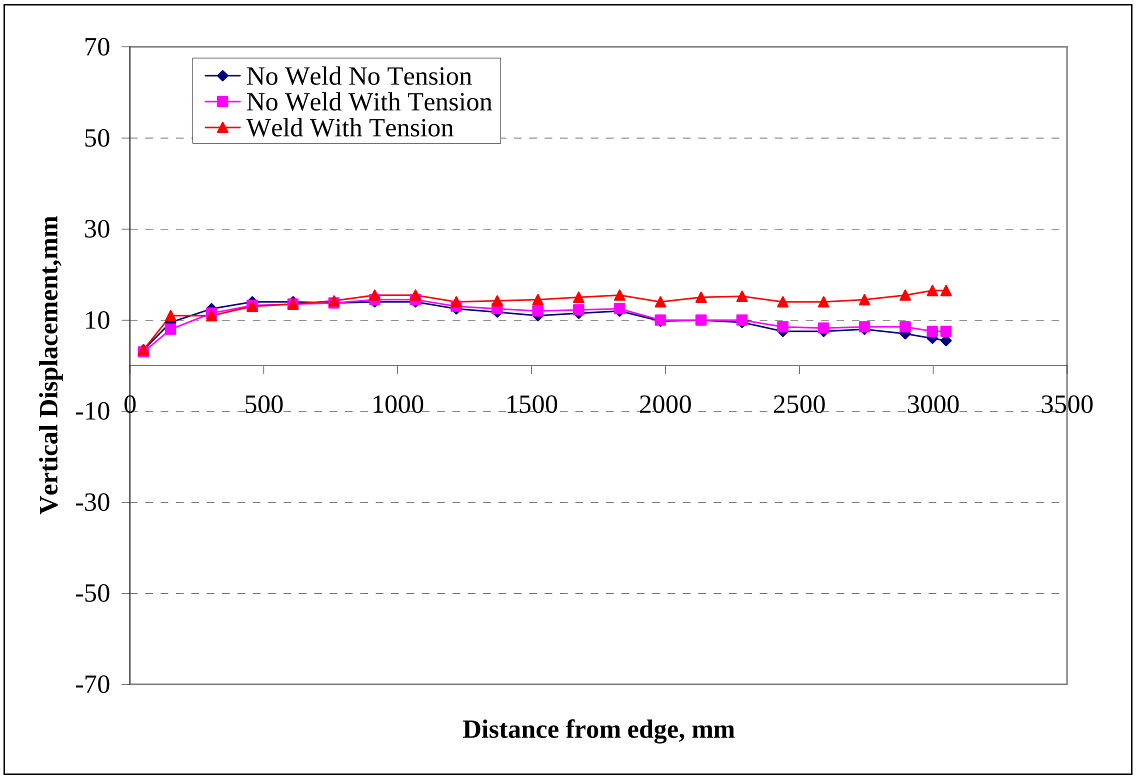


Figure 17: Longitudinal Section C

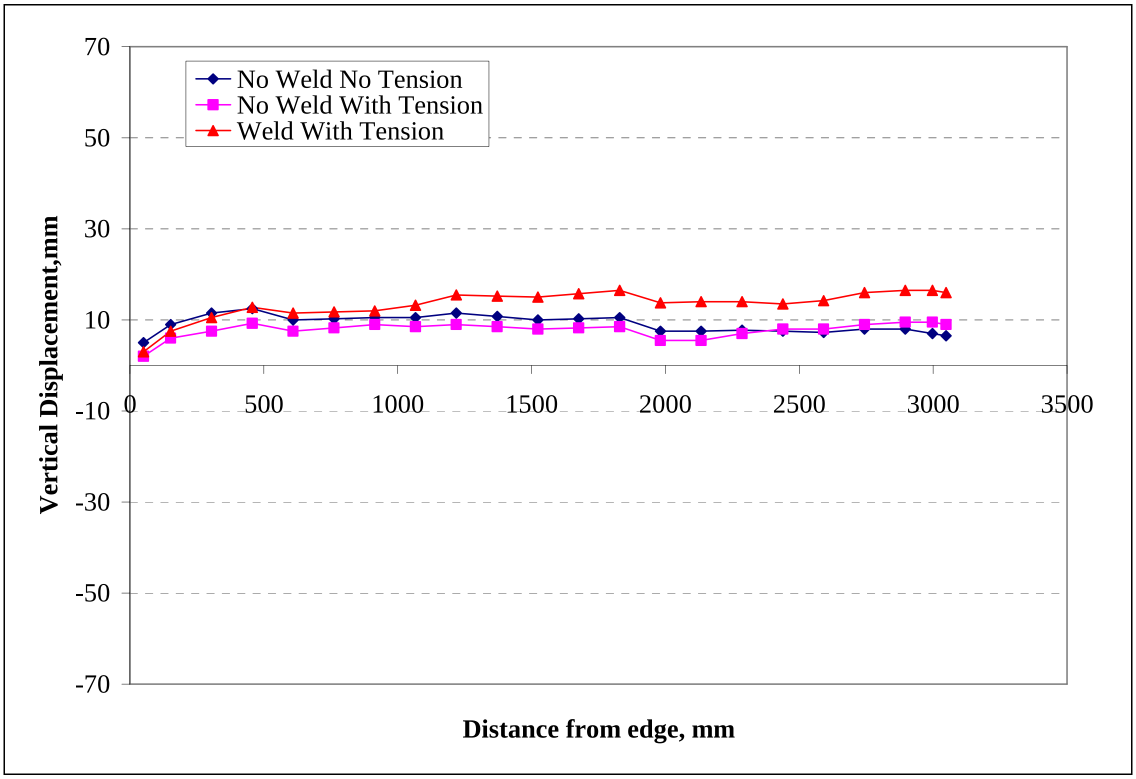


Figure 18: Longitudinal Section D

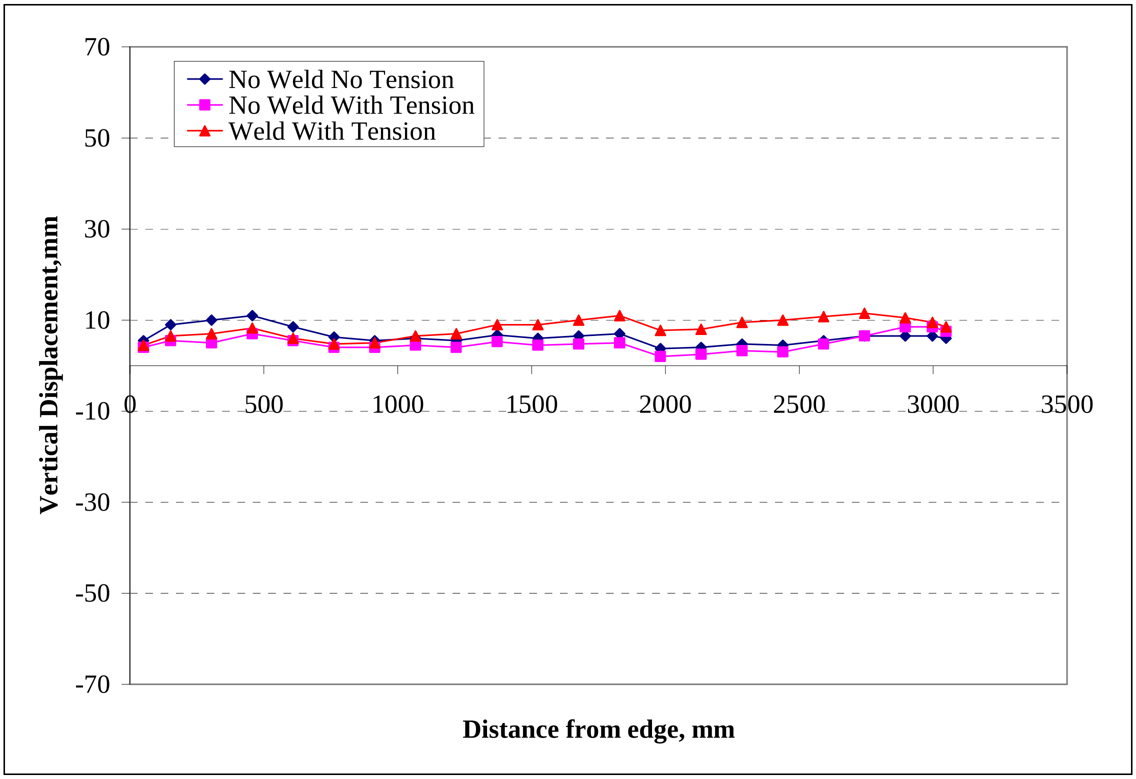


Figure 19: Longitudinal Section E

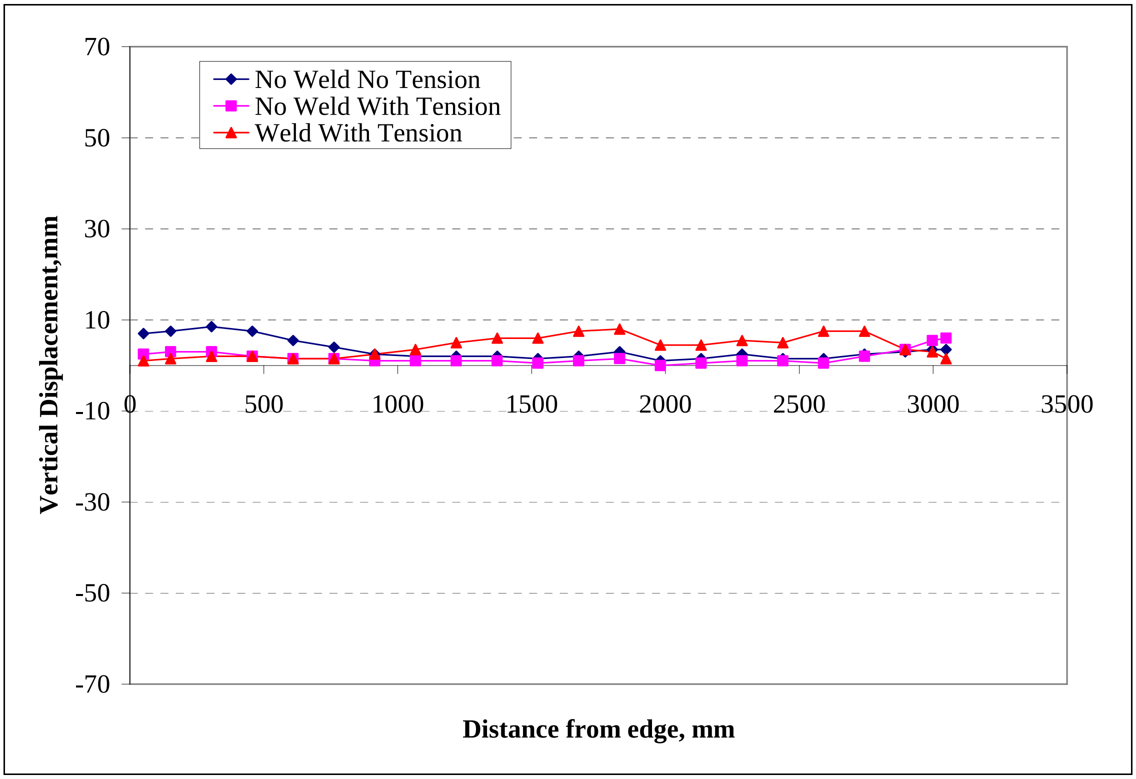


Figure 20: Longitudinal Section F

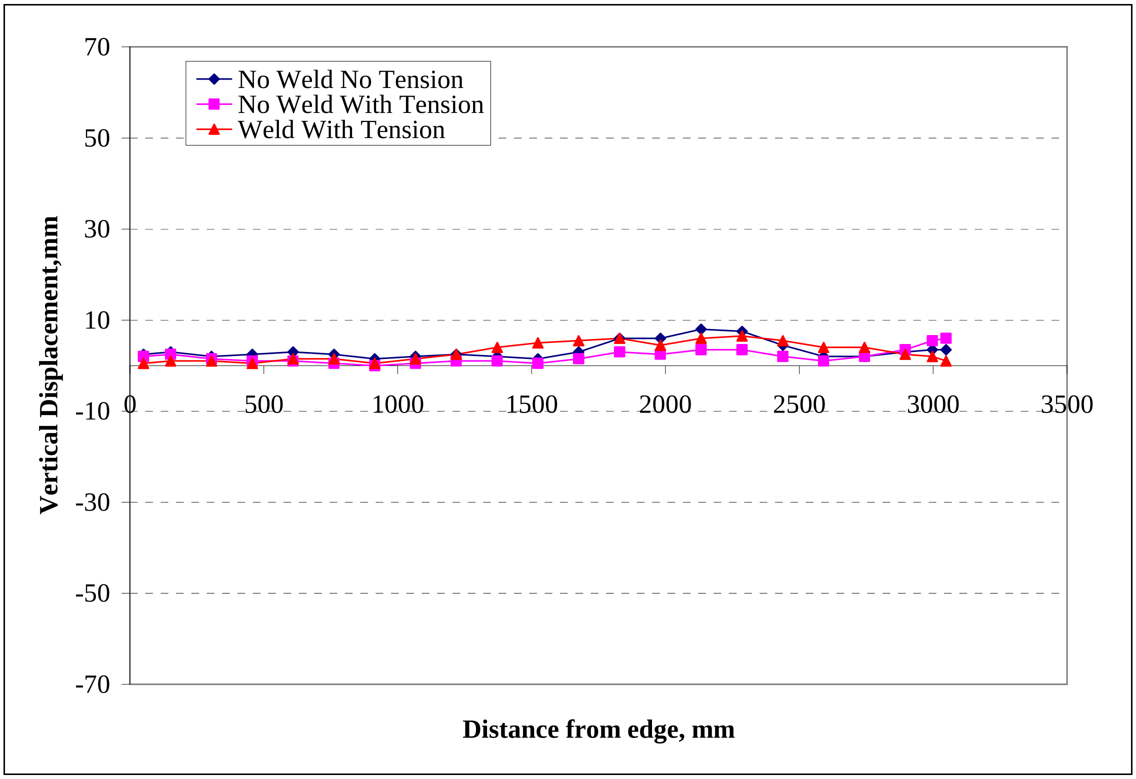


Figure 21: Longitudinal Section G

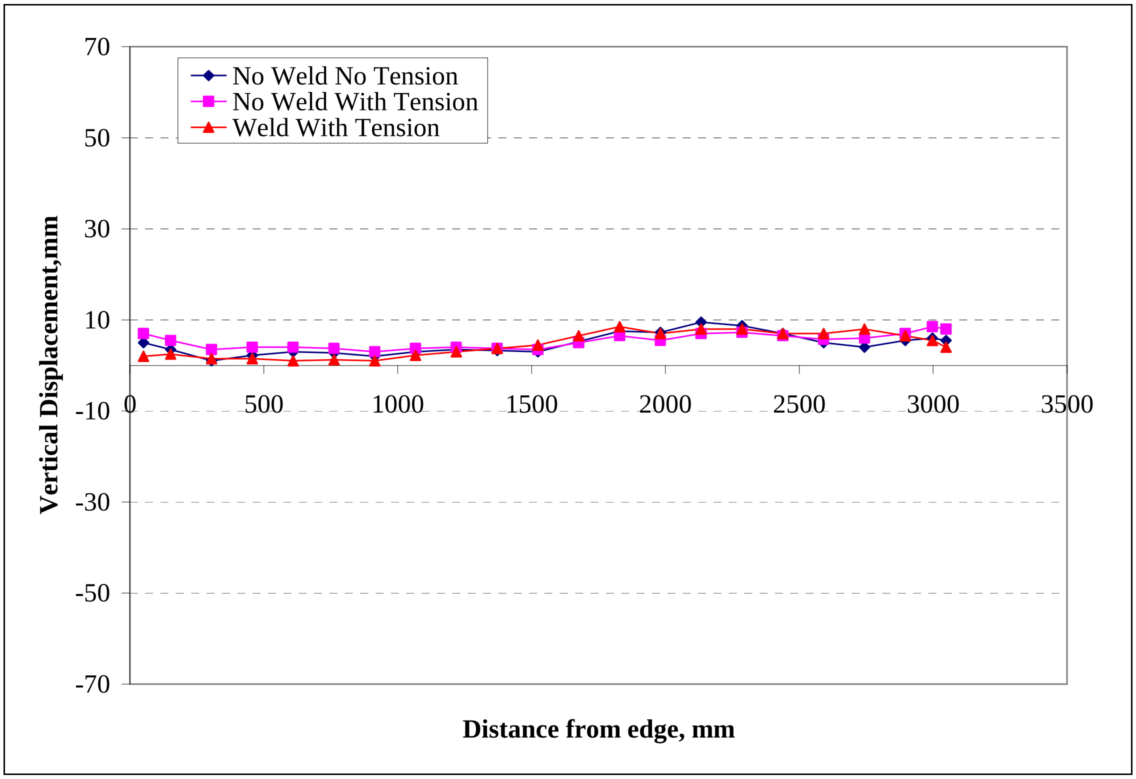


Figure 22: Longitudinal Section H

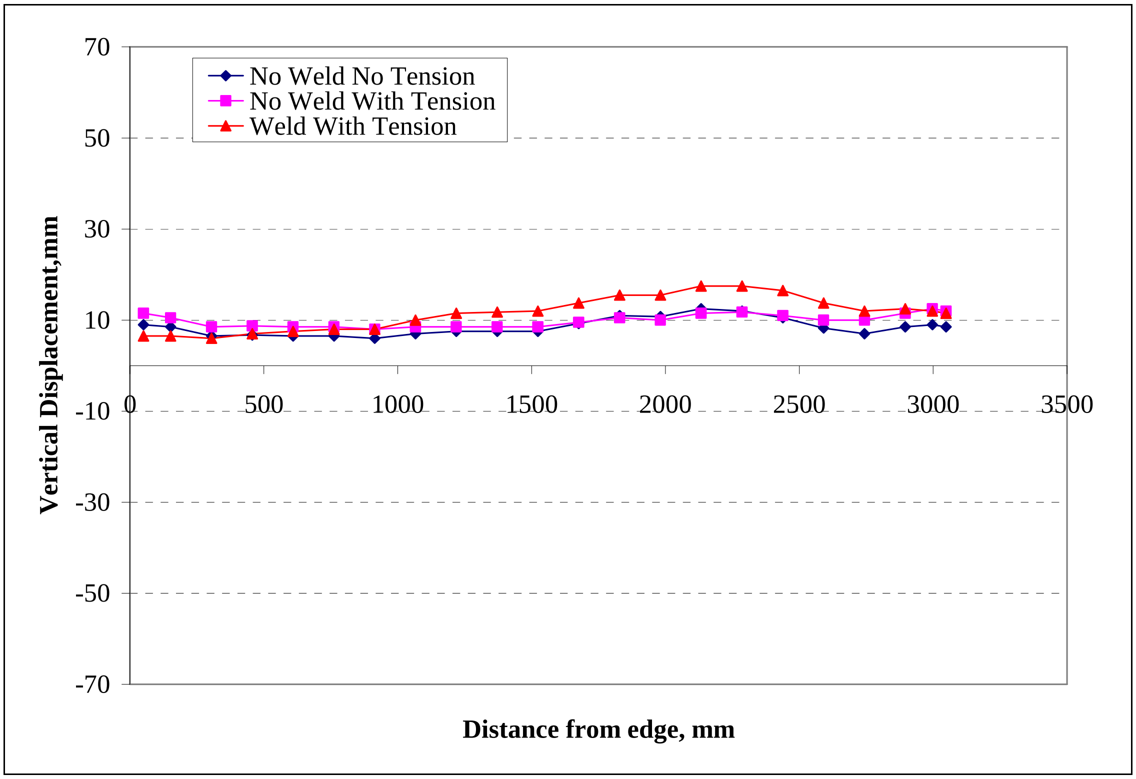


Figure 23: Longitudinal Section I

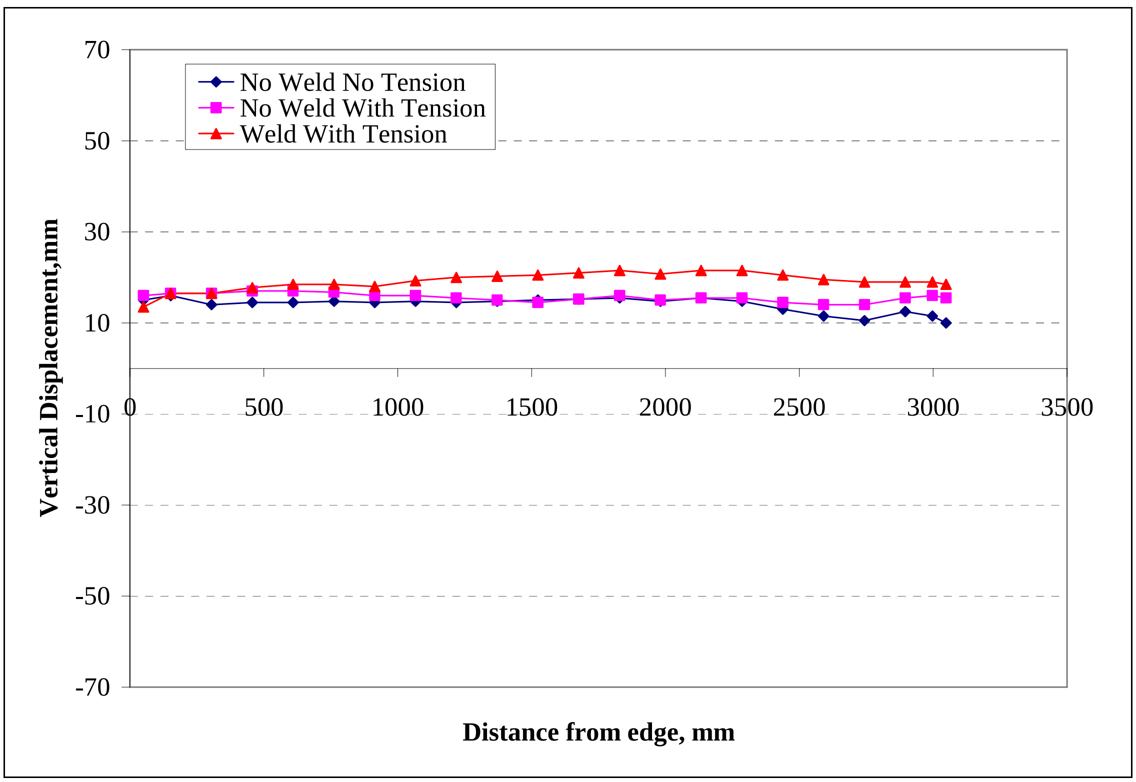


Figure 24: Longitudinal Section J

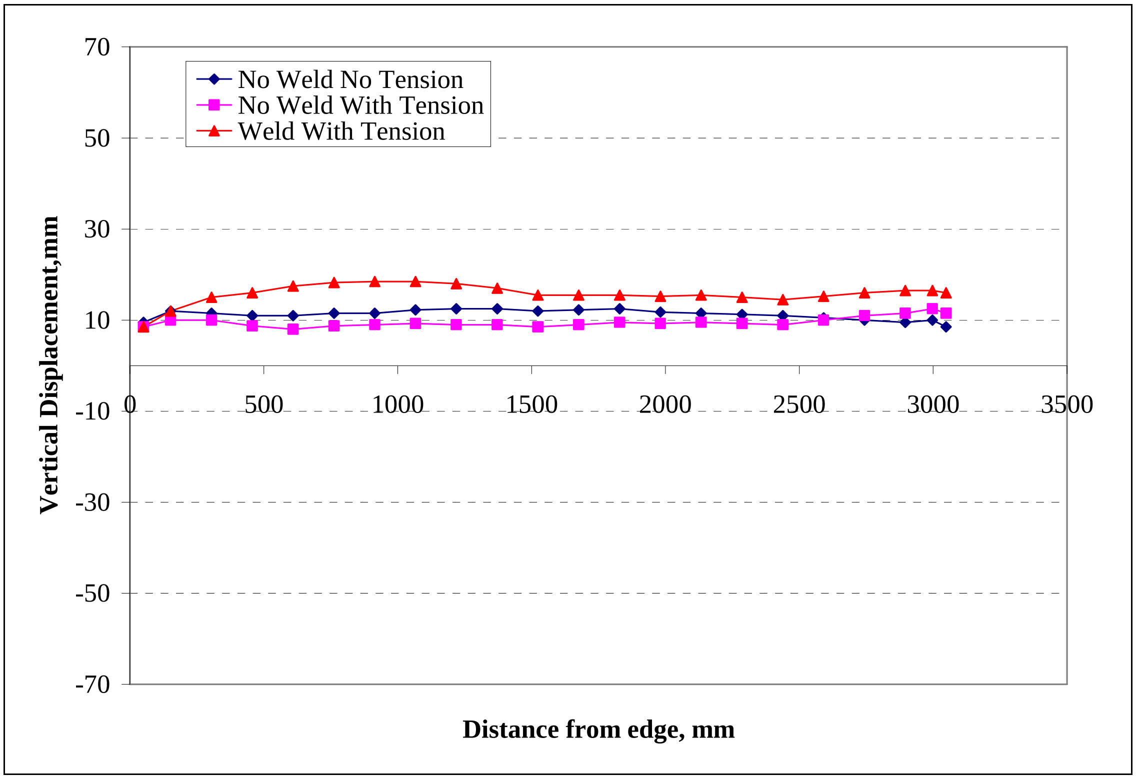


Figure 25: Longitudinal Section K

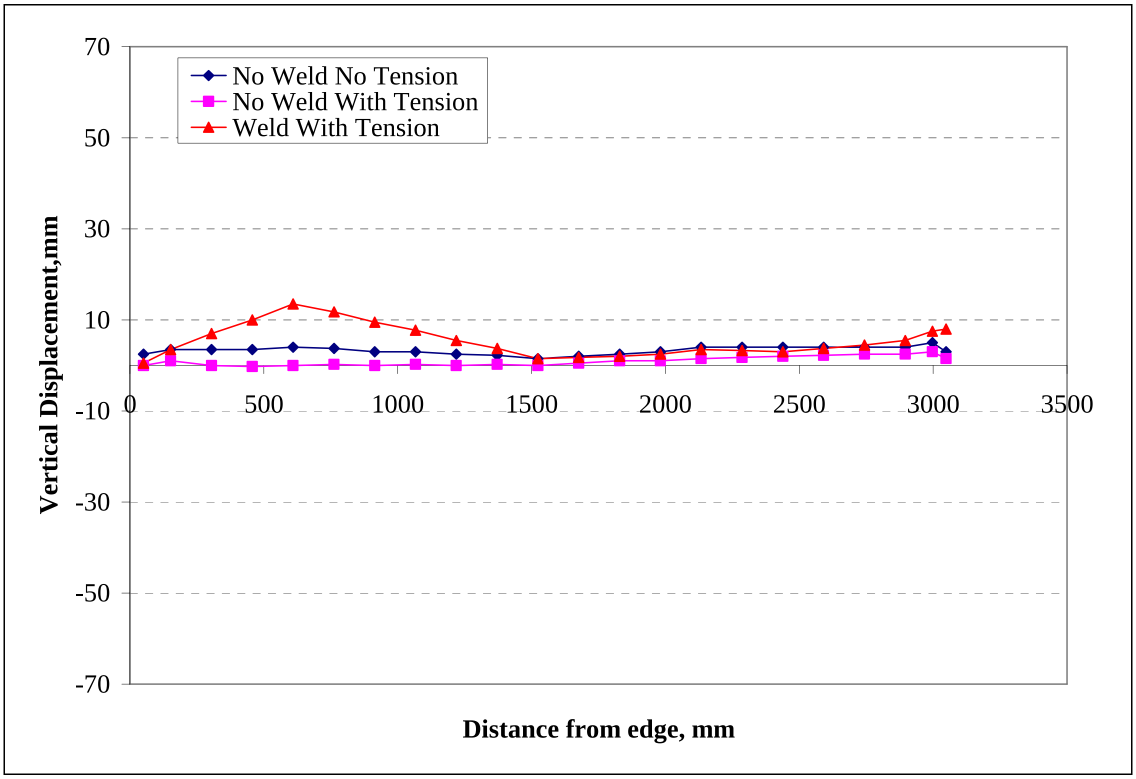


Figure 26: Longitudinal Section L

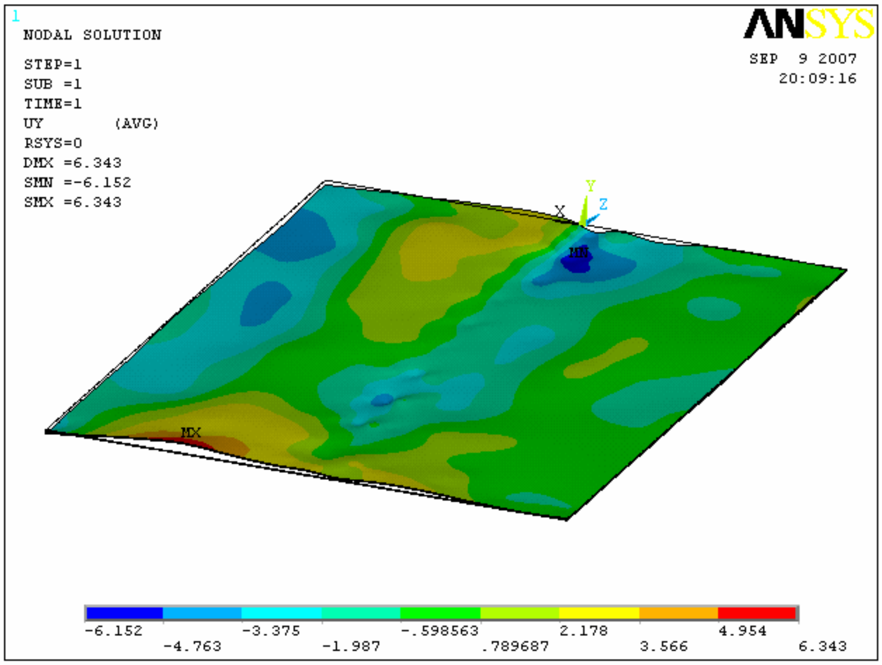


Figure 27: Net Plate Deformation after Welding
(No Weld No Tension- Weld With Tension)

PLATE 3 – SIDE 1

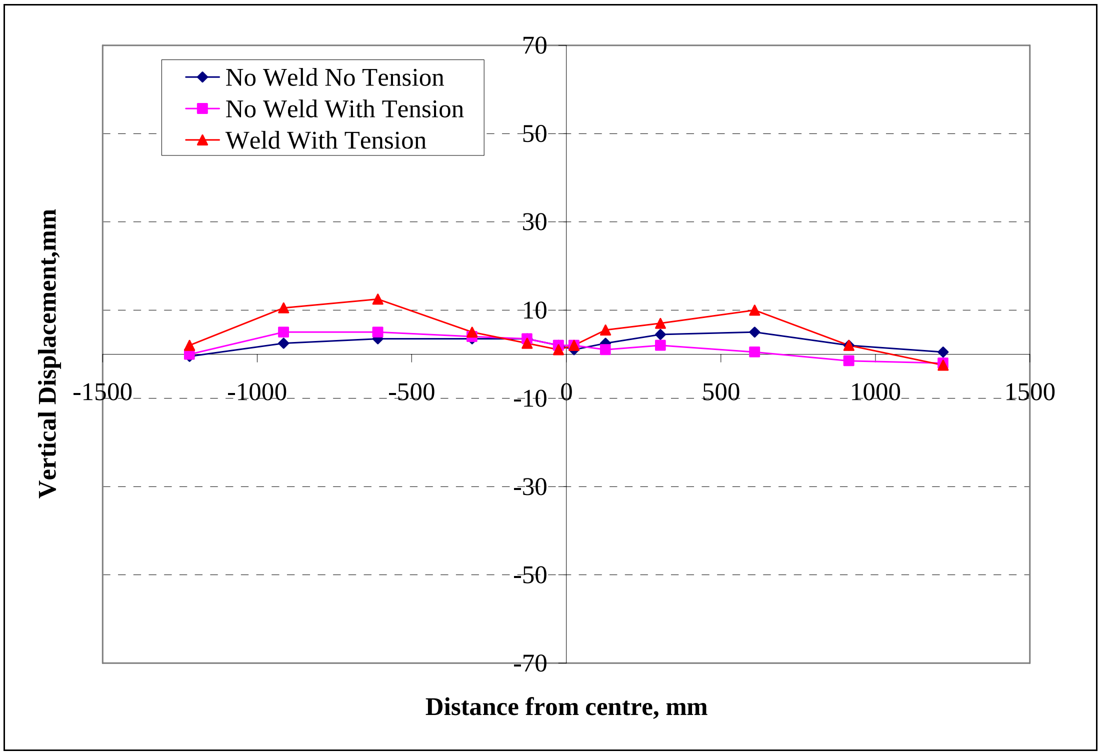


Figure 1: Transverse Section A1

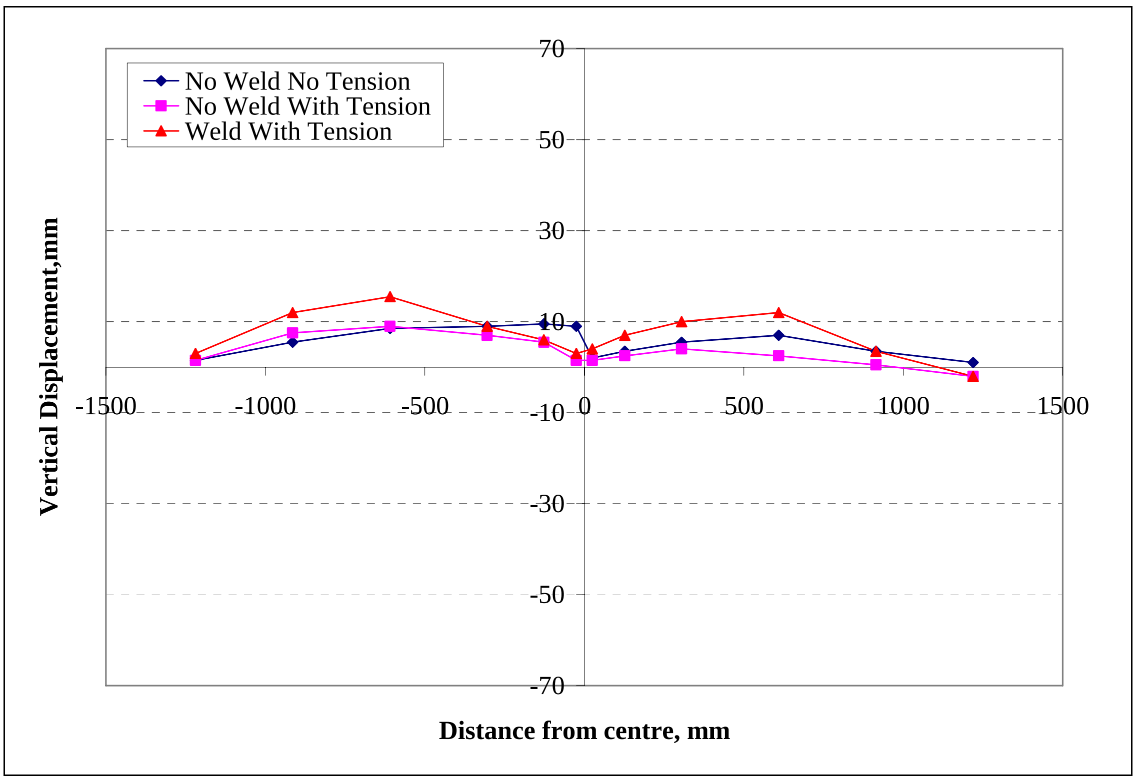


Figure 2: Transverse Section A2

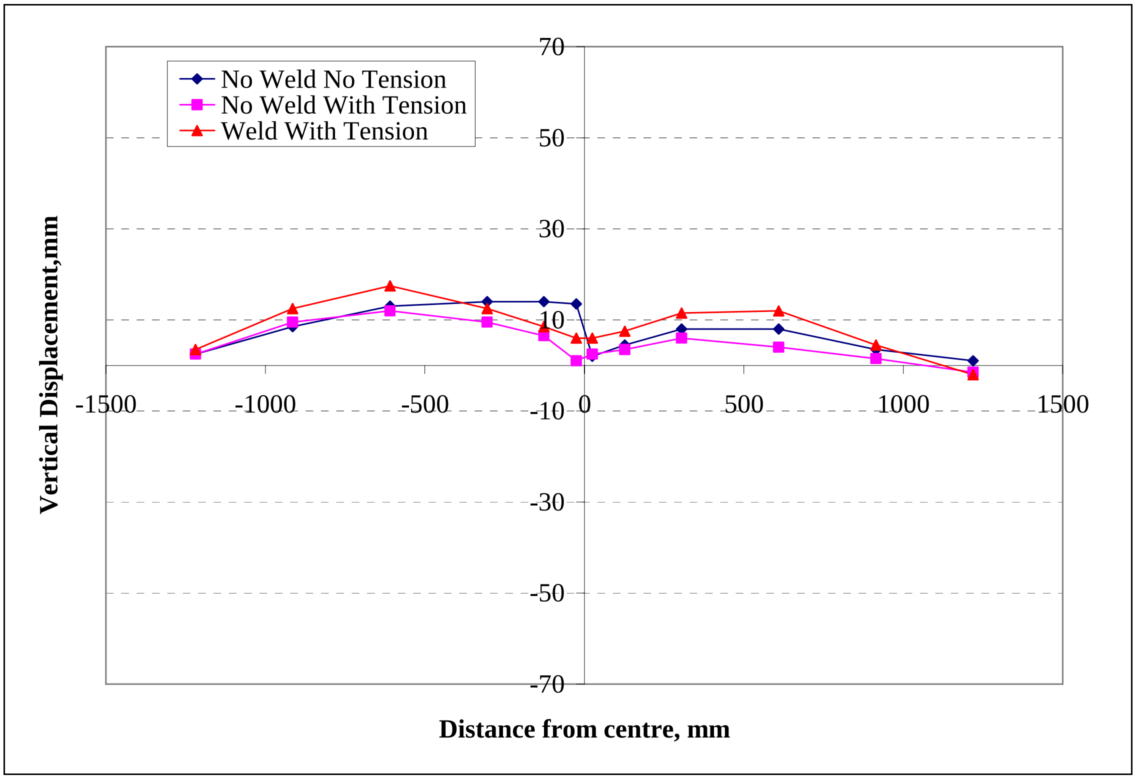


Figure 3: Transverse Section A3

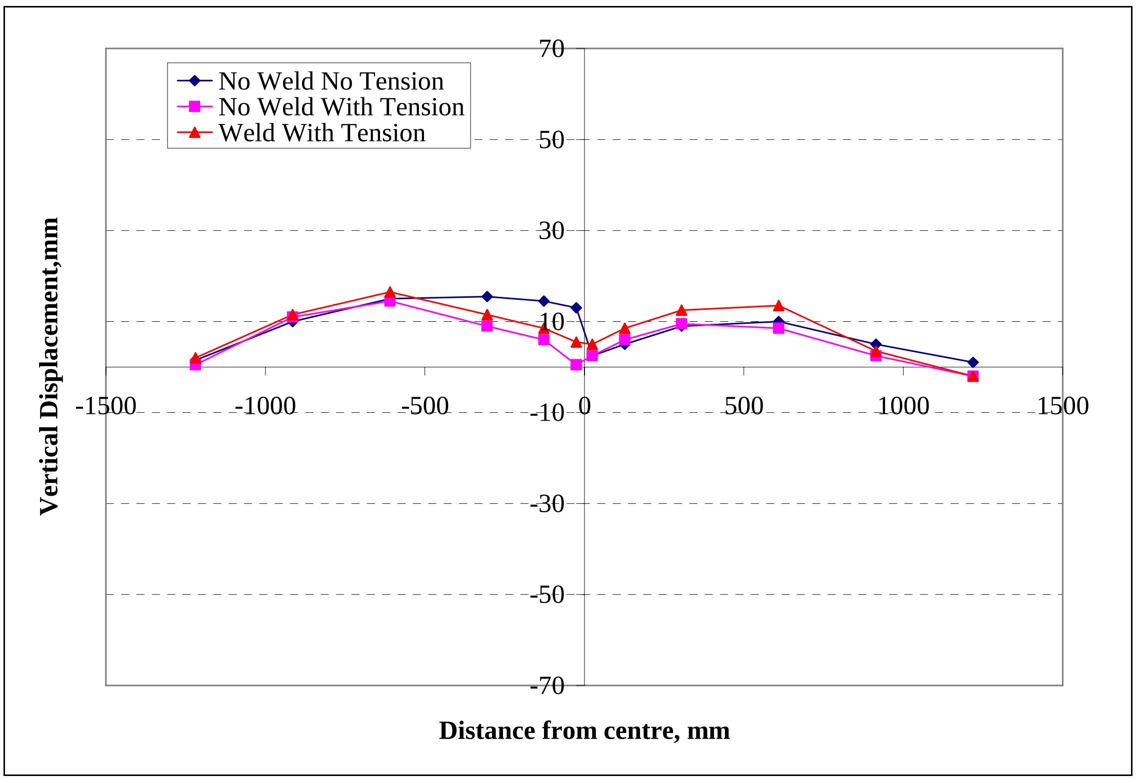


Figure 4: Transverse Section A5

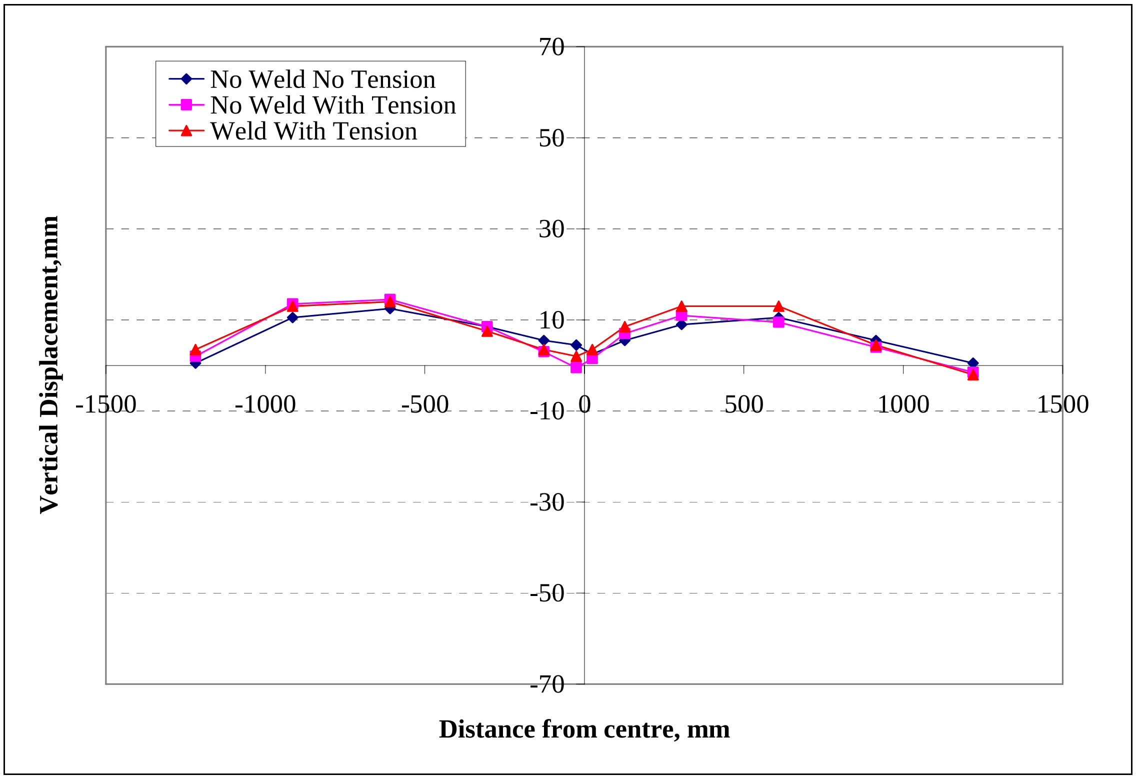


Figure 5: Transverse Section A7

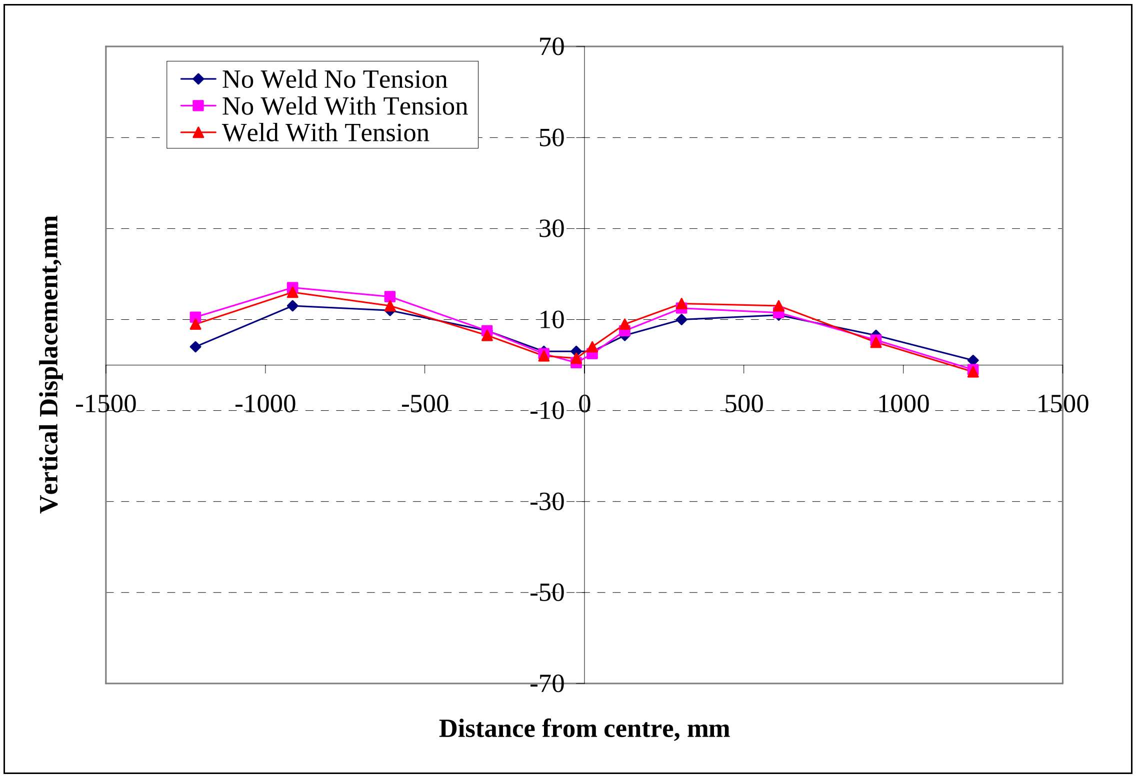


Figure 6: Transverse Section A9

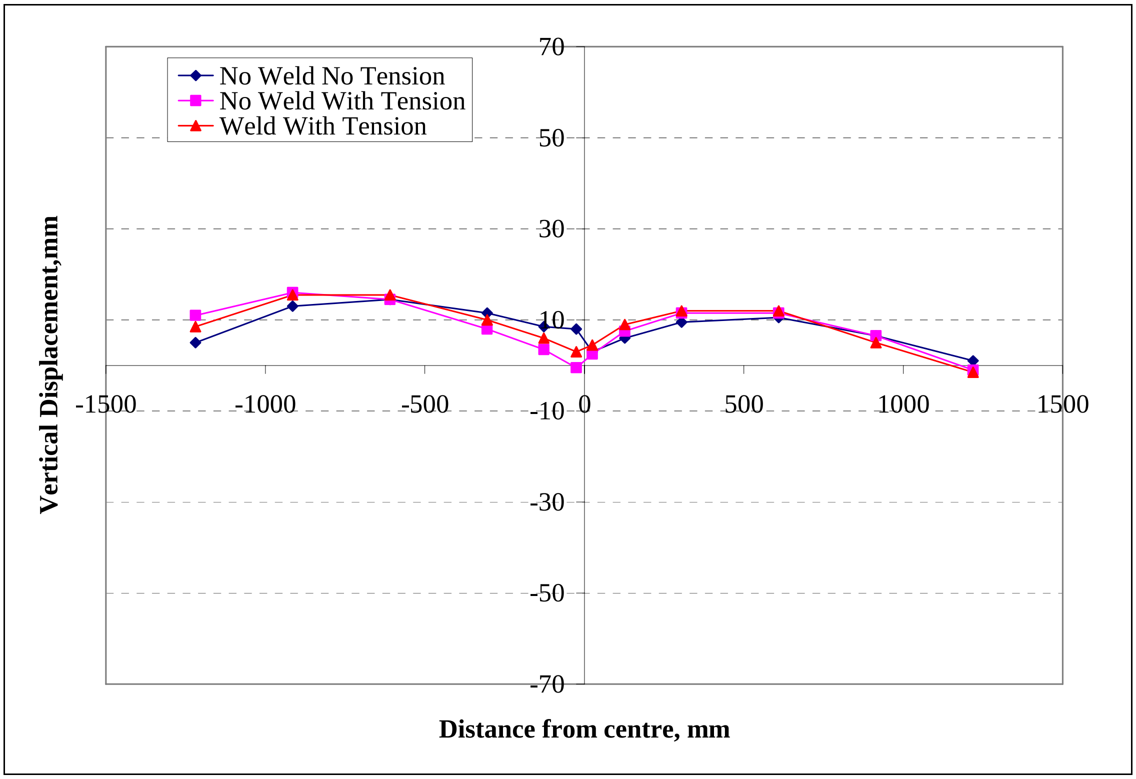


Figure 7: Transverse Section A11

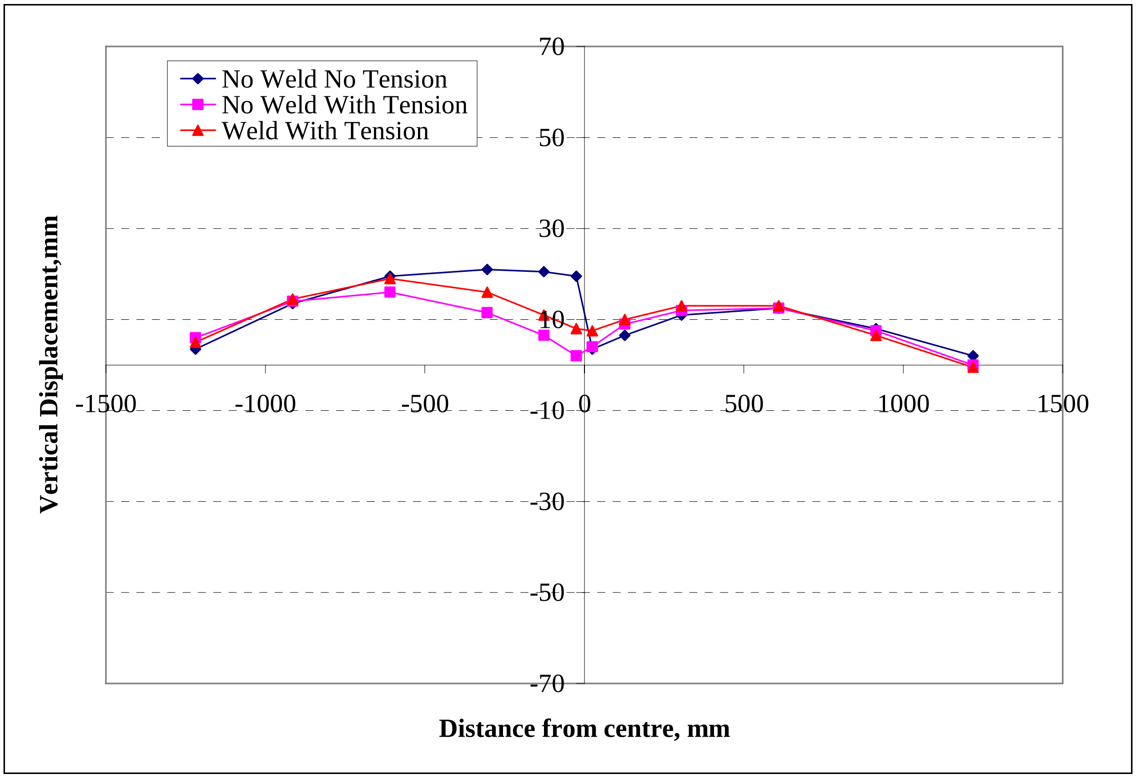


Figure 8: Transverse Section A13

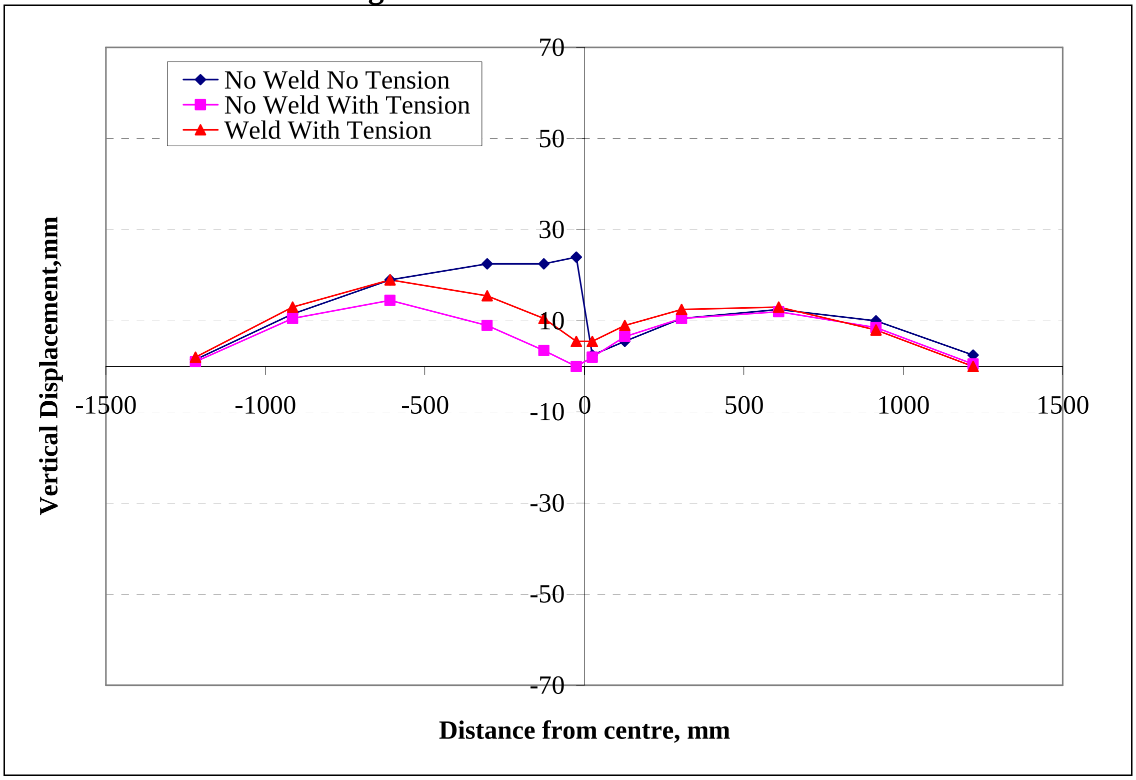


Figure 9: Transverse Section A15

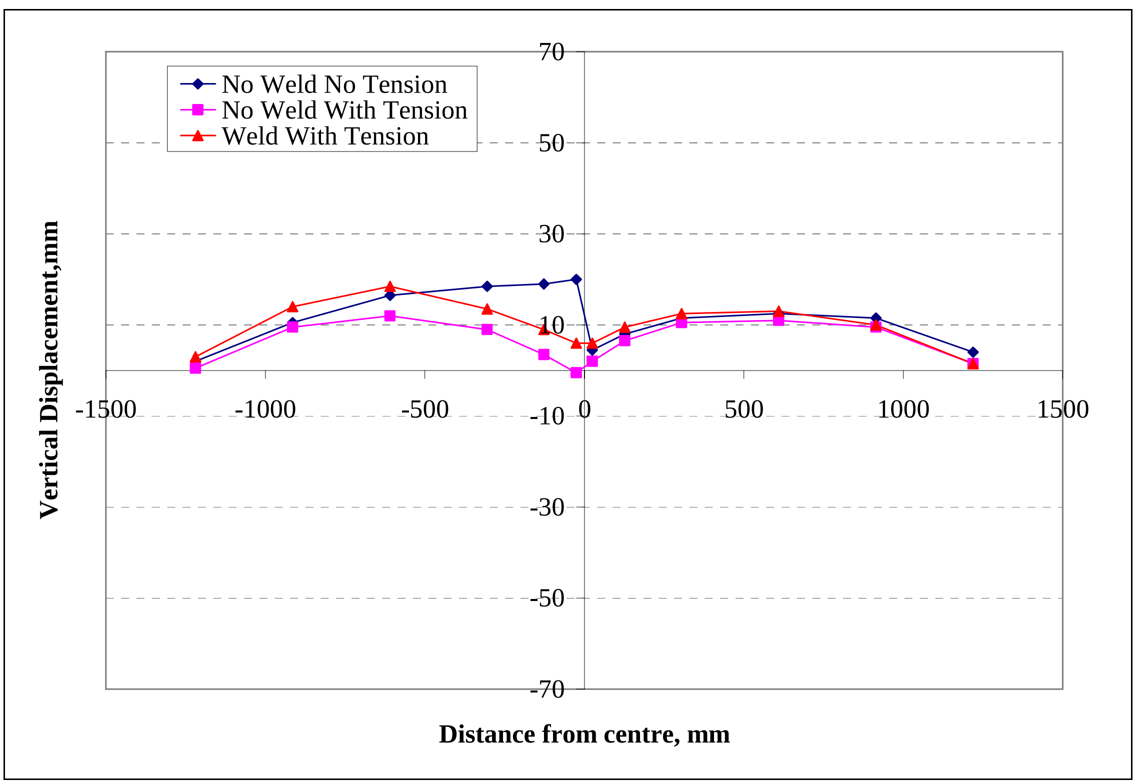


Figure 10: Transverse Section A17

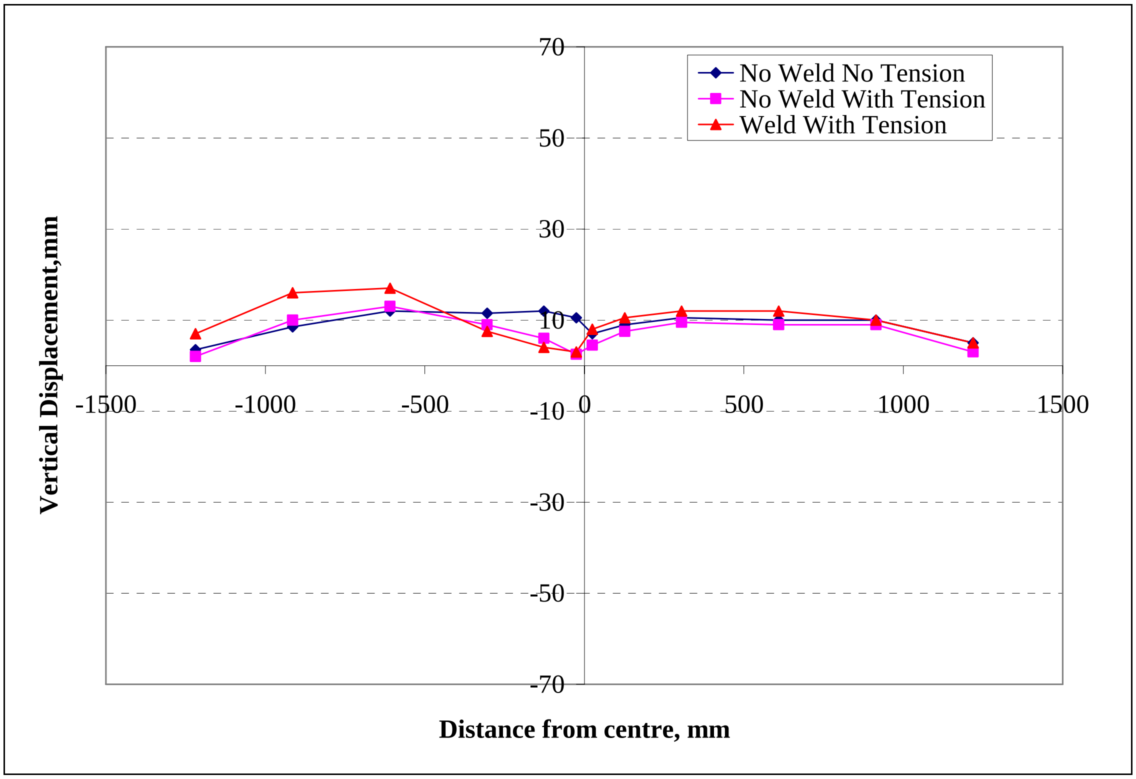


Figure 11: Transverse Section A19

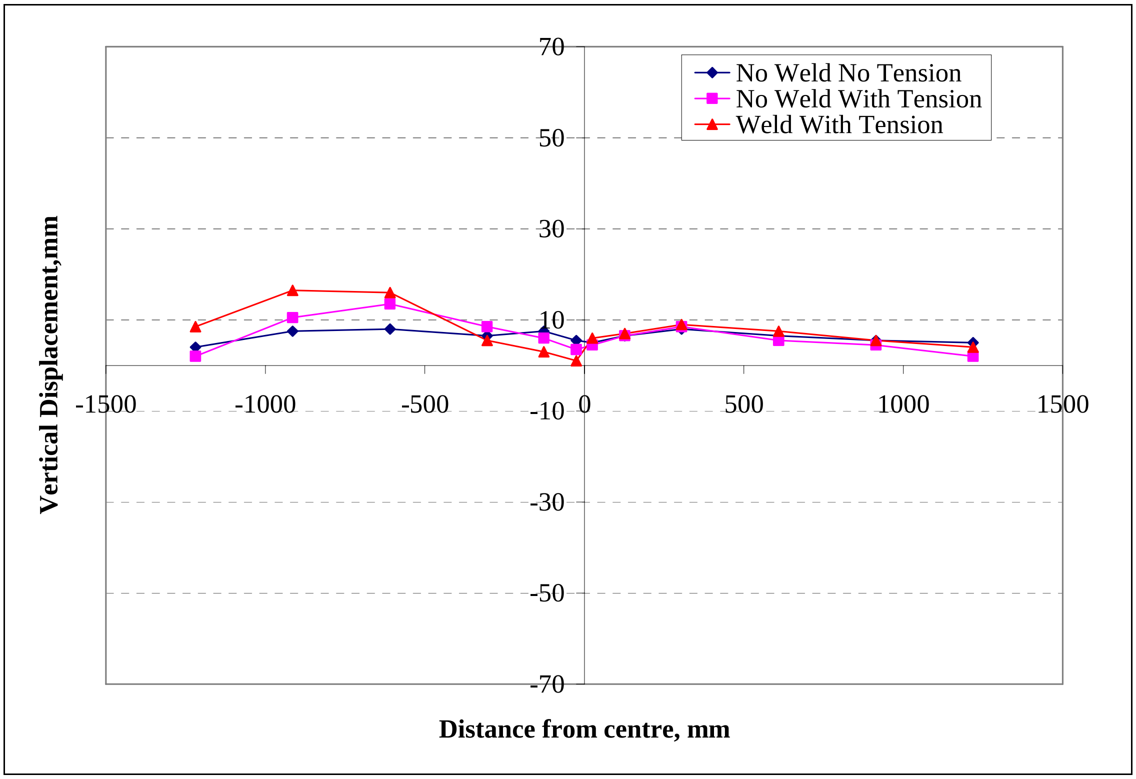


Figure 12: Transverse Section A20

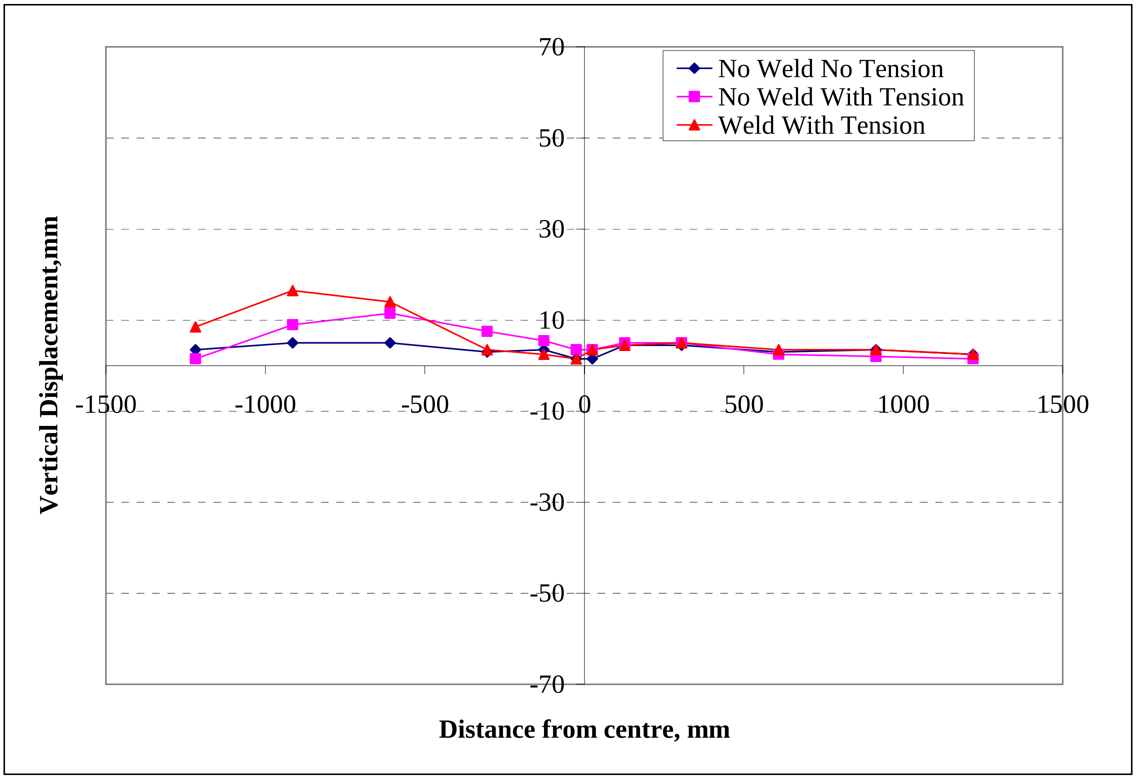


Figure 13: Transverse Section A21

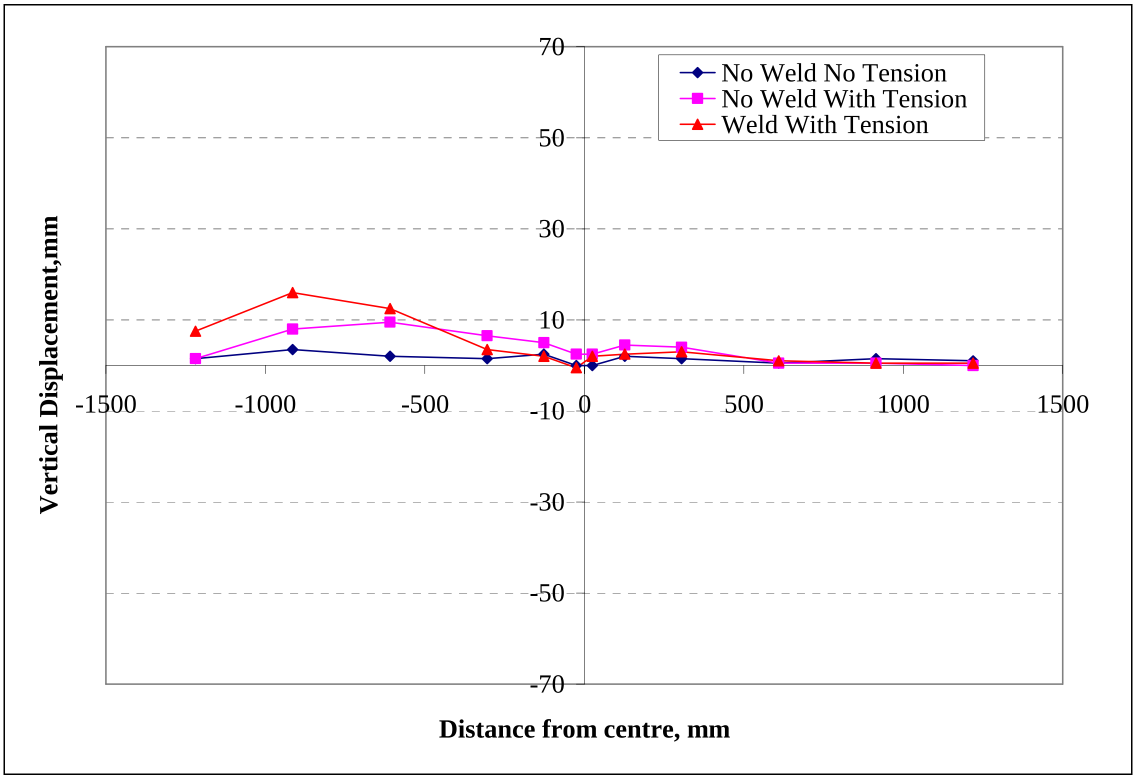


Figure 14: Transverse Section A22

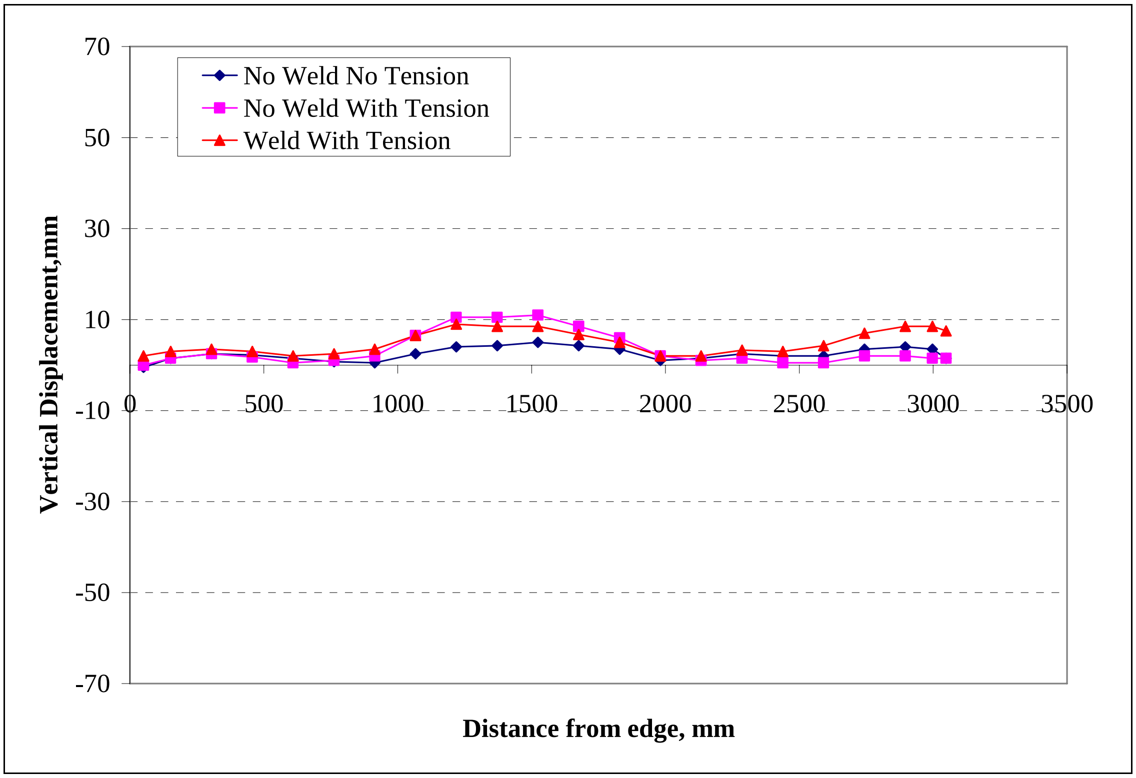


Figure 15: Longitudinal Section A

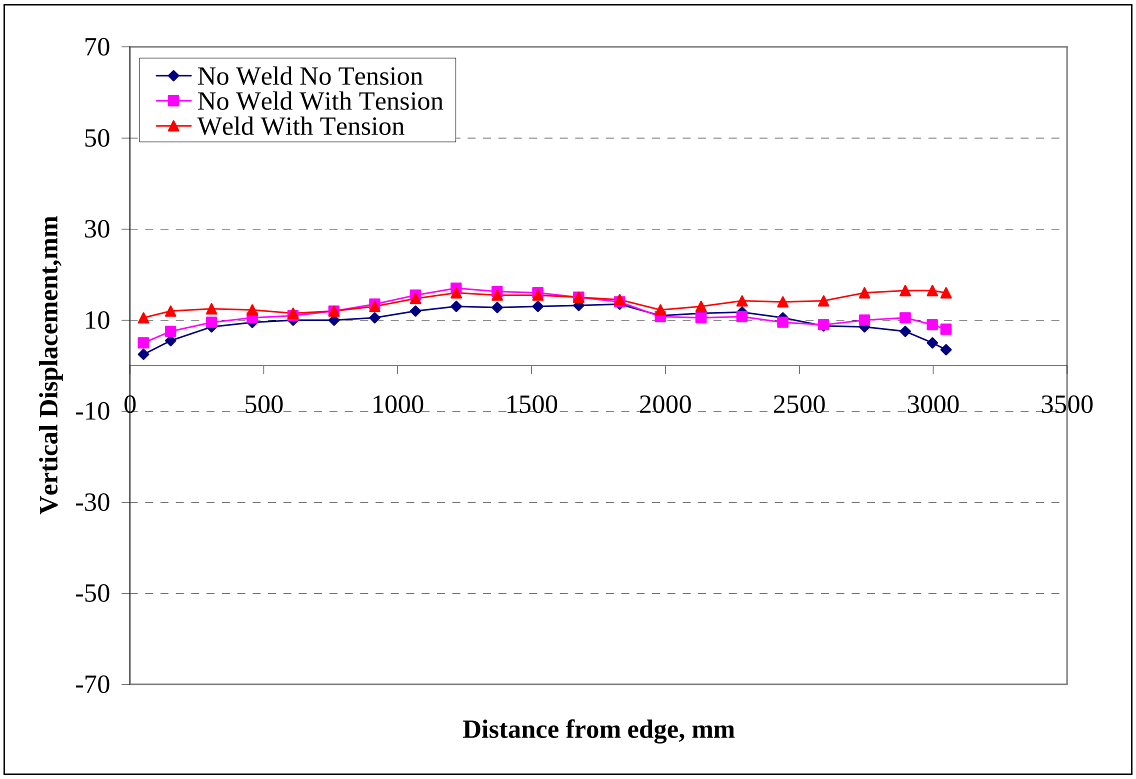


Figure 16: Longitudinal Section B

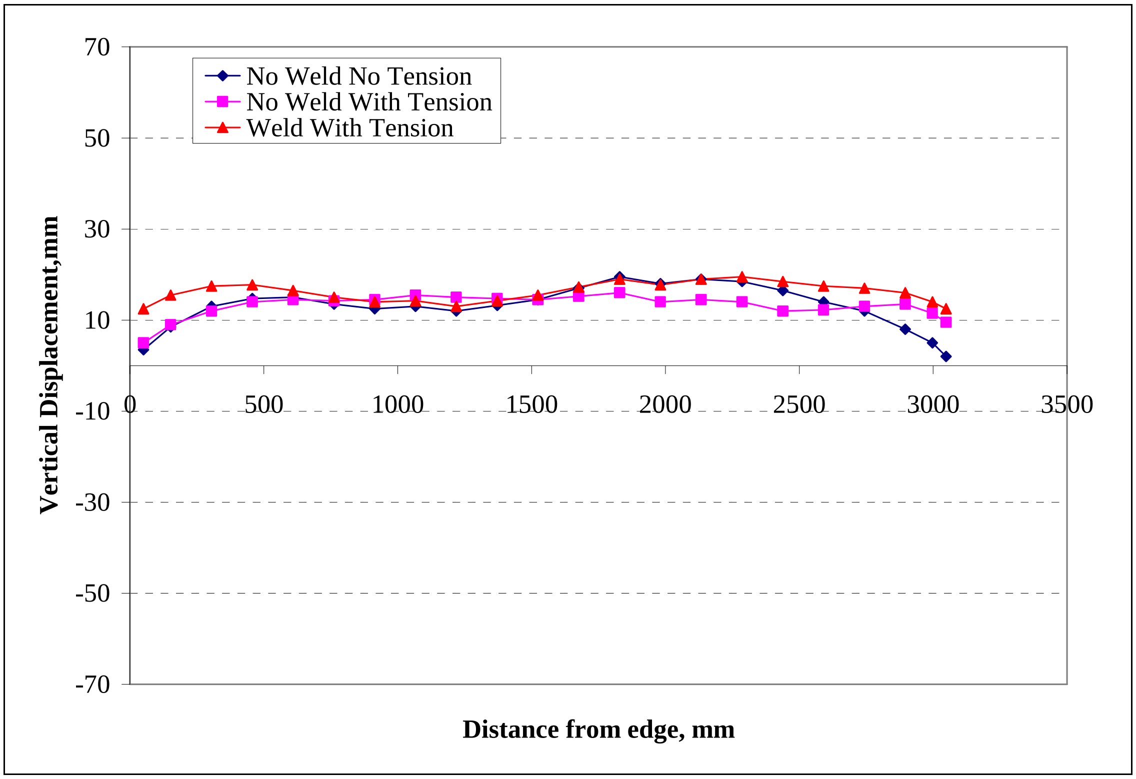


Figure 17: Longitudinal Section C

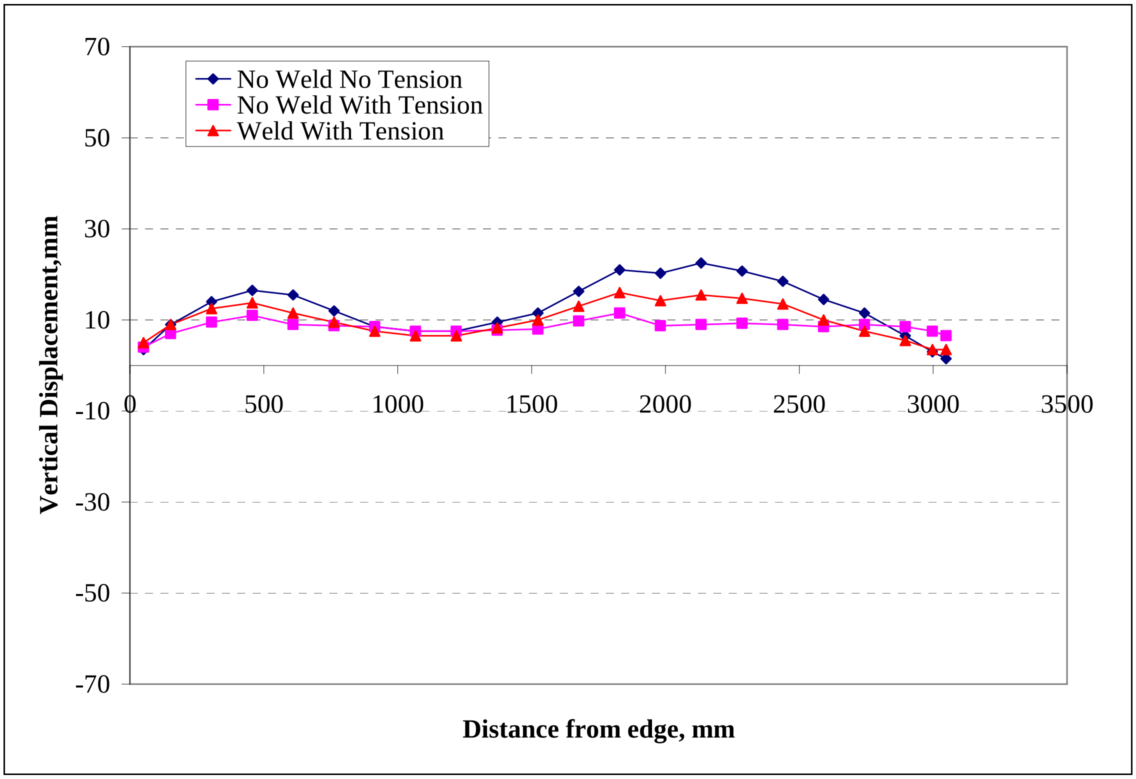


Figure 18: Longitudinal Section D

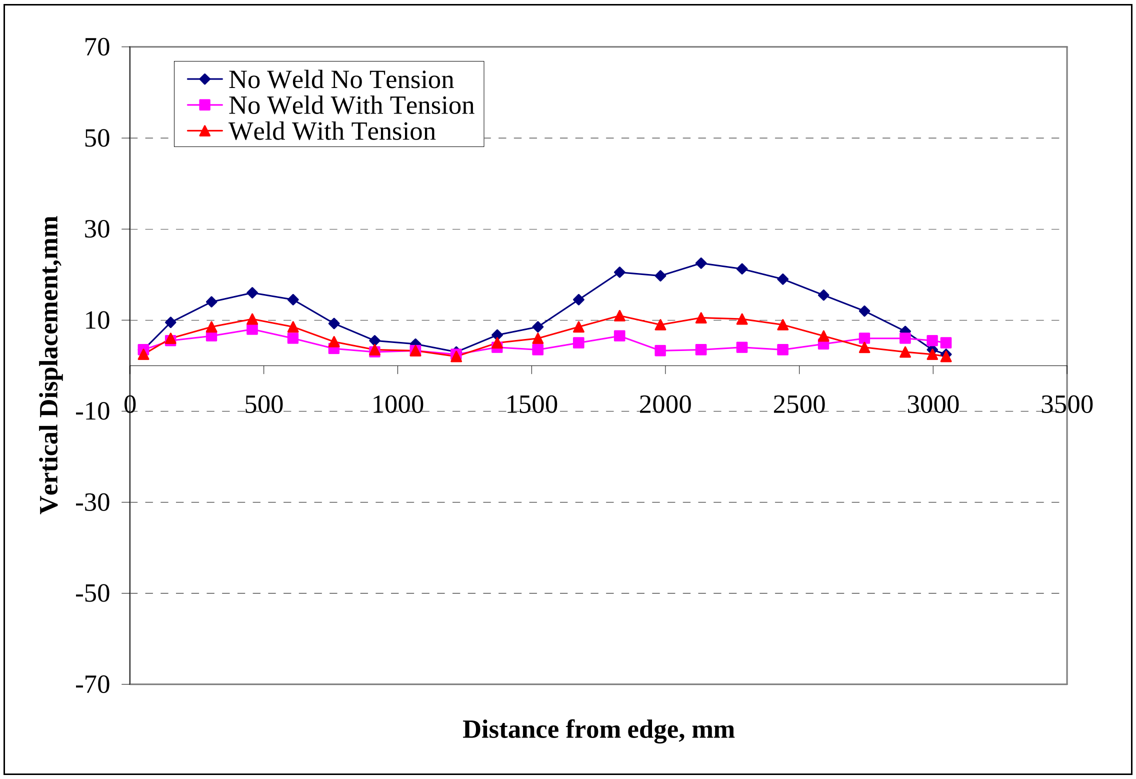


Figure 19: Longitudinal Section E

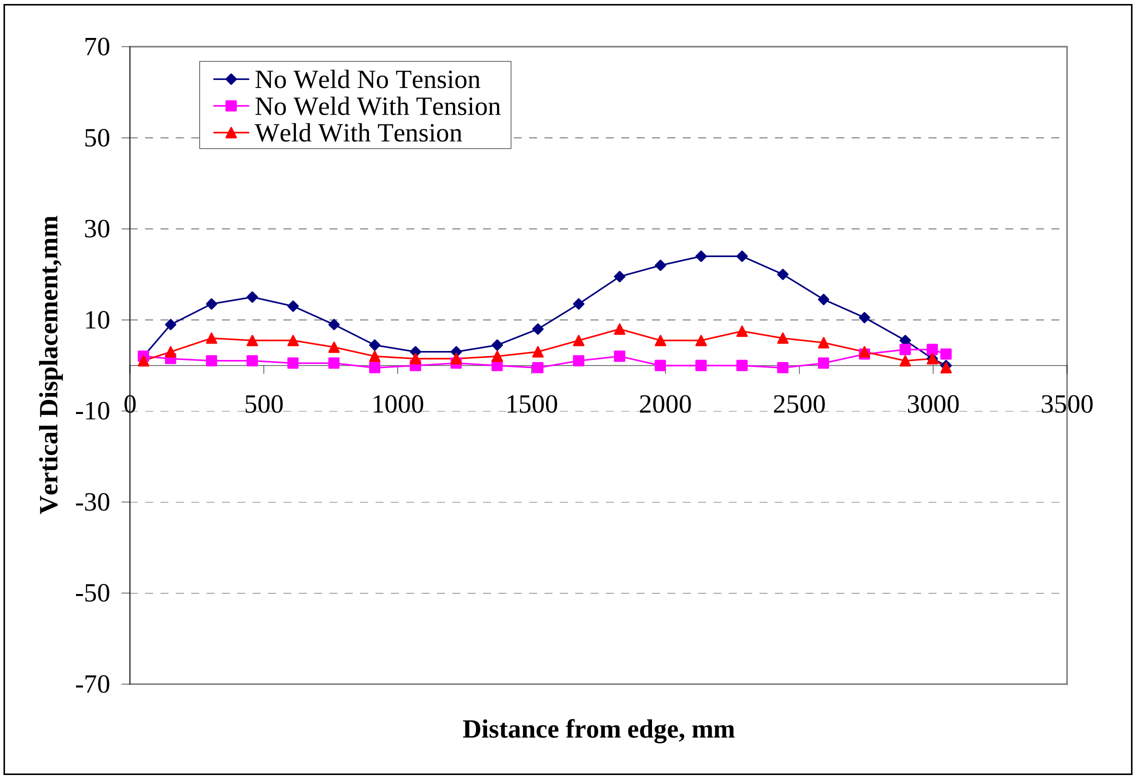


Figure 20: Longitudinal Section F

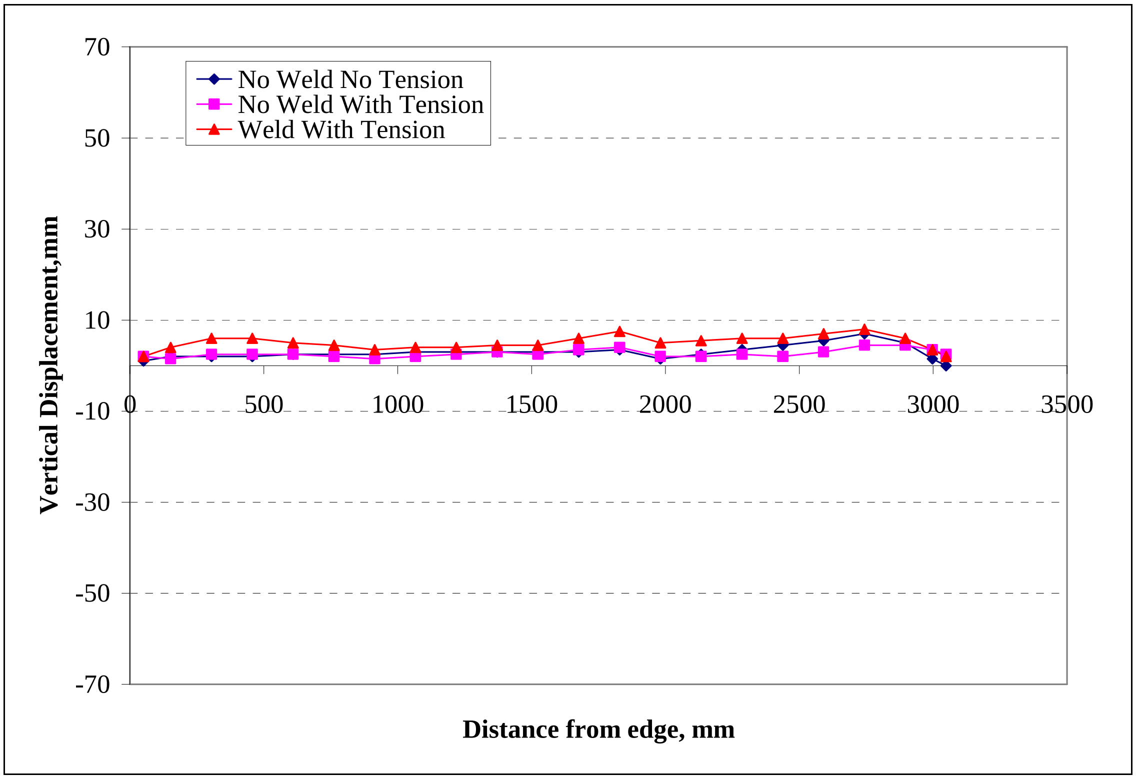


Figure 21: Longitudinal Section G

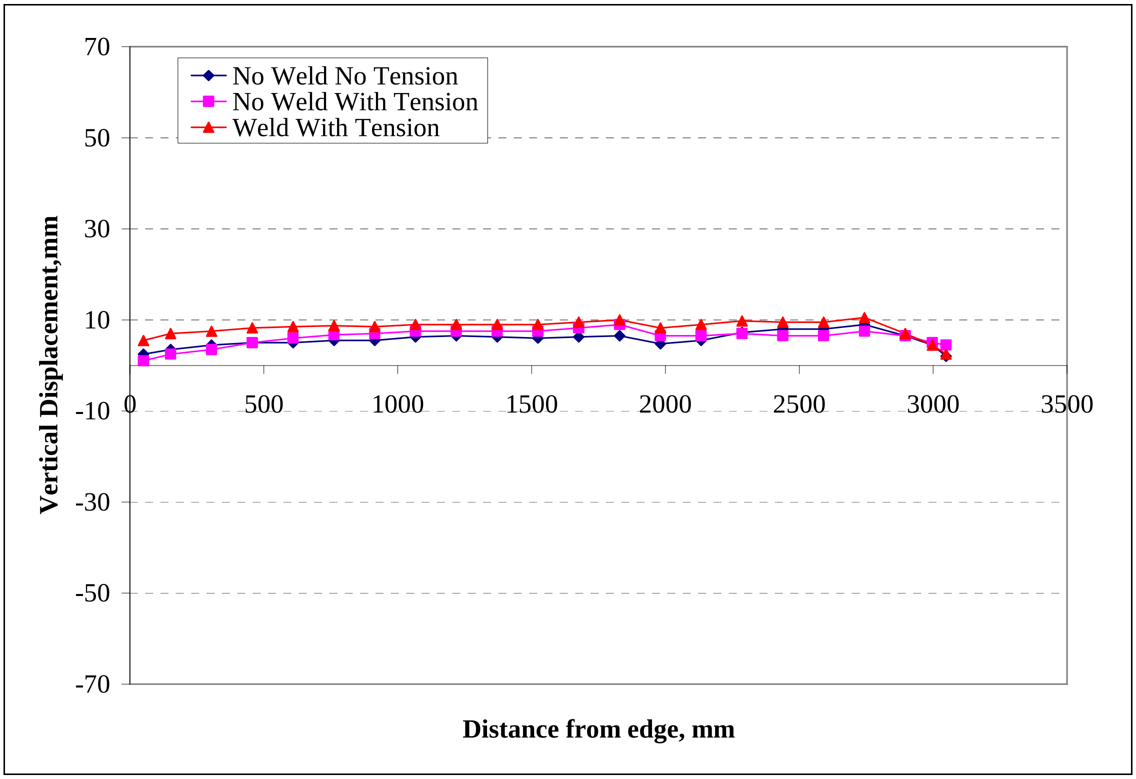


Figure 22: Longitudinal Section H

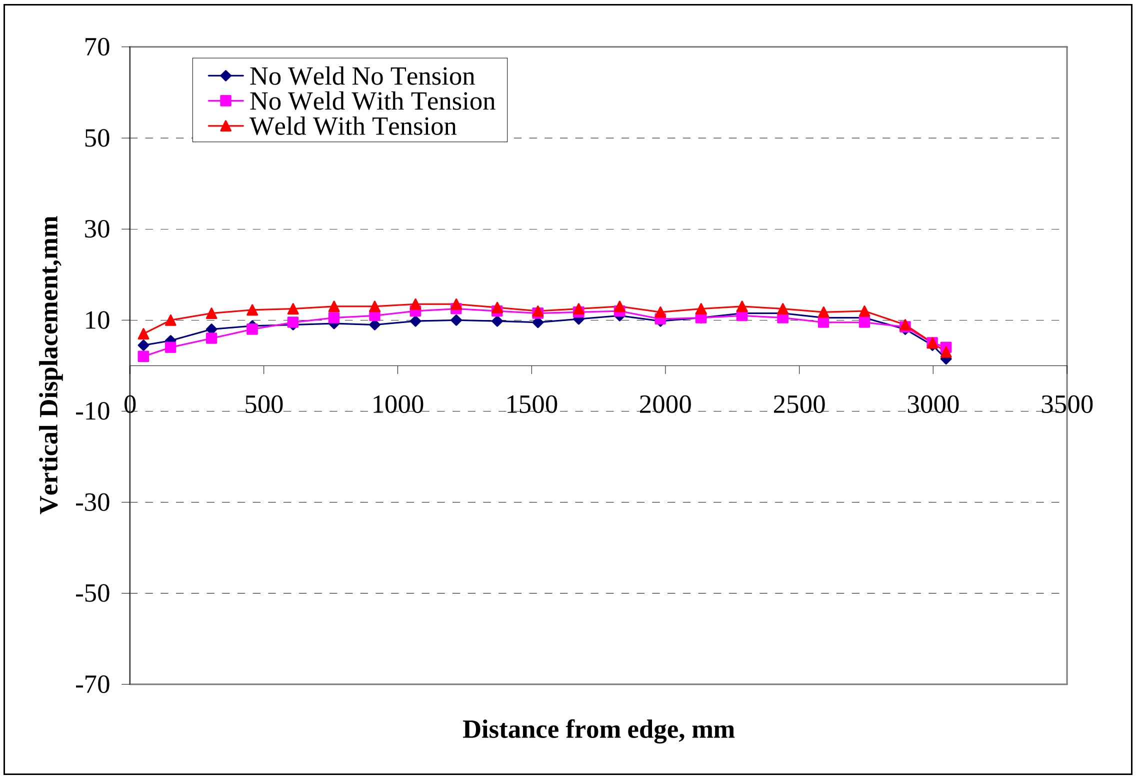


Figure 23: Longitudinal Section I

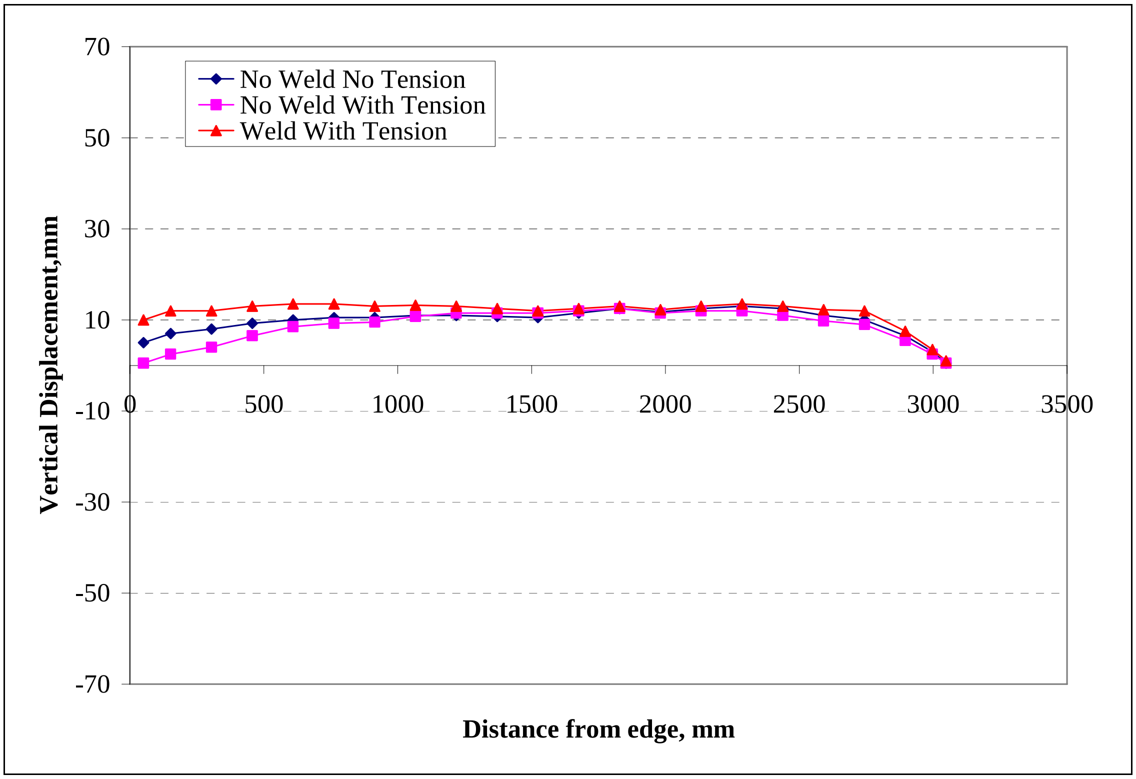


Figure 24: Longitudinal Section J

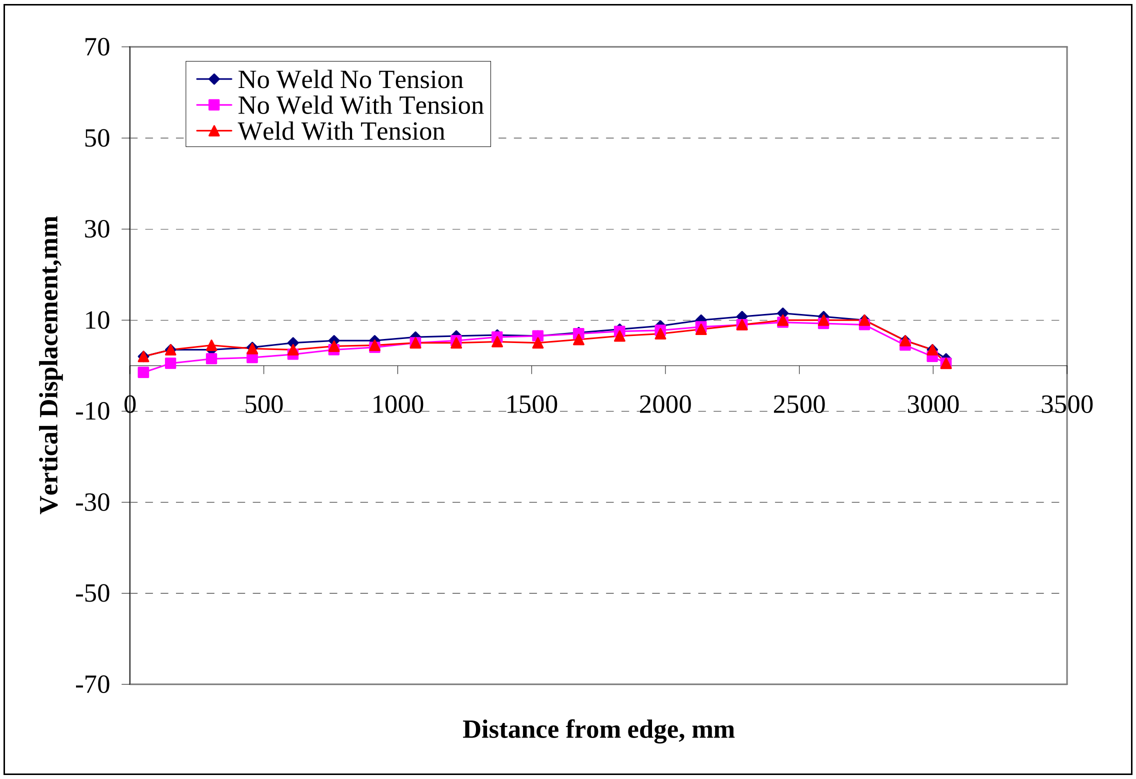


Figure 25: Longitudinal Section K

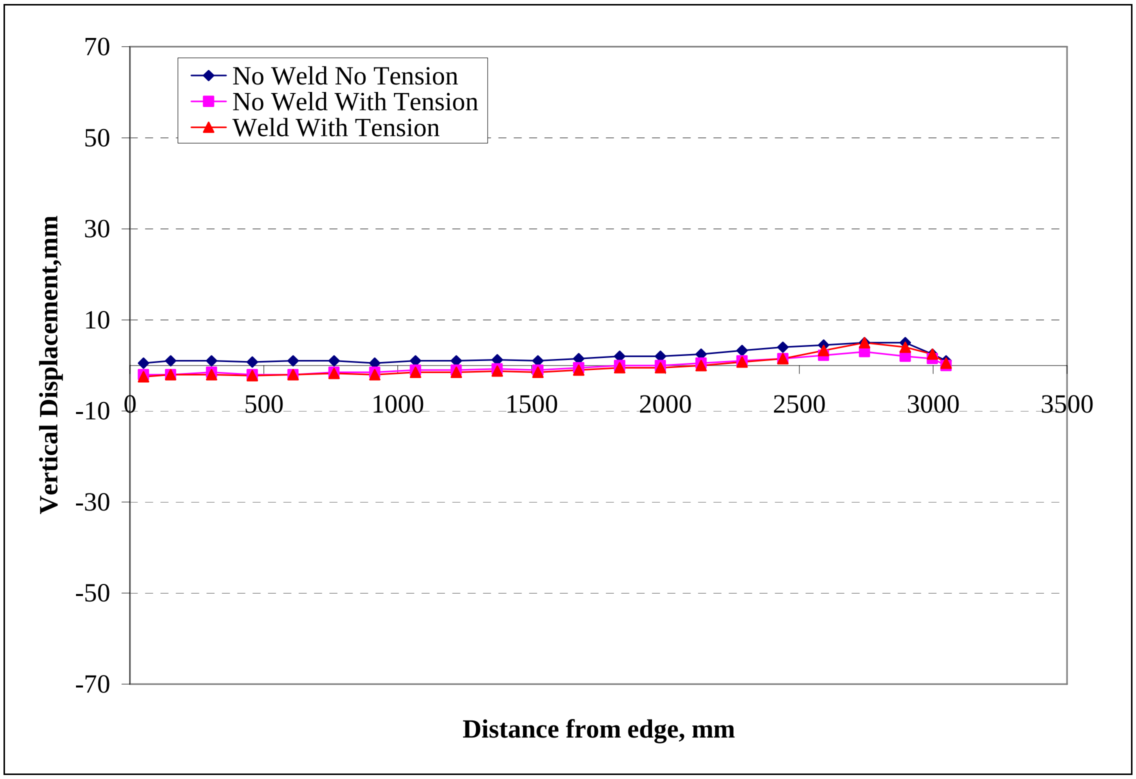


Figure 26: Longitudinal Section L

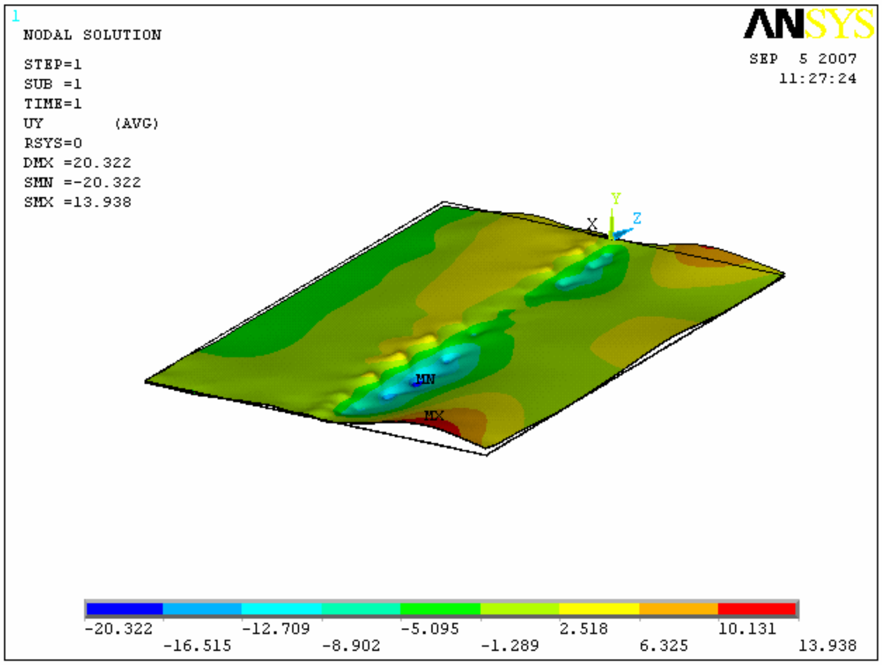


Figure 27: Net Plate Deformation (No Weld -Weld under Tension)

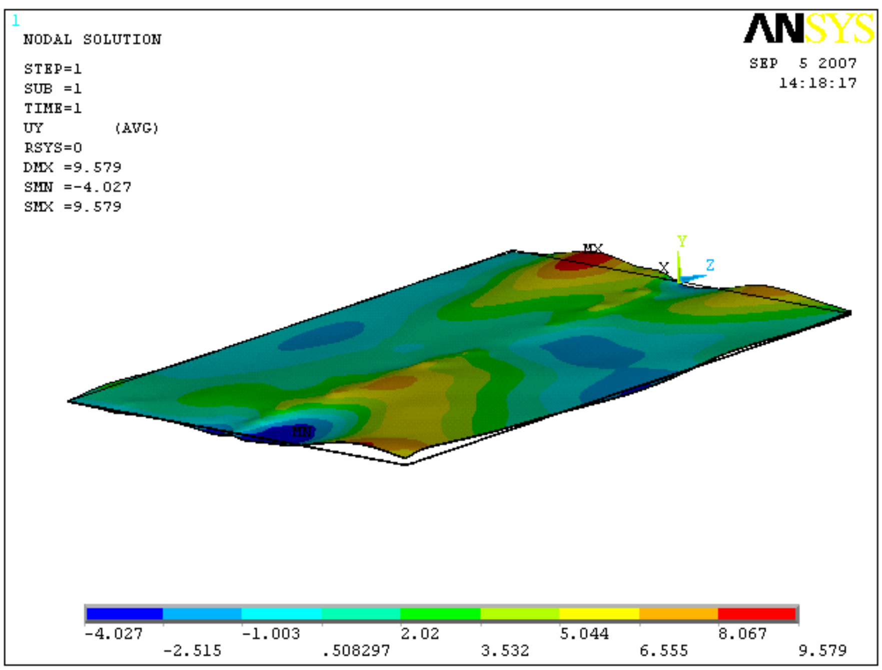


Figure 28: Net Plate Deformation after Welding (No Weld Tension-Weld under Tension)

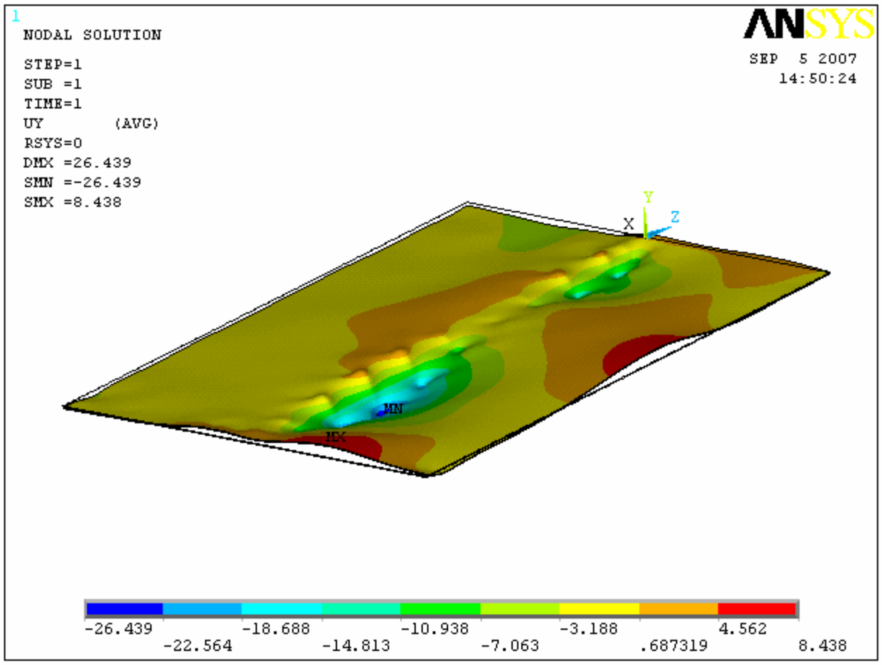


Figure 29: Net Plate Deformation after Welding (No Weld No Tension-No Weld with Tension)

PLATE 3 – SIDE 2

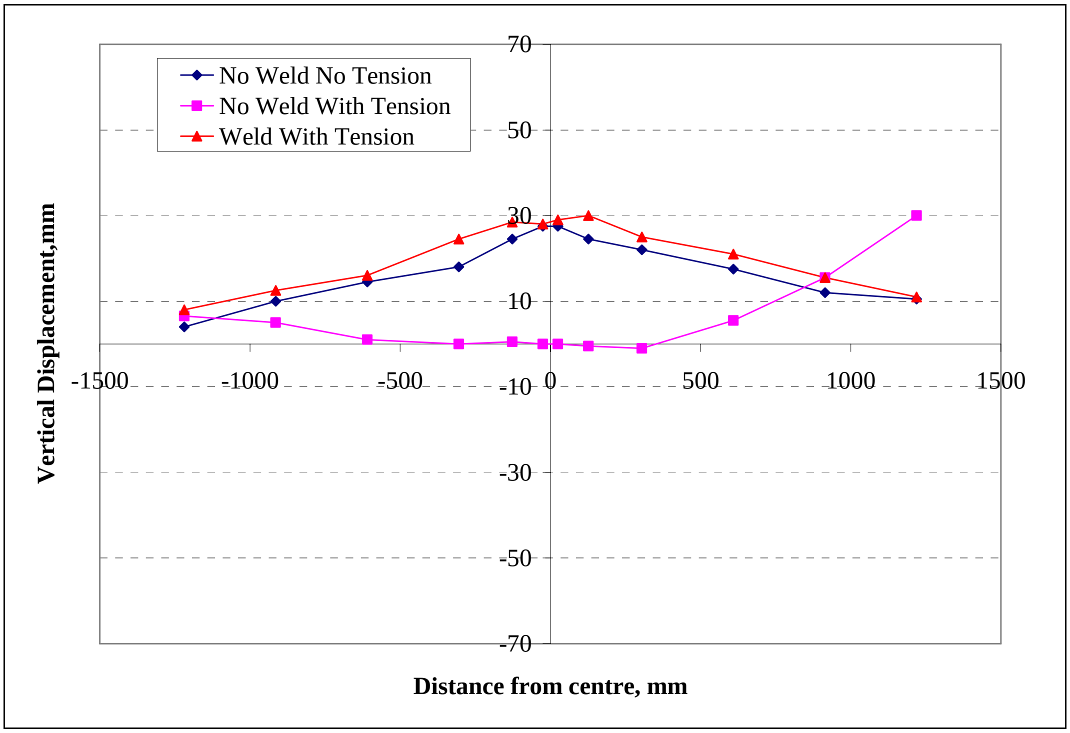


Figure 1: Transverse Section A1

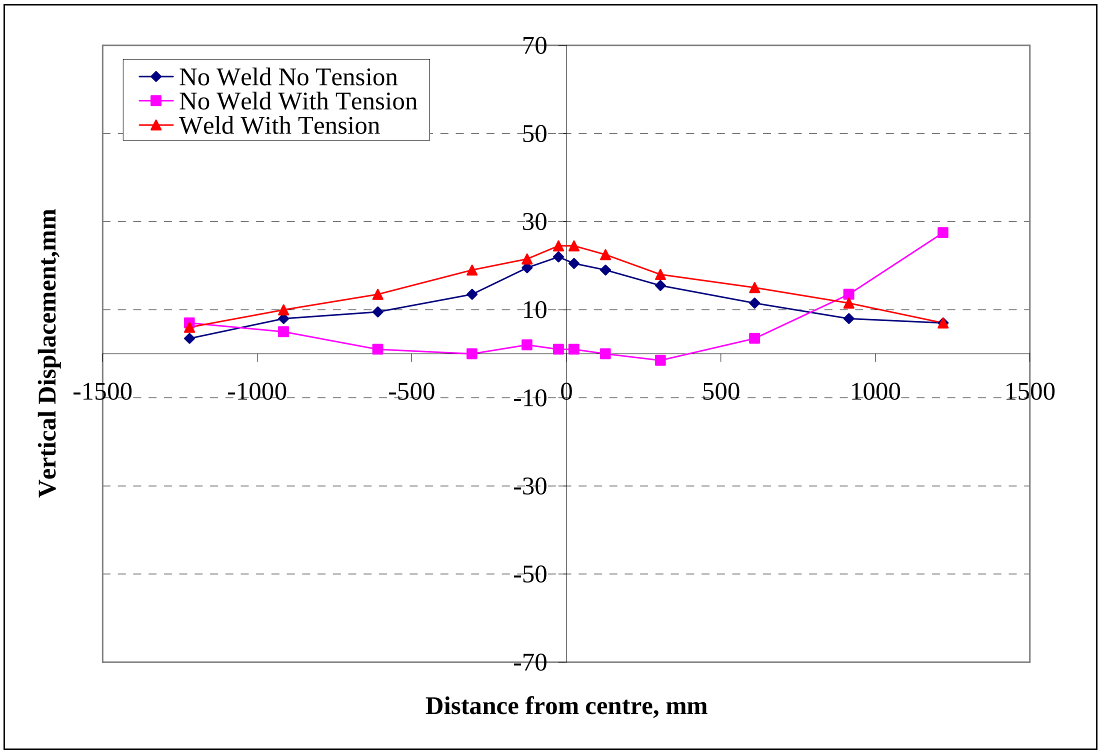


Figure 2: Transverse Section A2

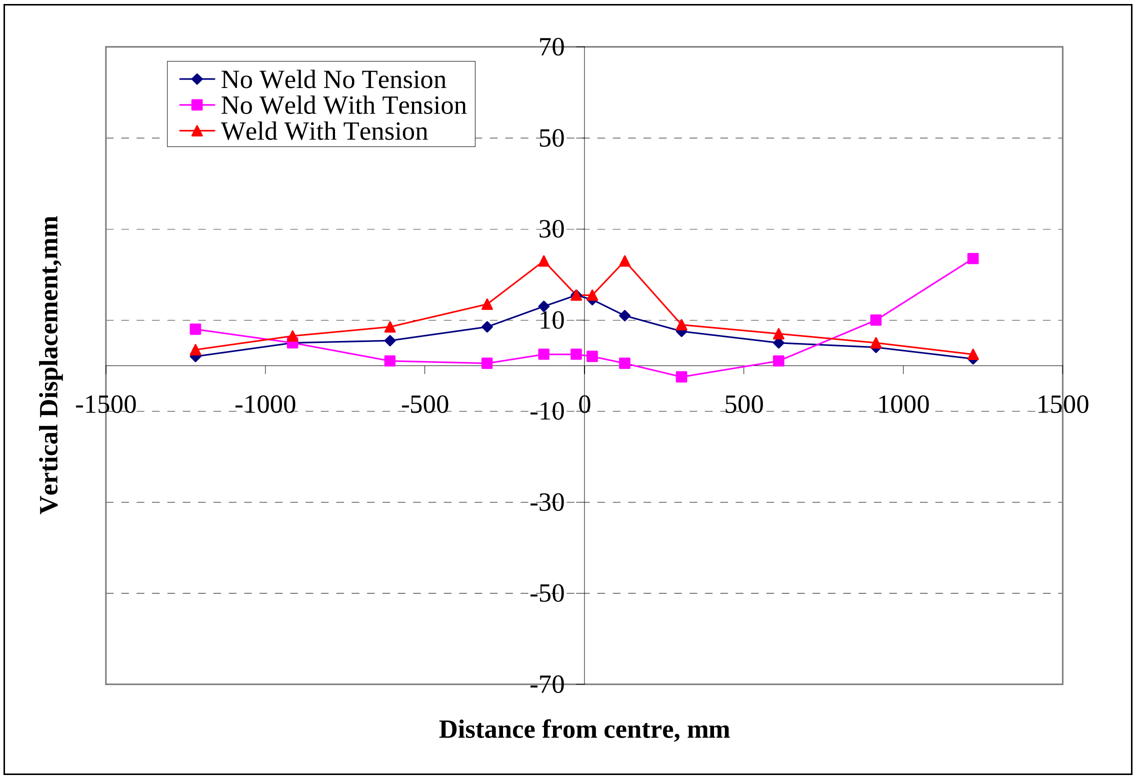


Figure 3: Transverse Section A3

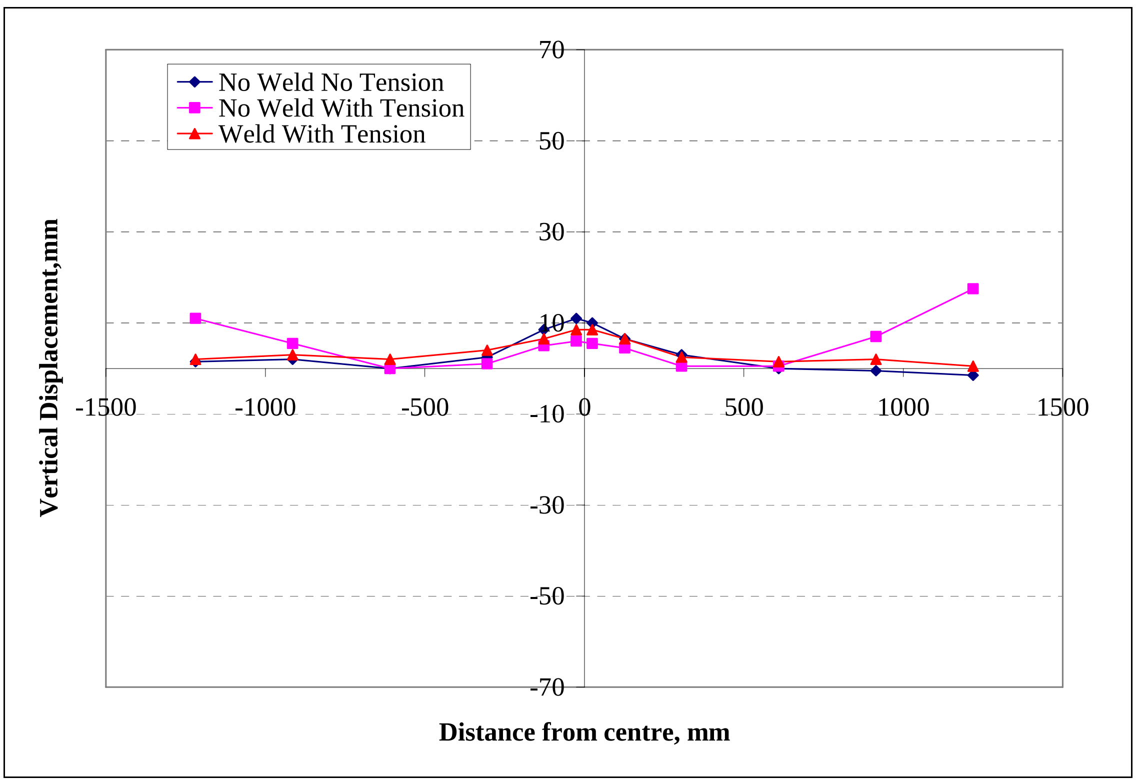


Figure 4: Transverse Section A5

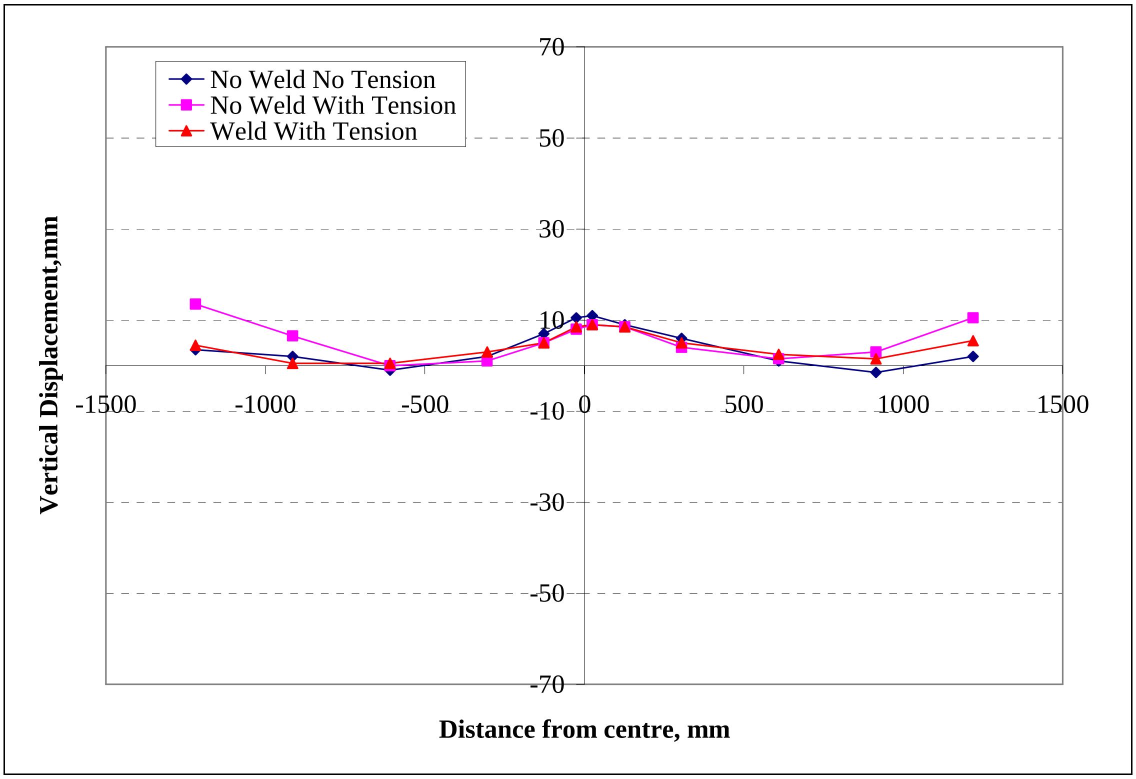


Figure 5: Transverse Section A7

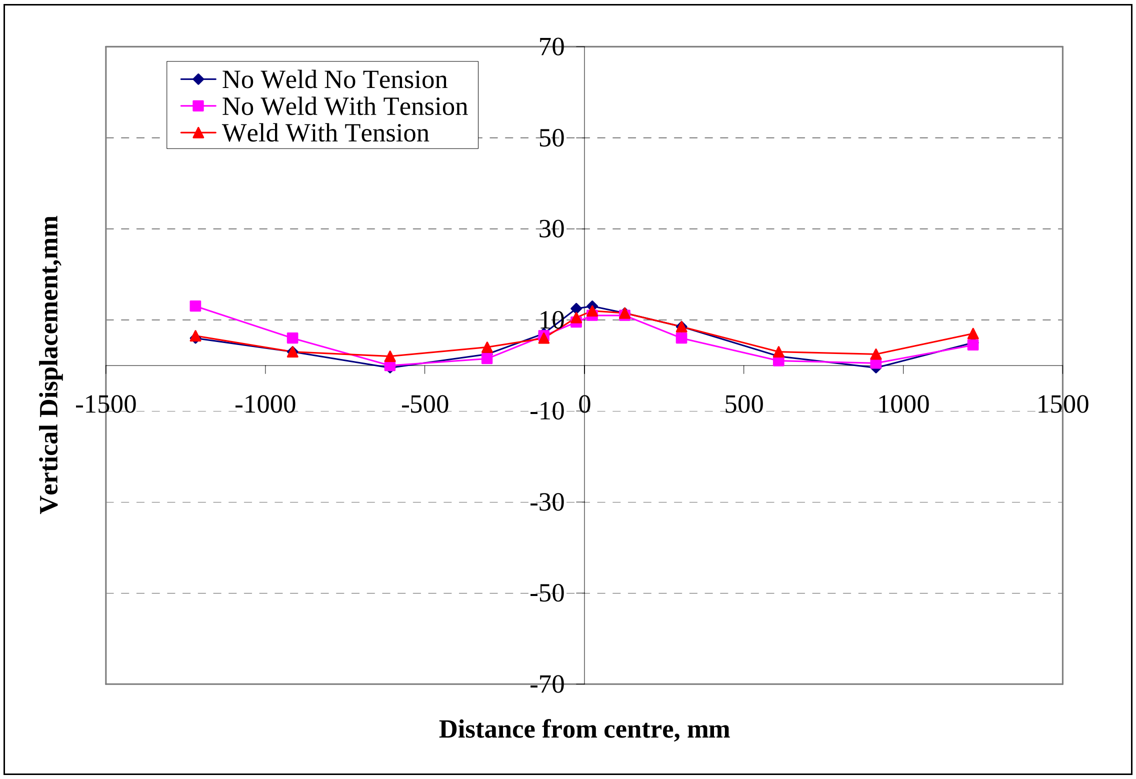


Figure 6: Transverse Section A9

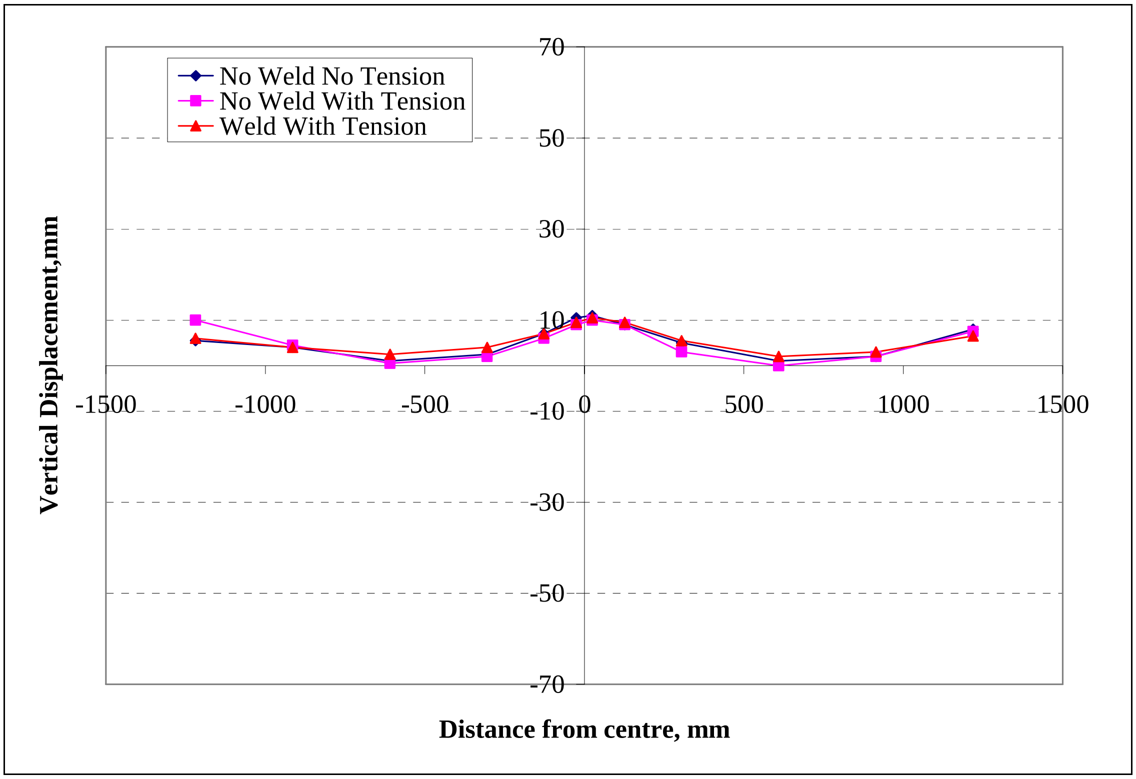


Figure 7: Transverse Section A11

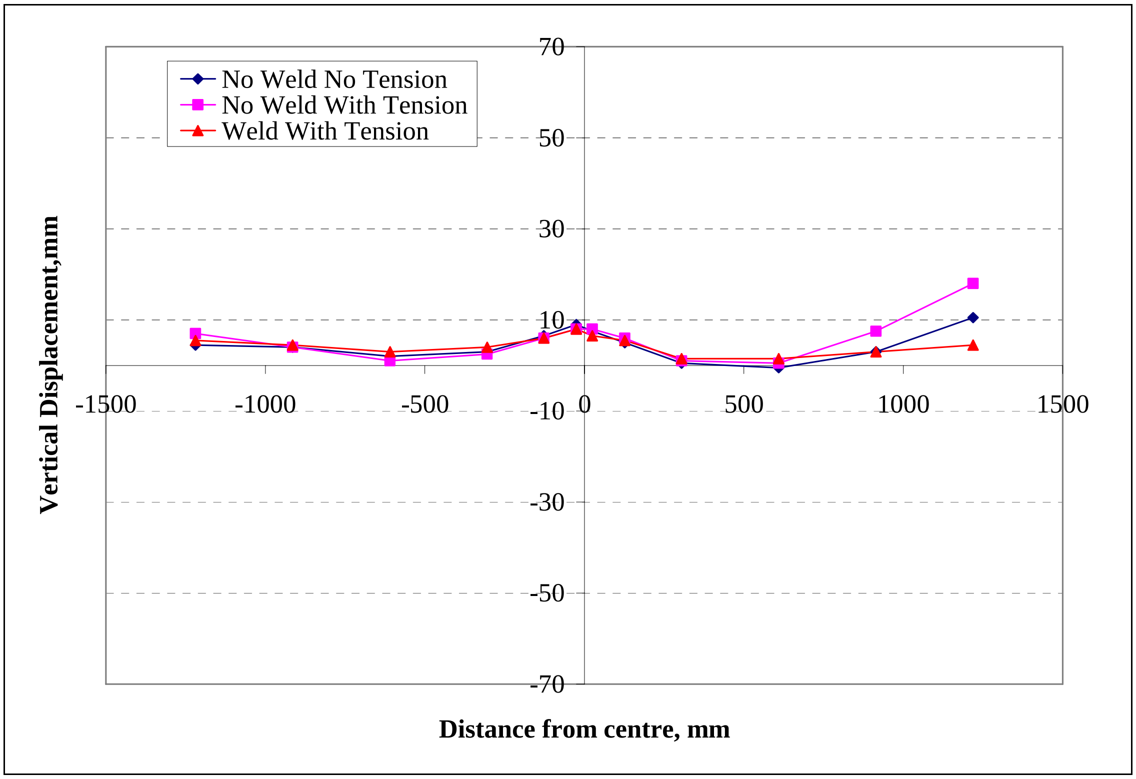


Figure 8: Transverse Section A13

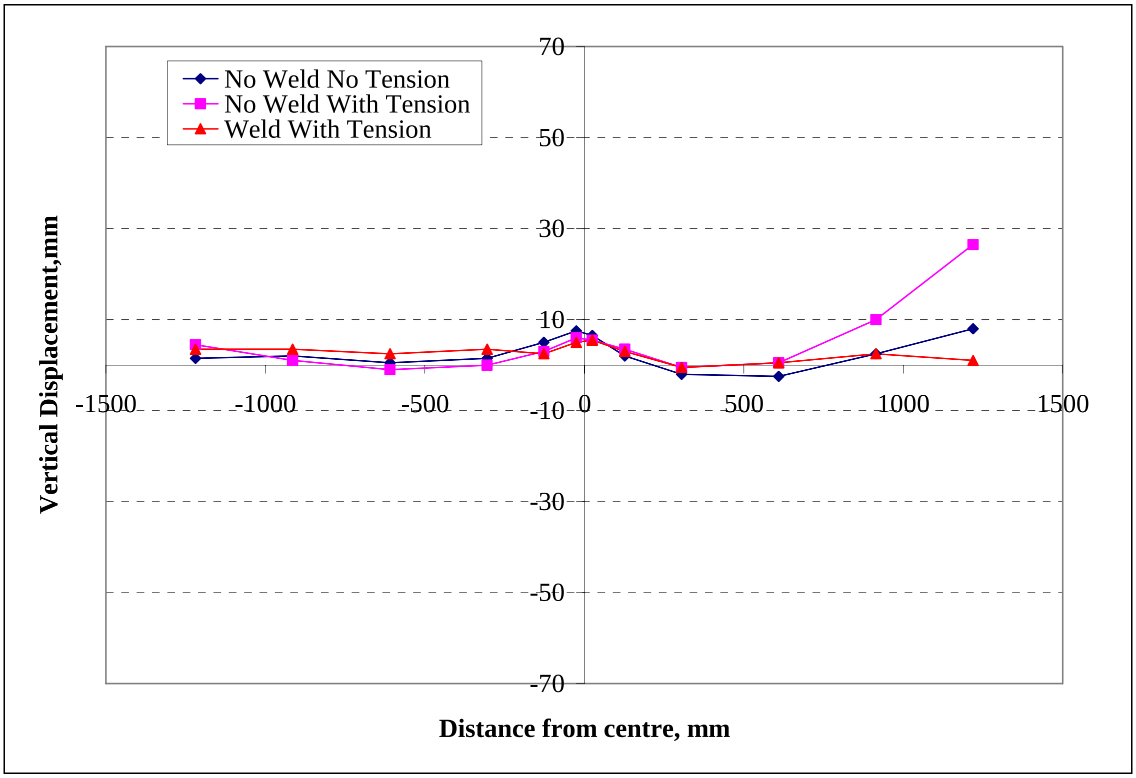


Figure 9: Transverse Section A15

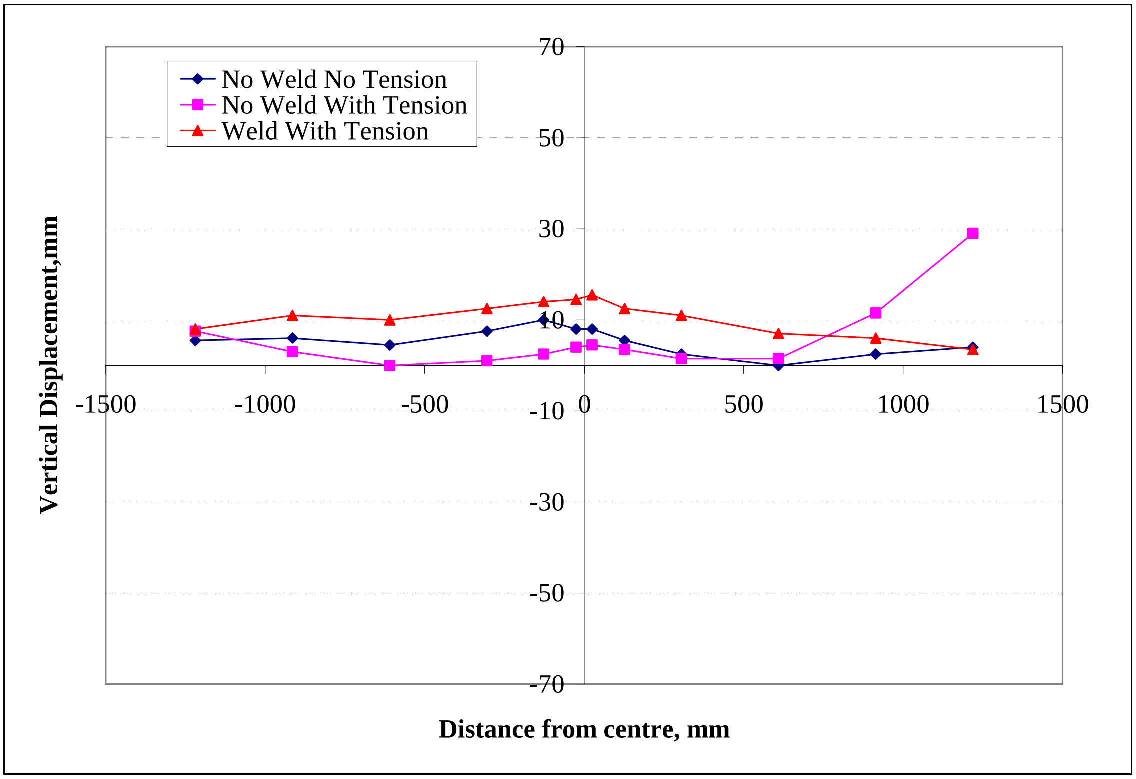


Figure 10: Transverse Section A17

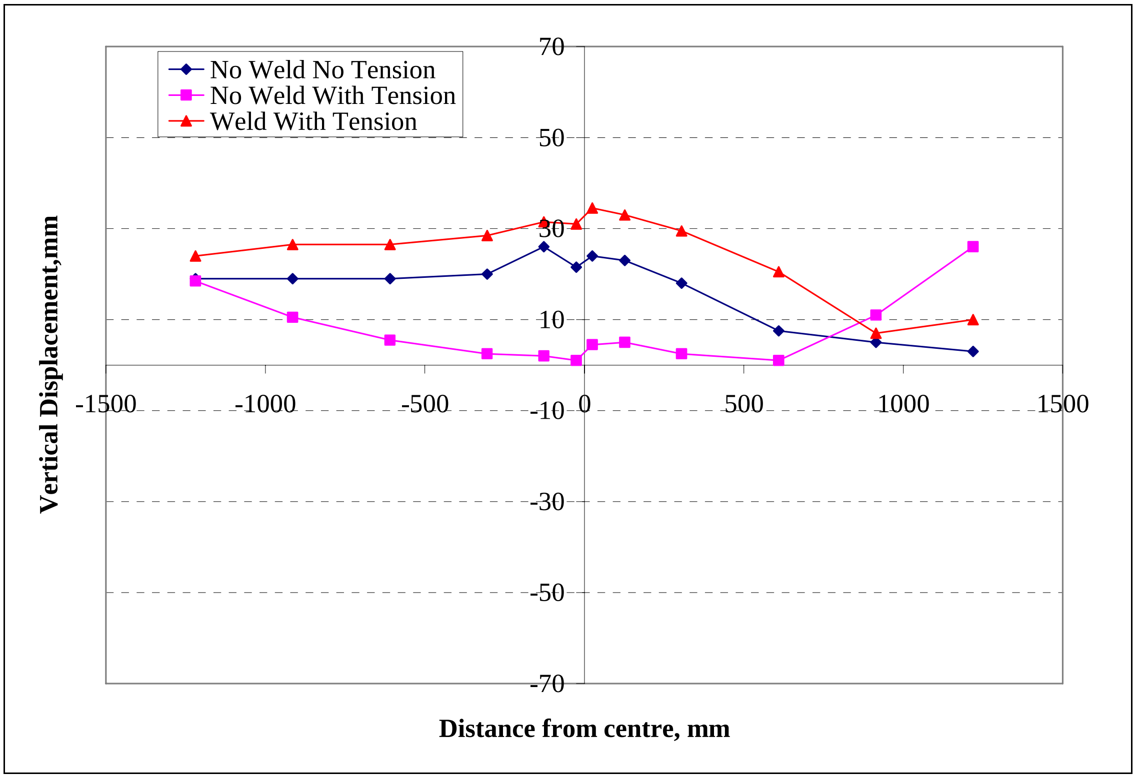


Figure 11: Transverse Section A19

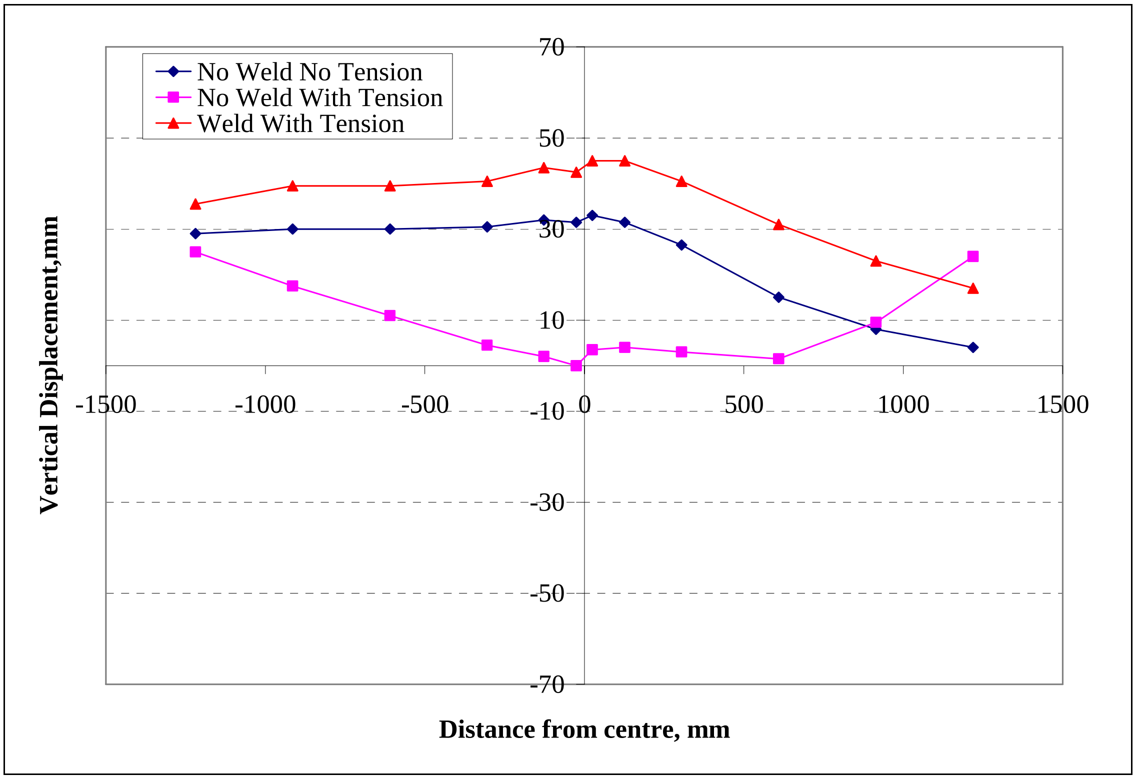


Figure 12: Transverse Section A20

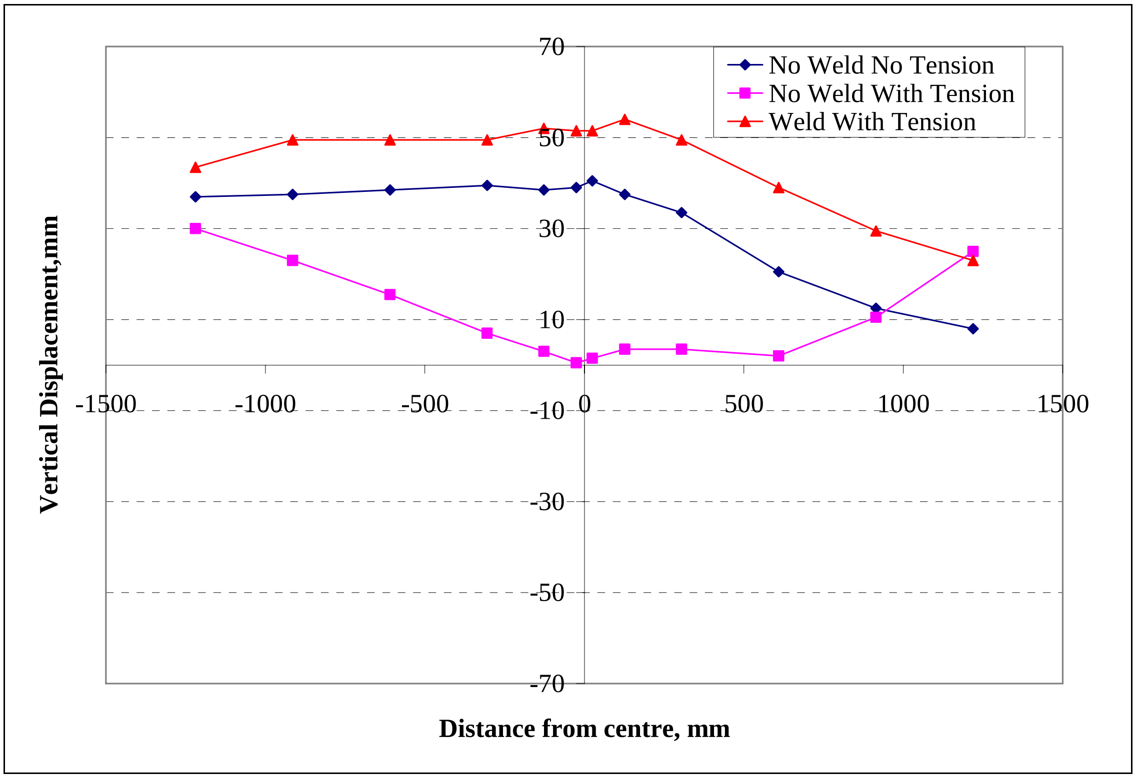


Figure 13: Transverse Section A21

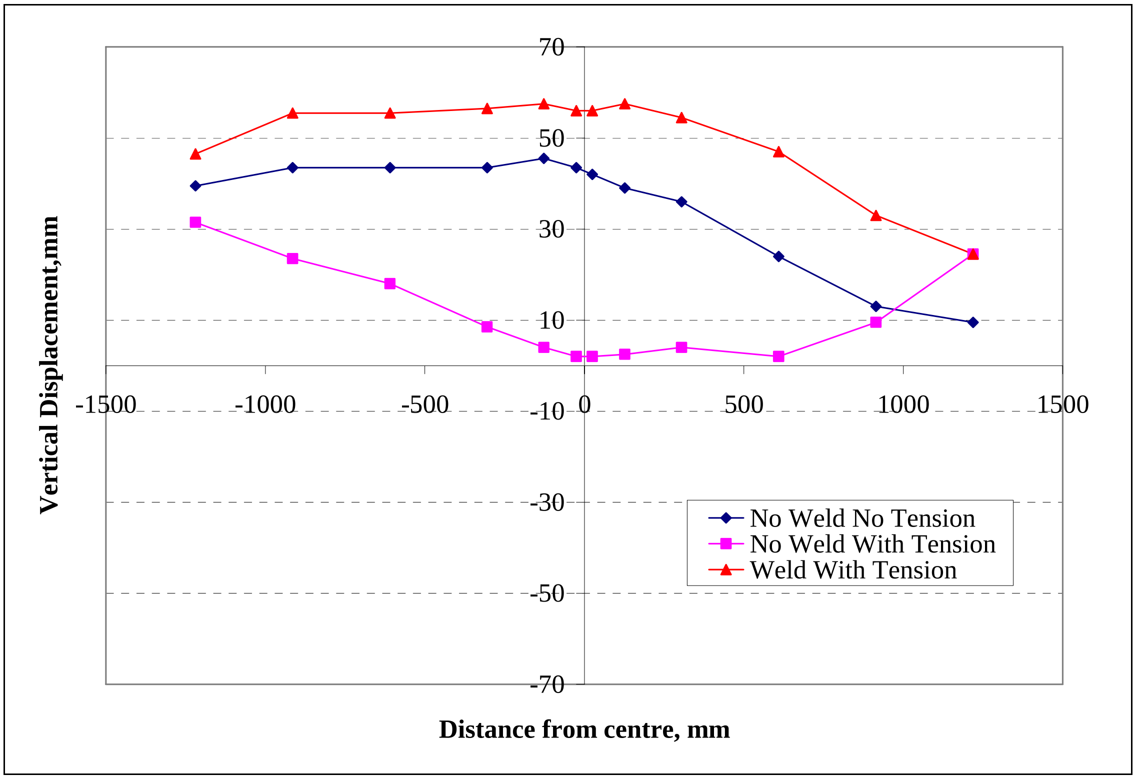


Figure 14: Transverse Section A22

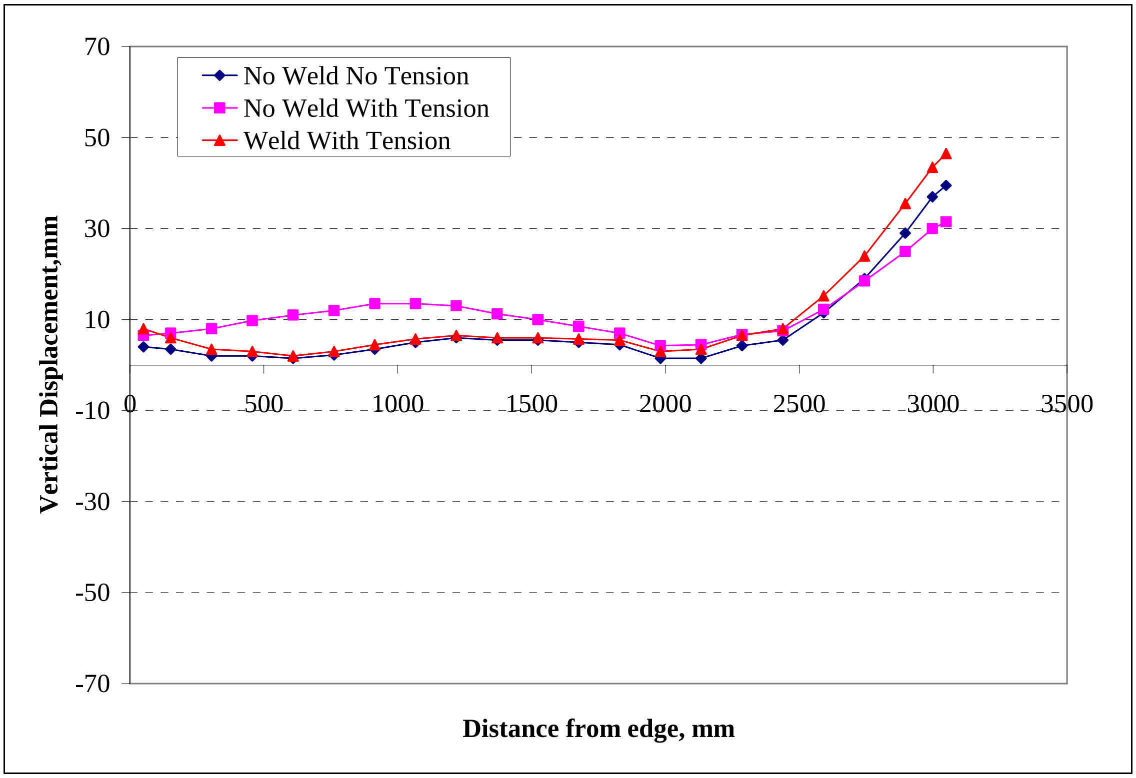


Figure 15: Longitudinal Section A

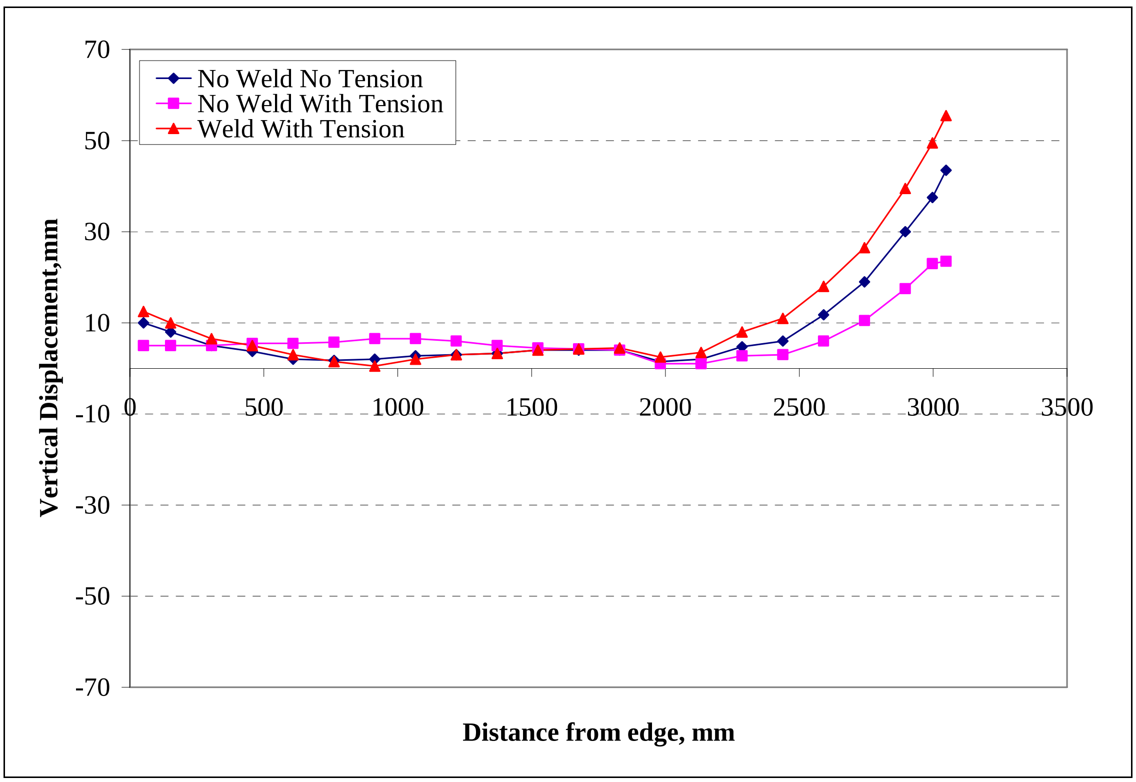


Figure 16: Longitudinal Section B

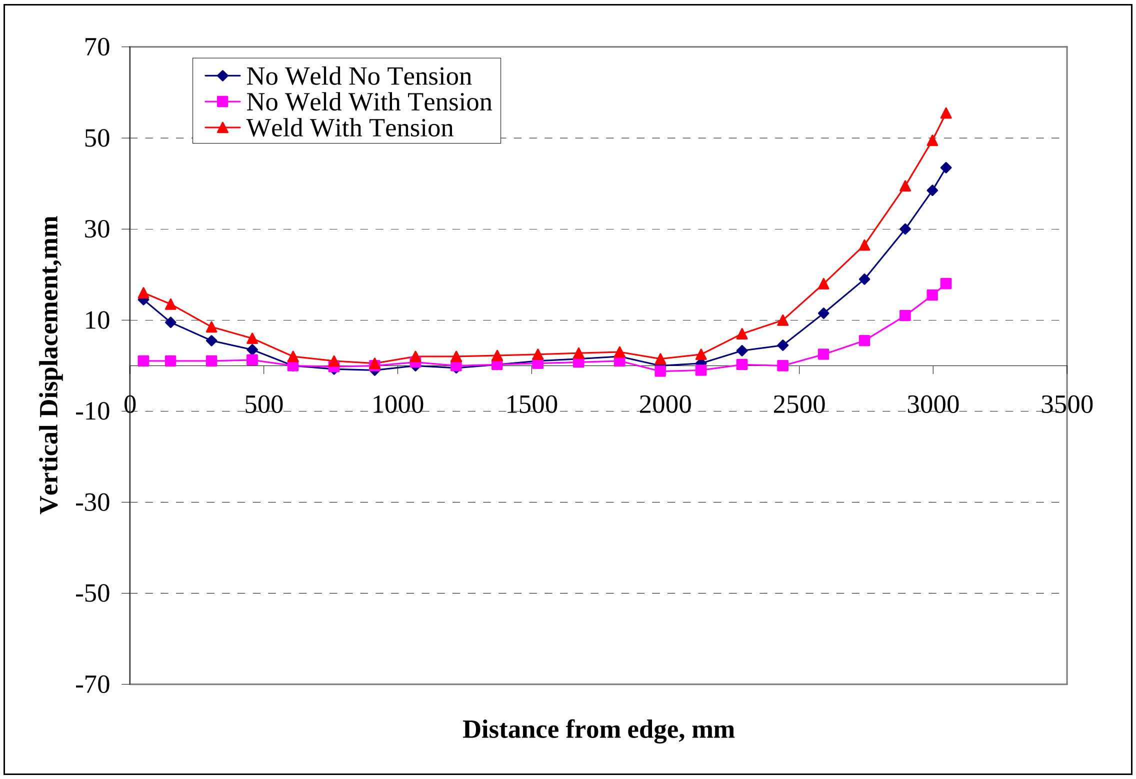


Figure 17: Longitudinal Section C

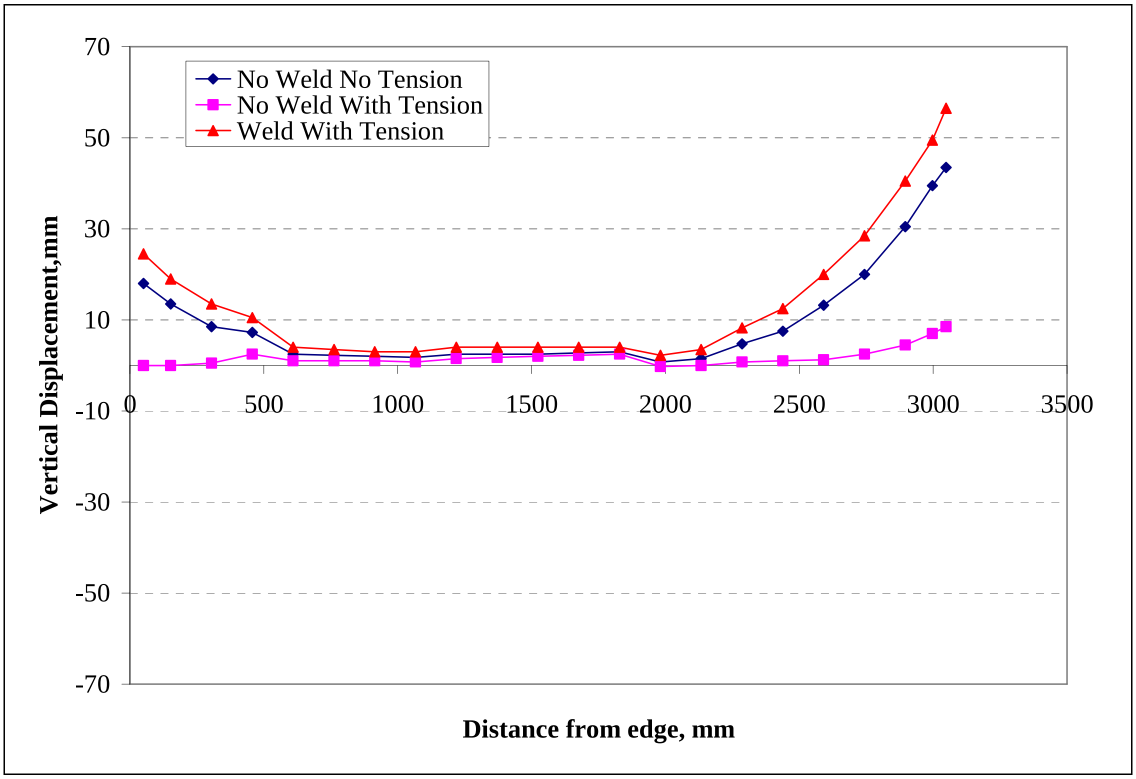


Figure 18: Longitudinal Section D

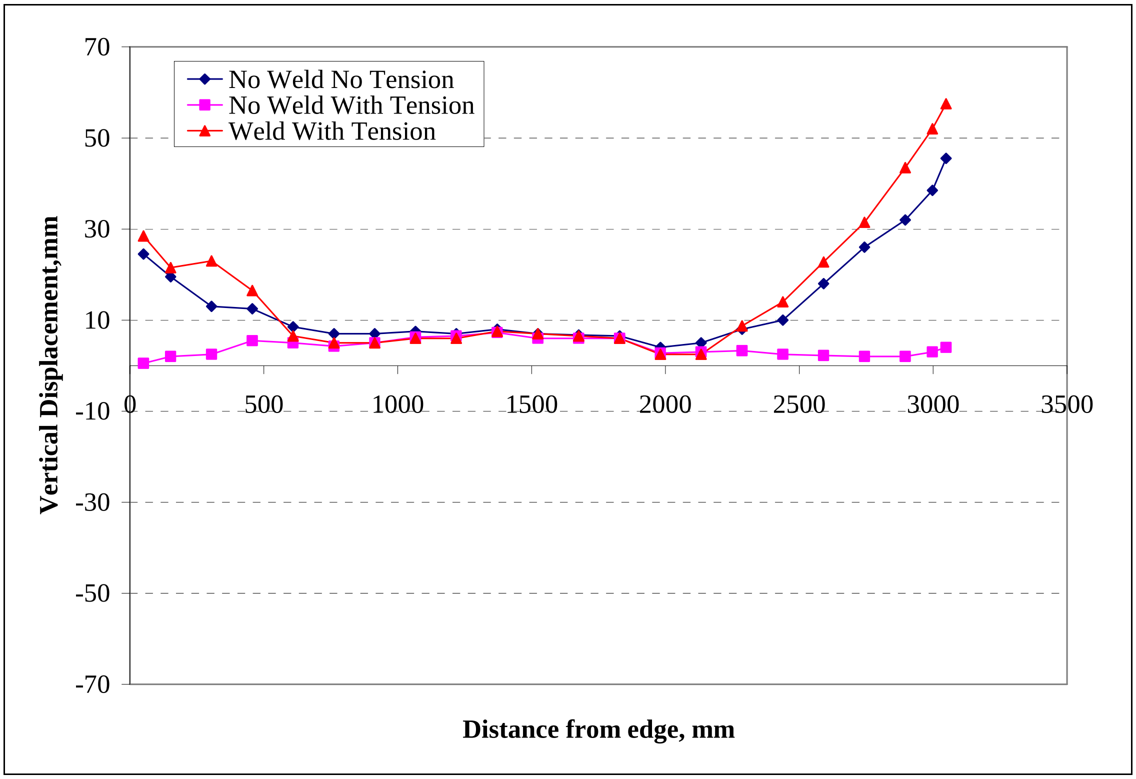


Figure 19: Longitudinal Section E

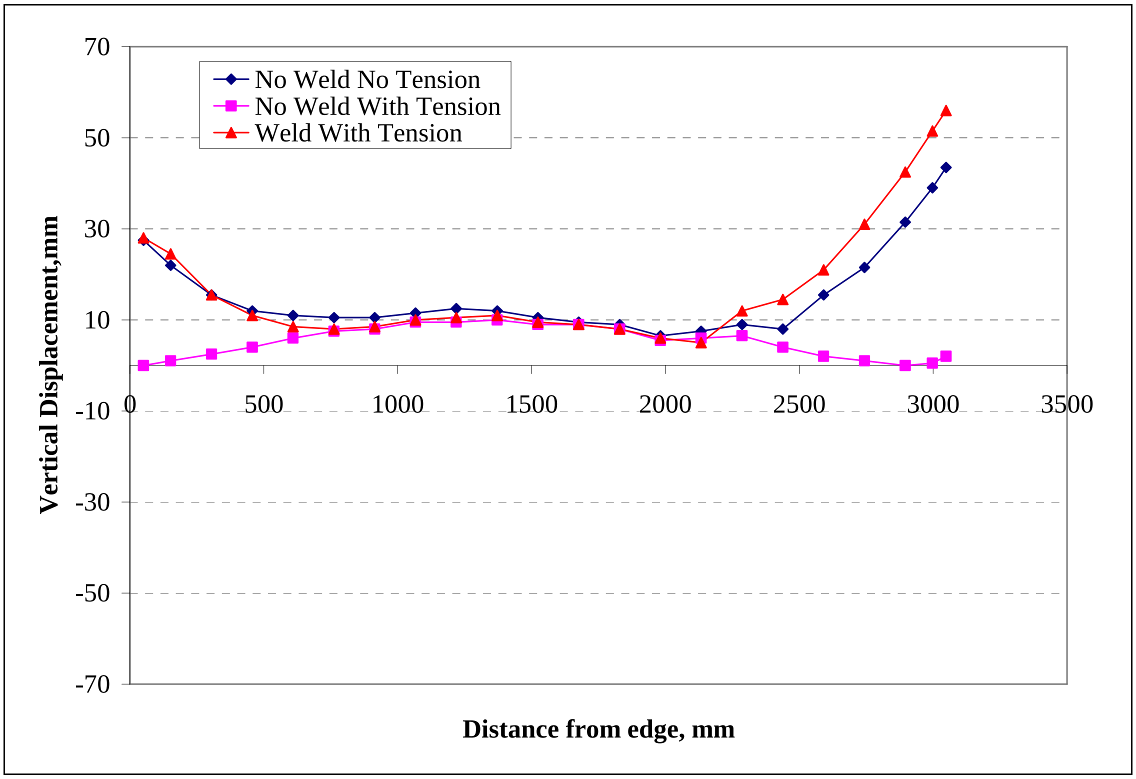


Figure 20: Longitudinal Section F

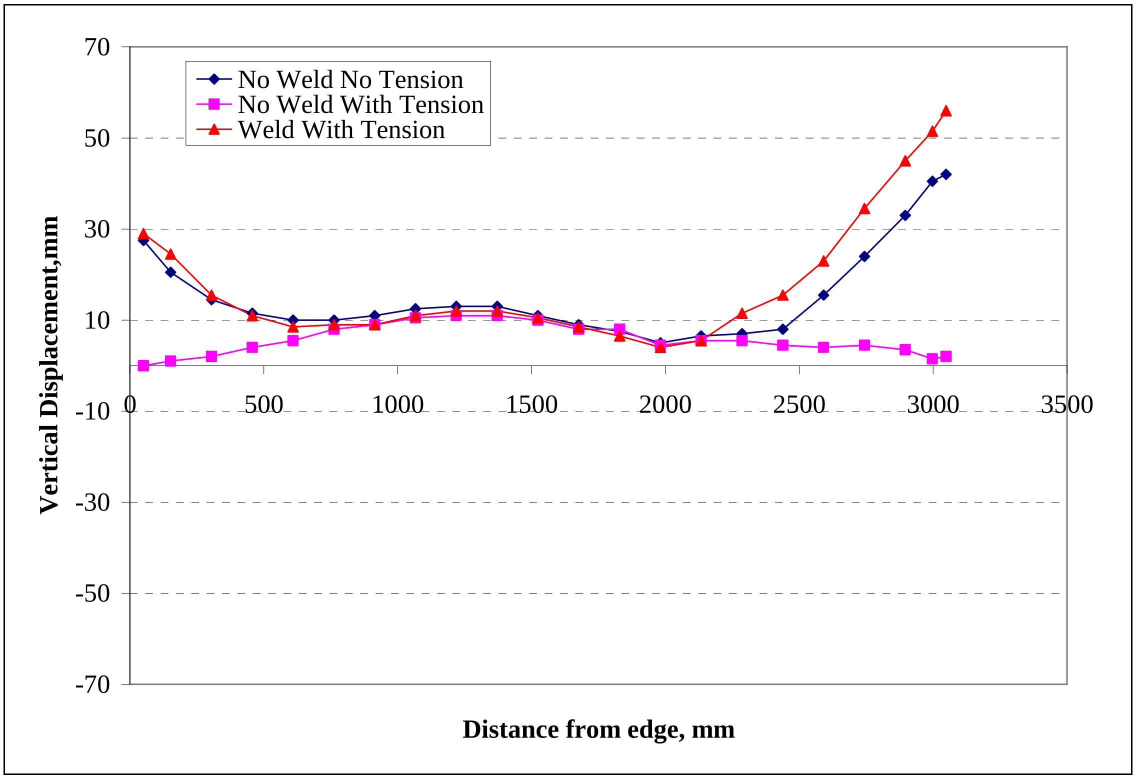


Figure 21: Longitudinal Section G

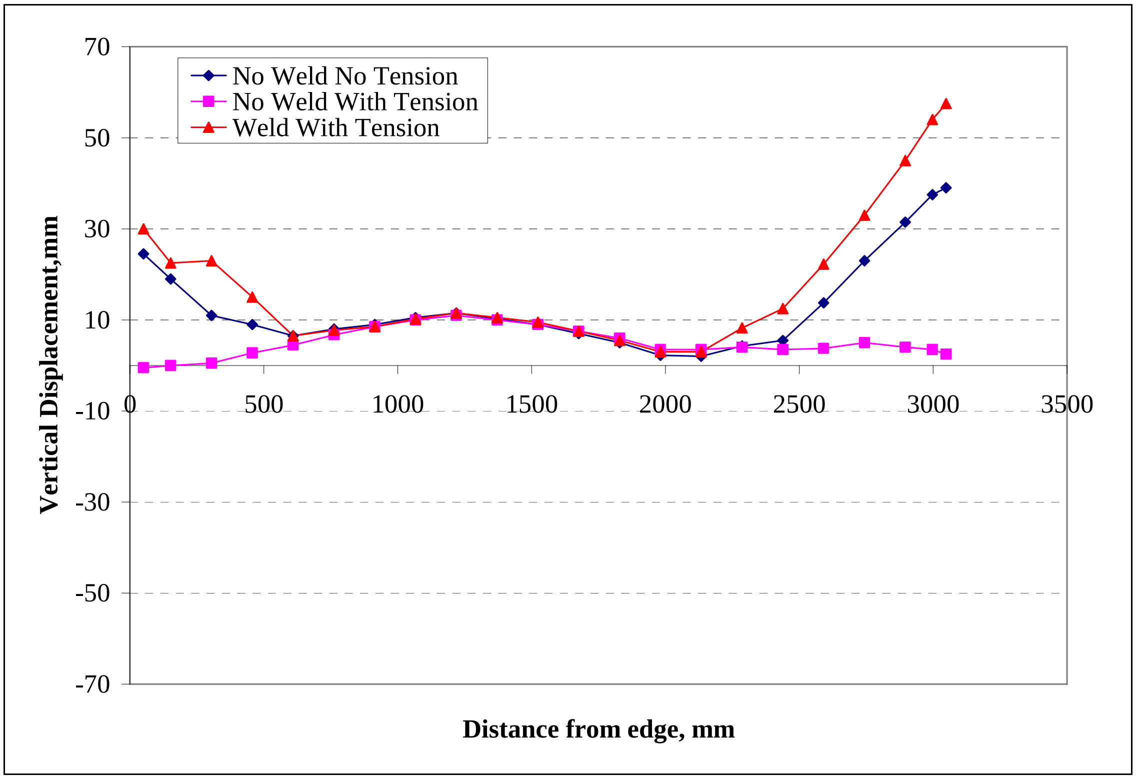


Figure 22: Longitudinal Section H

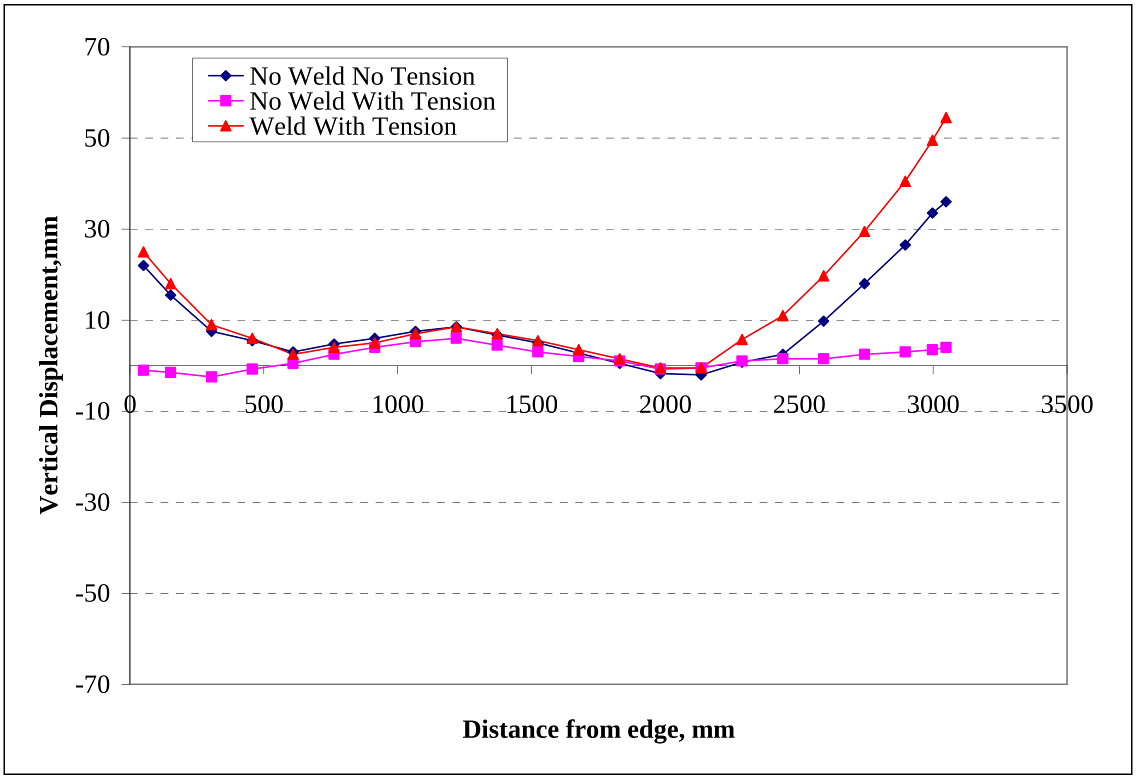


Figure 23: Longitudinal Section I

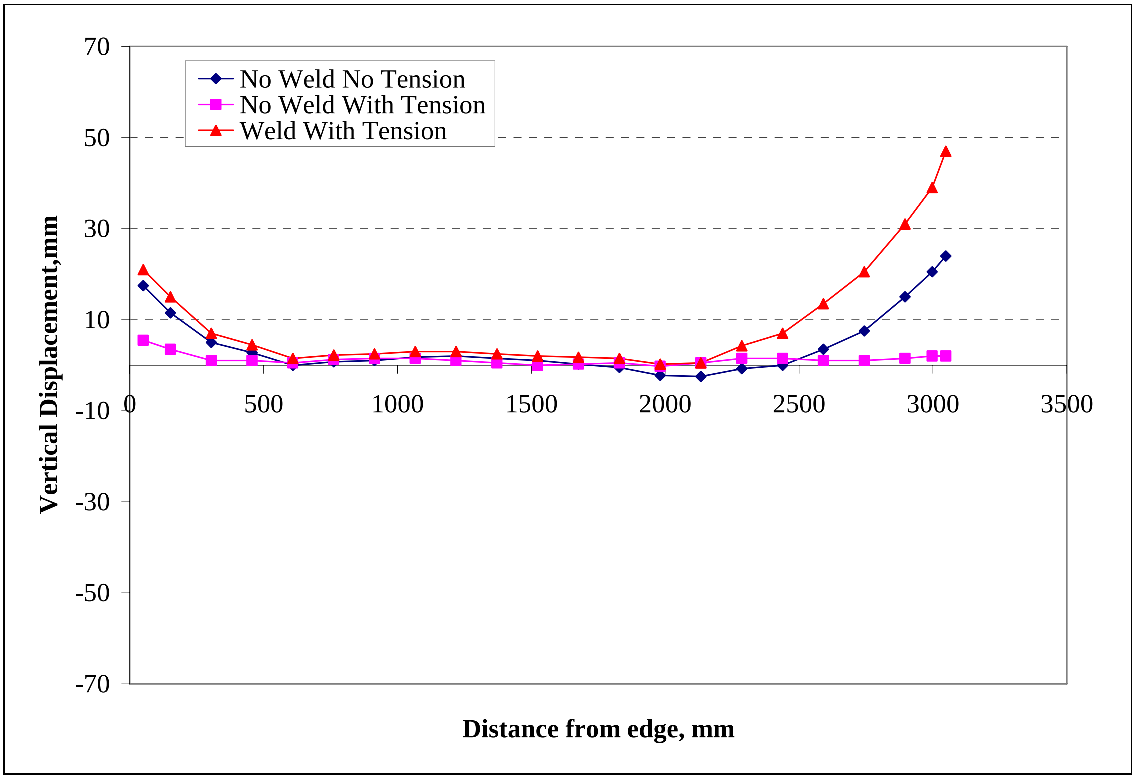


Figure 24: Longitudinal Section J

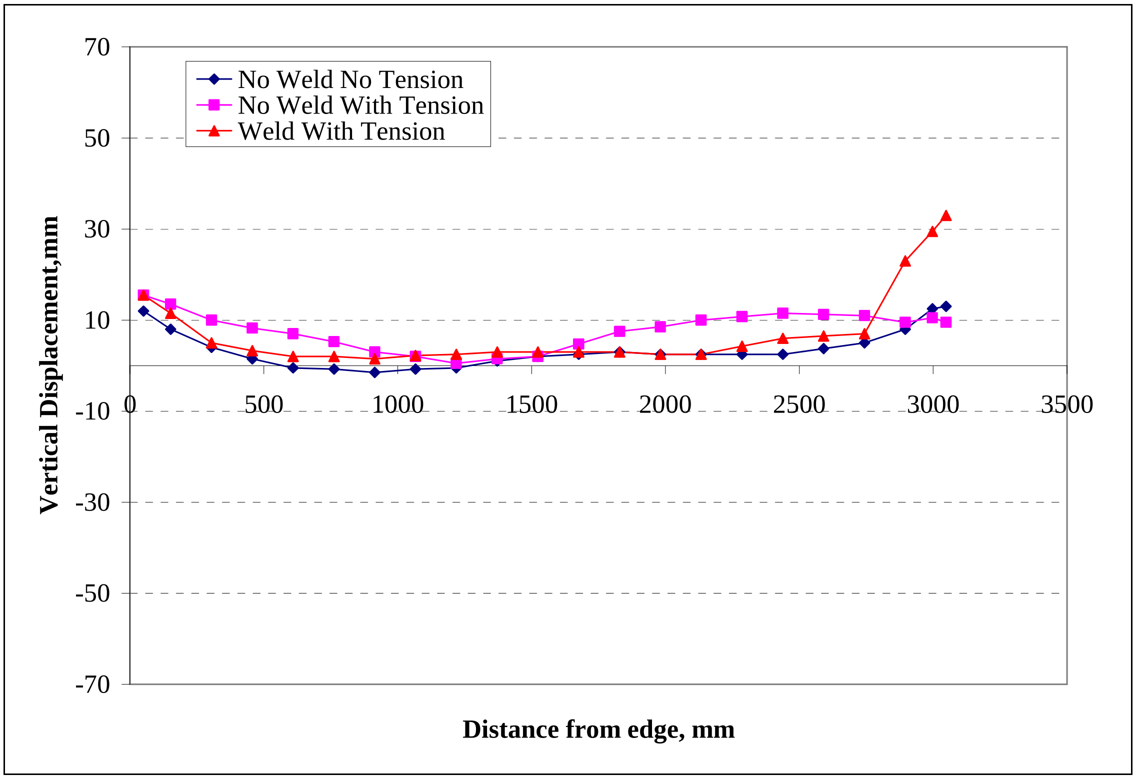


Figure 25: Longitudinal Section K

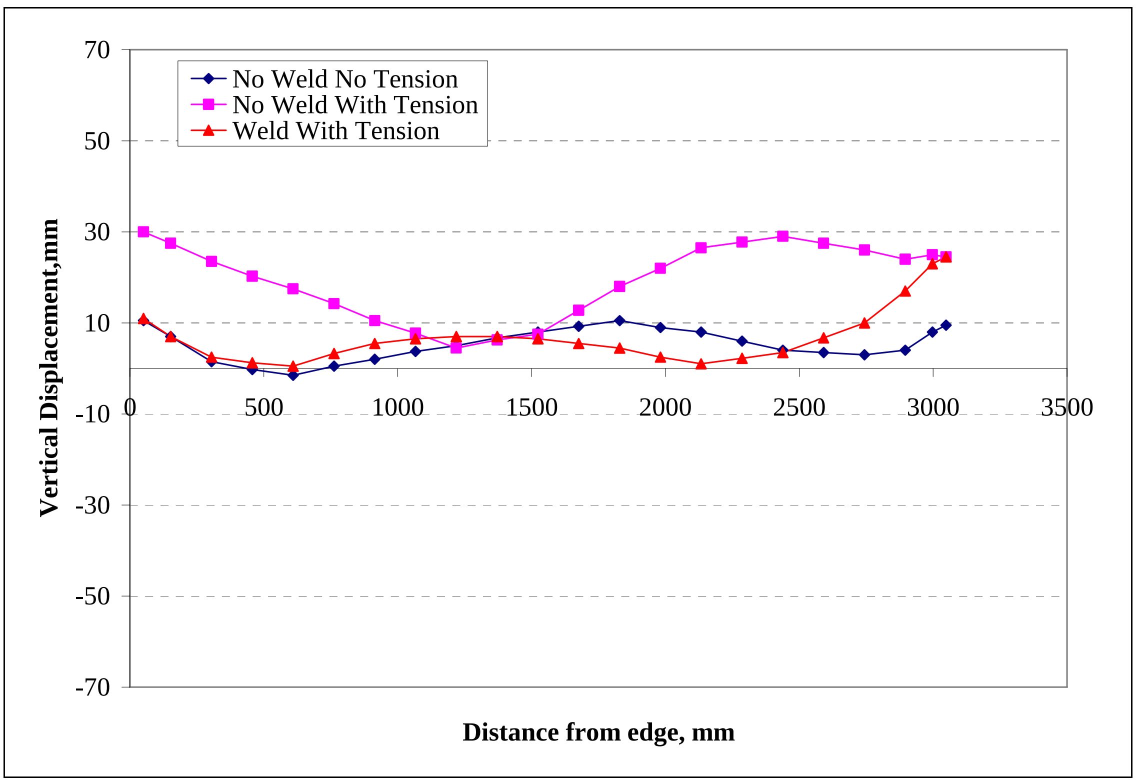


Figure 26: Longitudinal Section L

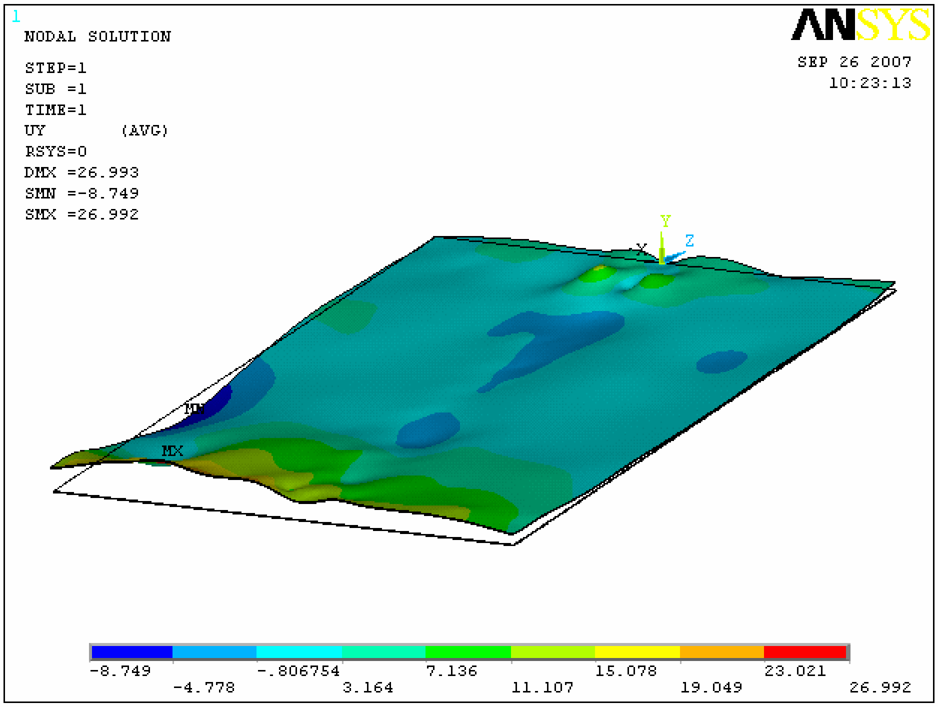


Figure 27: Net Plate Deformation after Welding (No Weld -Weld under Tension)

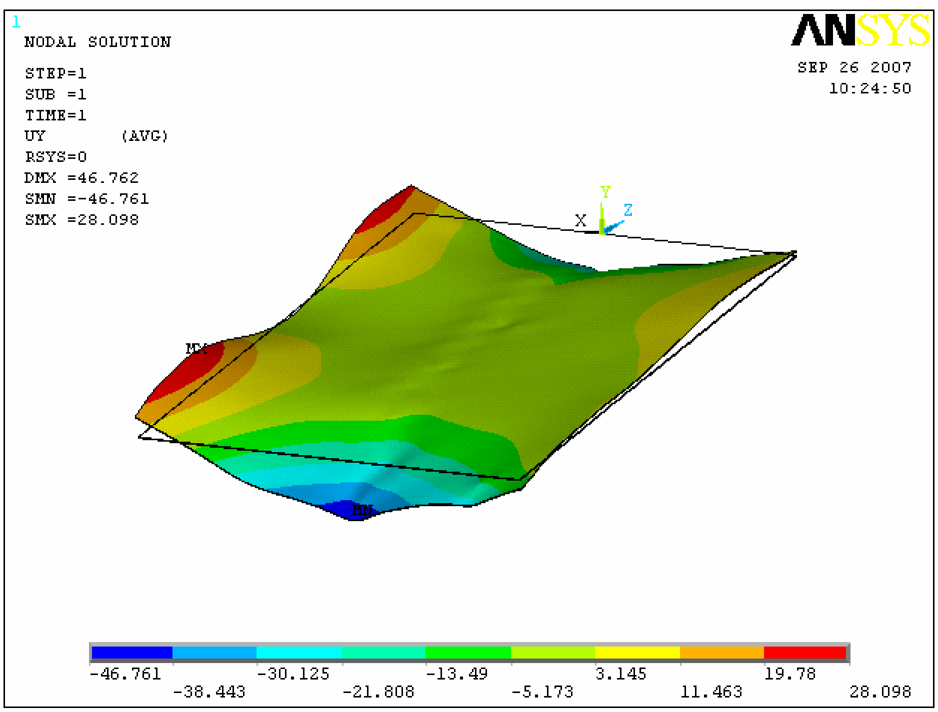


Figure 28: Net Plate Deformation before Welding
(No Weld No Tension-No Weld with Tension)

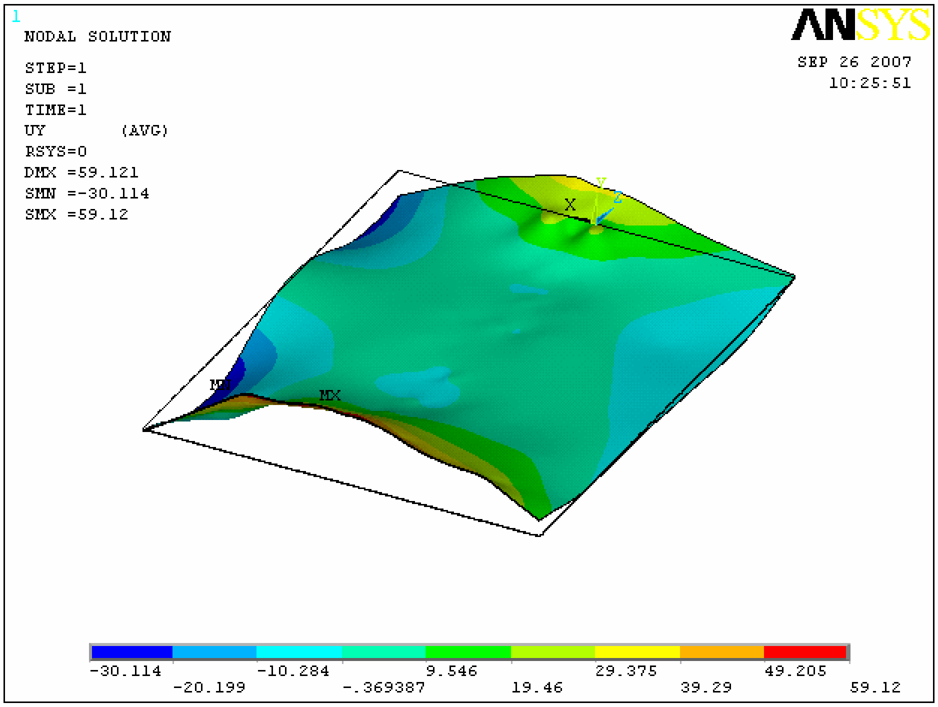


Figure 29: Net Plate Deformation under Tension (No Weld with Tension-Weld under Tension)

PLATE 4 – SIDE 1

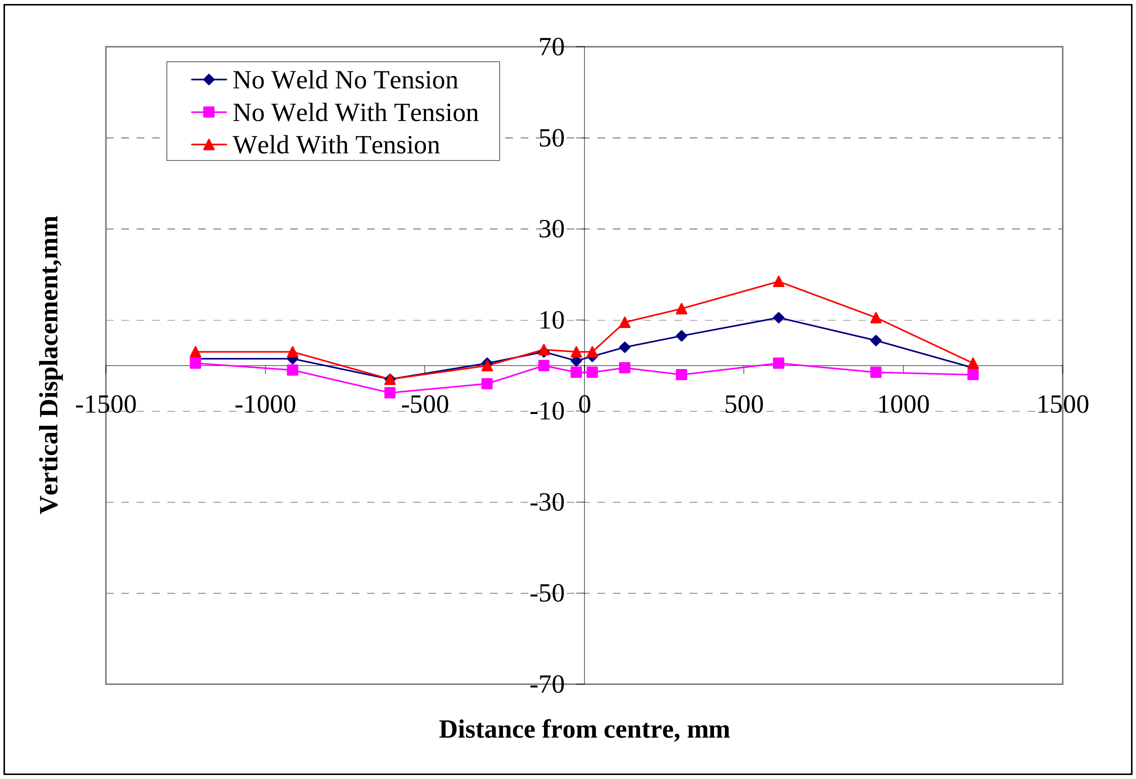


Figure 1: Transverse Section A1

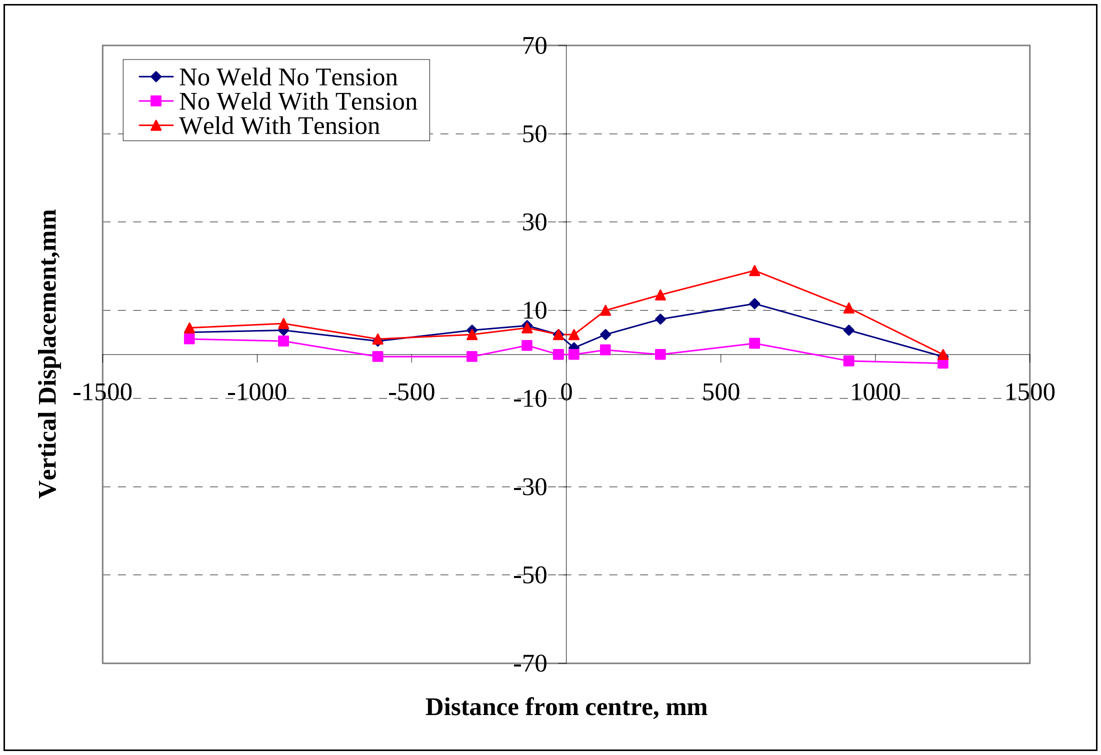


Figure 2: Transverse Section A2

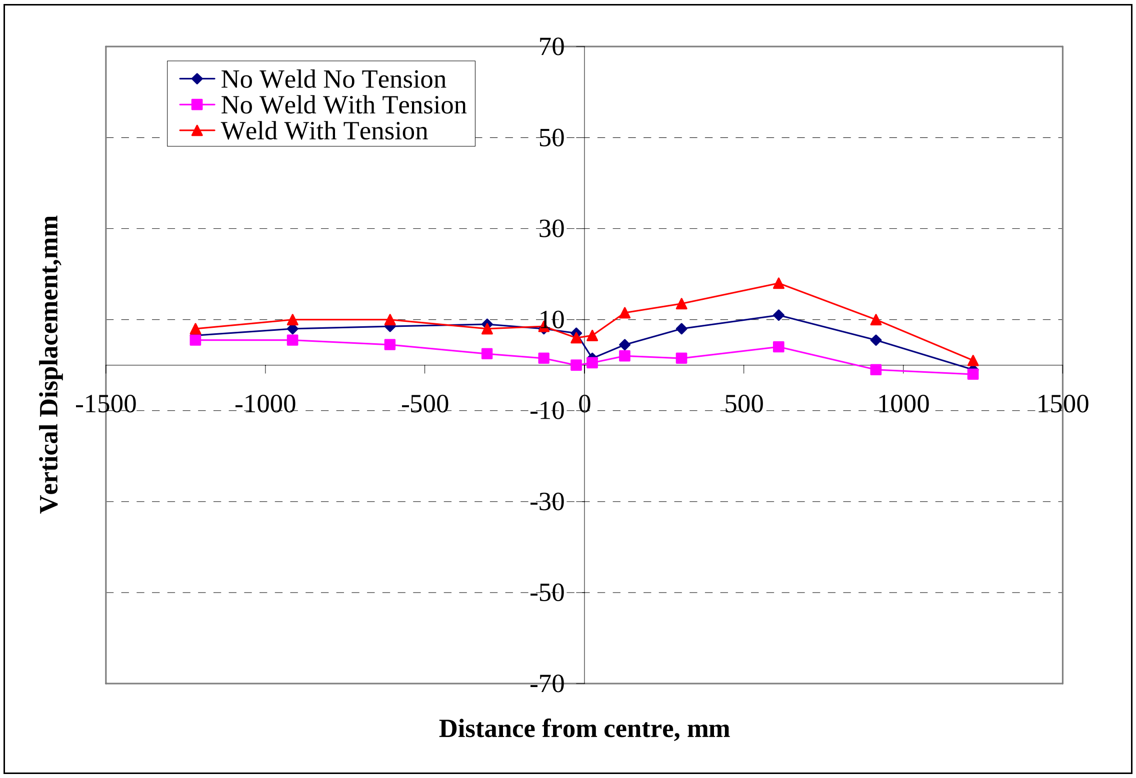


Figure 3: Transverse Section A3

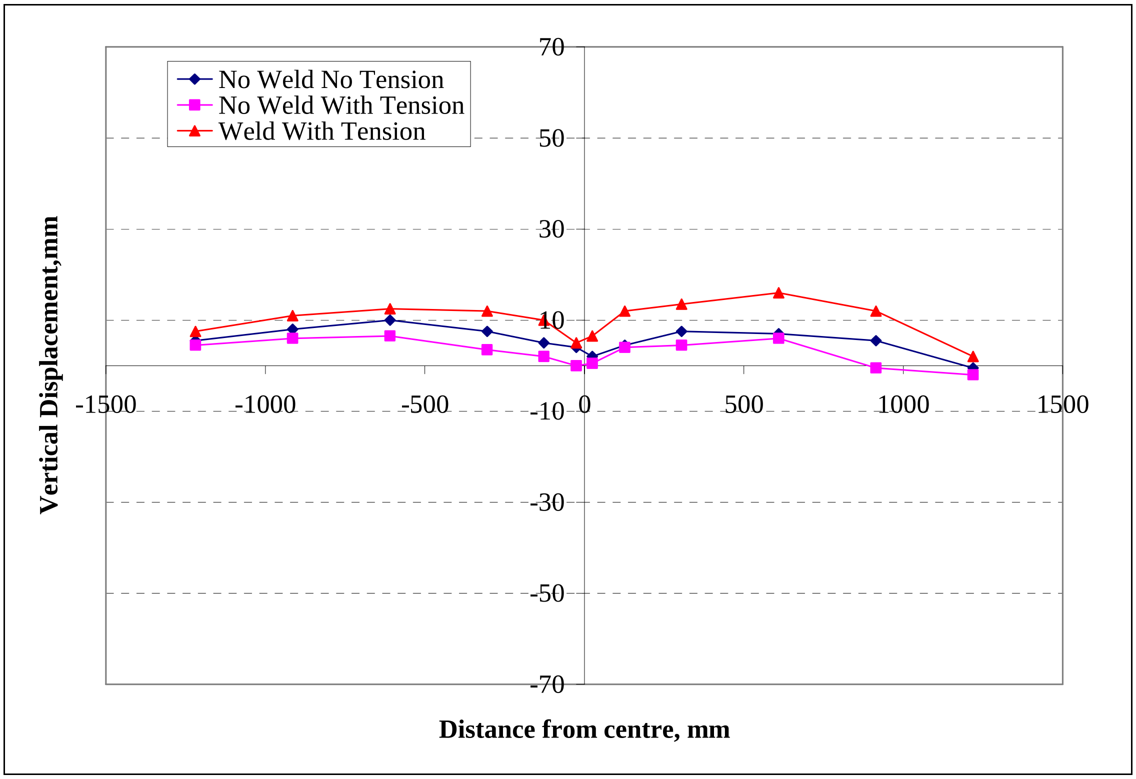


Figure 4: Transverse Section A5

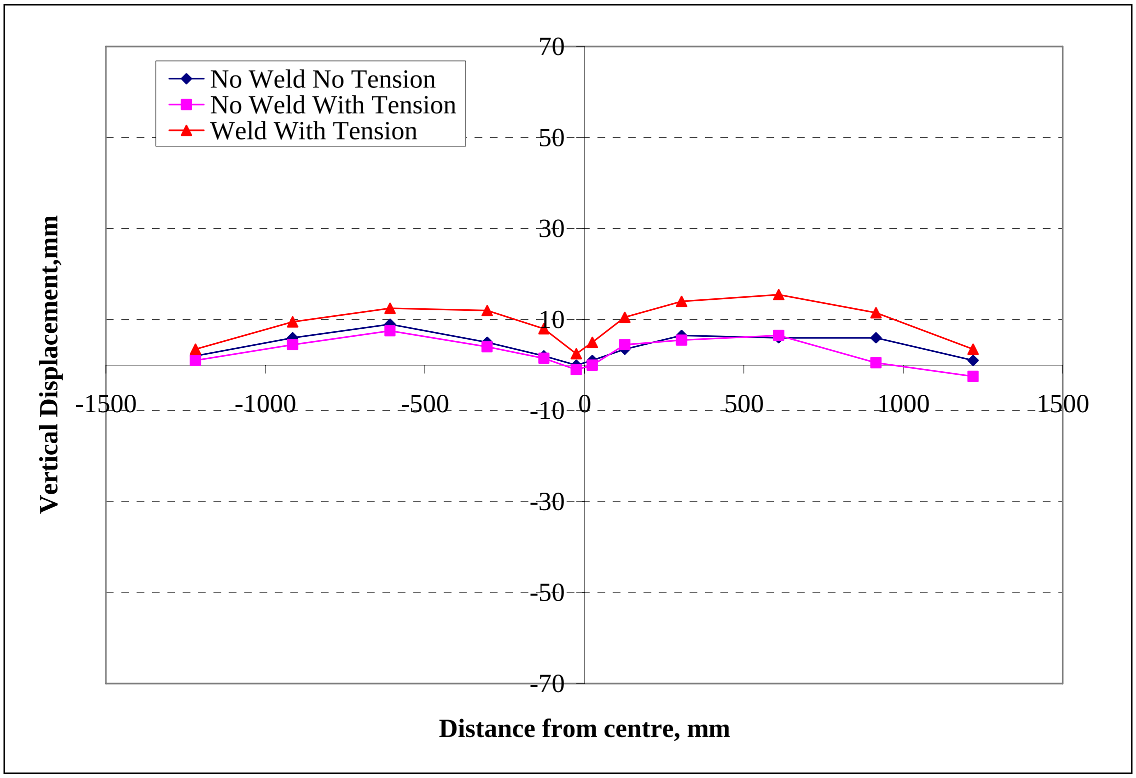


Figure 5: Transverse Section A7

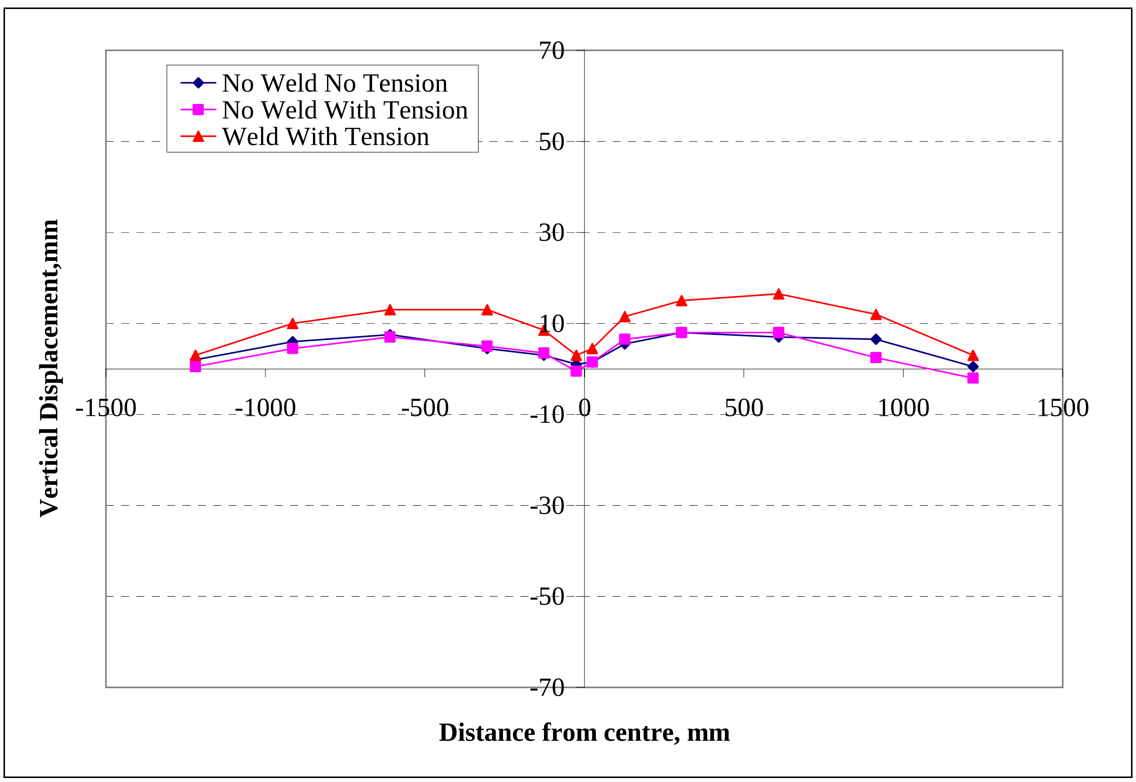


Figure 6: Transverse Section A9

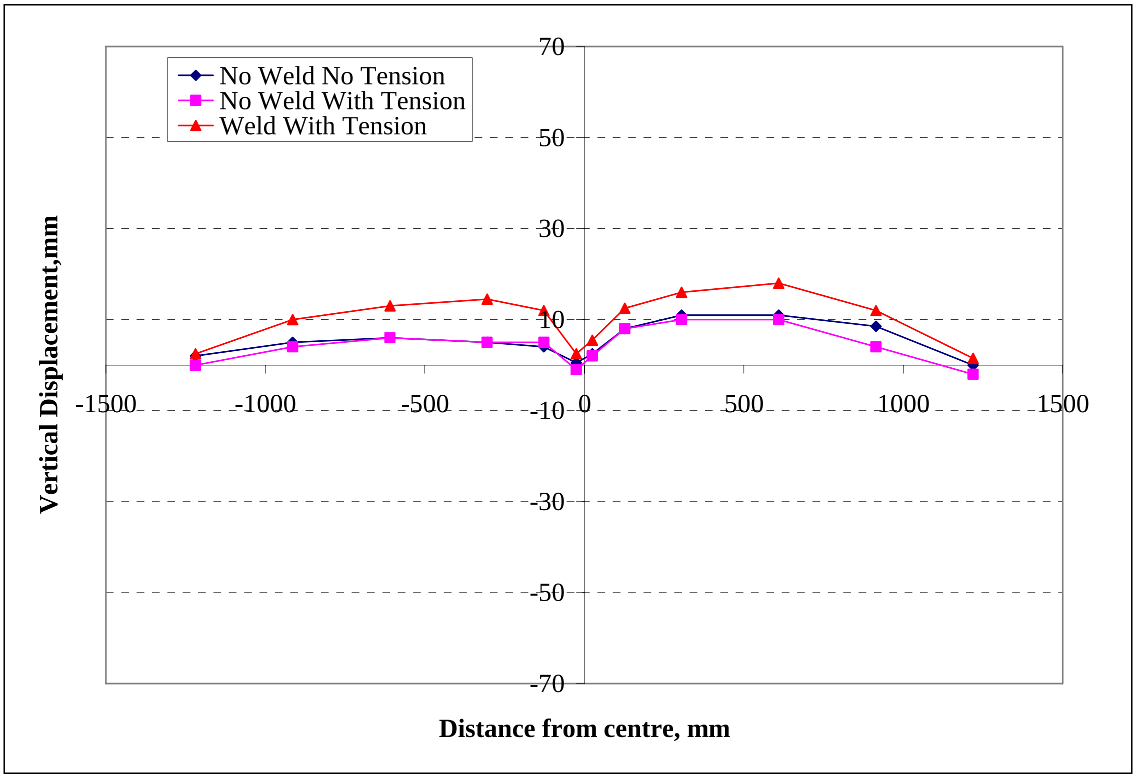


Figure 7: Transverse Section A11

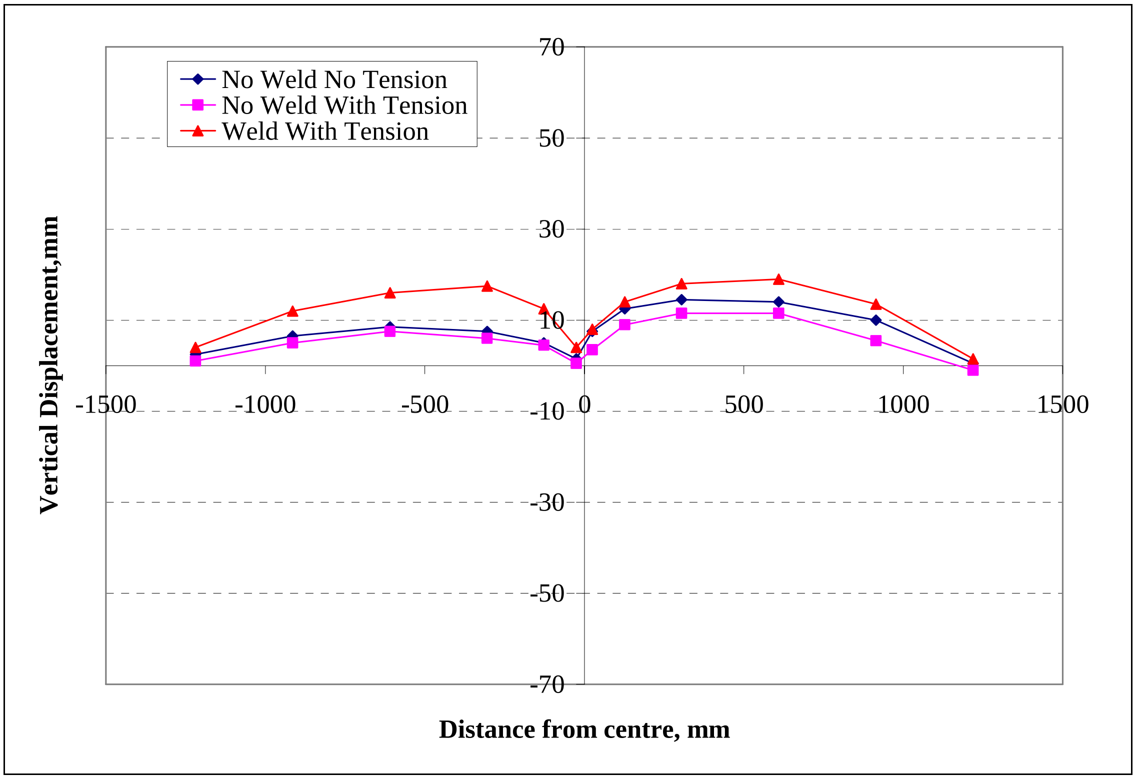


Figure 8: Transverse Section A13

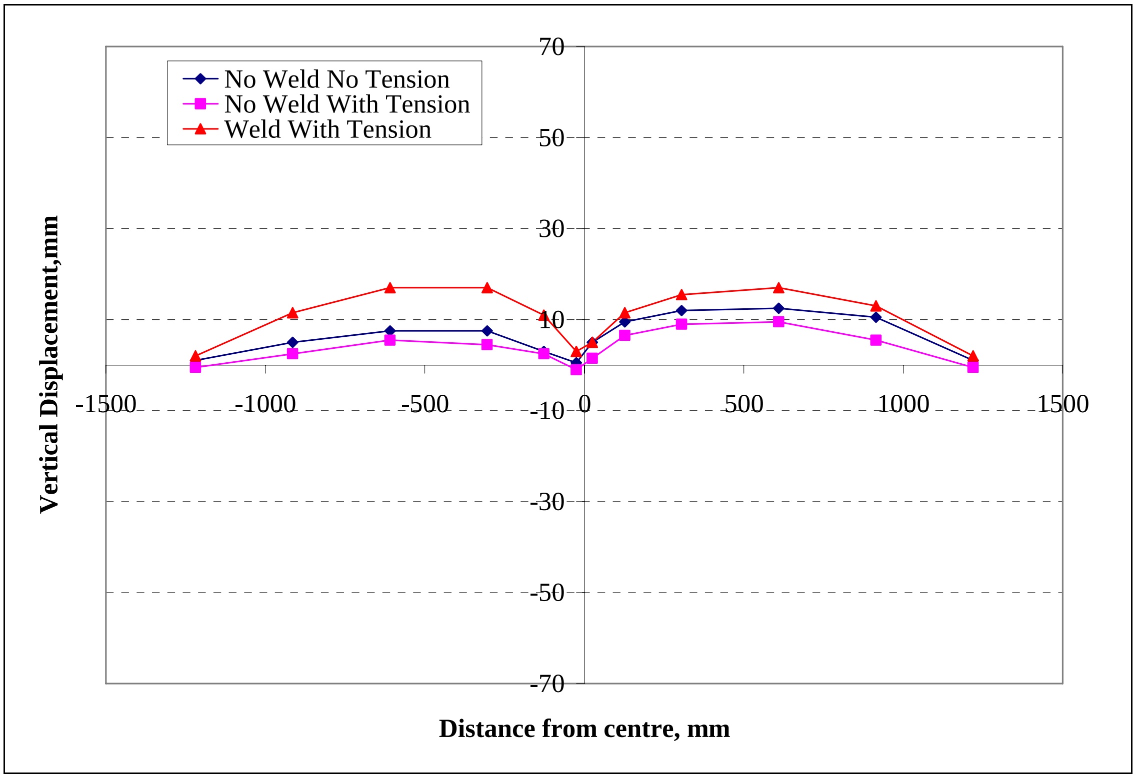


Figure 9: Transverse Section A15

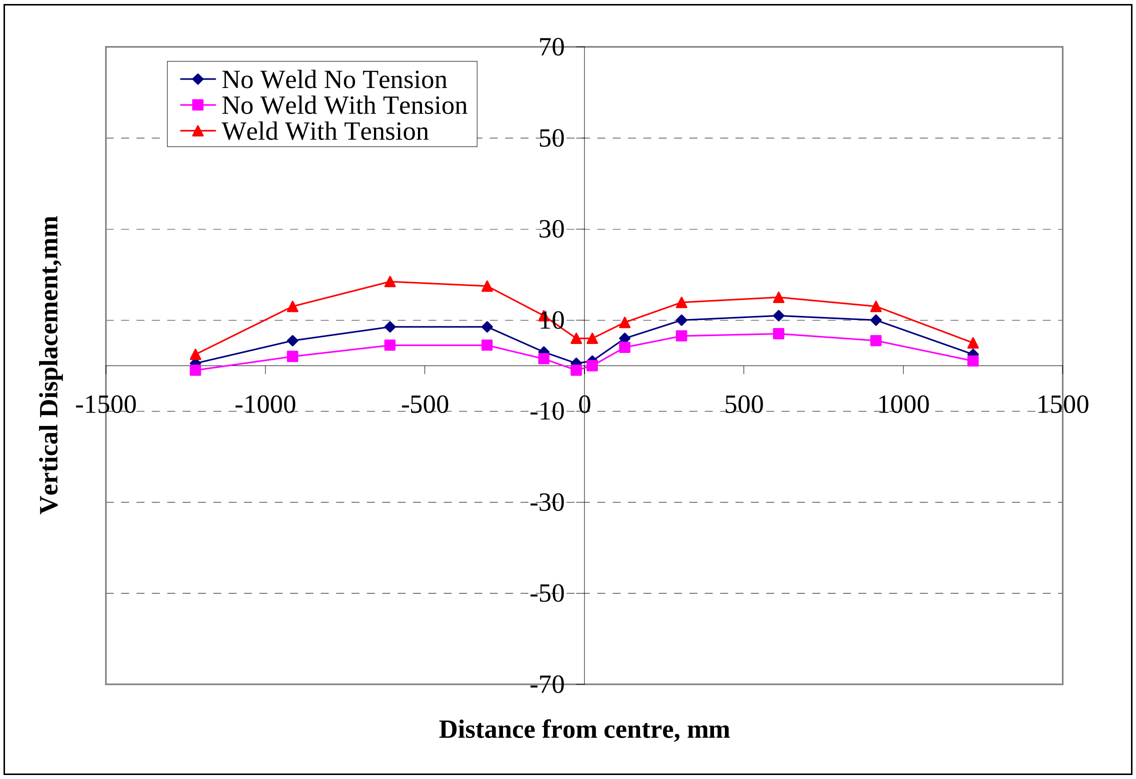


Figure 10: Transverse Section A17

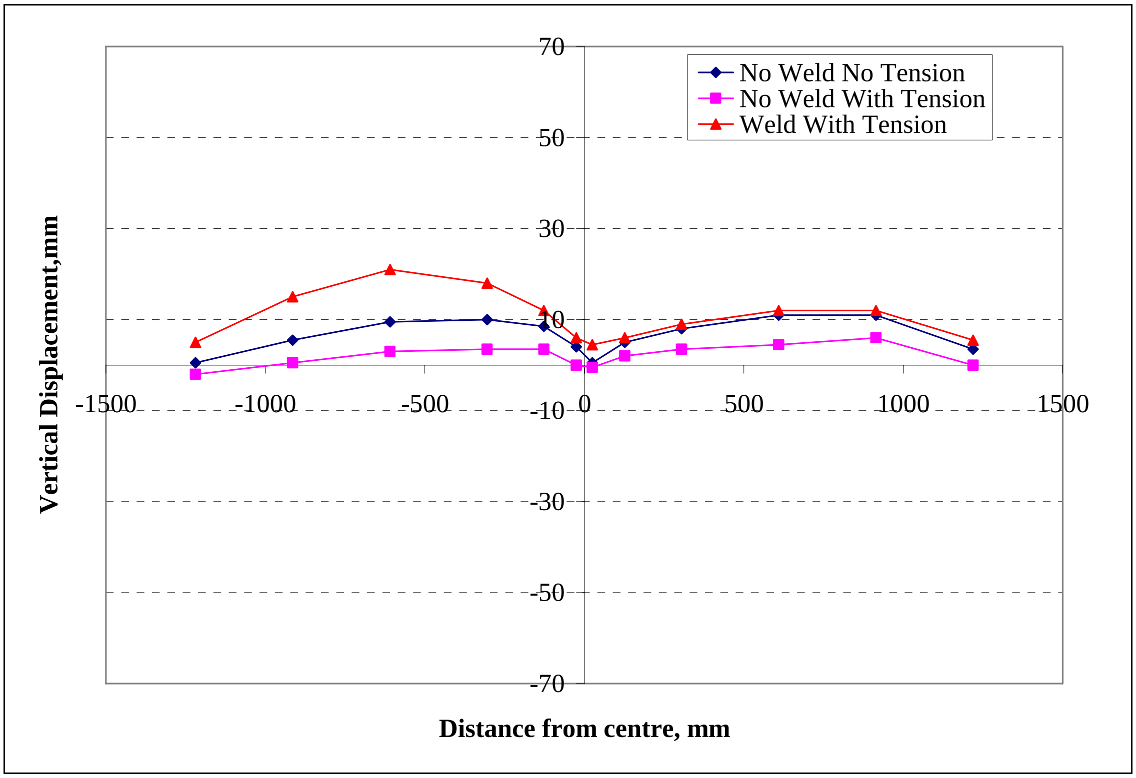


Figure 11: Transverse Section A19

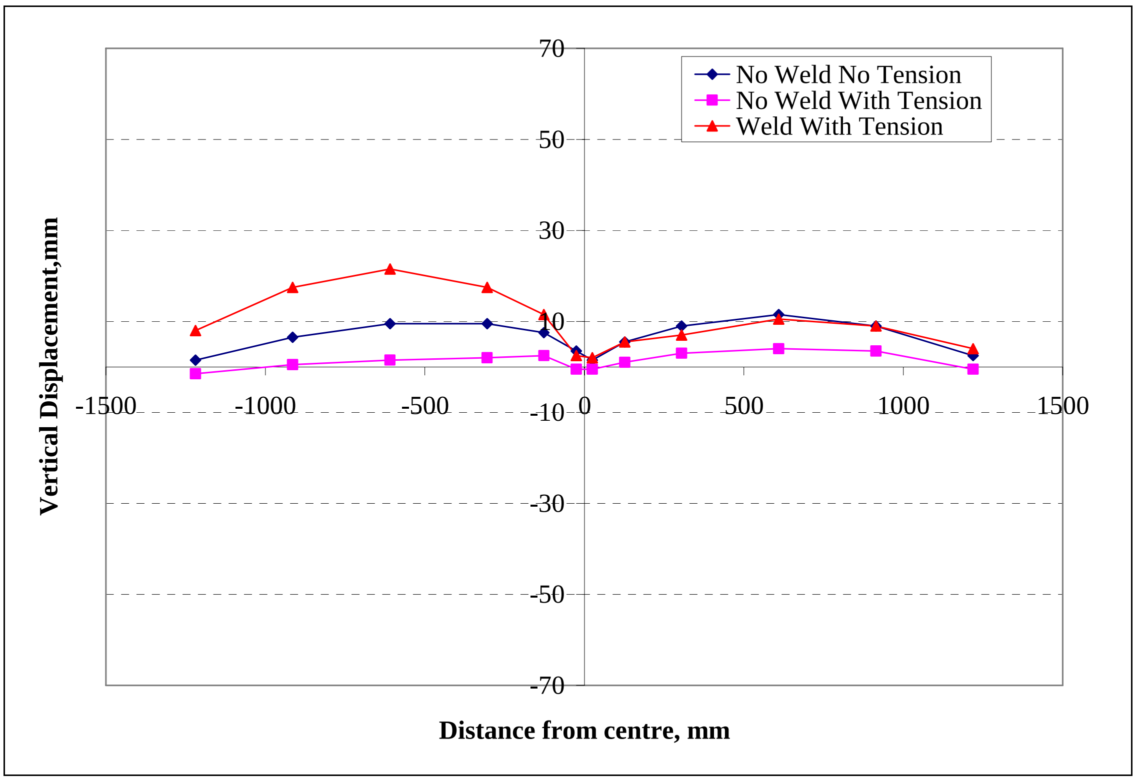


Figure 12: Transverse Section A20

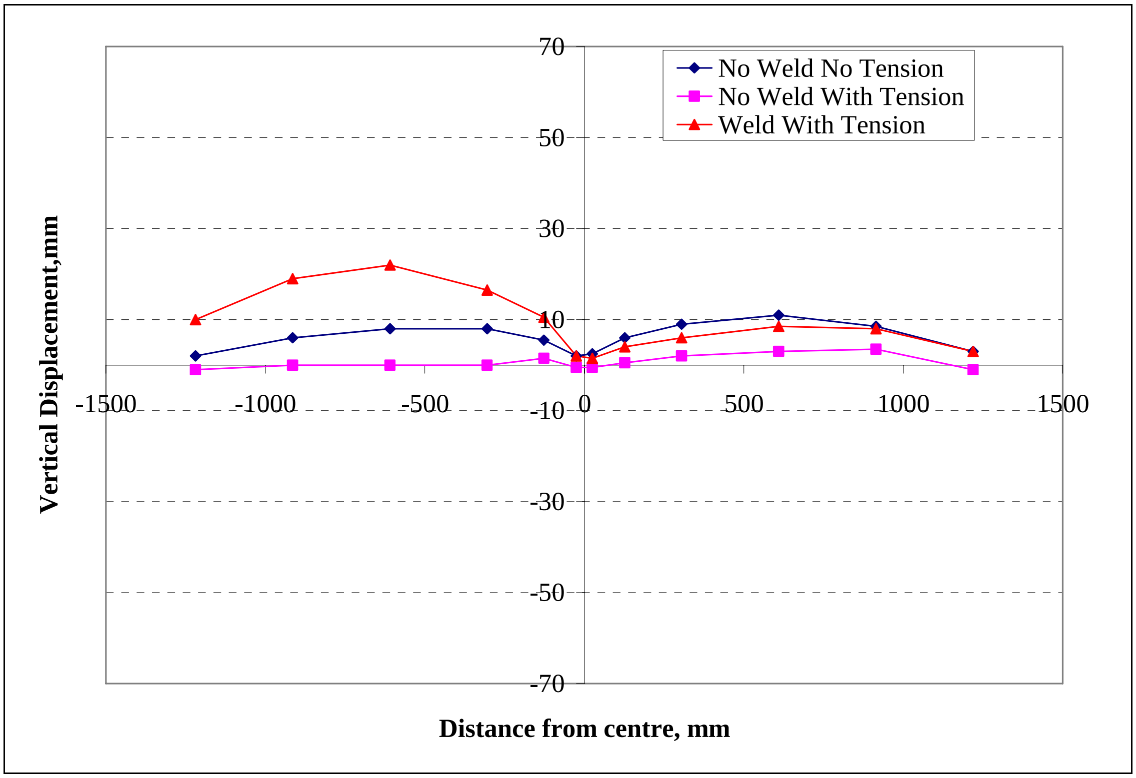


Figure 13: Transverse Section A21

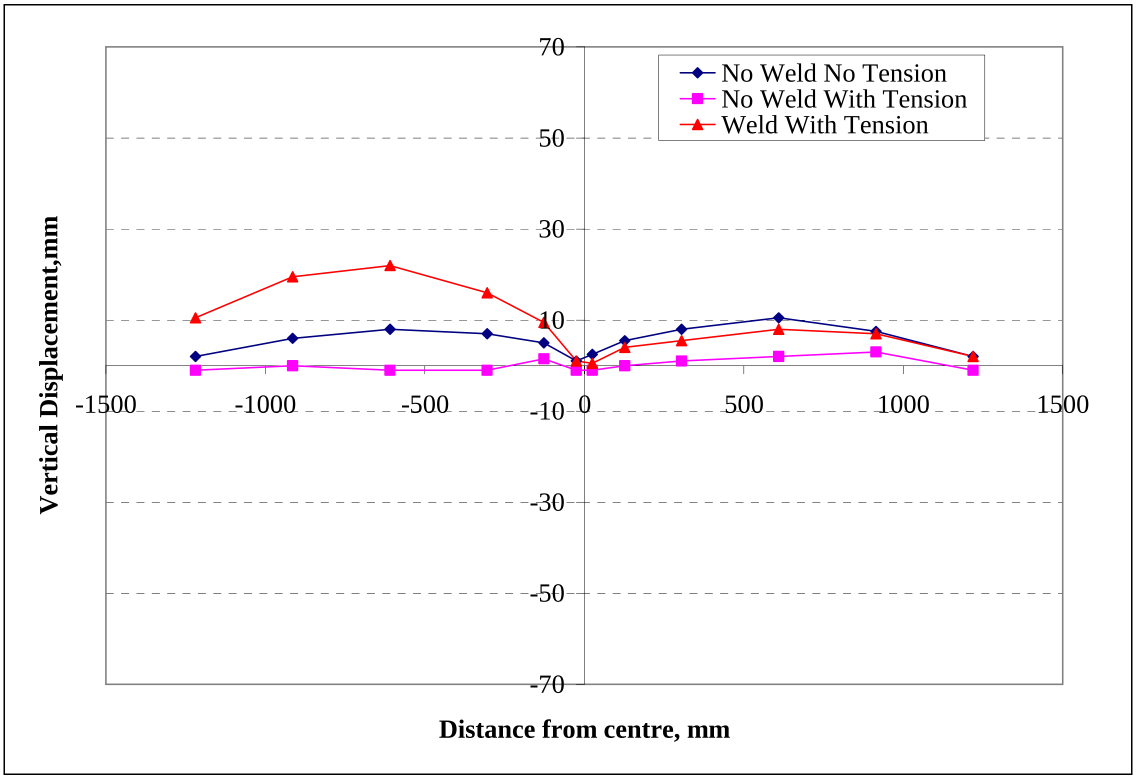


Figure 14: Transverse Section A22

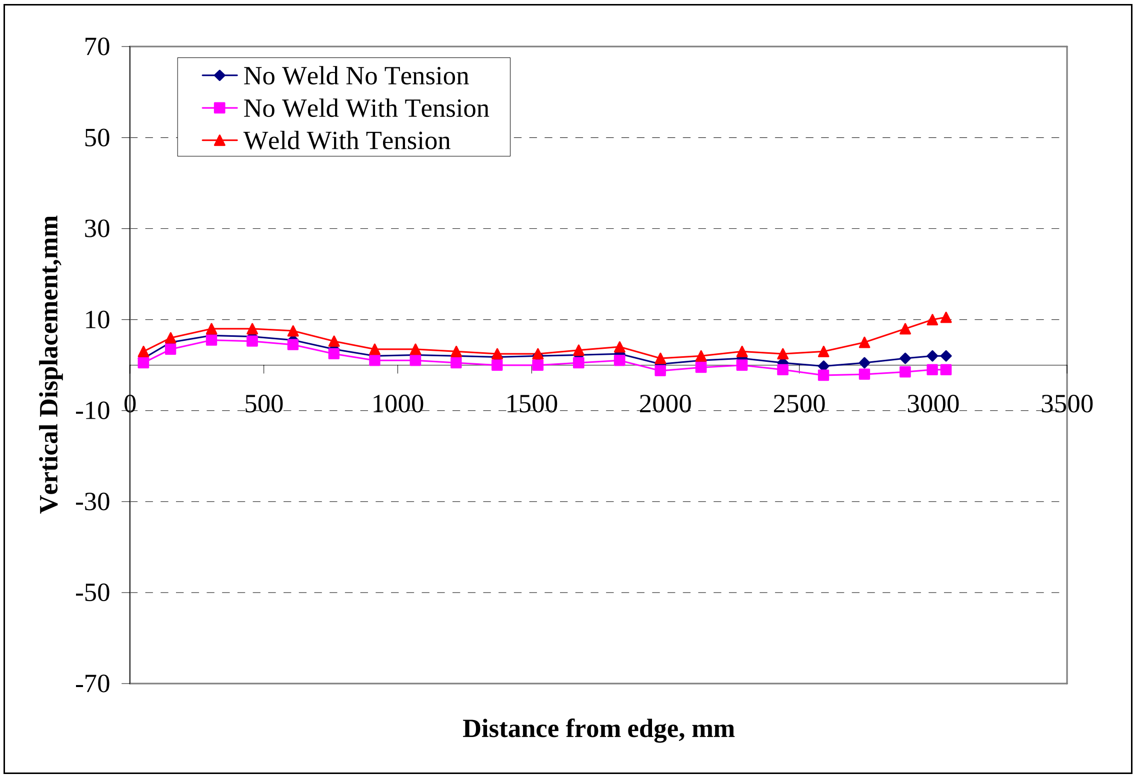


Figure 15: Longitudinal Section A

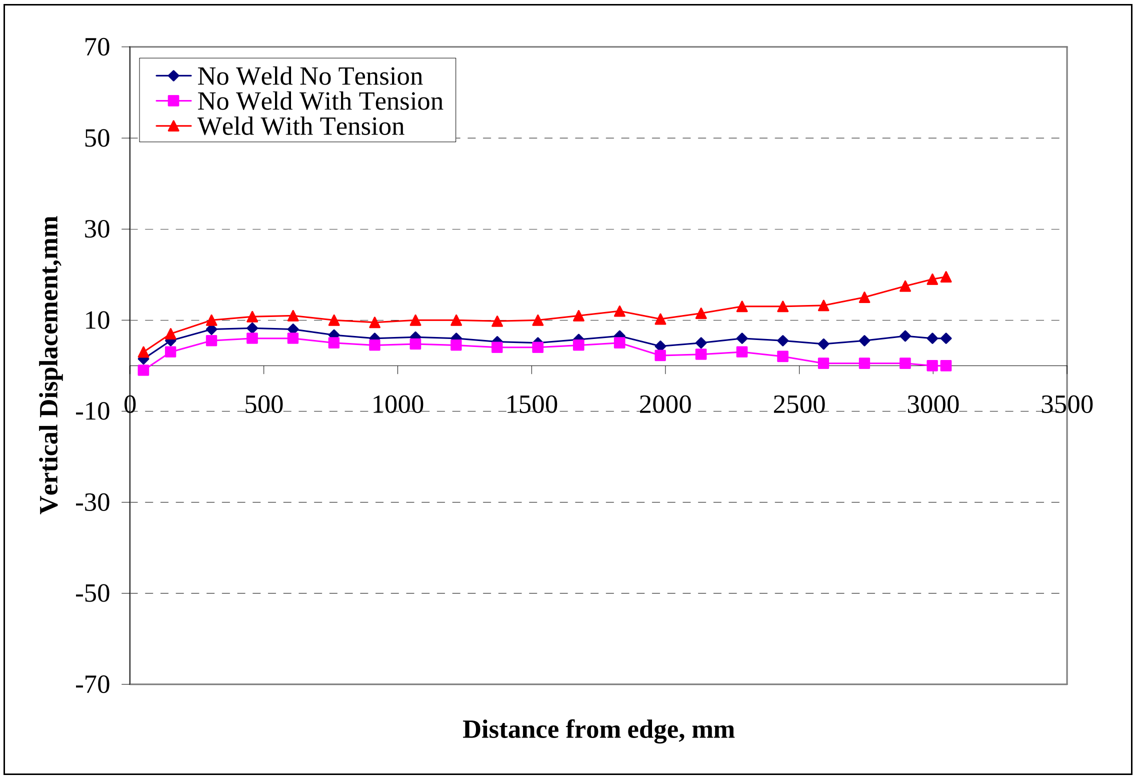


Figure 16: Longitudinal Section B

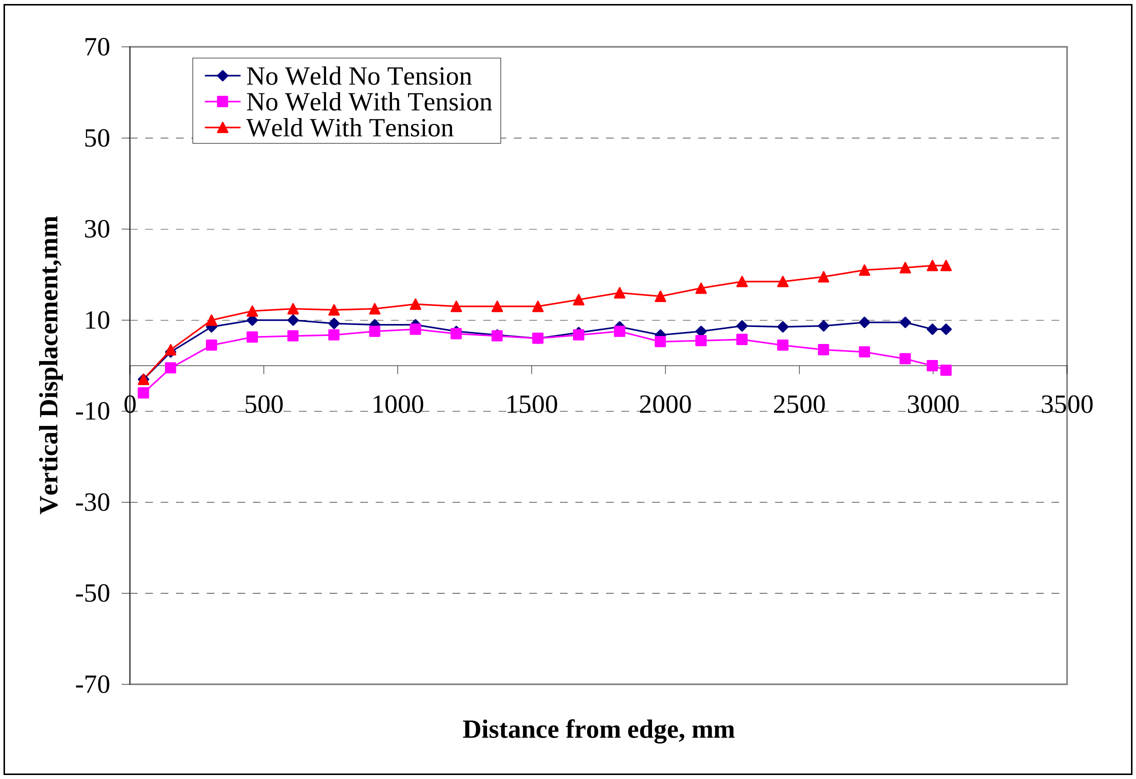


Figure 17: Longitudinal Section C

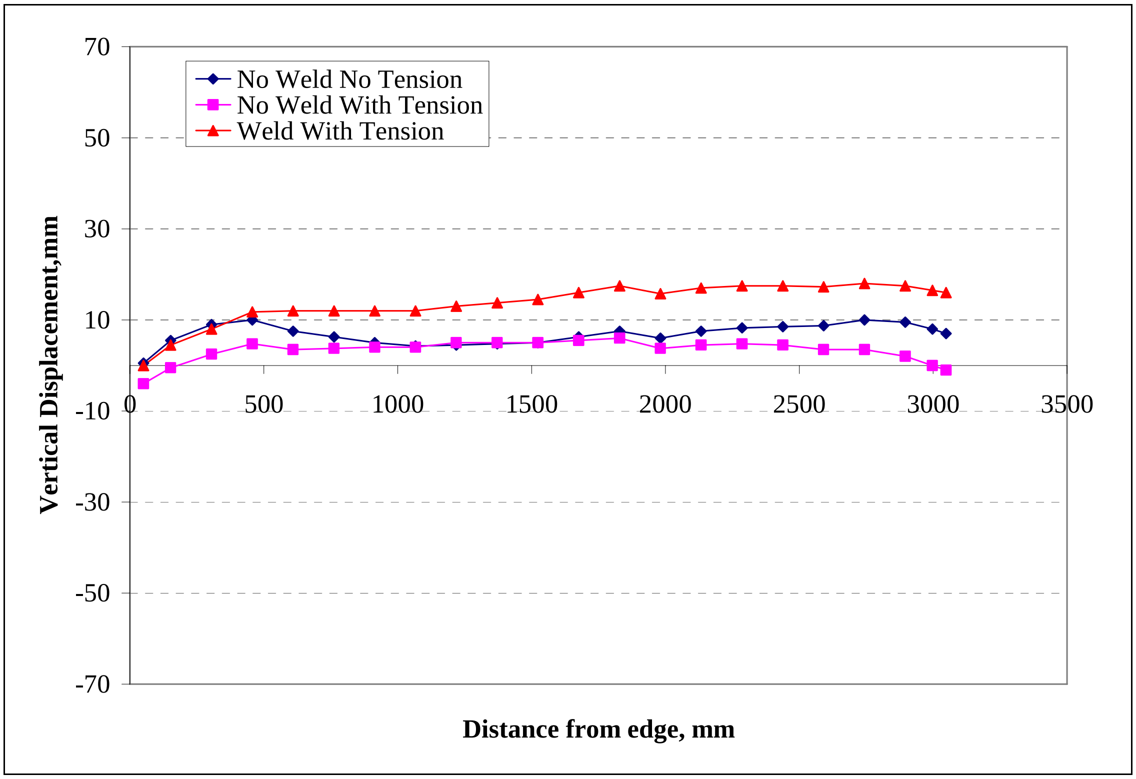


Figure 18: Longitudinal Section D

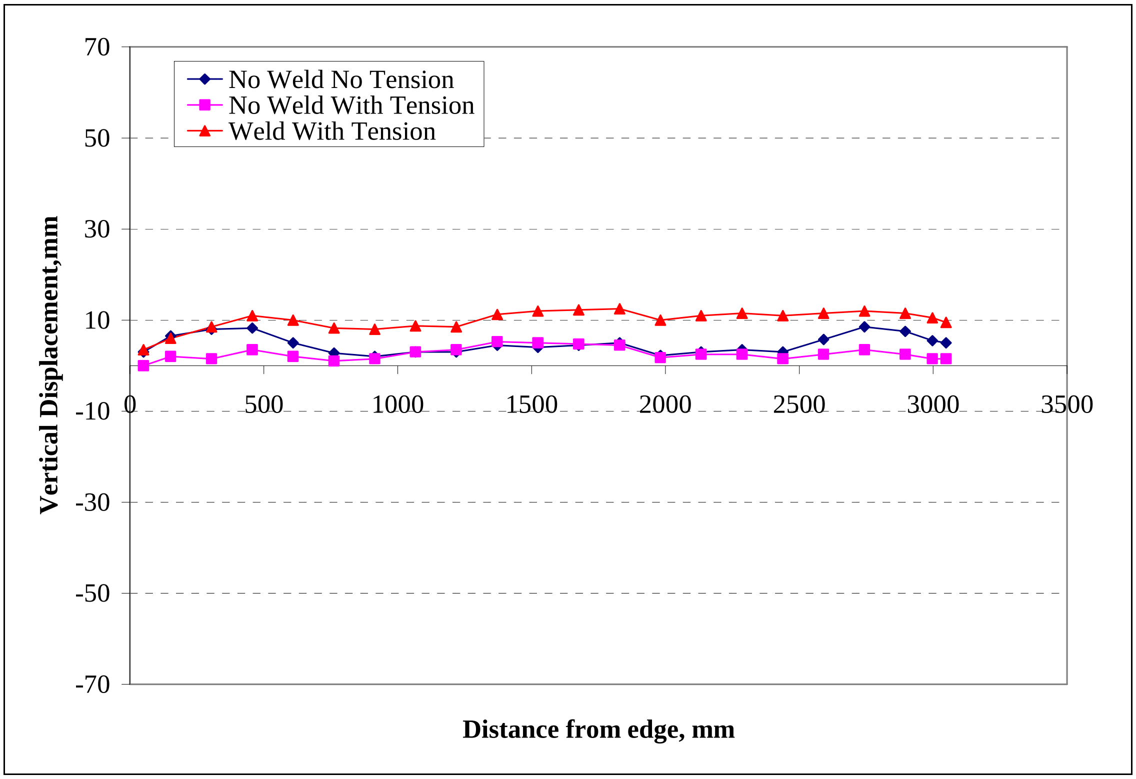


Figure 19: Longitudinal Section E

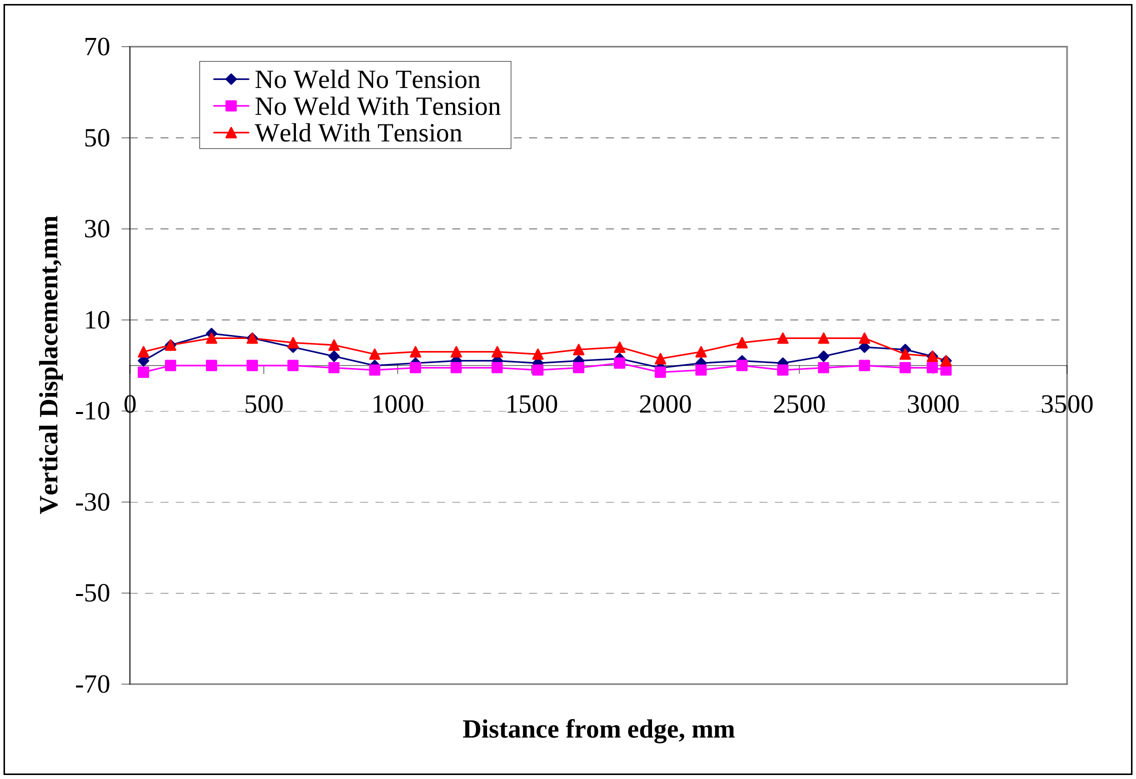


Figure 20: Longitudinal Section F

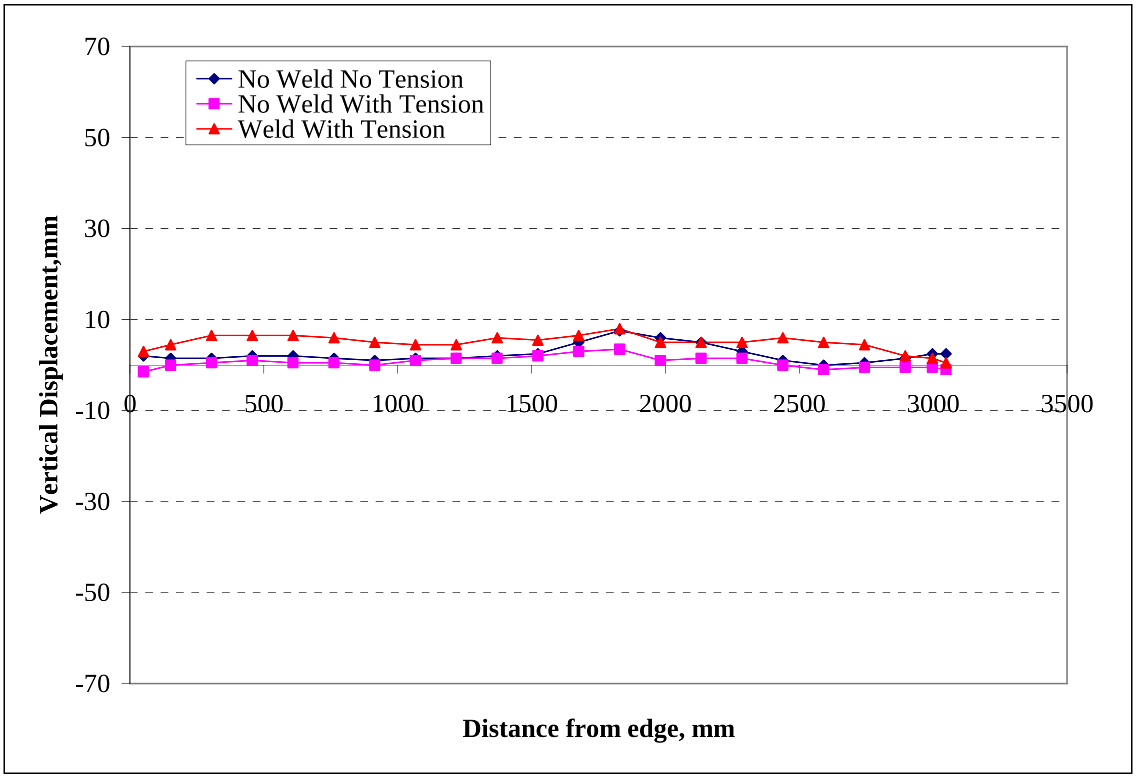


Figure 21: Longitudinal Section G

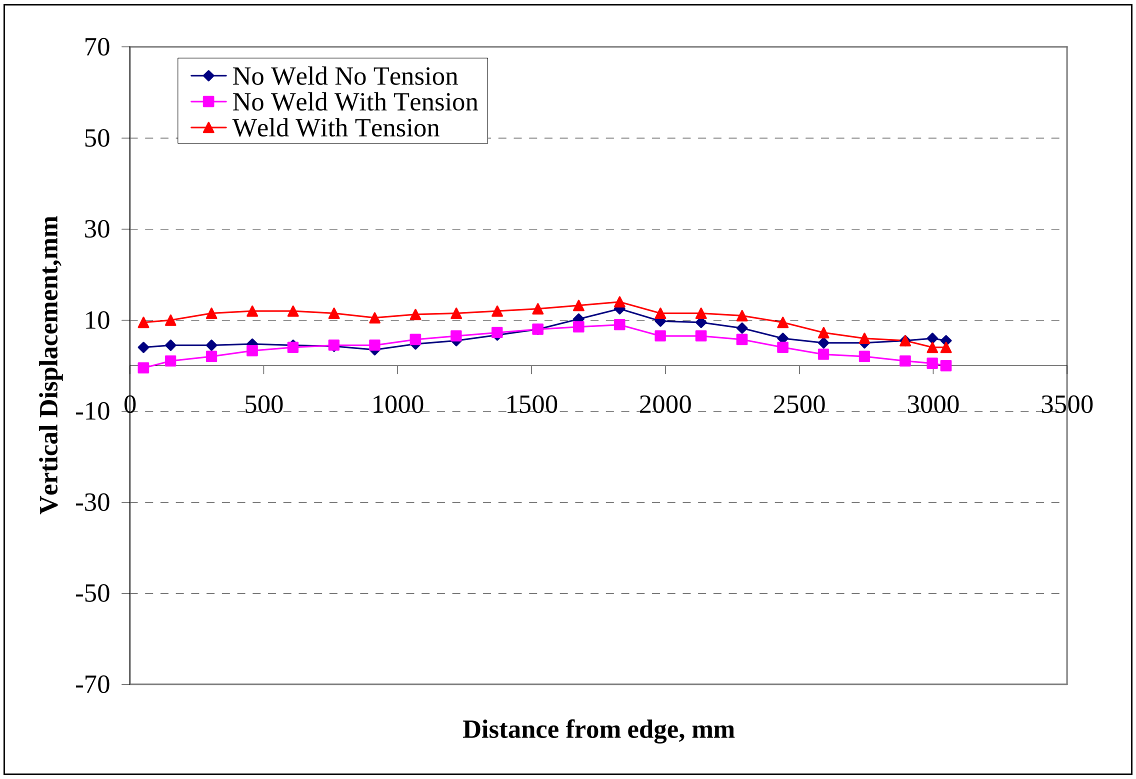


Figure 22: Longitudinal Section H

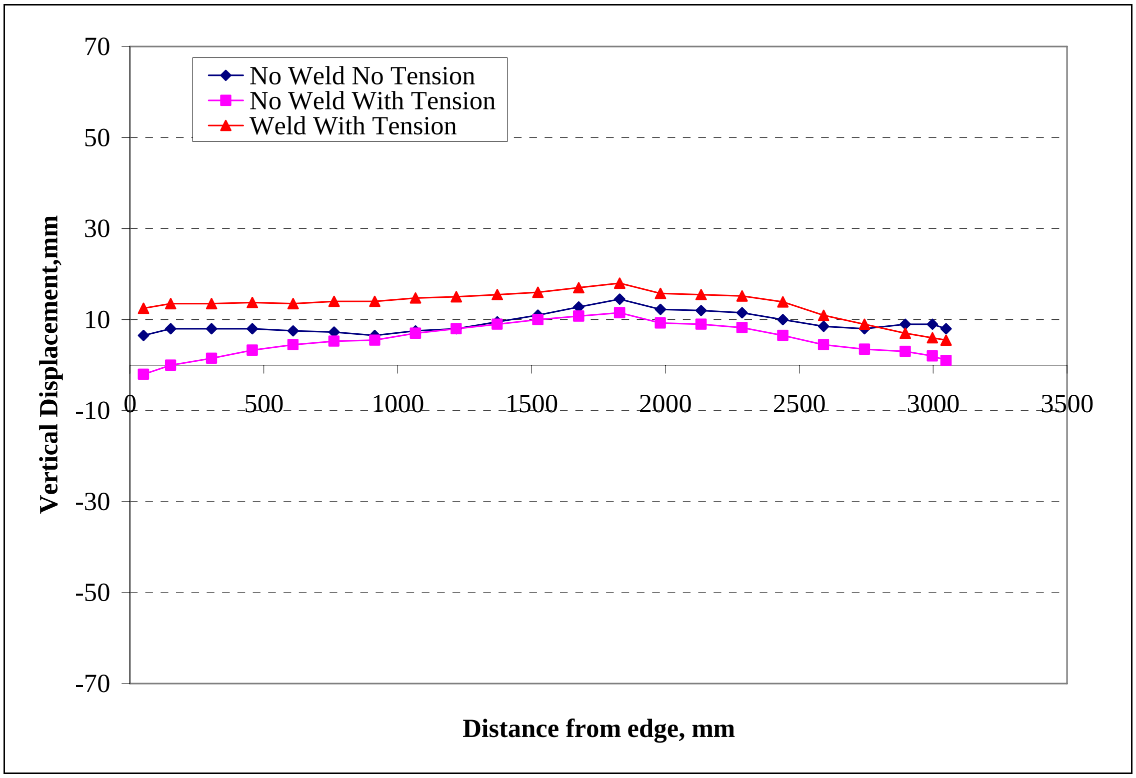


Figure 23: Longitudinal Section I

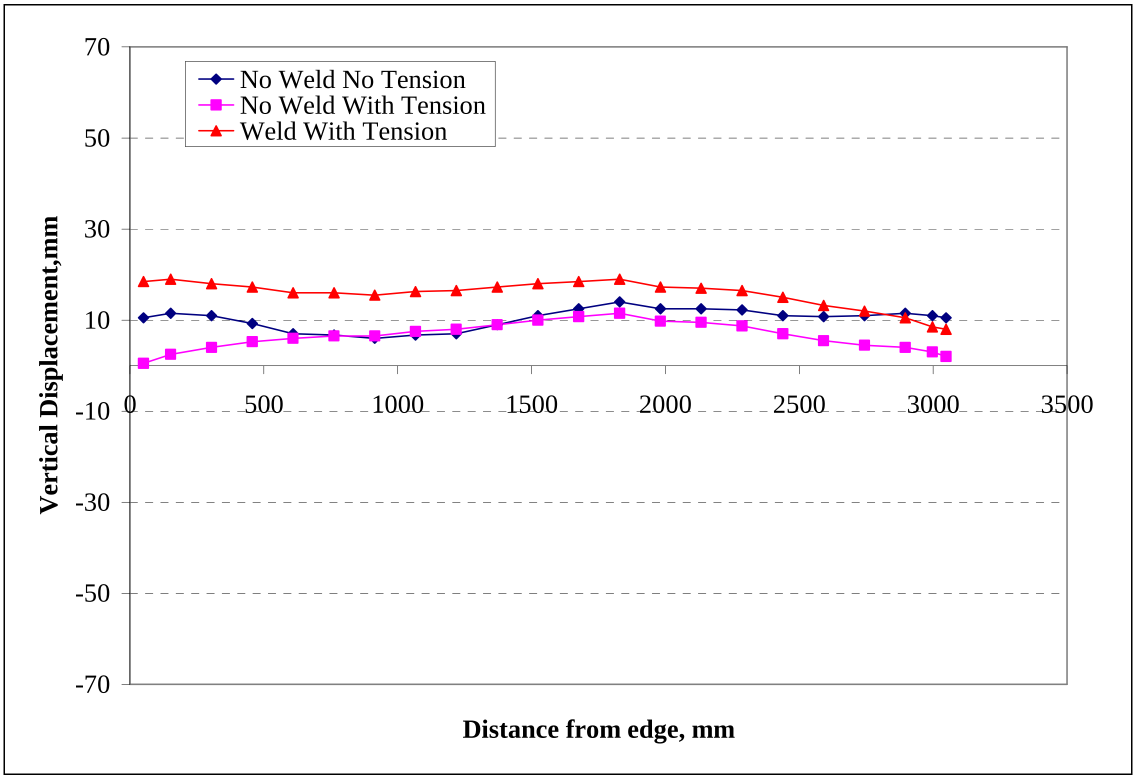


Figure 24: Longitudinal Section J

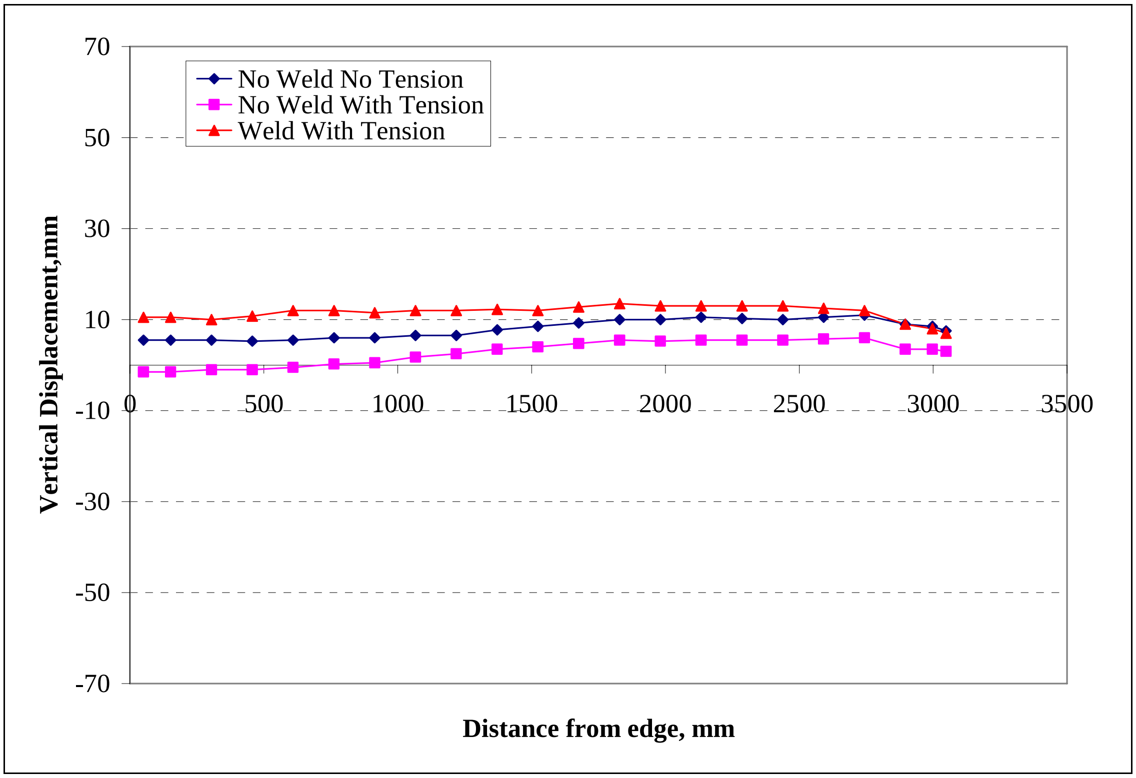


Figure 25: Longitudinal Section K

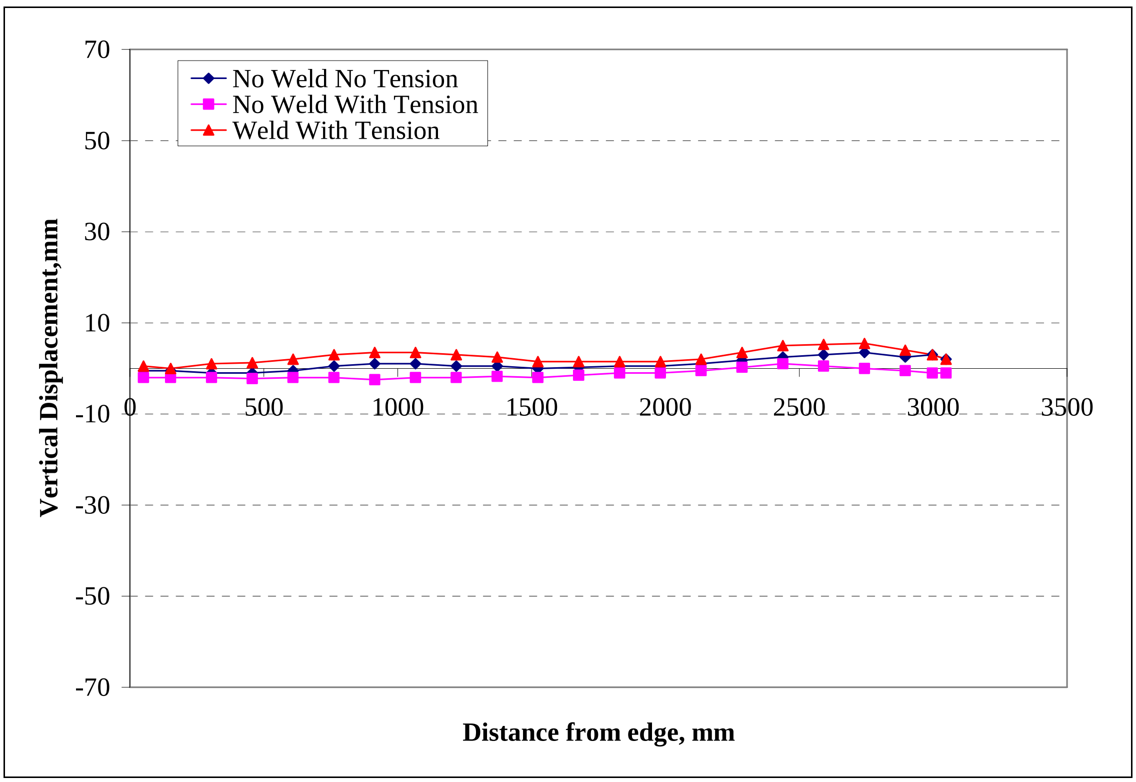


Figure 26: Longitudinal Section L

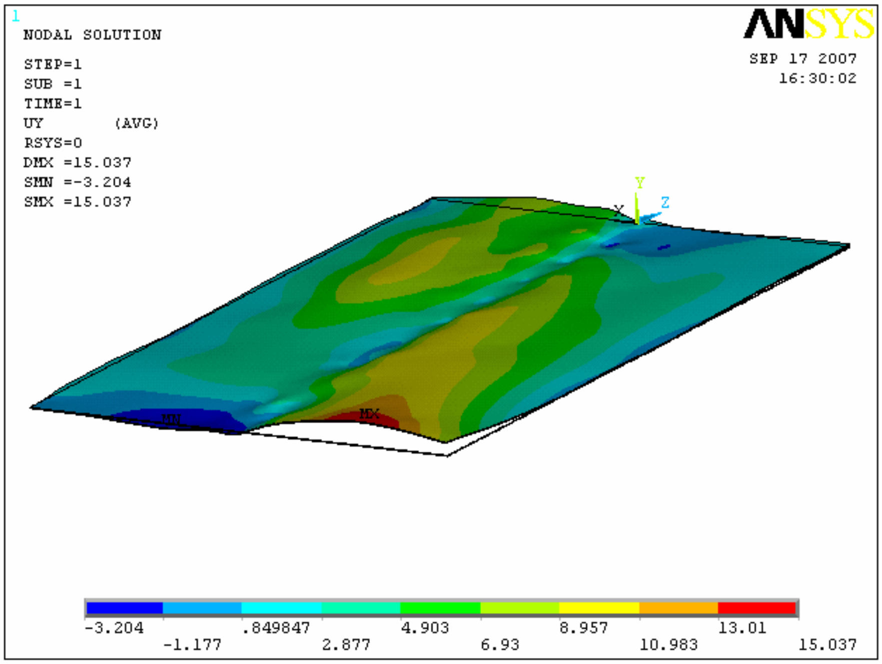


Figure 27: Net Plate Deformation (No Weld No Tension -Weld under Tension)

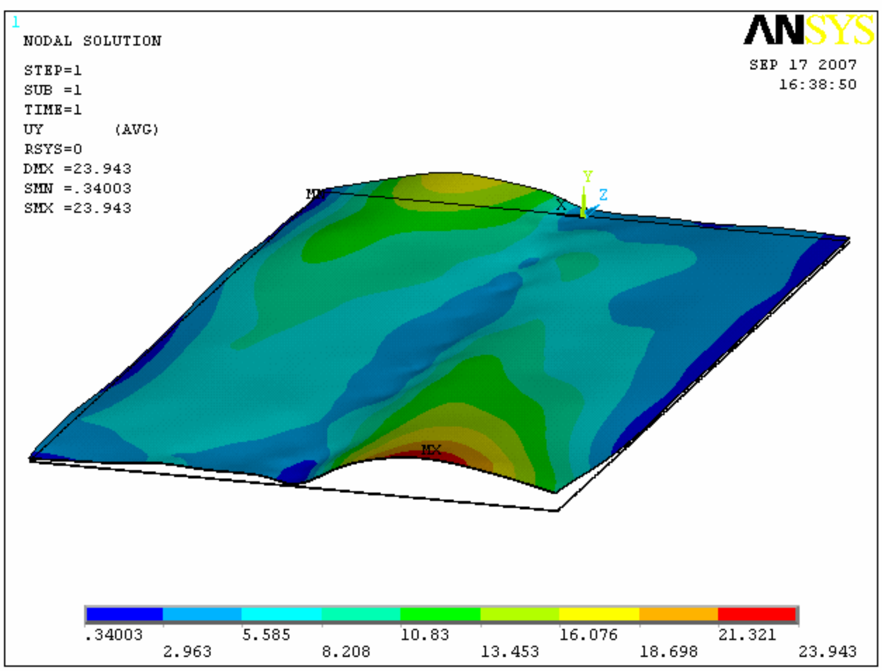


Figure 28: Net Plate Deformation after Welding (Tension Case)
(No Weld with Tension-Weld under Tension)

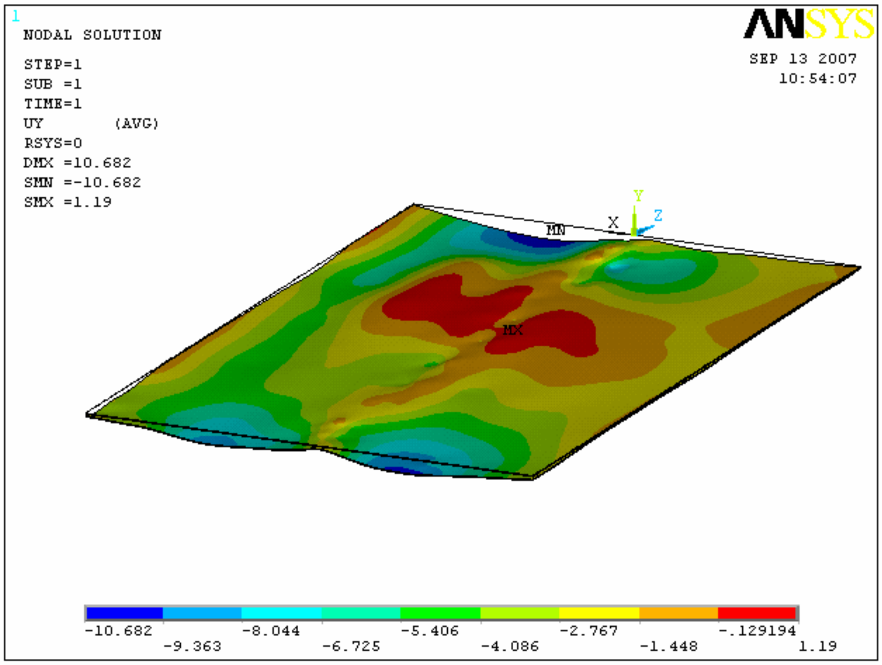


Figure 29: Net Plate Deformation before Welding (No Weld)
(No Weld No Tension-No Weld with Tension)

PLATE 4 – SIDE 2

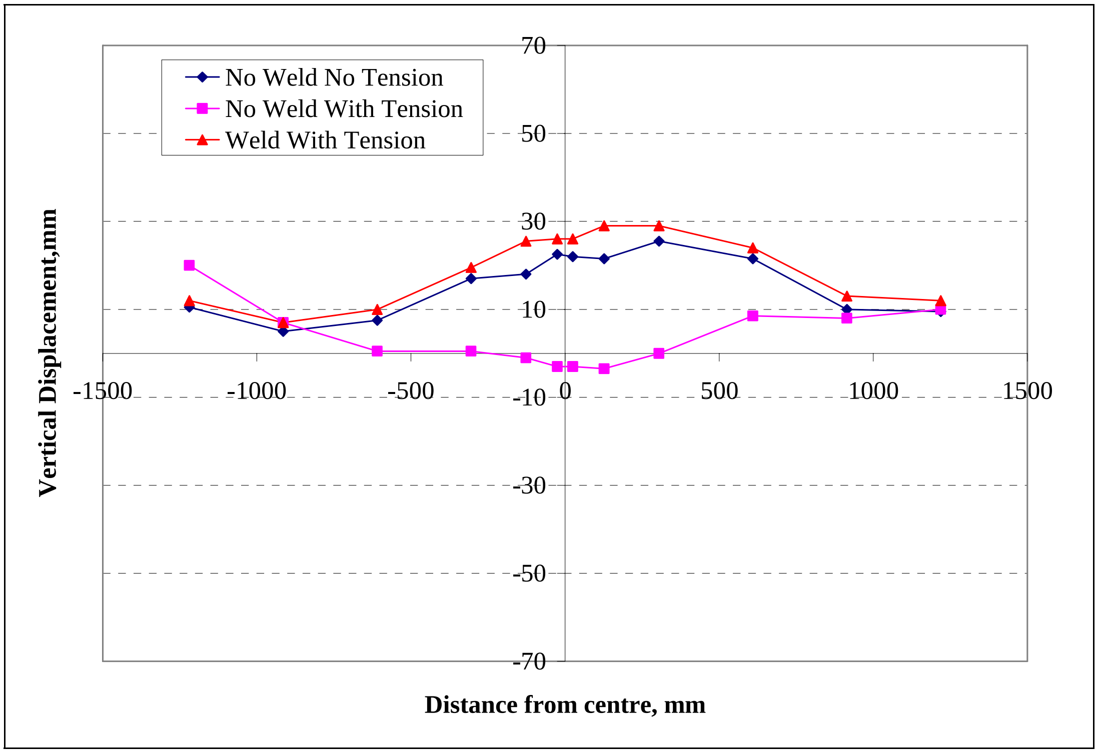


Figure 1: Transverse Section A1

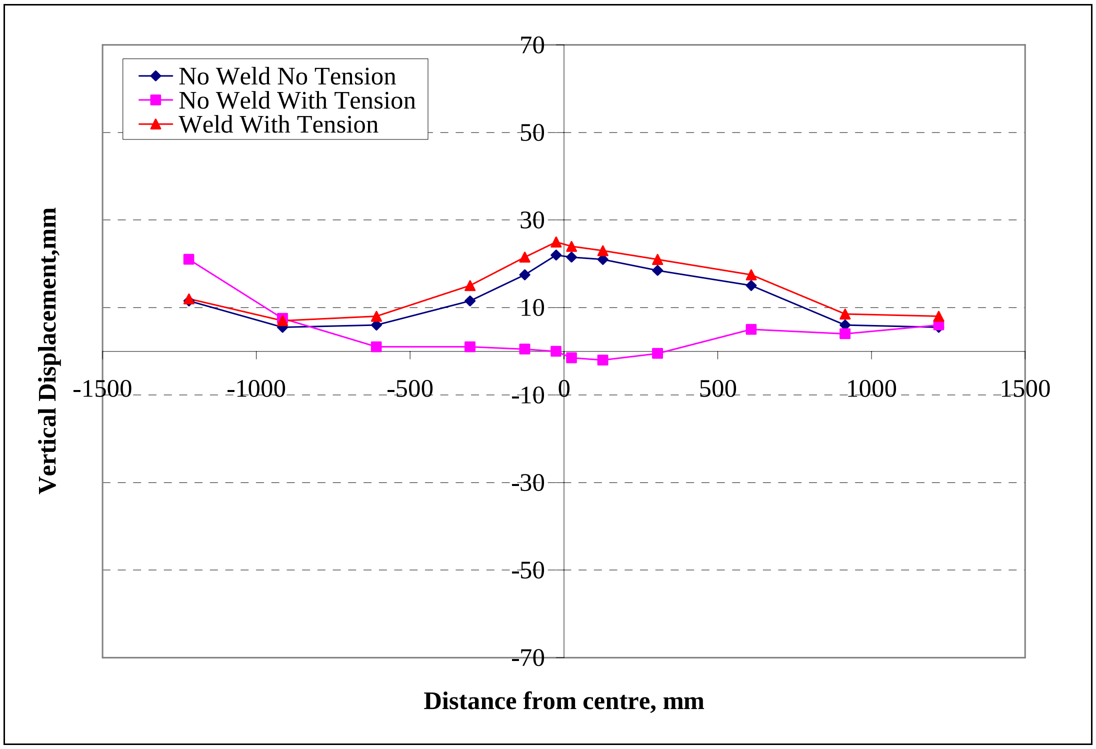


Figure 2: Transverse Section A2

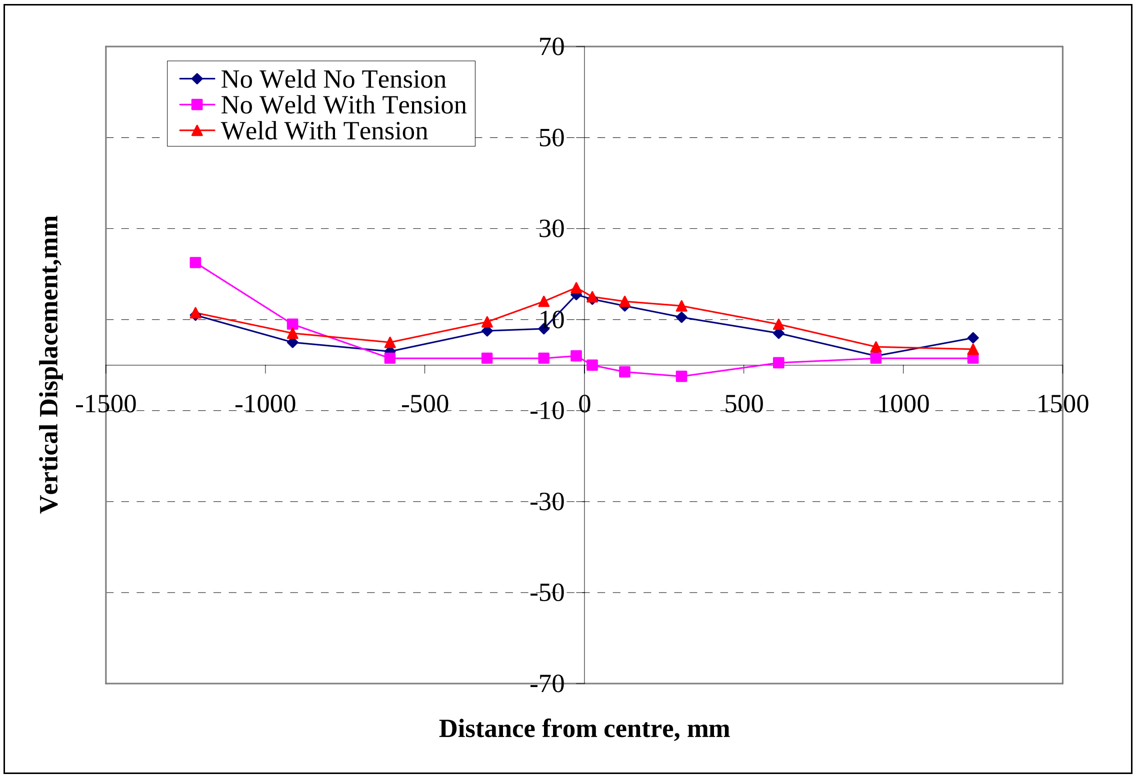


Figure 3: Transverse Section A3

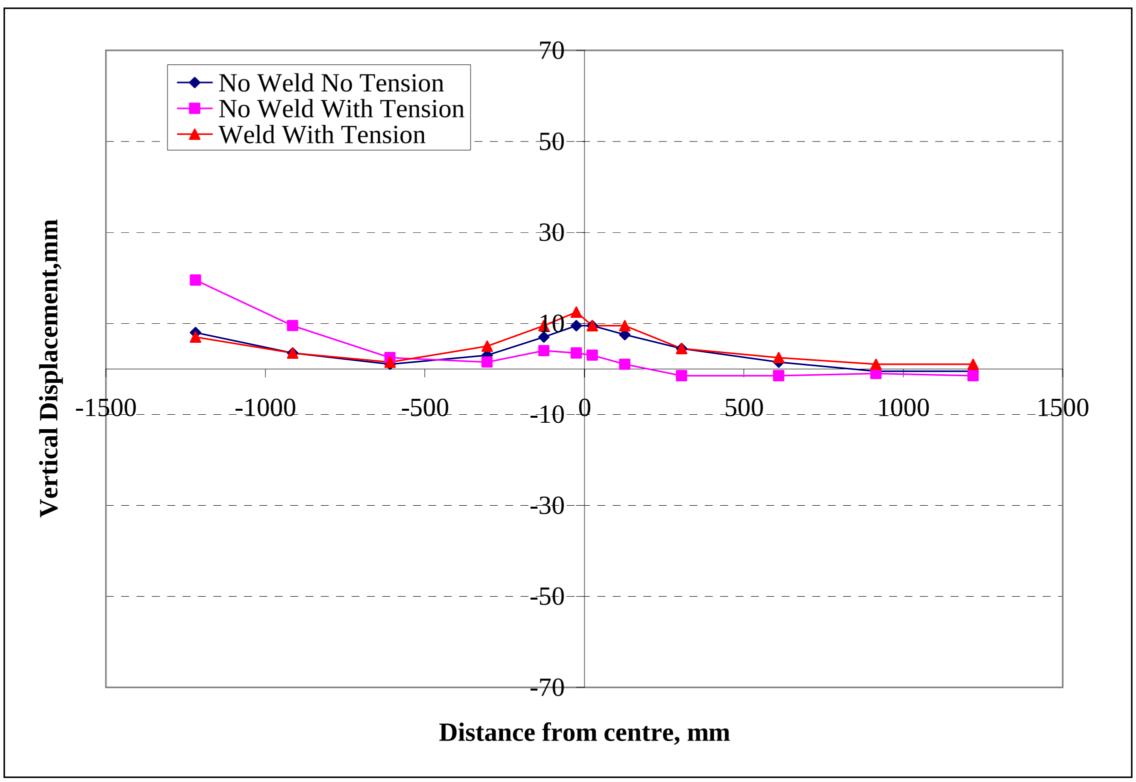


Figure 4: Transverse Section A5

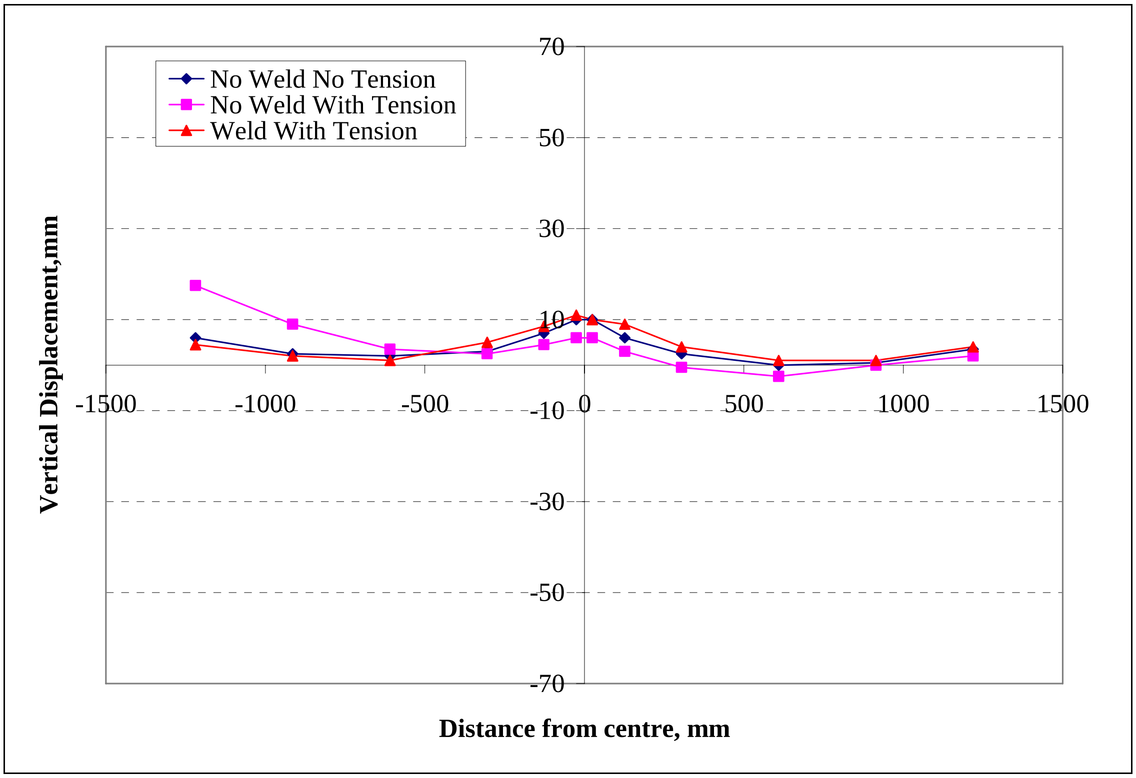


Figure 5: Transverse Section A7

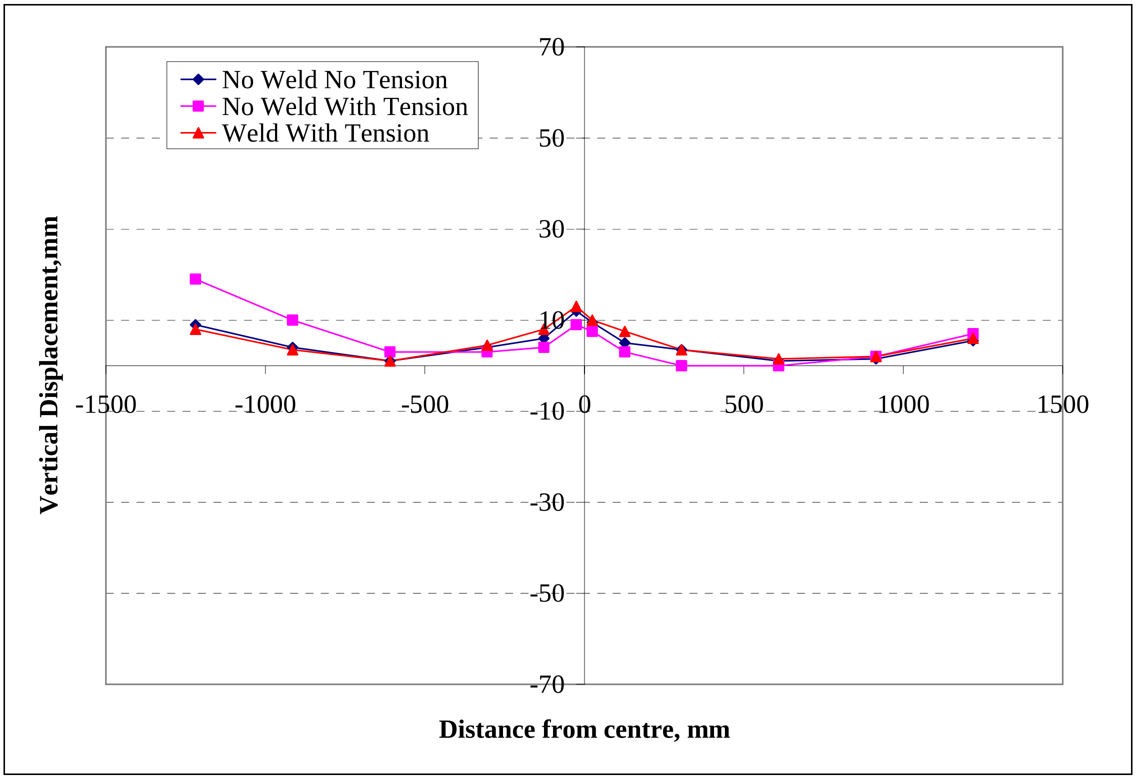


Figure 6: Transverse Section A9

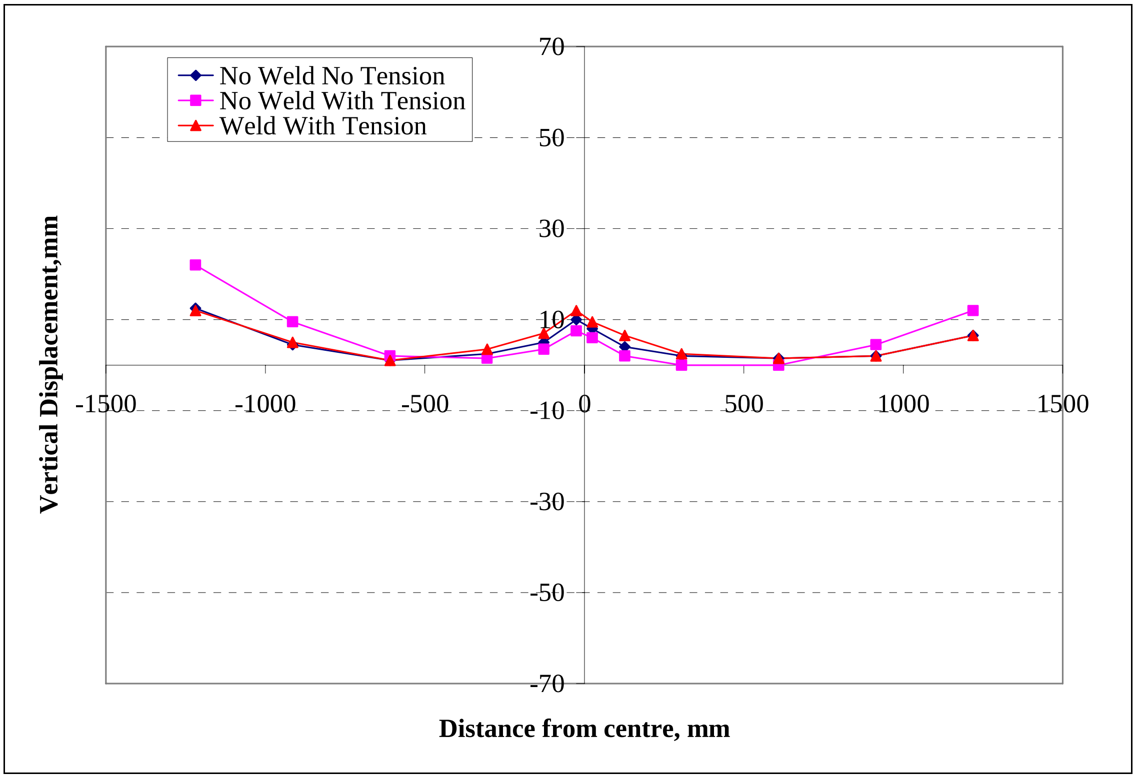


Figure 7: Transverse Section A11

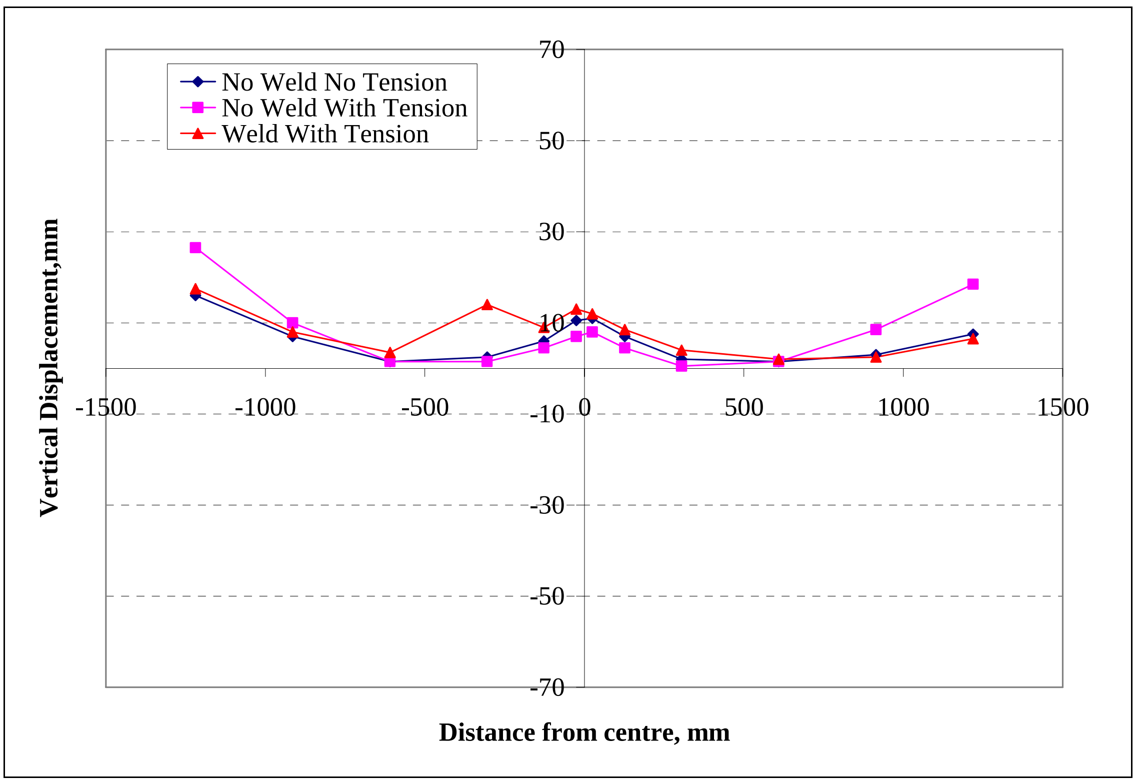


Figure 8: Transverse Section A13

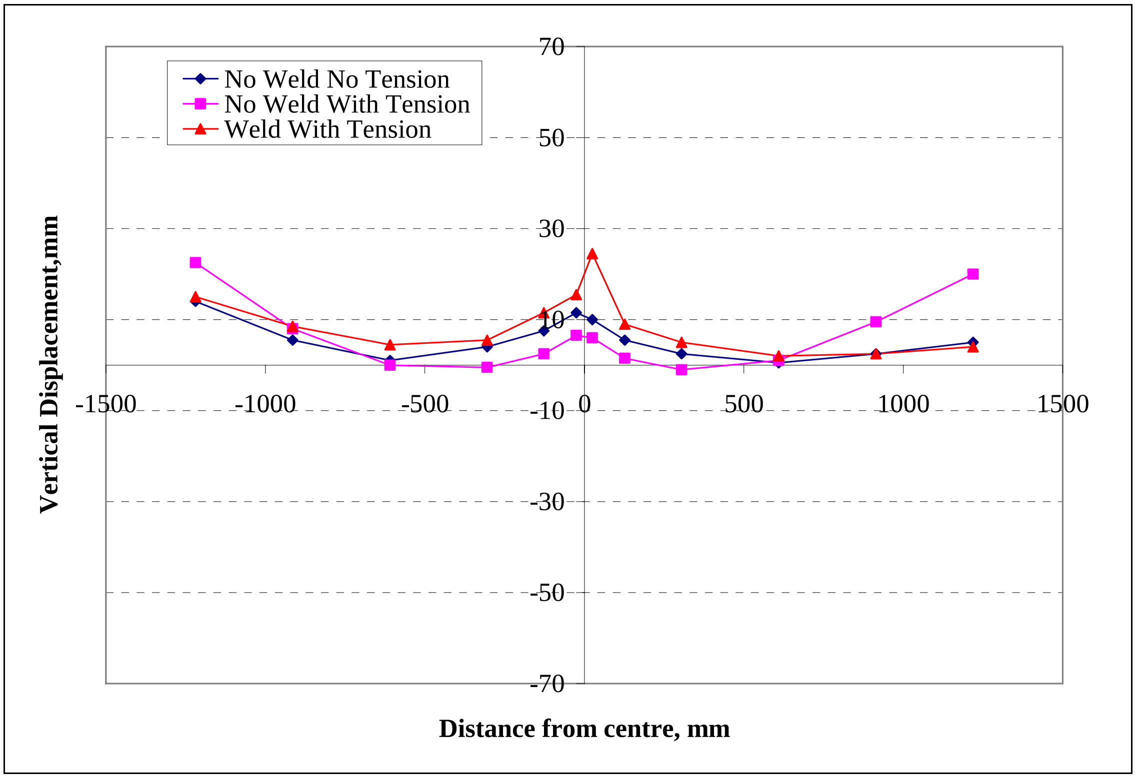


Figure 9: Transverse Section A15

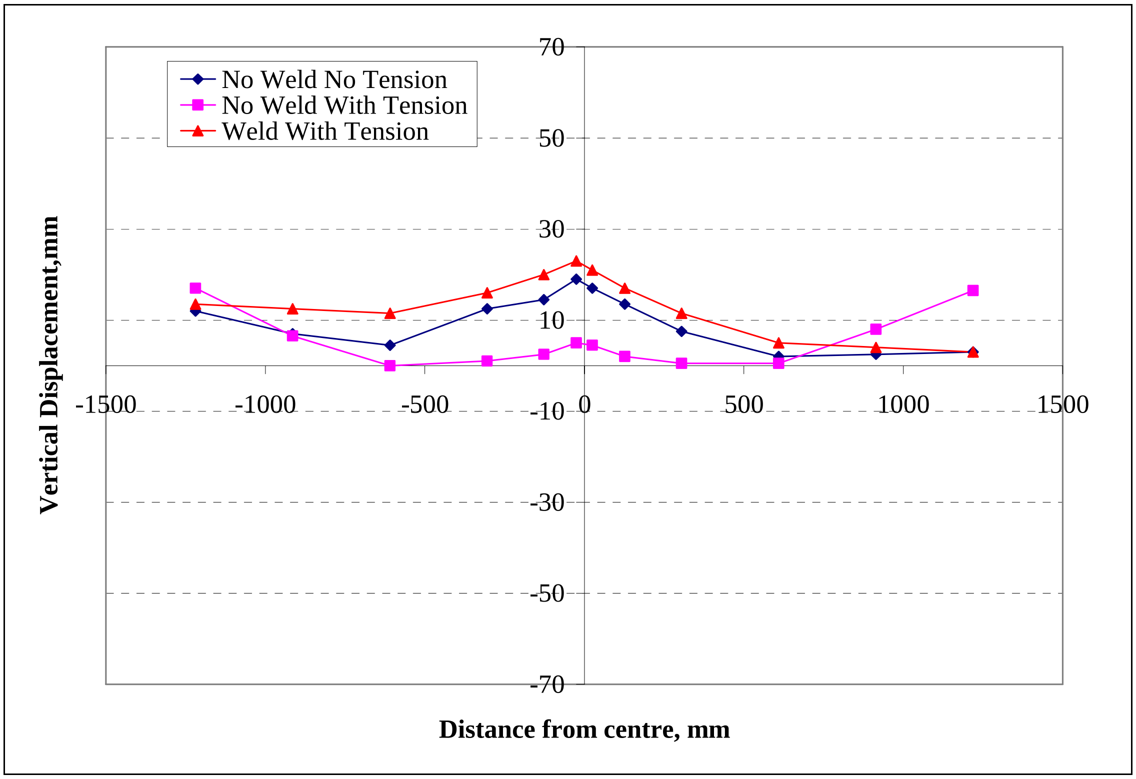


Figure 10: Transverse Section A17

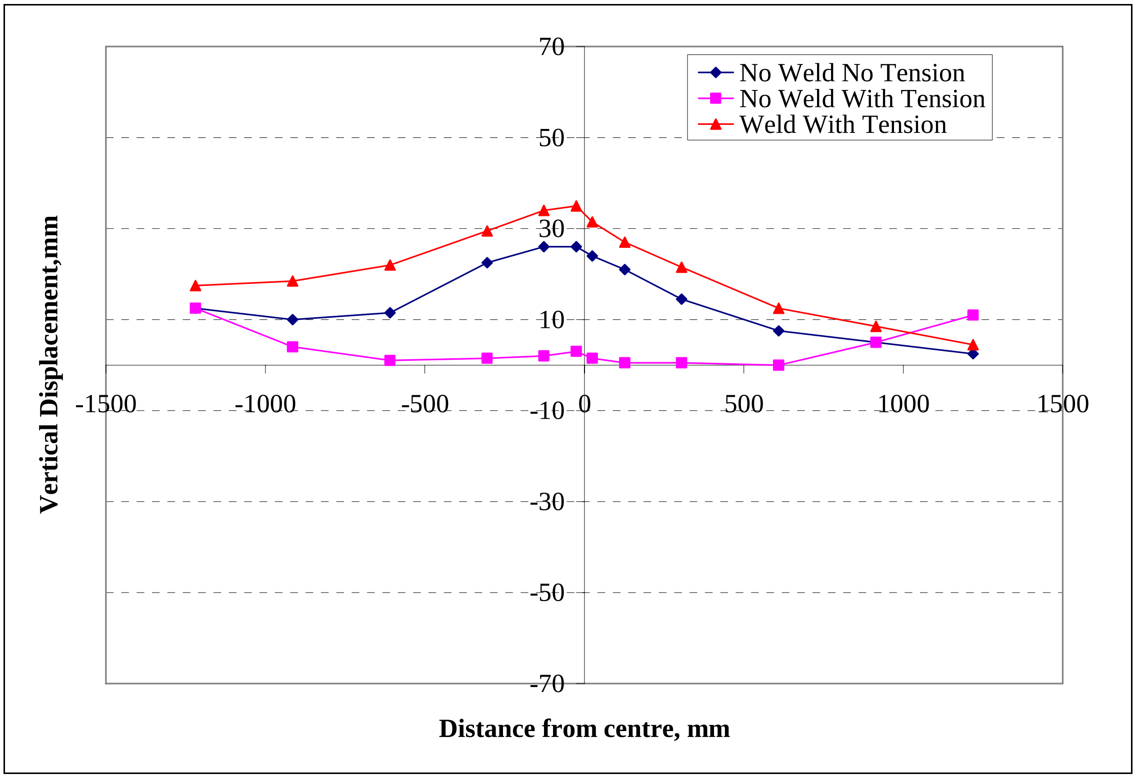


Figure 11: Transverse Section A19

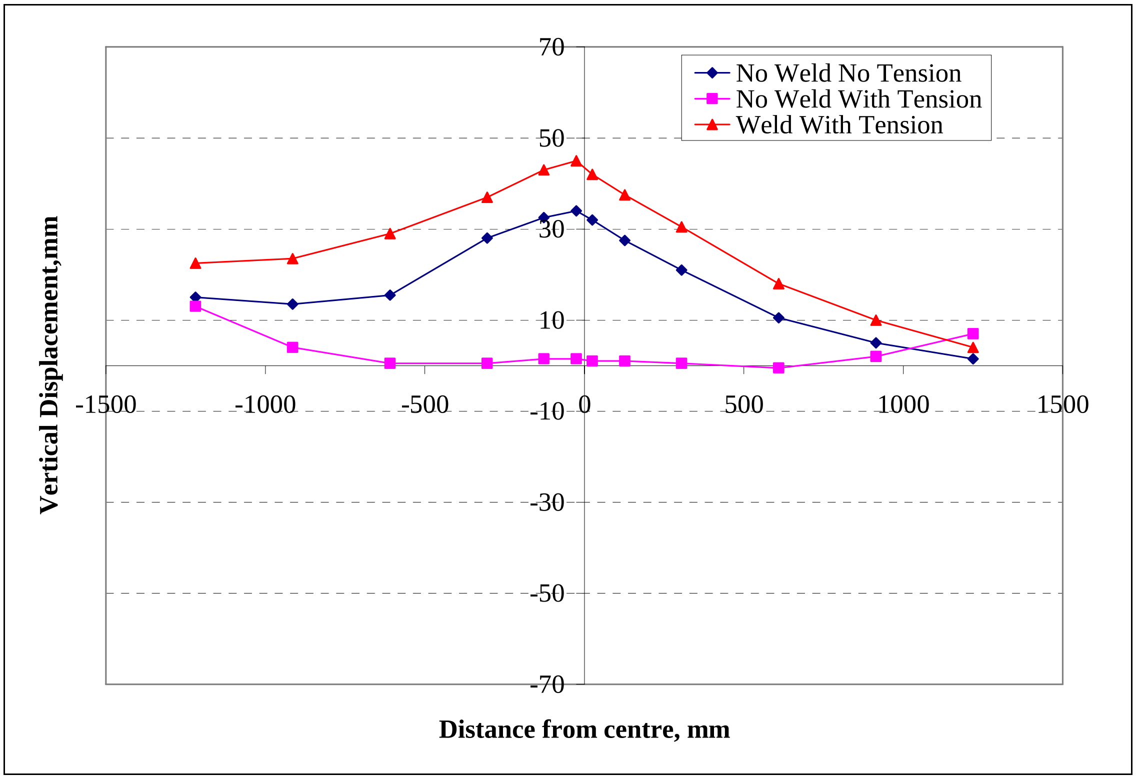


Figure 12: Transverse Section A20

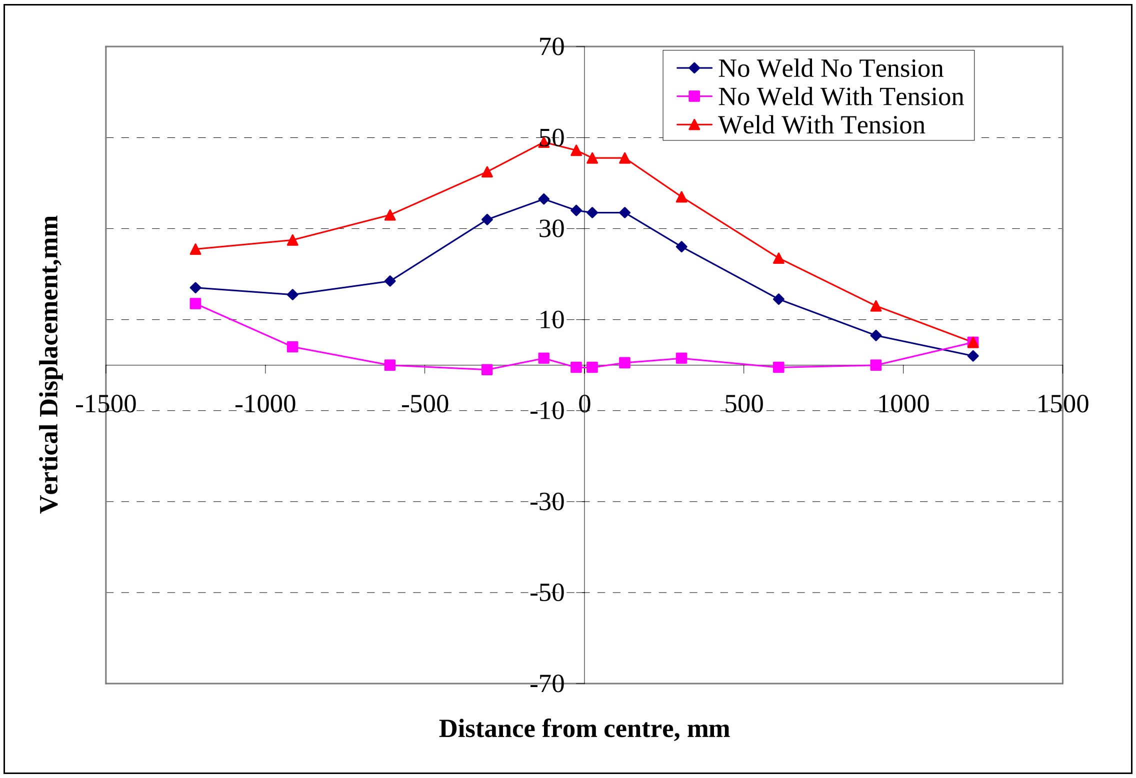


Figure 13: Transverse Section A21

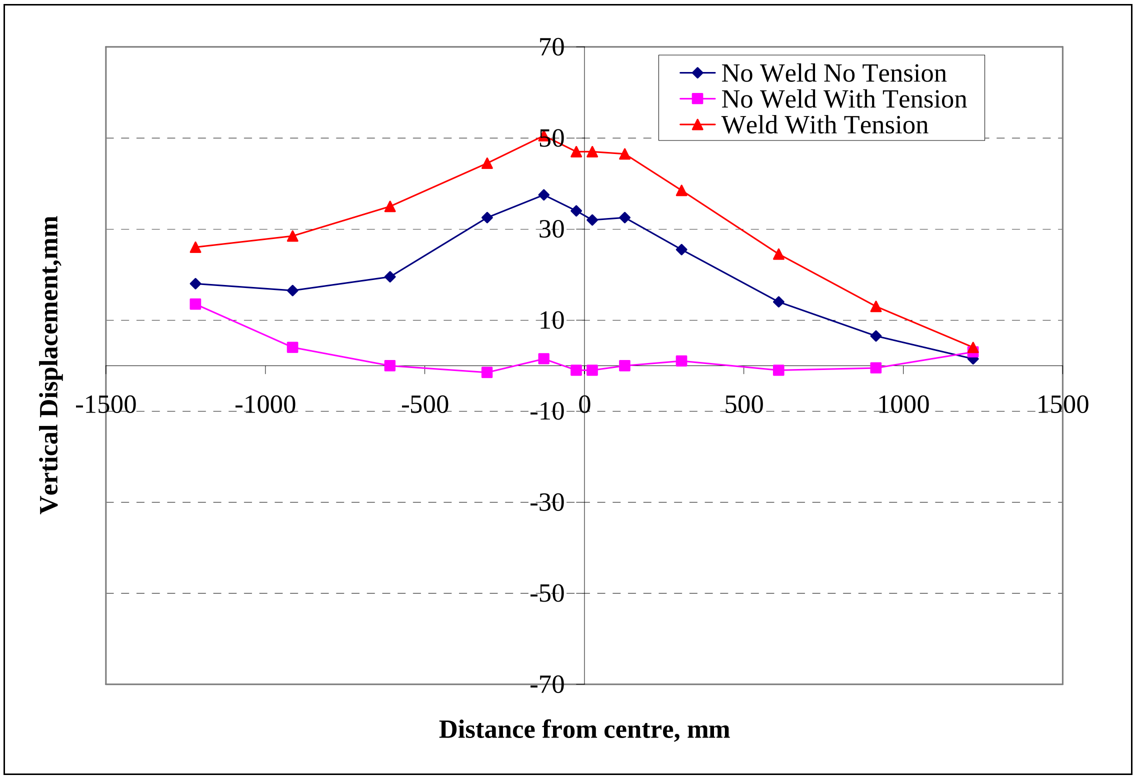


Figure 14: Transverse Section A22

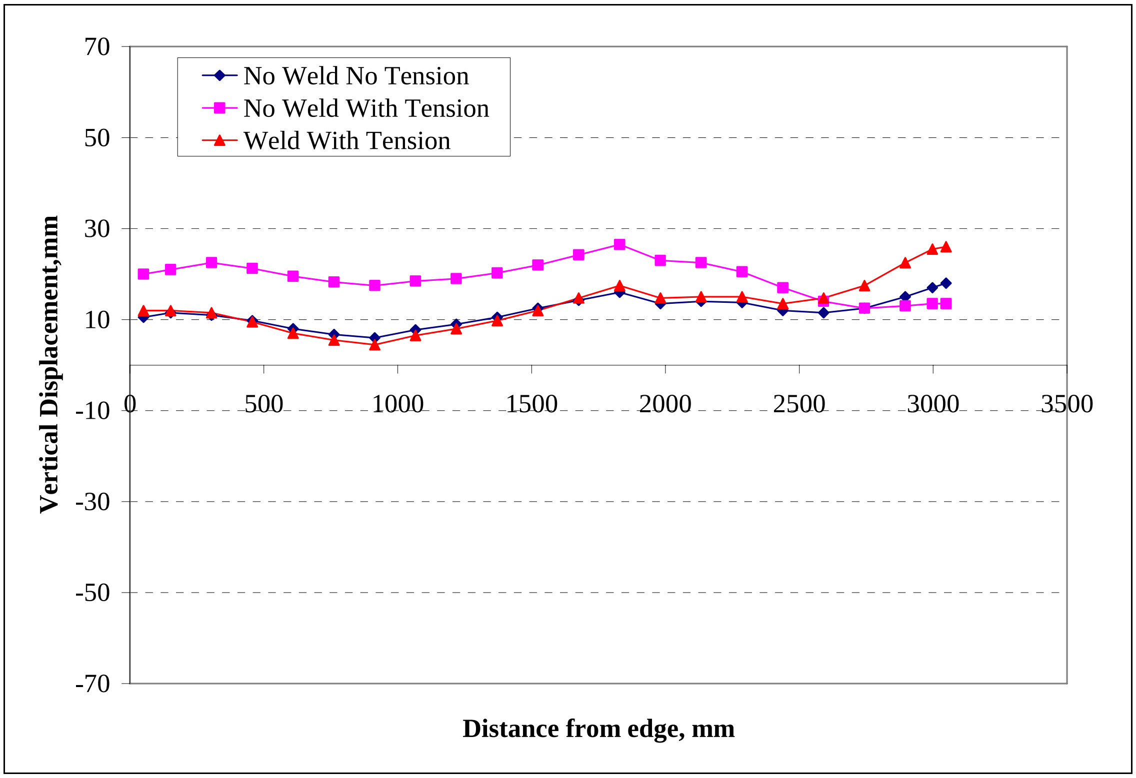


Figure 15: Longitudinal Section A

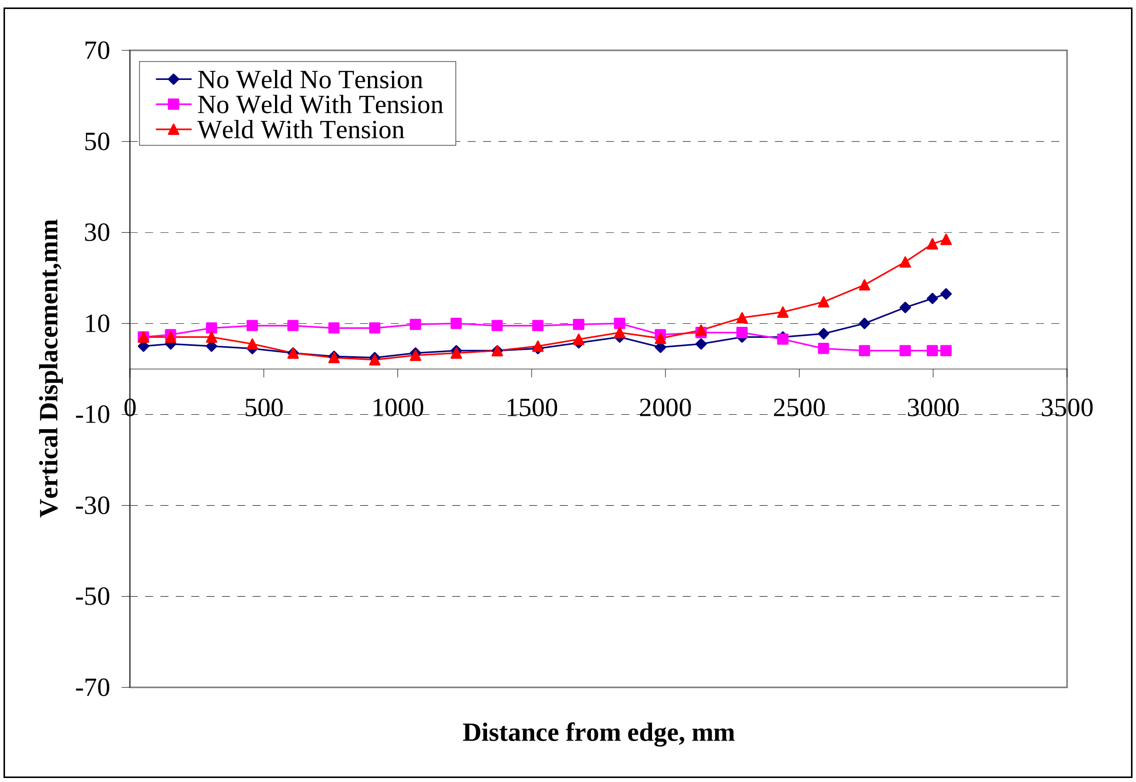


Figure 16: Longitudinal Section B

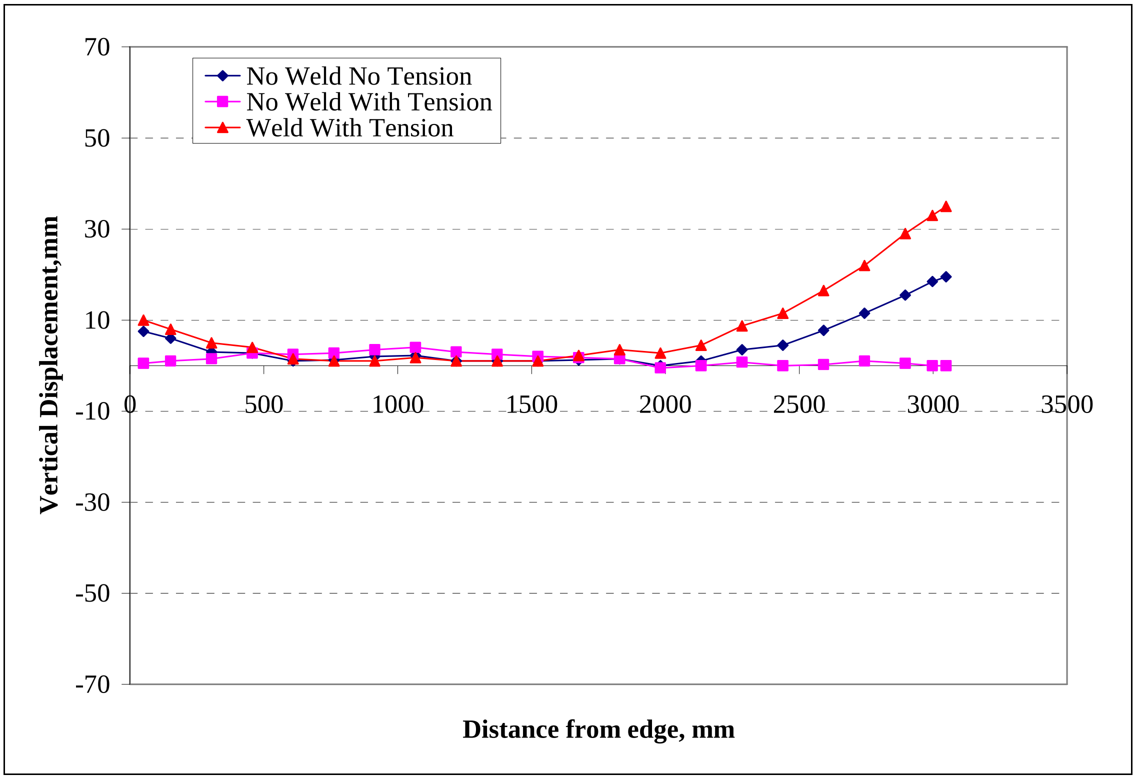


Figure 17: Longitudinal Section C

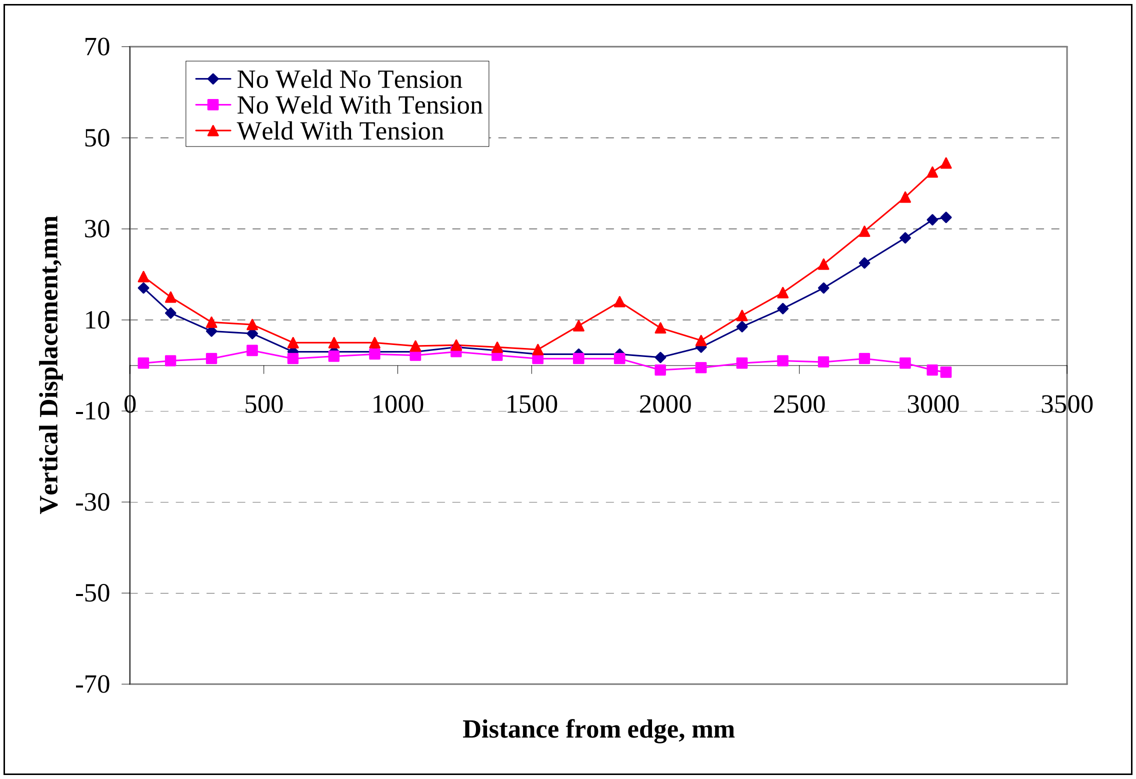


Figure 18: Longitudinal Section D

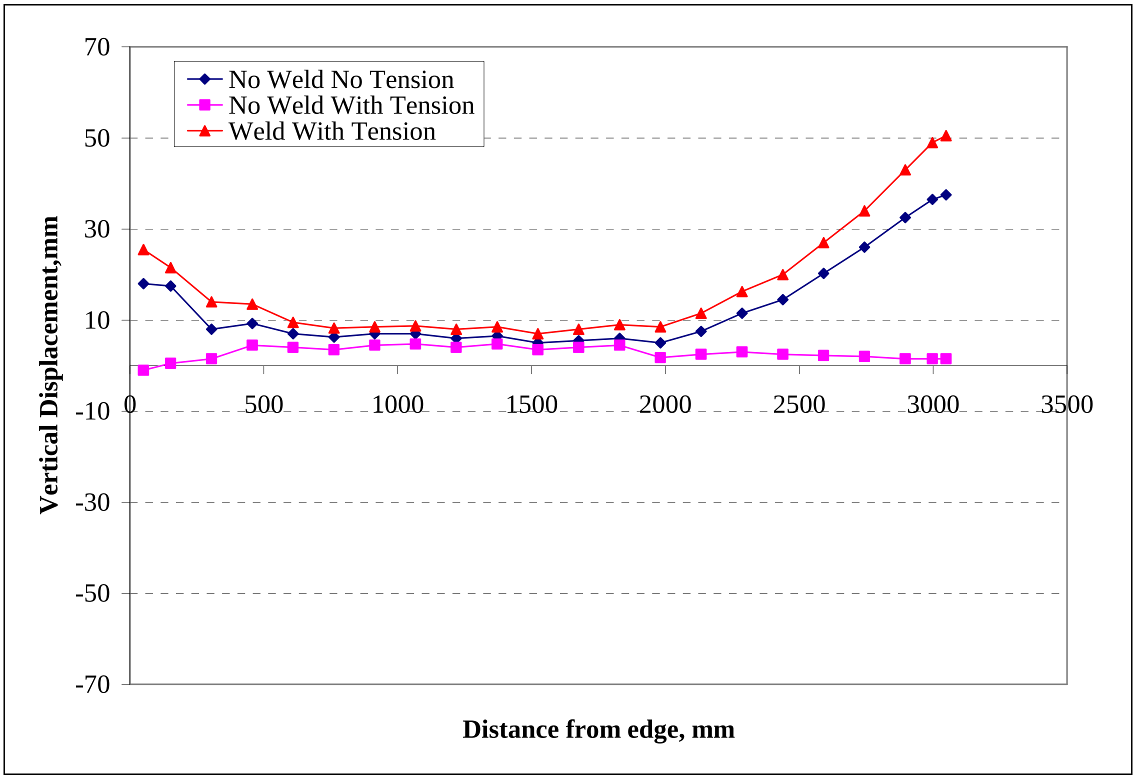


Figure 19: Longitudinal Section E

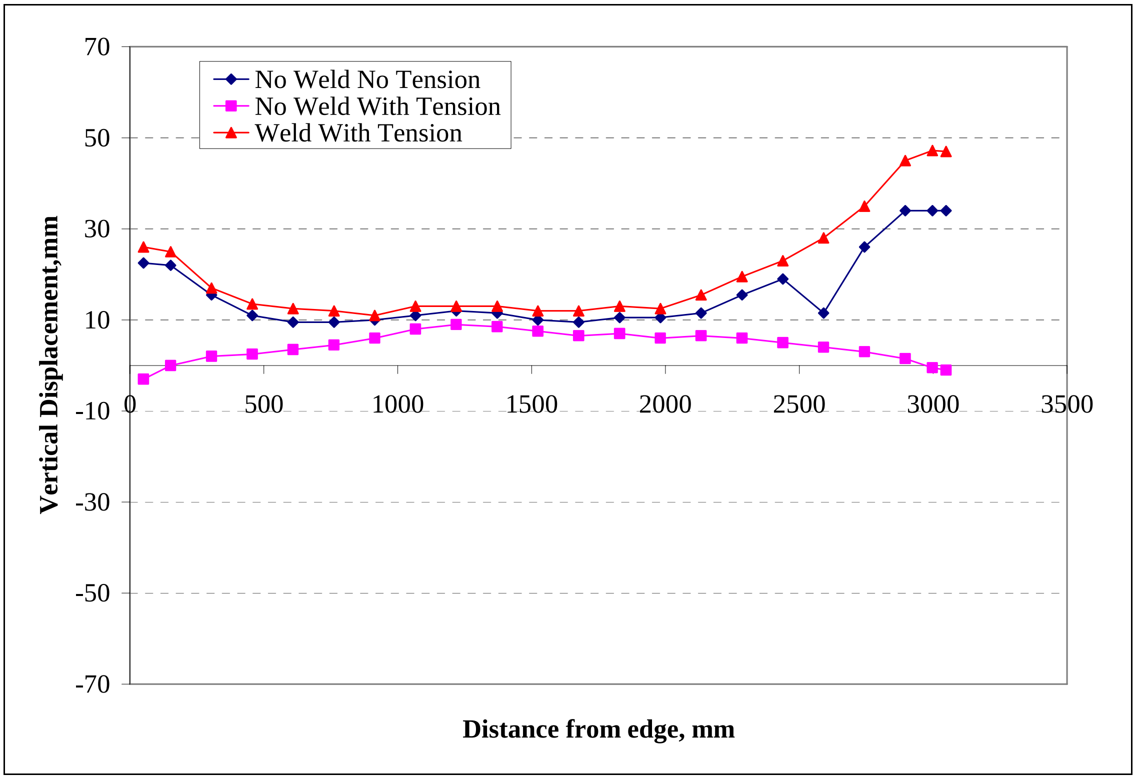


Figure 20: Longitudinal Section F

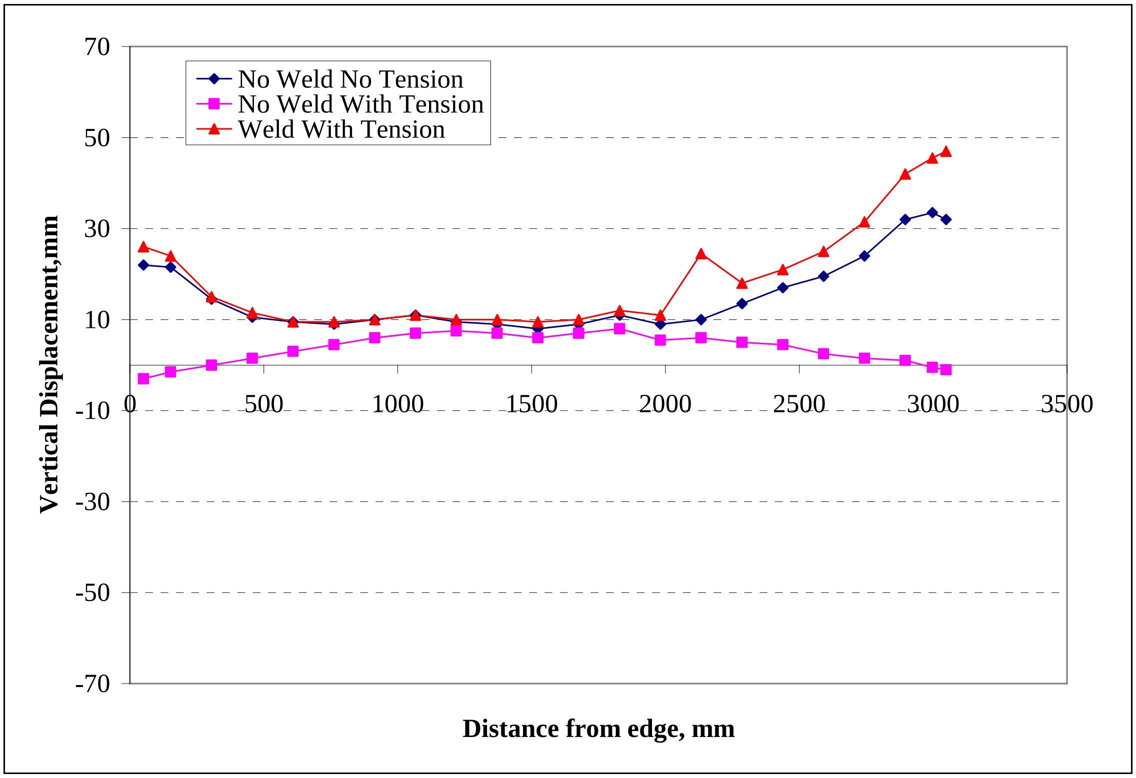


Figure 21: Longitudinal Section G

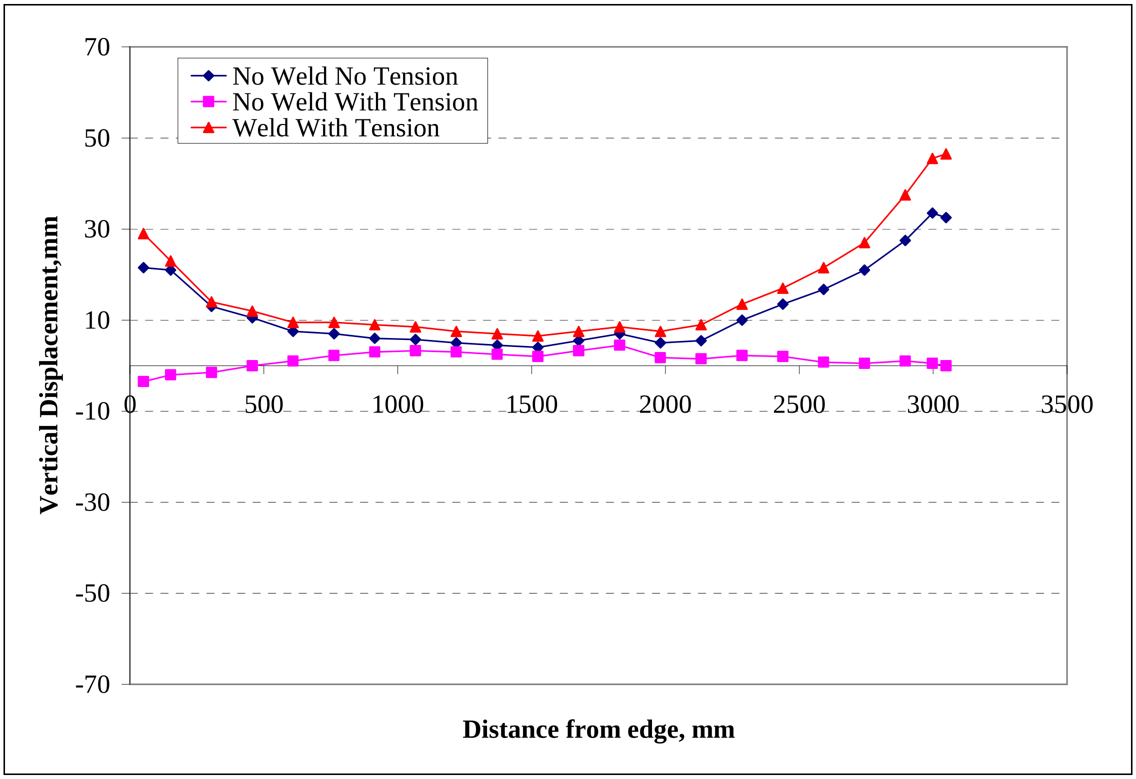


Figure 22: Longitudinal Section H

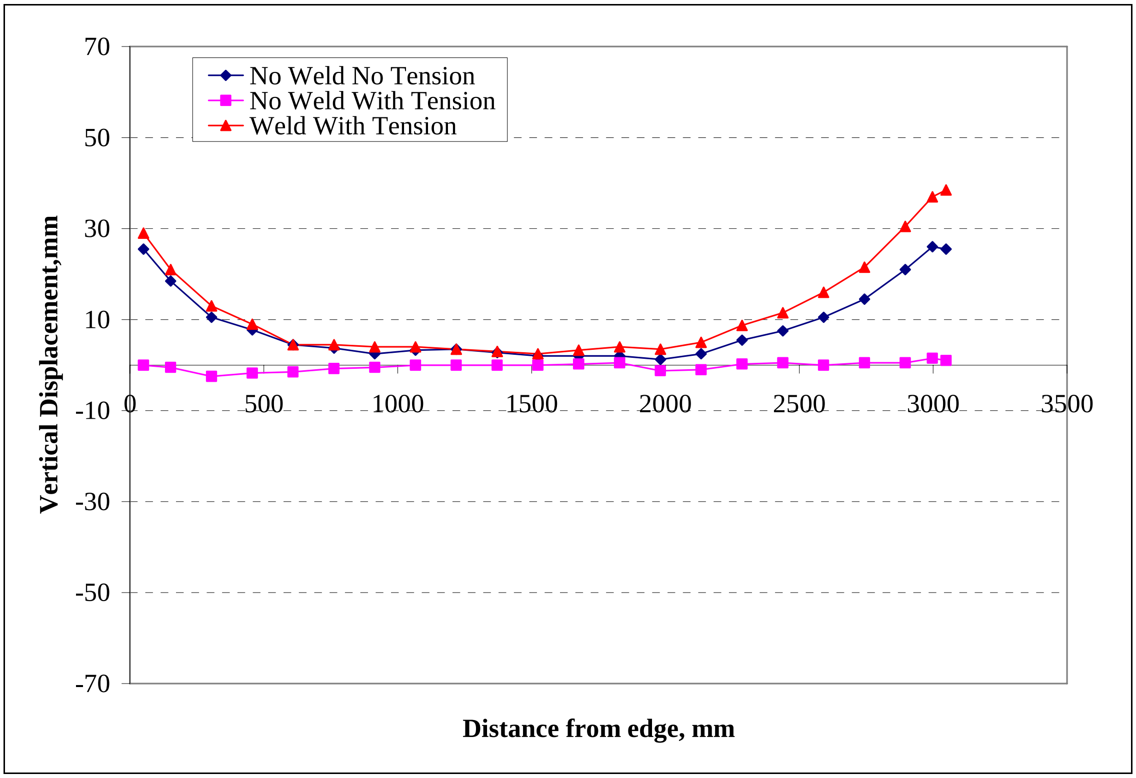


Figure 23: Longitudinal Section I

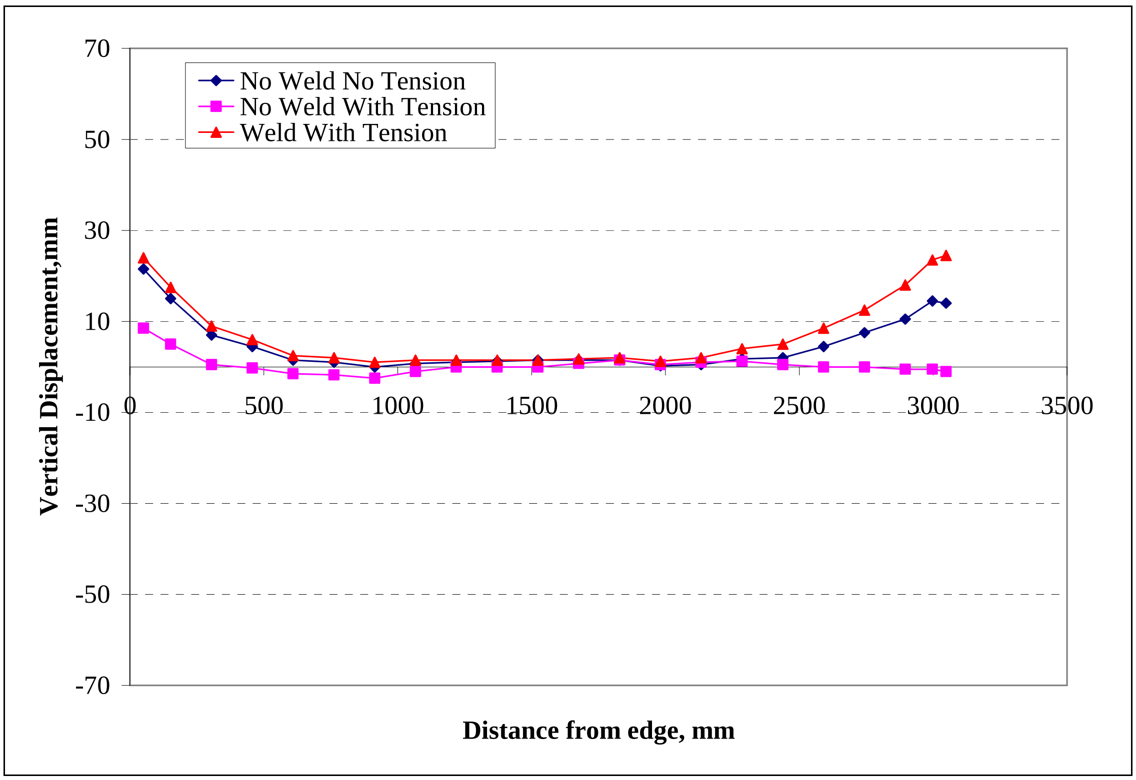


Figure 24: Longitudinal Section J

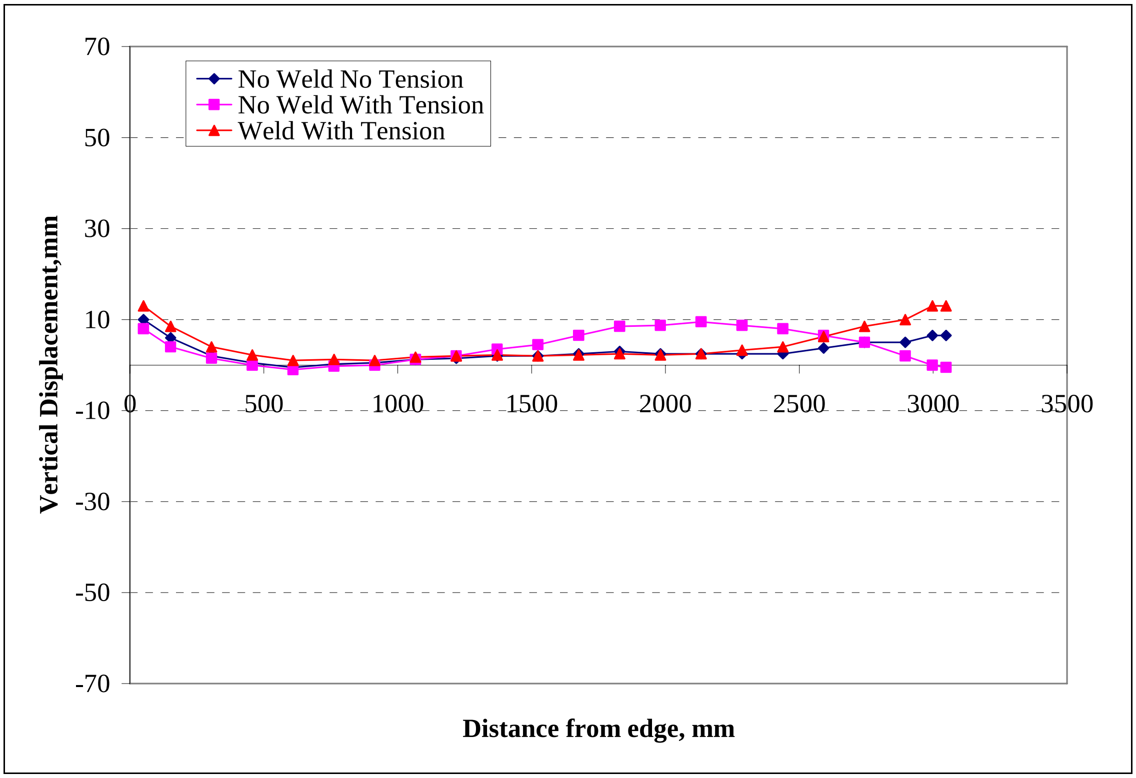


Figure 25: Longitudinal Section K

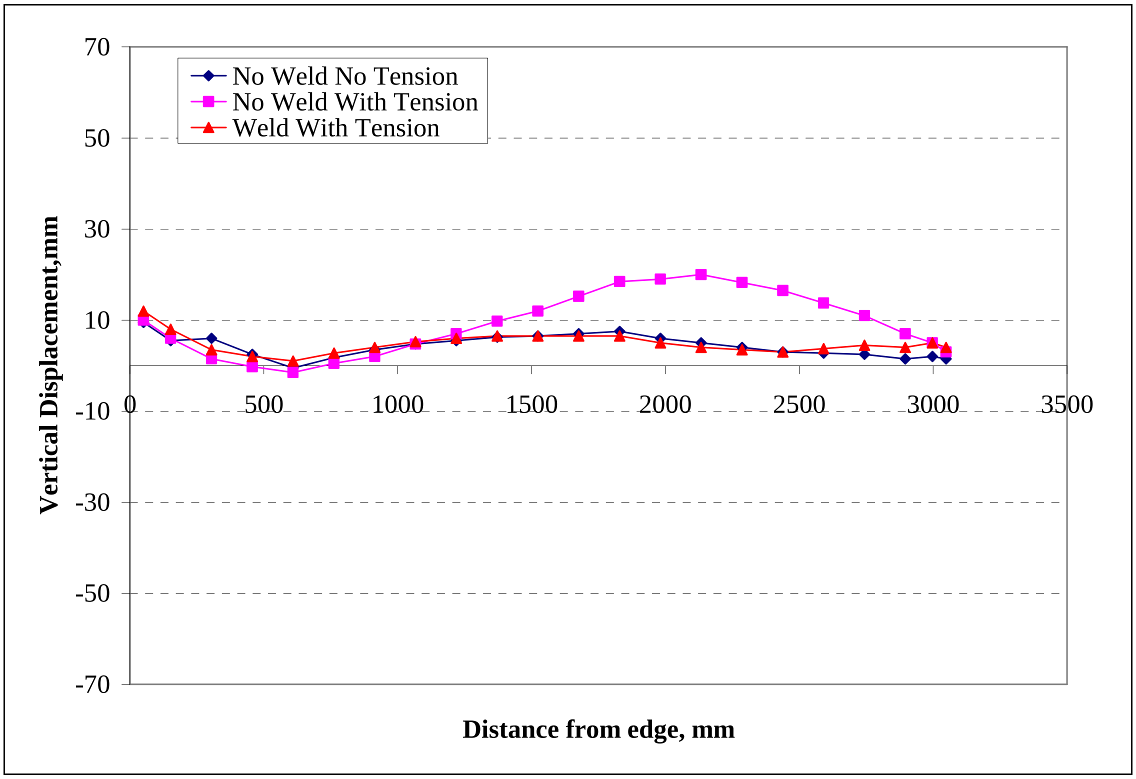


Figure 26: Longitudinal Section L

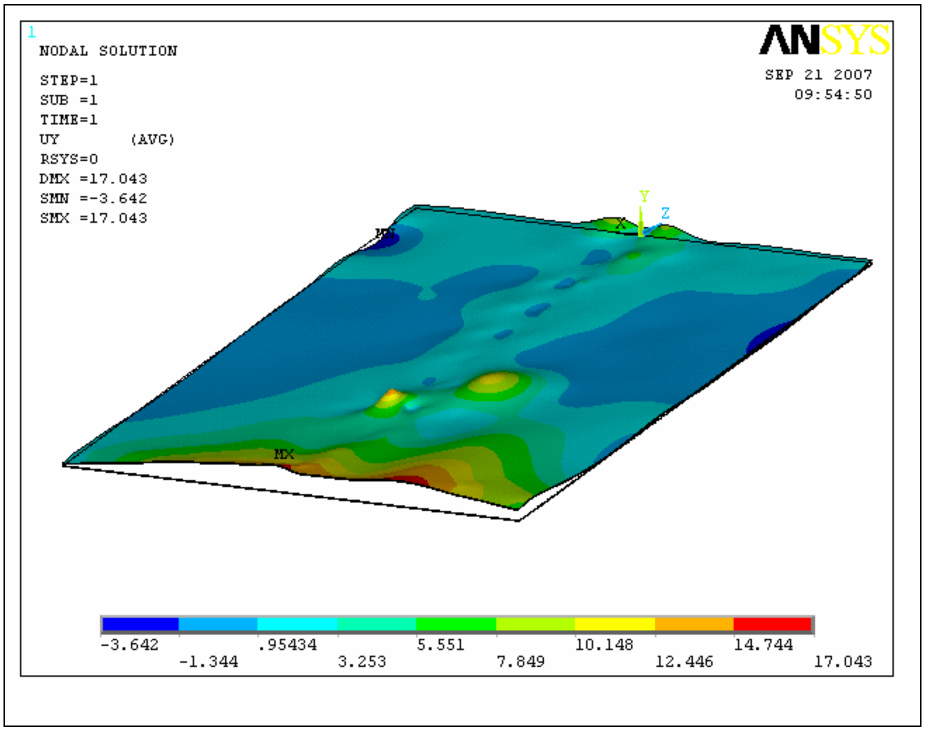


Figure 27: Net Plate Deformation (No Weld No Tension -Weld under Tension)

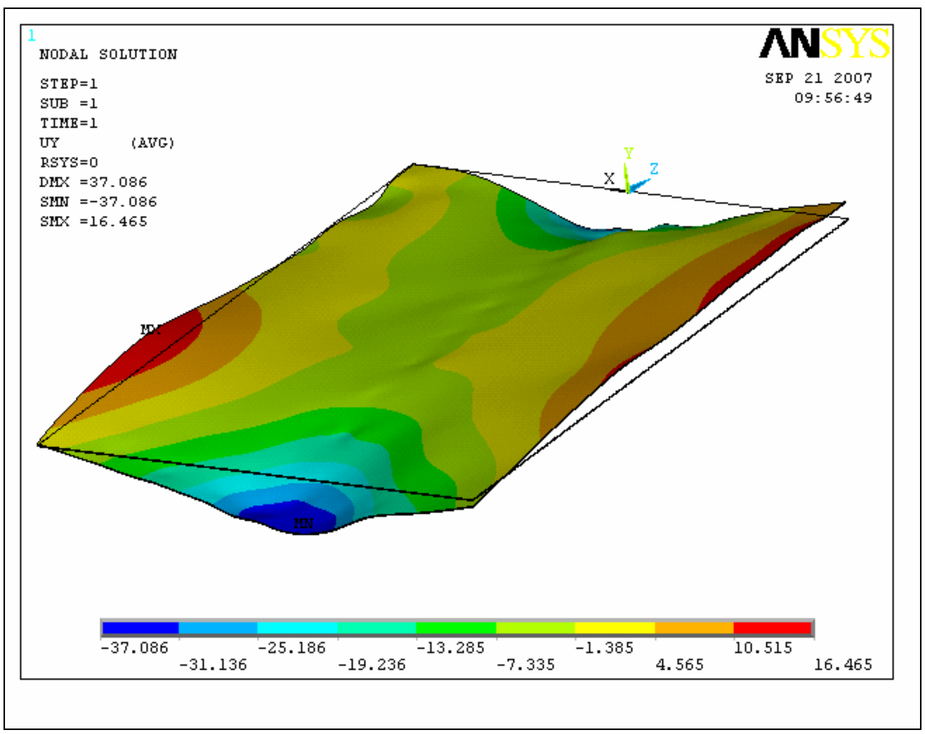


Figure 28: Net Plate Deformation after Welding (No Weld with Tension-Weld under Tension)

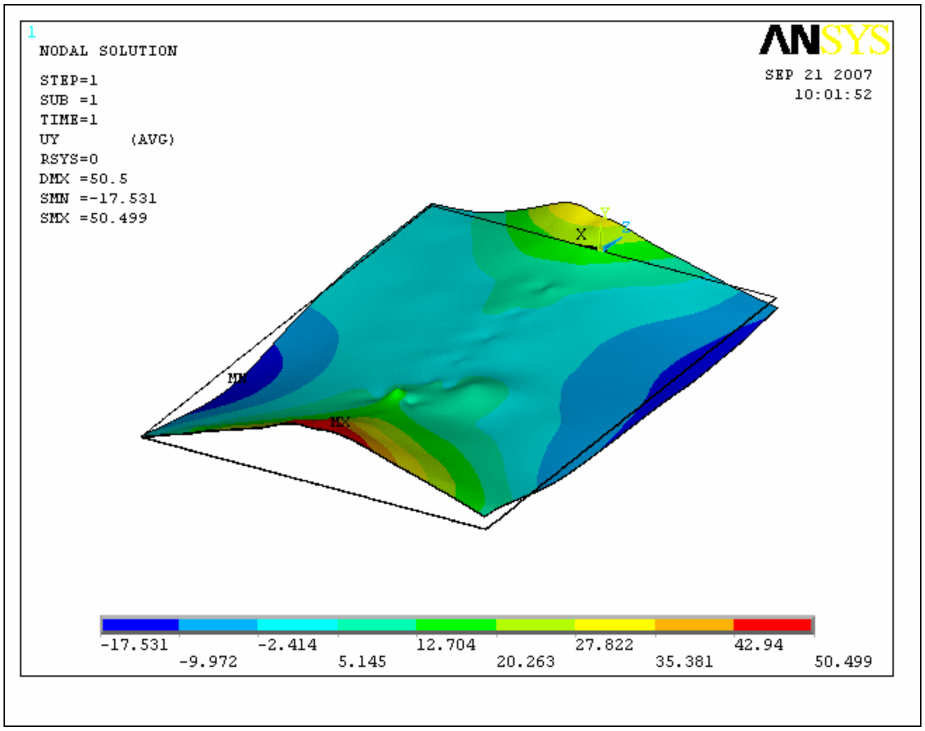


Figure 29: Net Plate Deformation before Welding (No Weld No Tension-No Weld with Tension)

PLATE 5 – SIDE 1

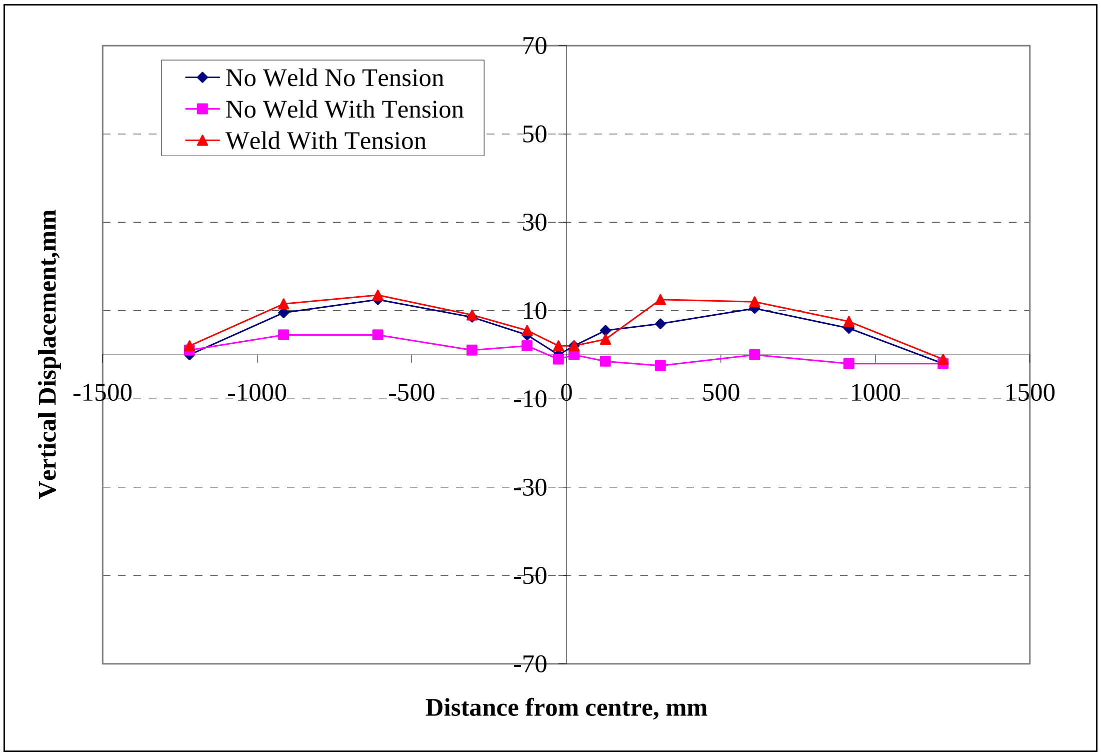


Figure 1: Transverse Section A1

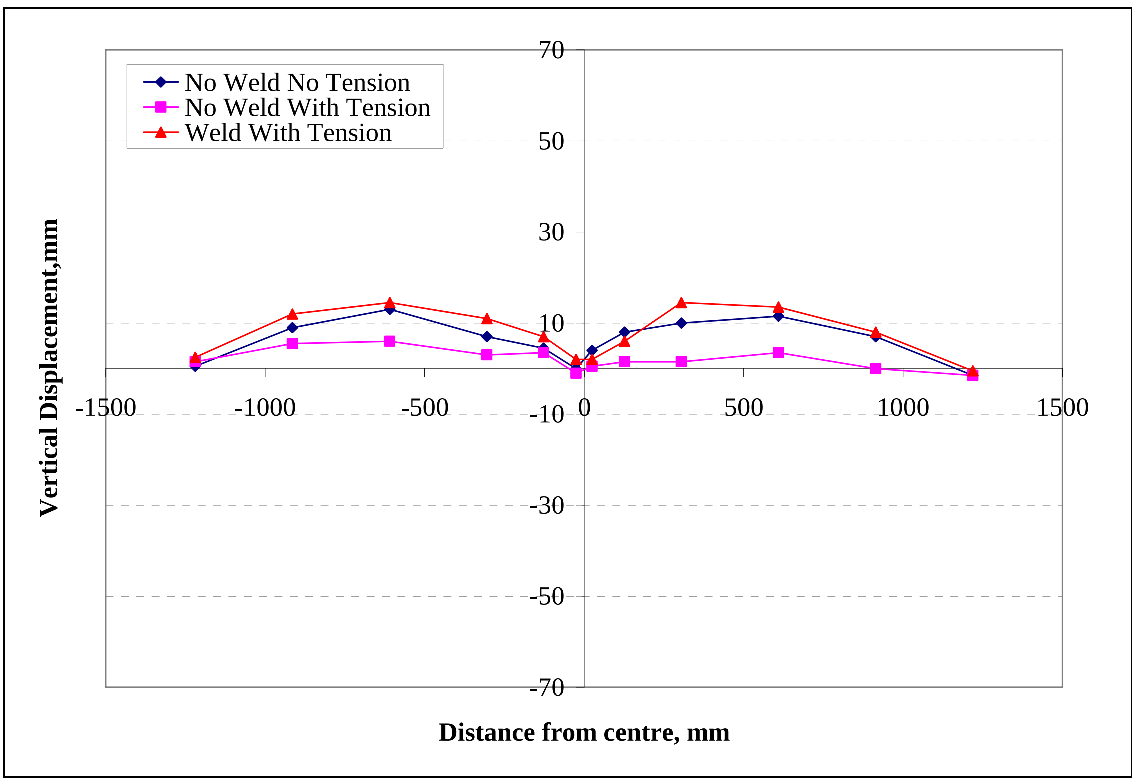


Figure 2: Transverse Section A2

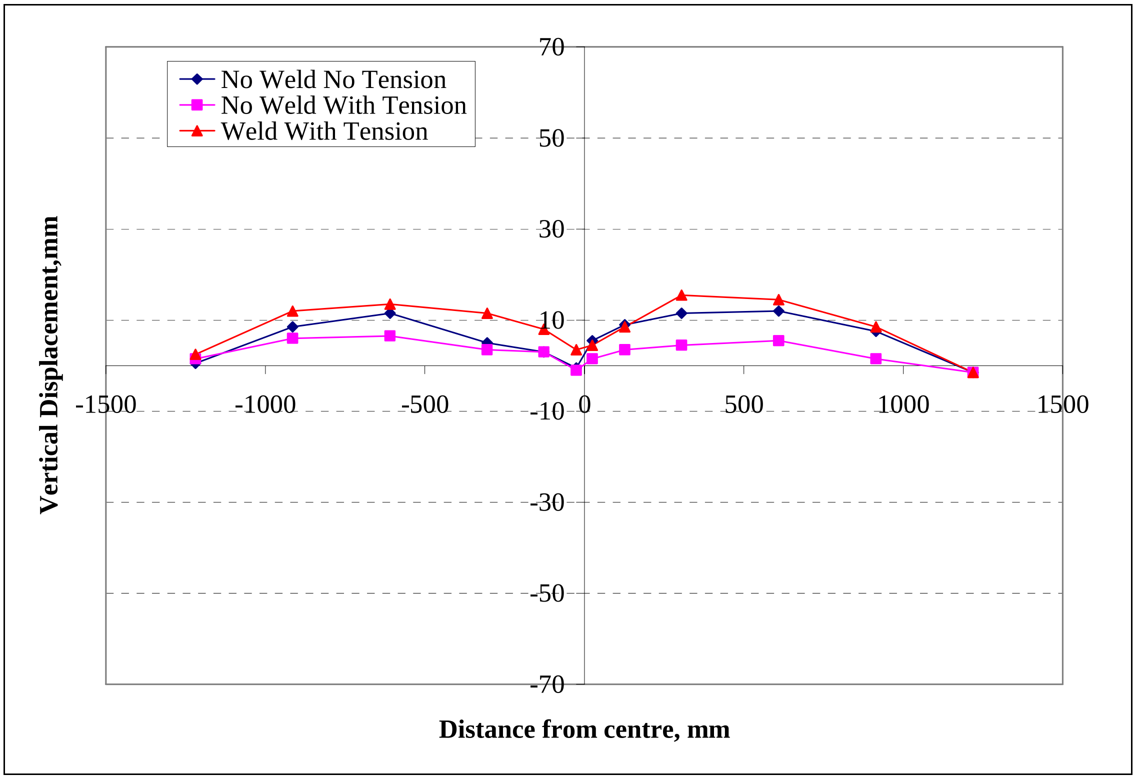


Figure 3: Transverse Section A3

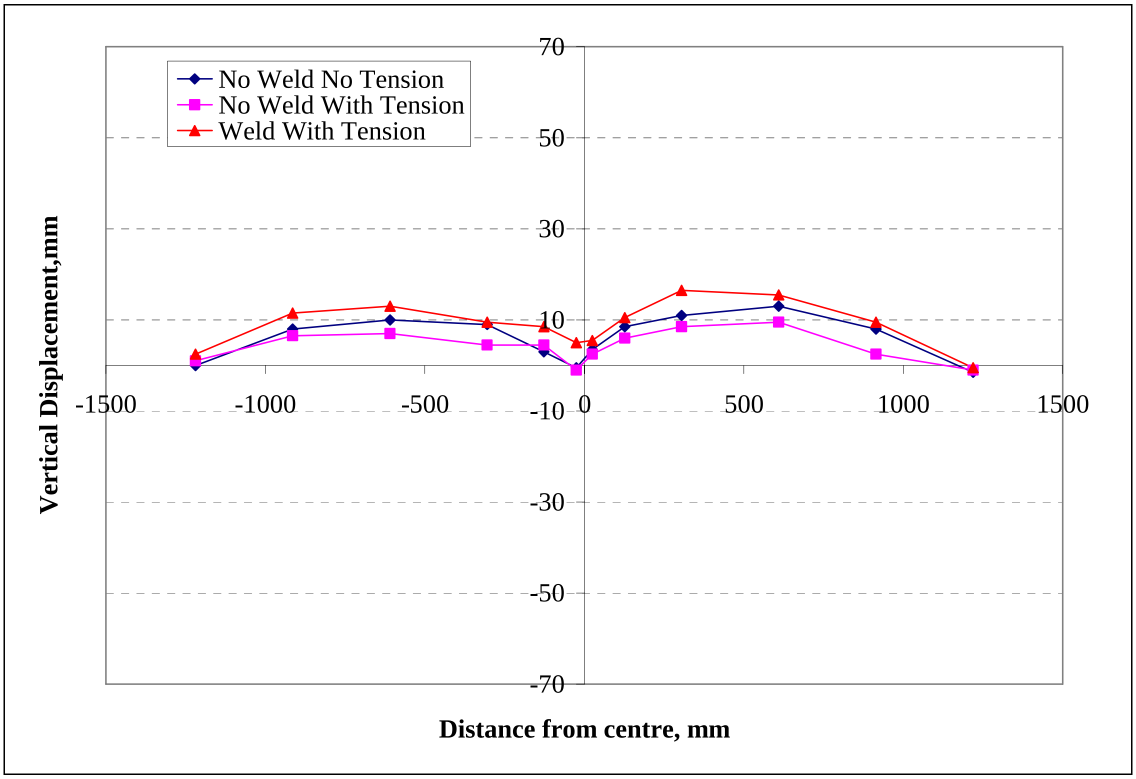


Figure 4: Transverse Section A5

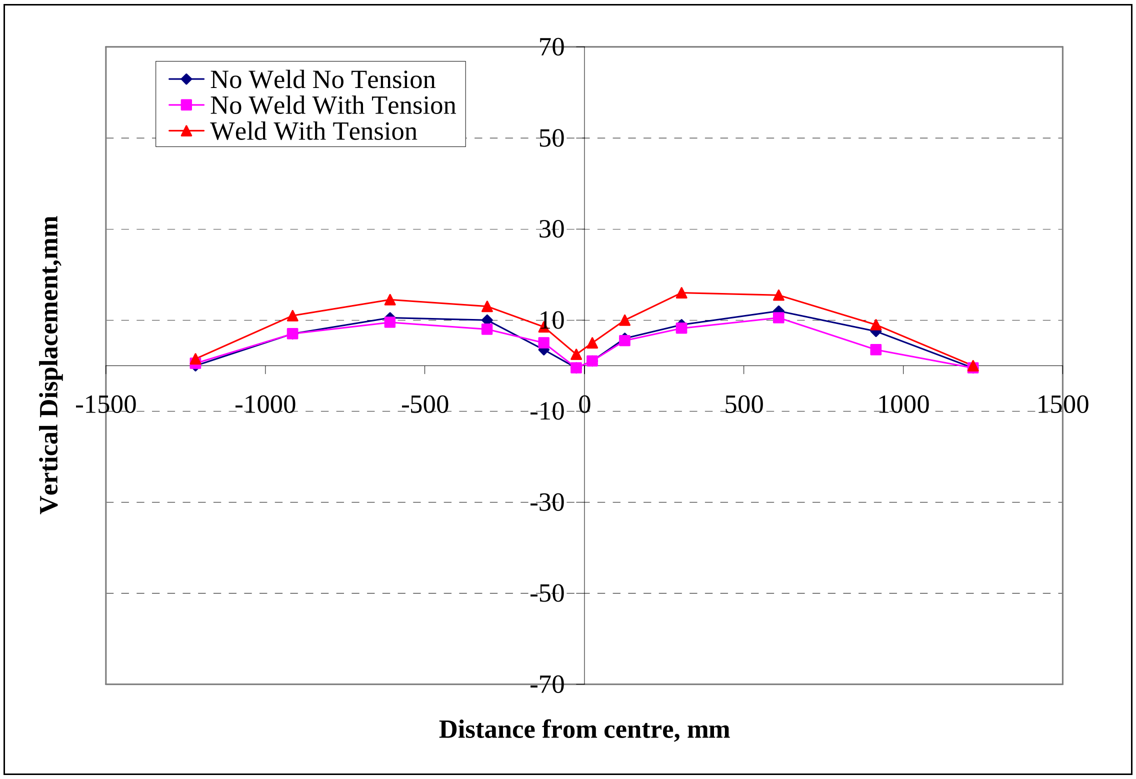


Figure 5: Transverse Section A7

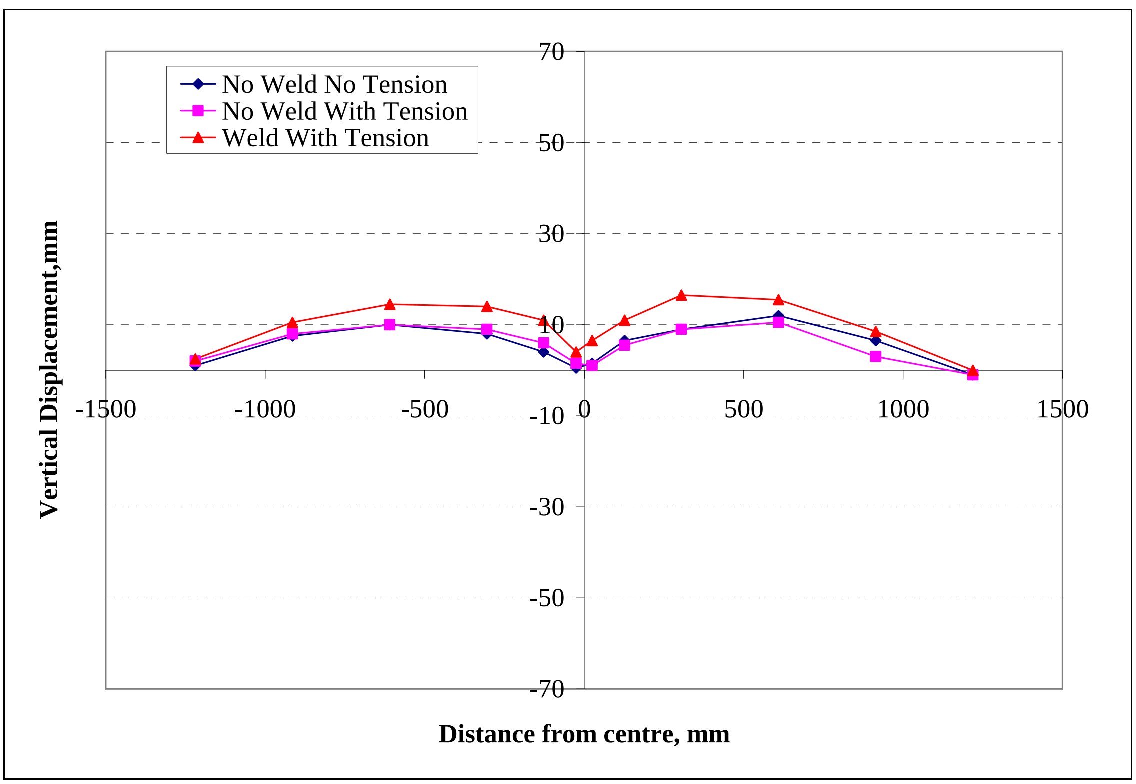


Figure 6: Transverse Section A9

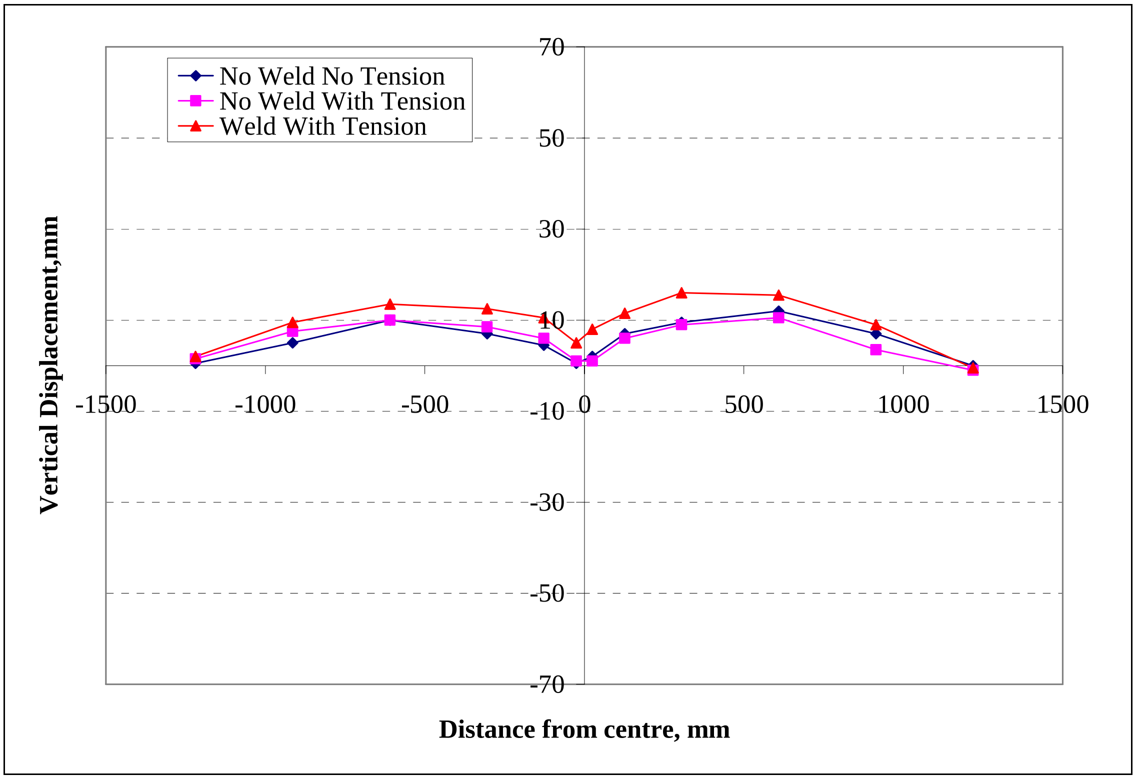


Figure 7: Transverse Section A11

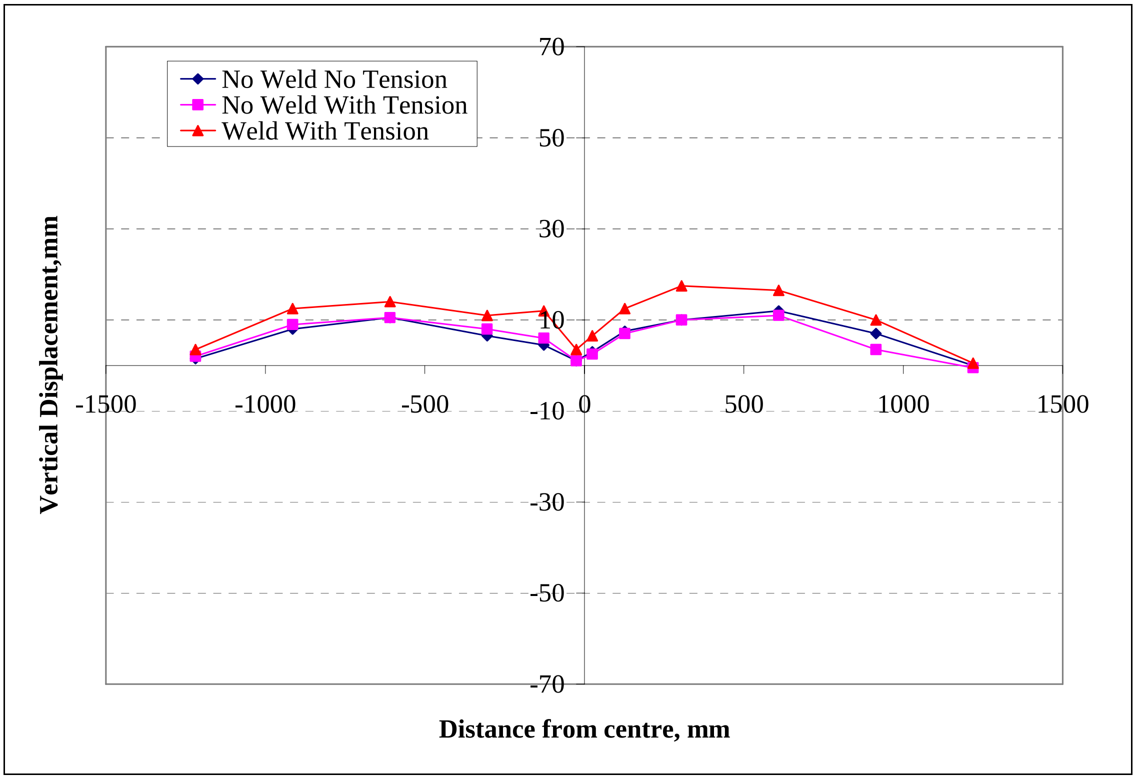


Figure 8: Transverse Section A13

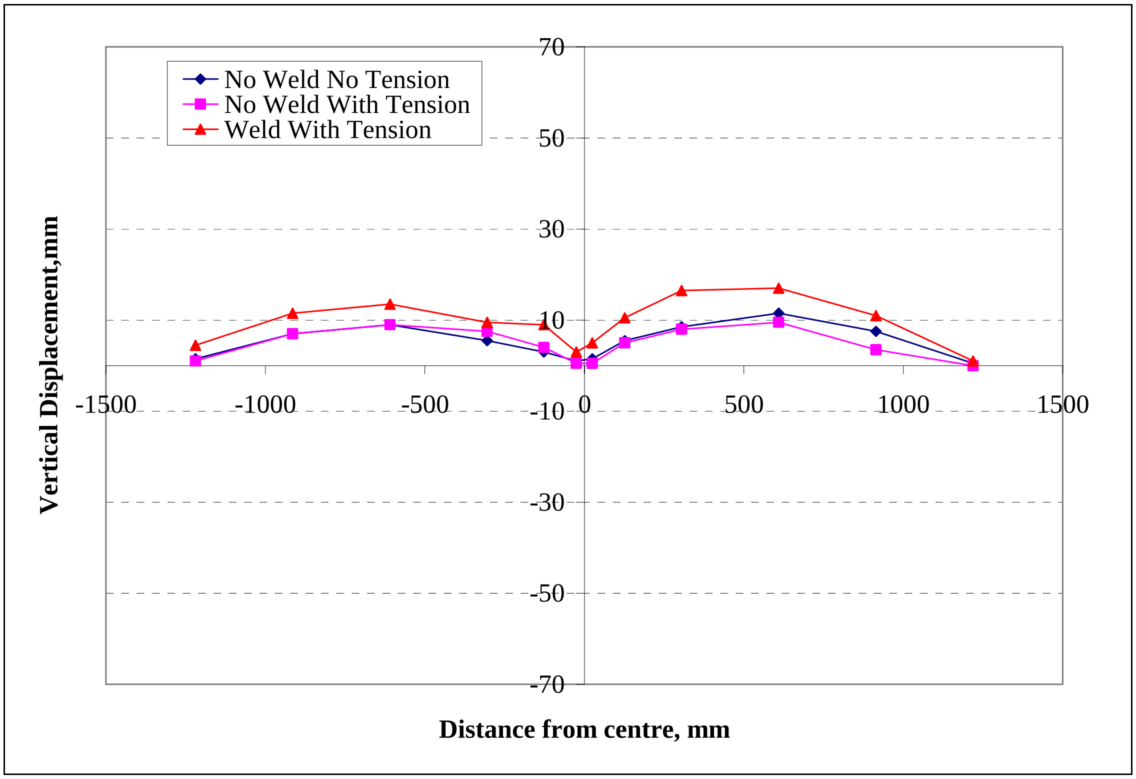


Figure 9: Transverse Section A15

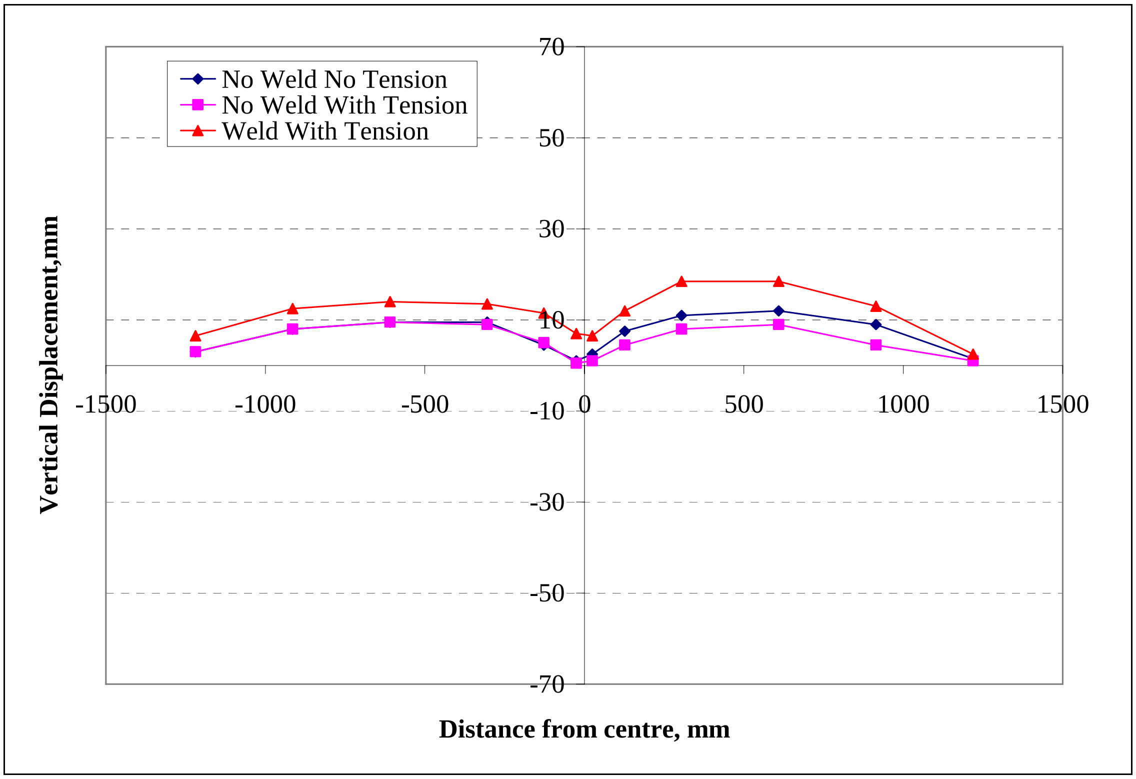


Figure 10: Transverse Section A17

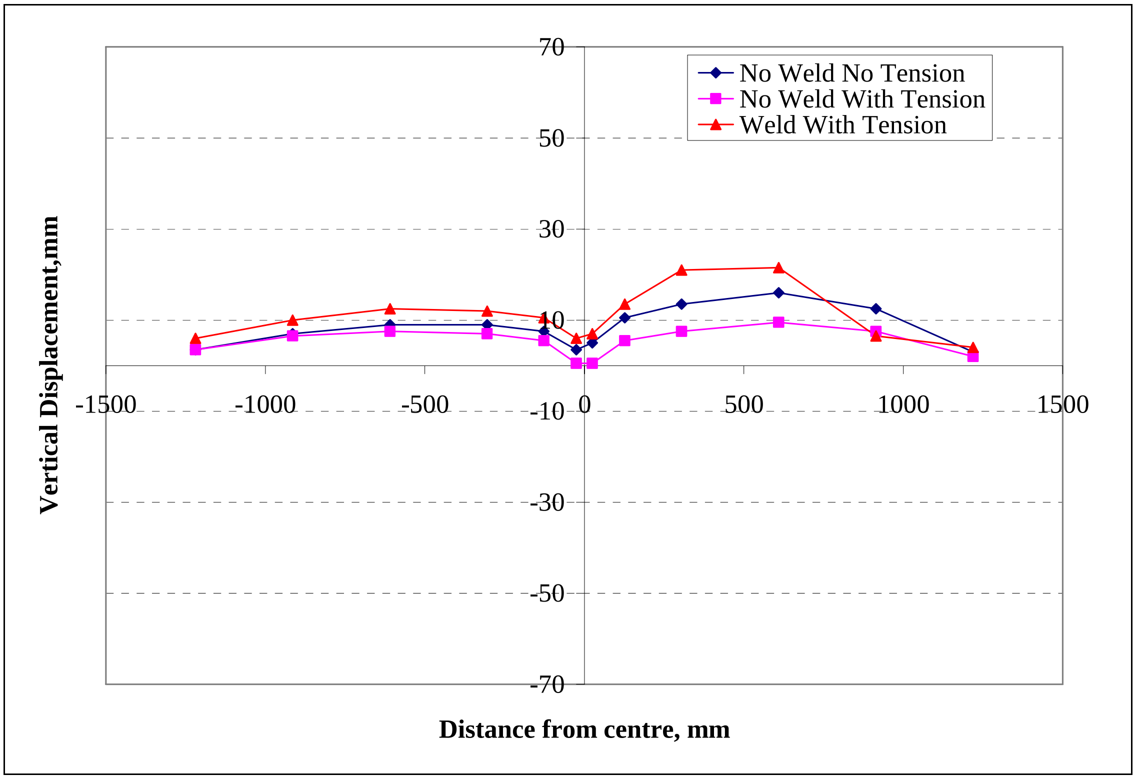


Figure 11: Transverse Section A19

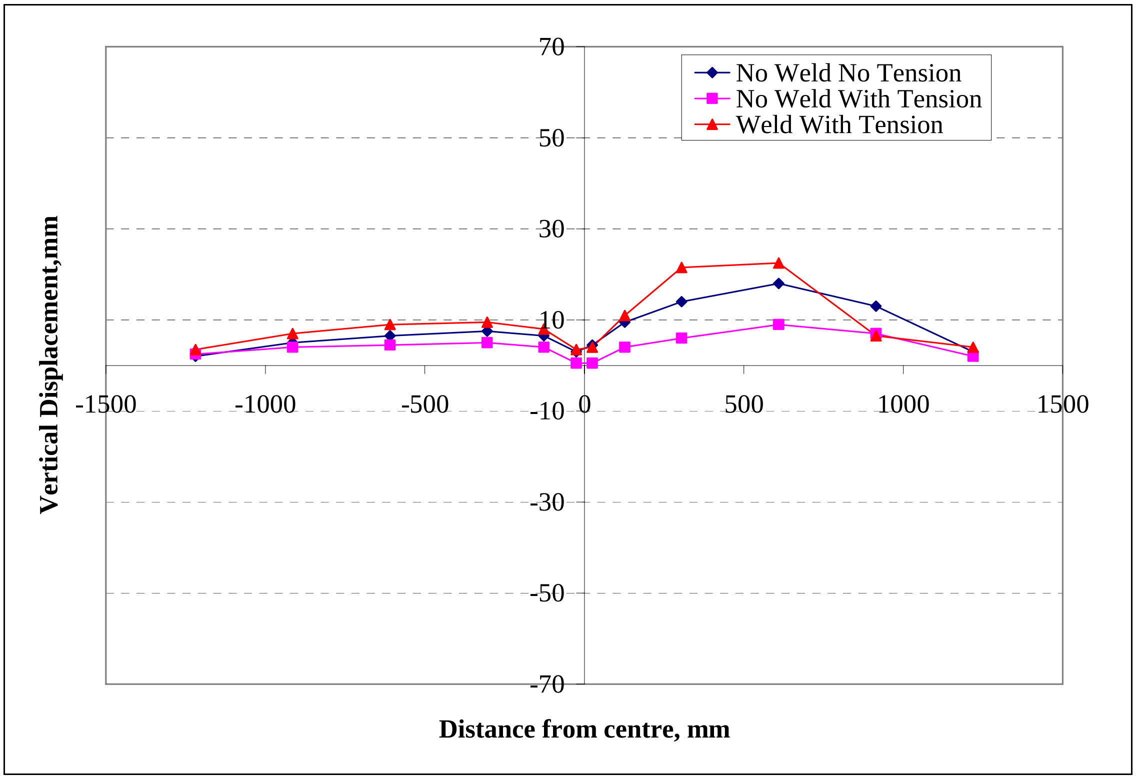


Figure 12: Transverse Section A20

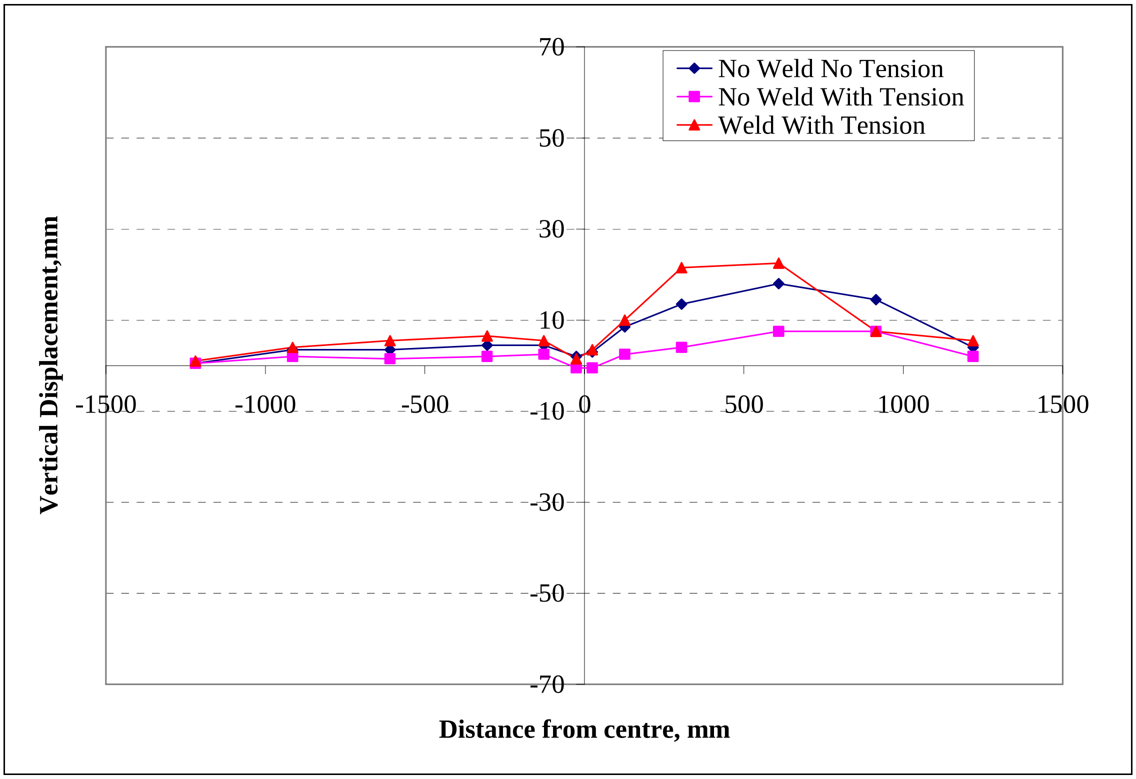


Figure 13: Transverse Section A21

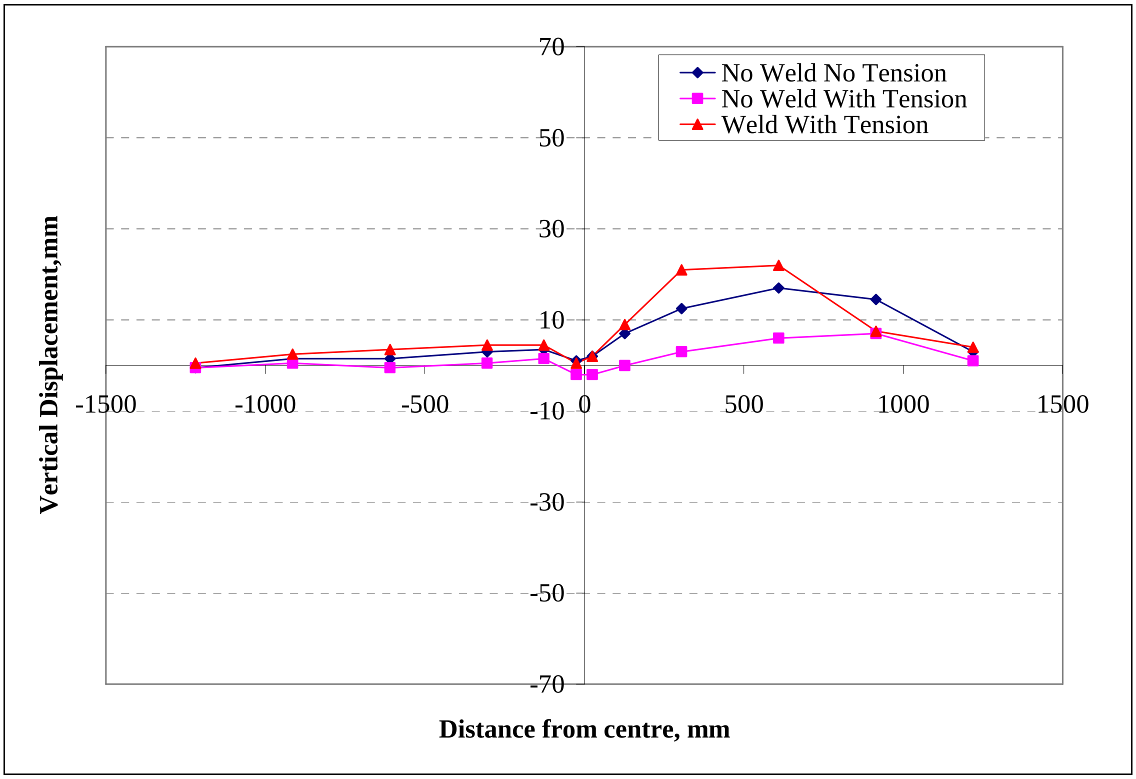


Figure 14: Transverse Section A22

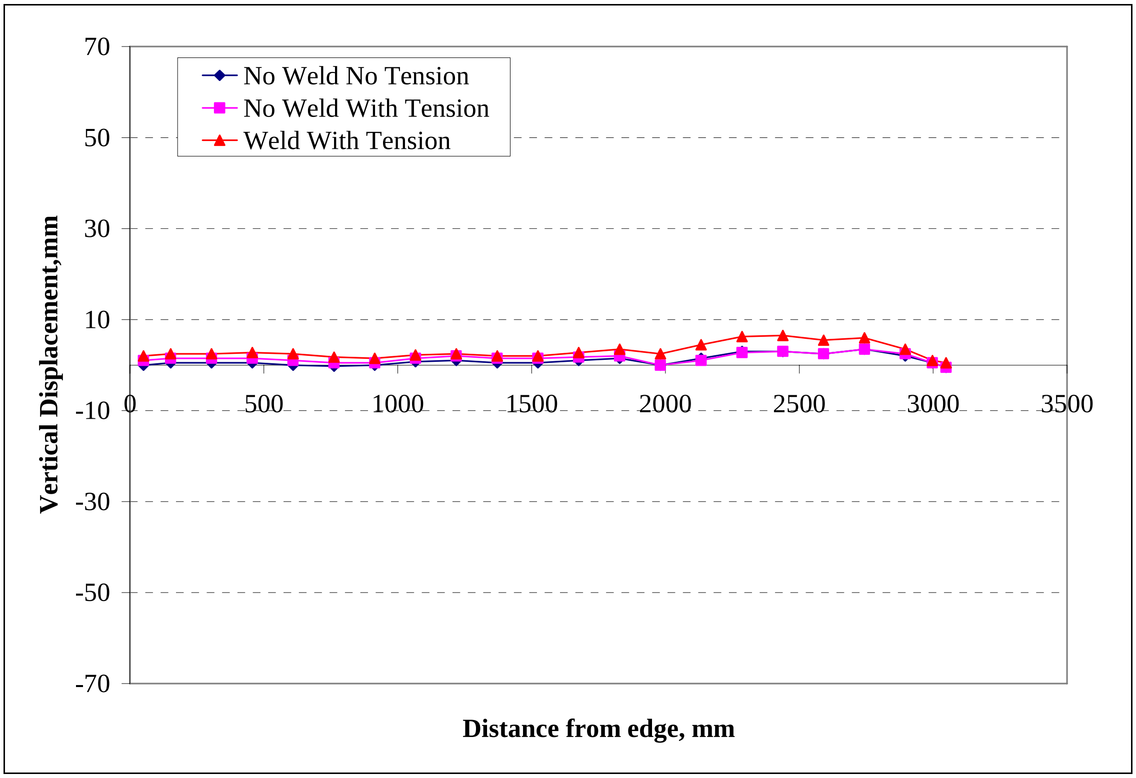


Figure 15: Longitudinal Section A

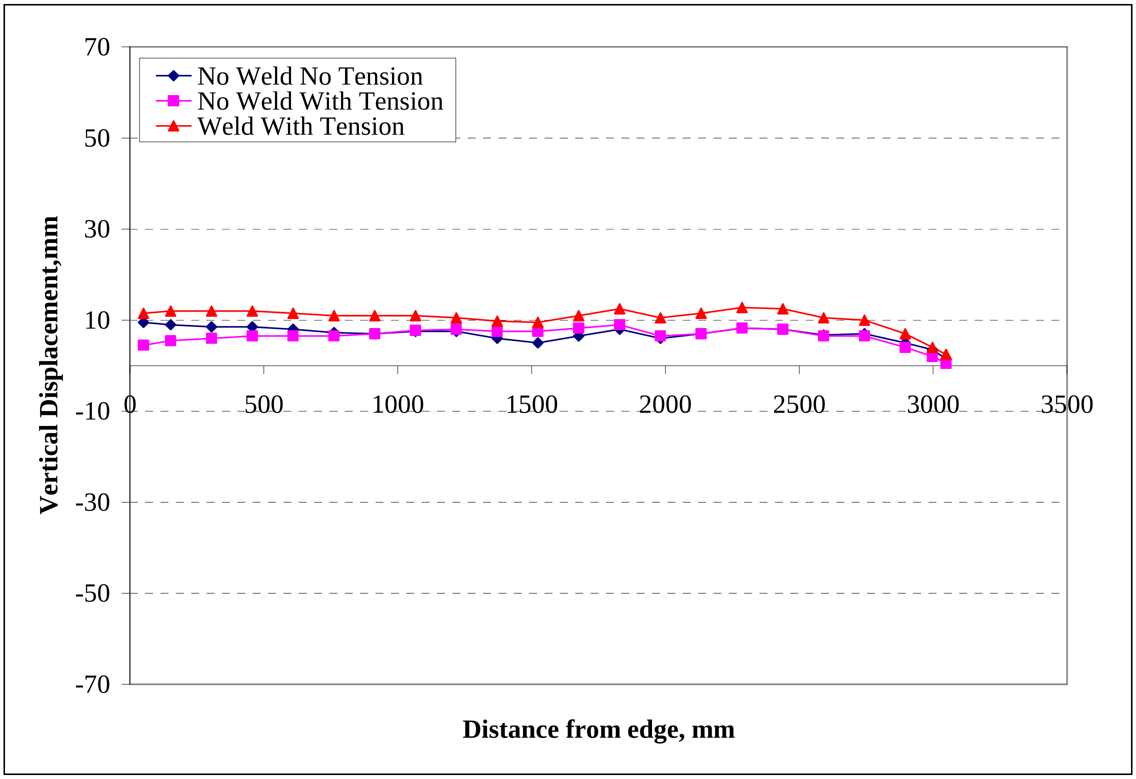


Figure 16: Longitudinal Section B

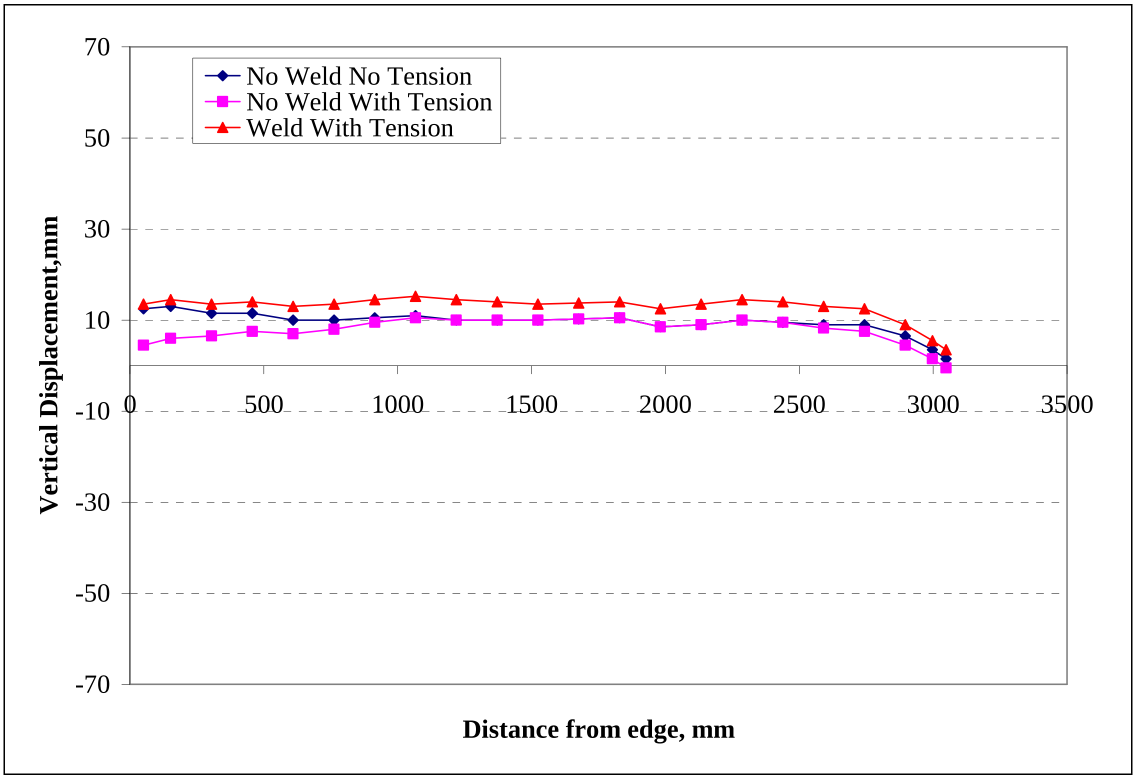


Figure 17: Longitudinal Section C

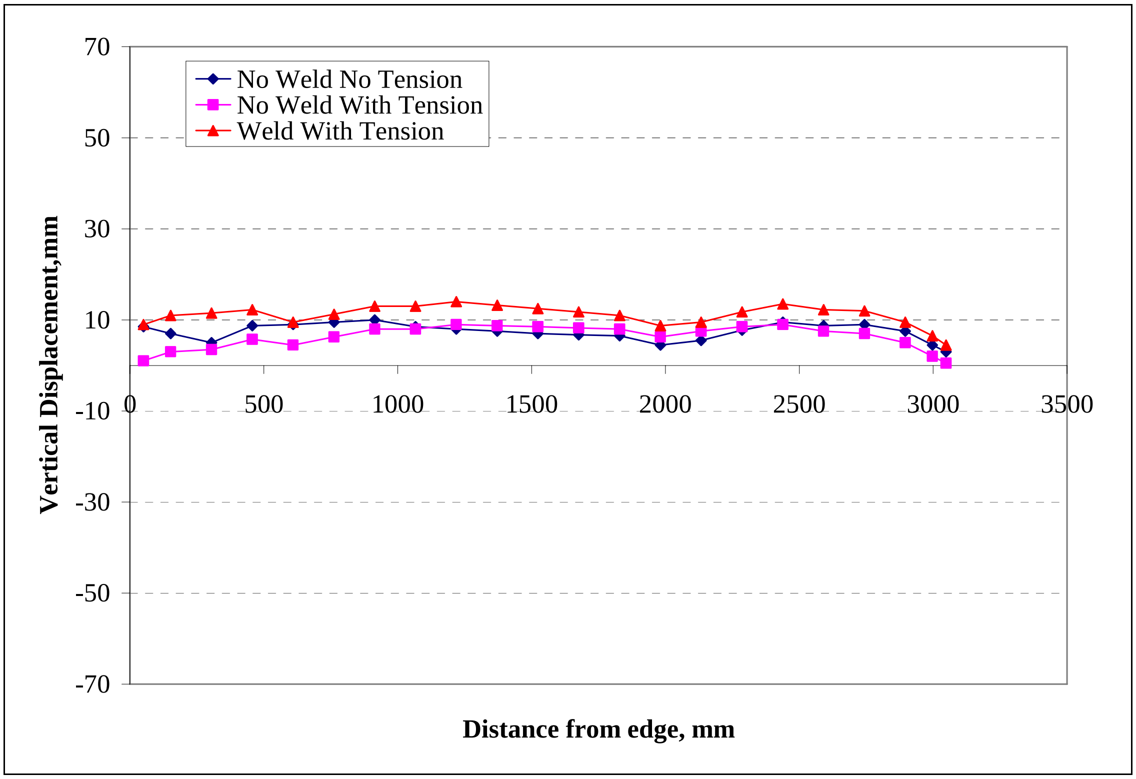


Figure 18: Longitudinal Section D

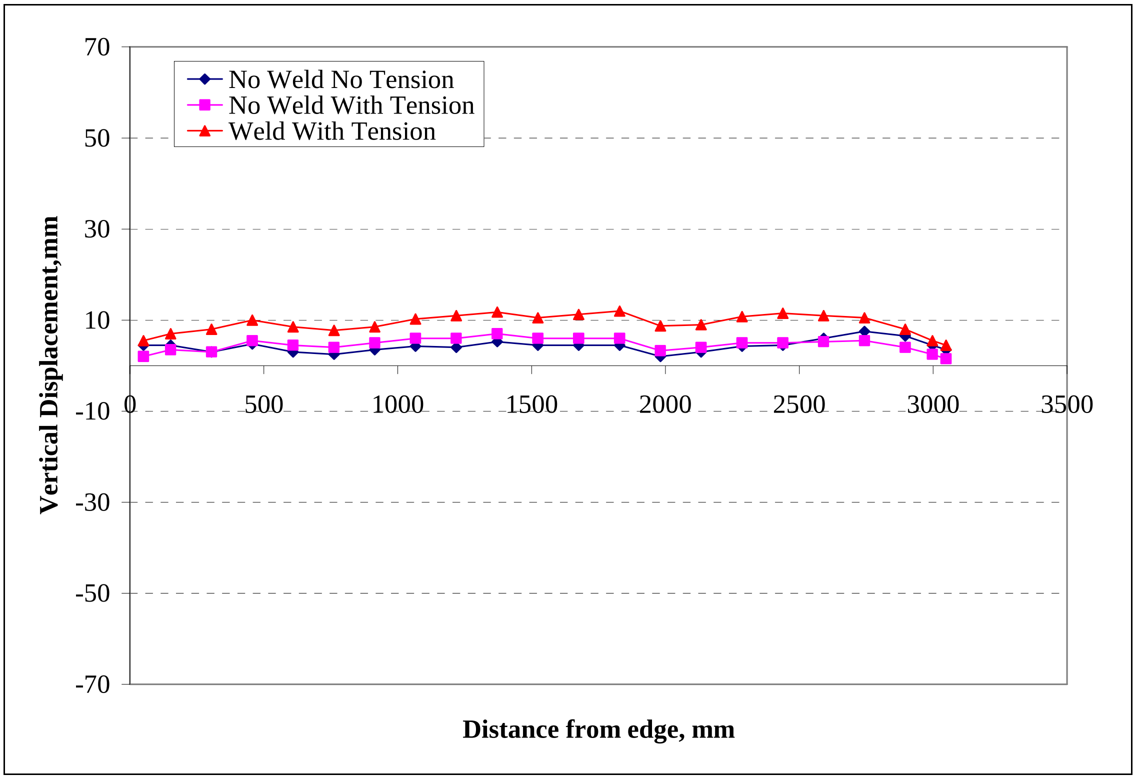


Figure 19: Longitudinal Section E

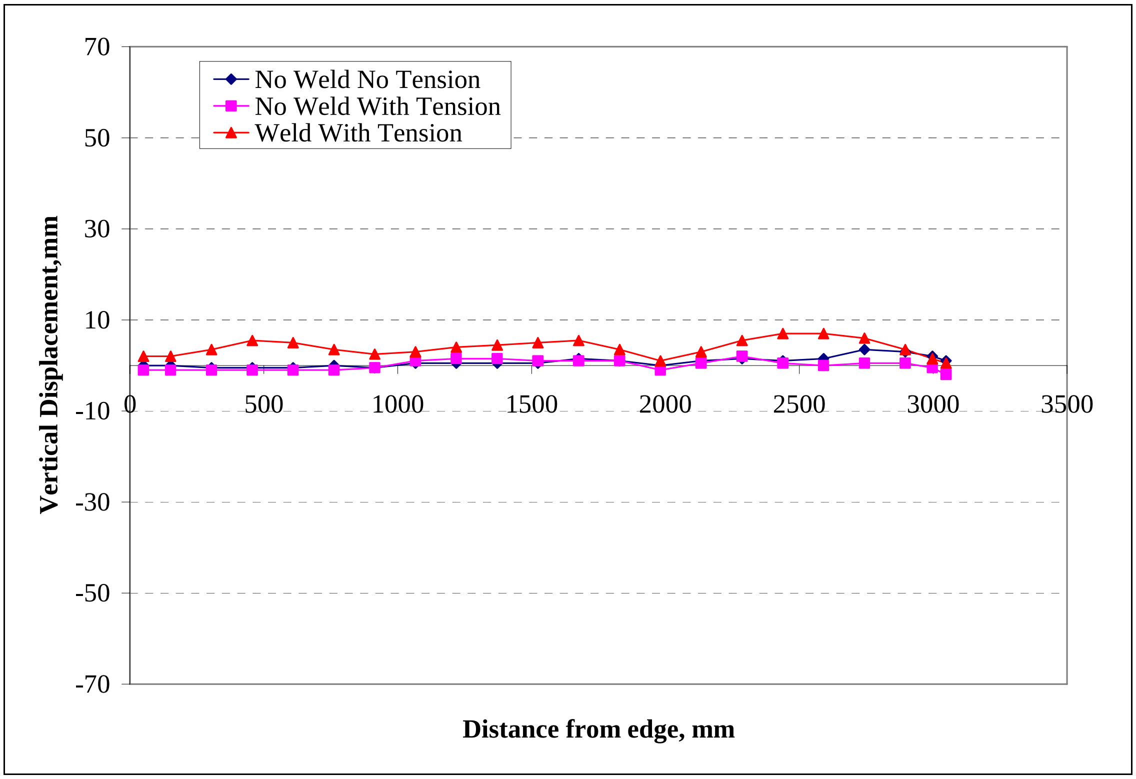


Figure 20: Longitudinal Section F

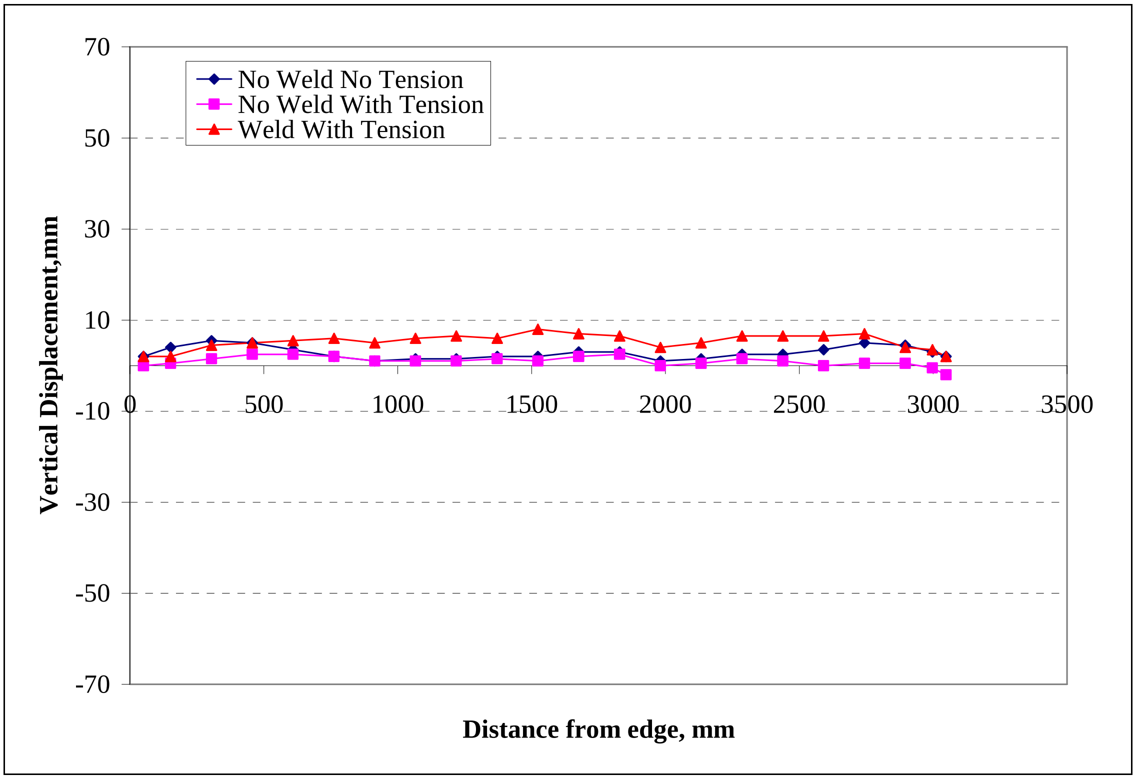


Figure 21: Longitudinal Section G

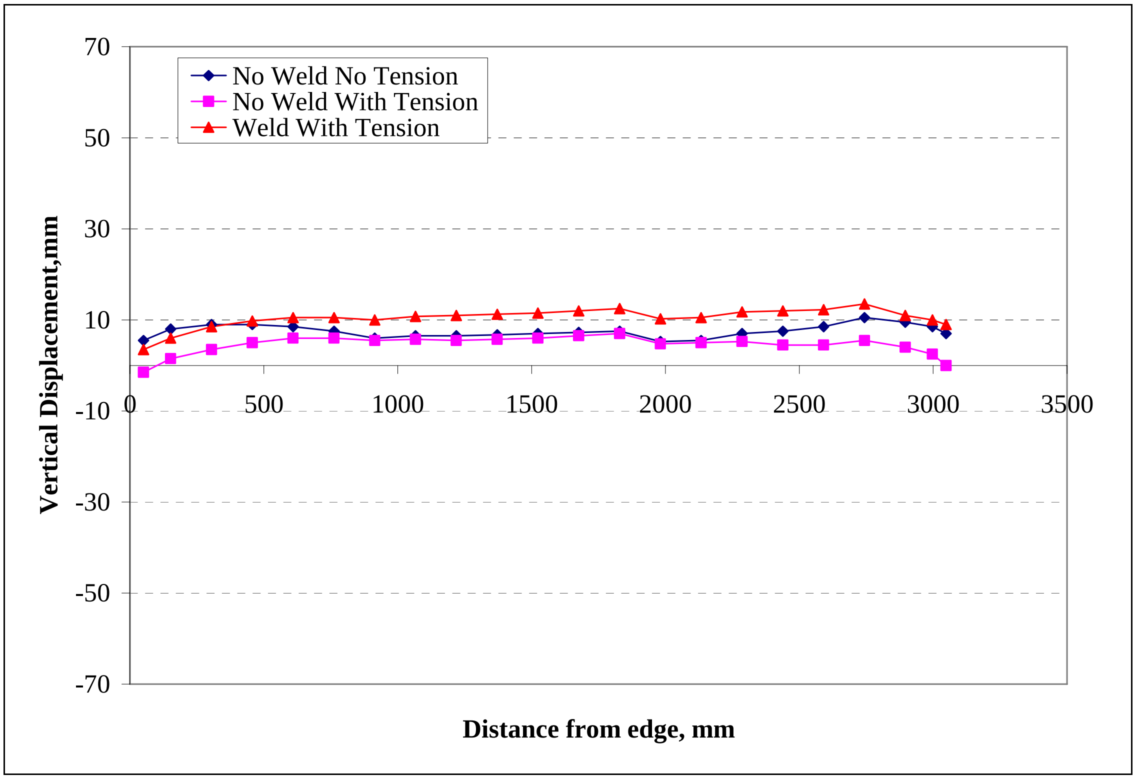


Figure 22: Longitudinal Section H

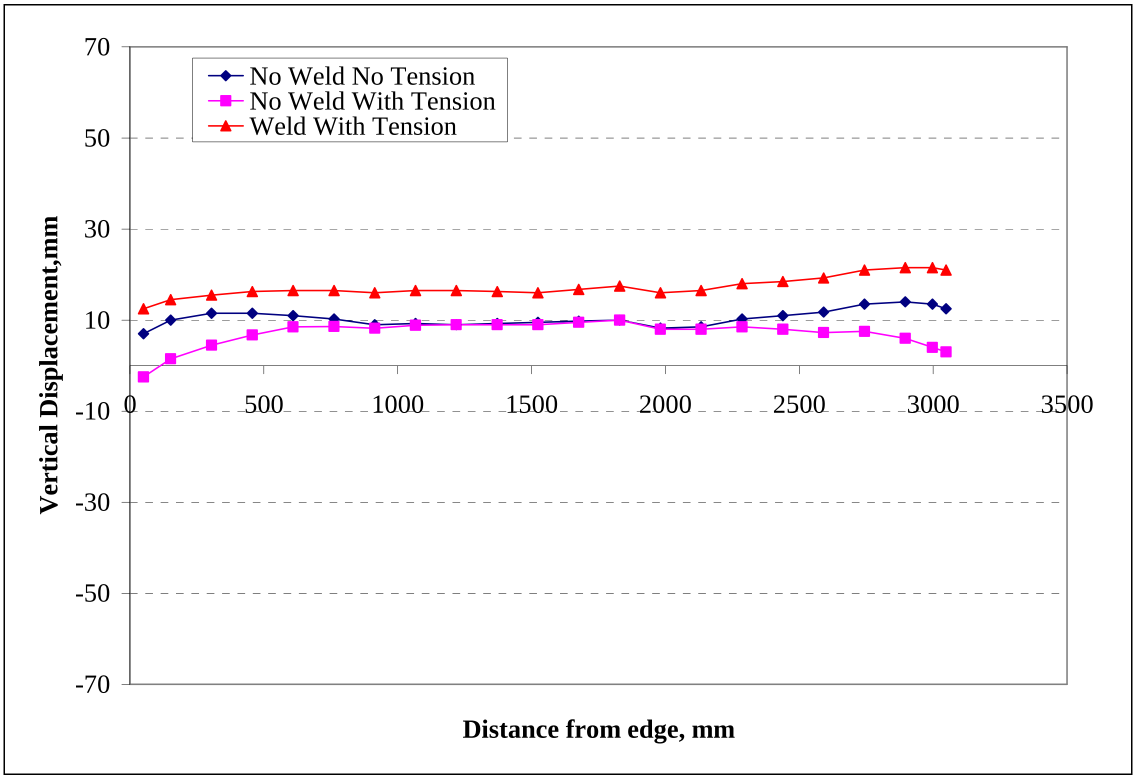


Figure 23: Longitudinal Section I

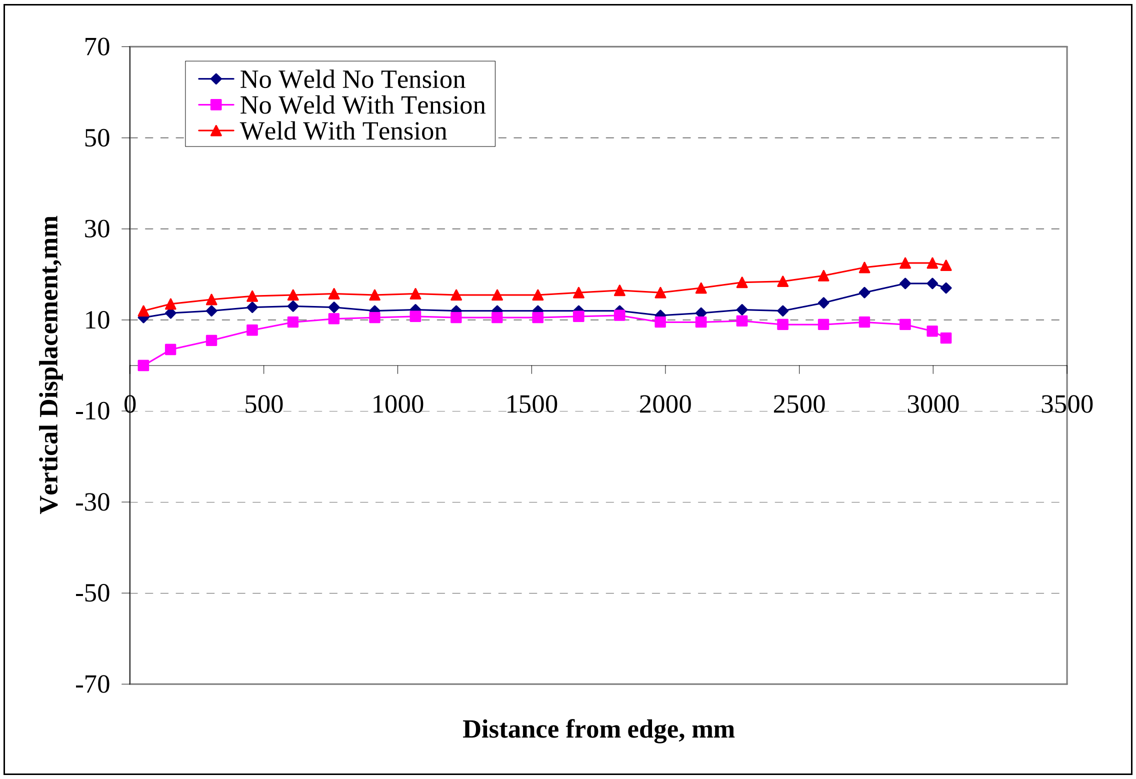


Figure 24: Longitudinal Section J

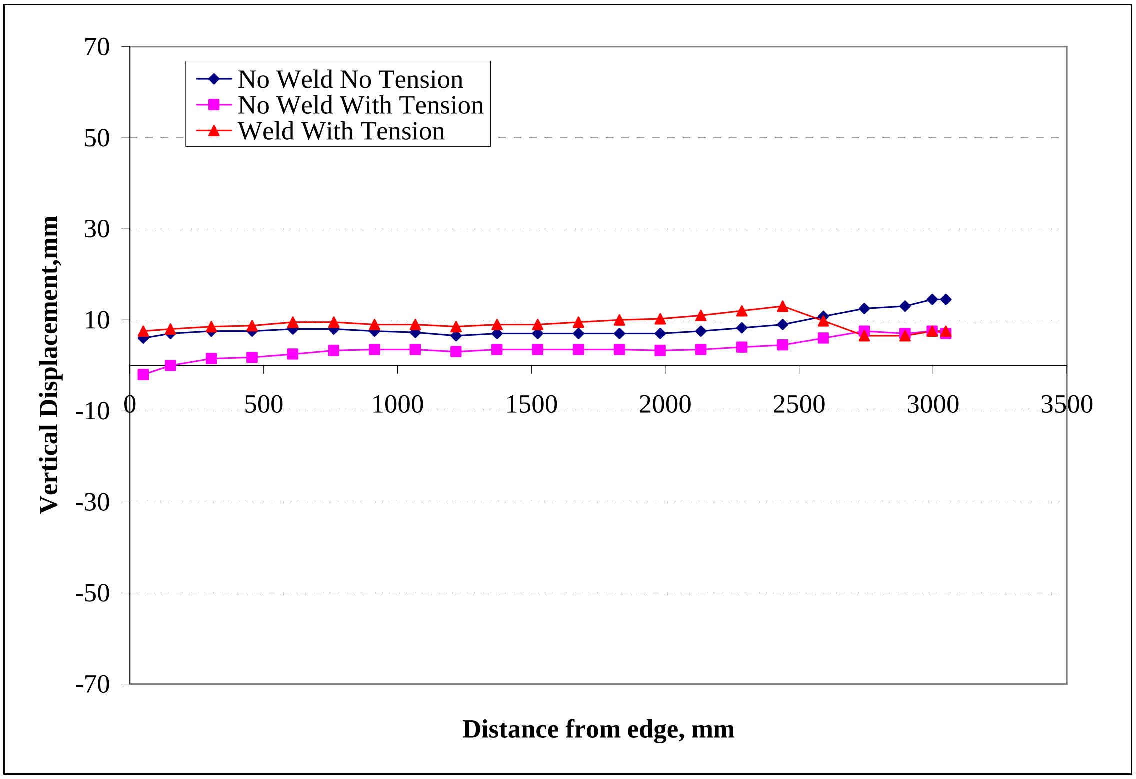


Figure 25: Longitudinal Section K

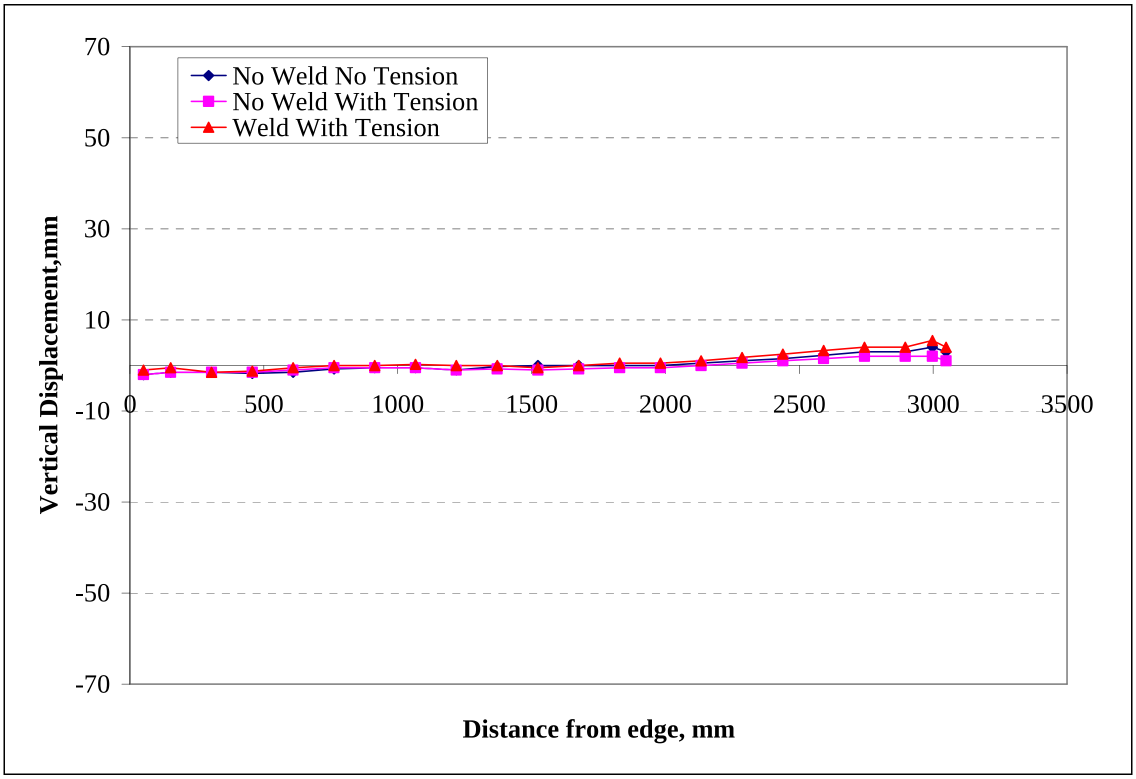


Figure 26: Longitudinal Section L

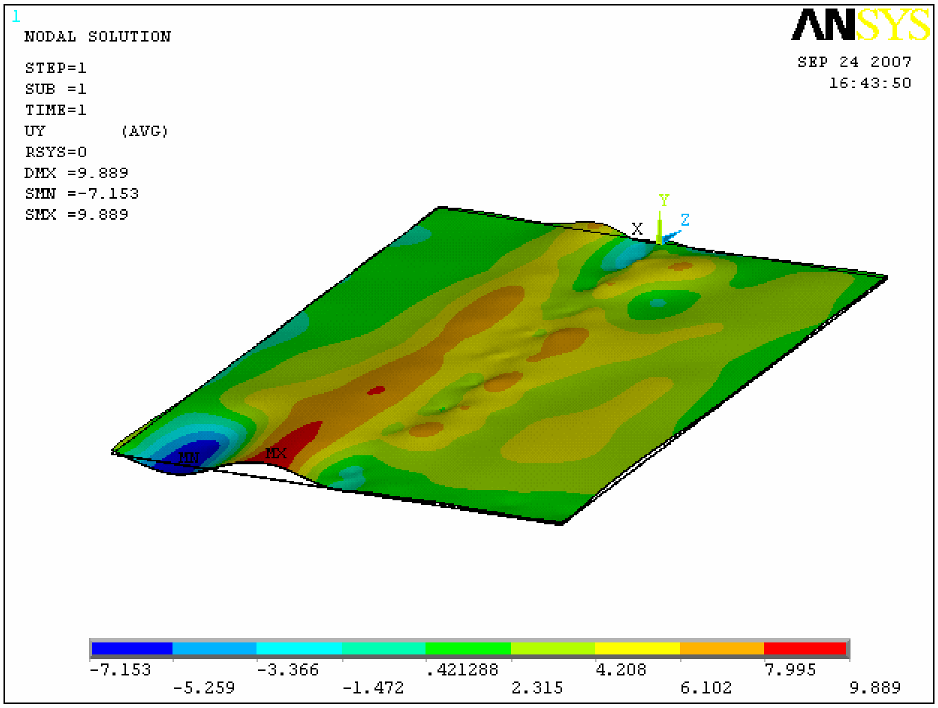


Figure 27: Net Plate Deformation (No Weld No Tension -Weld under Tension)

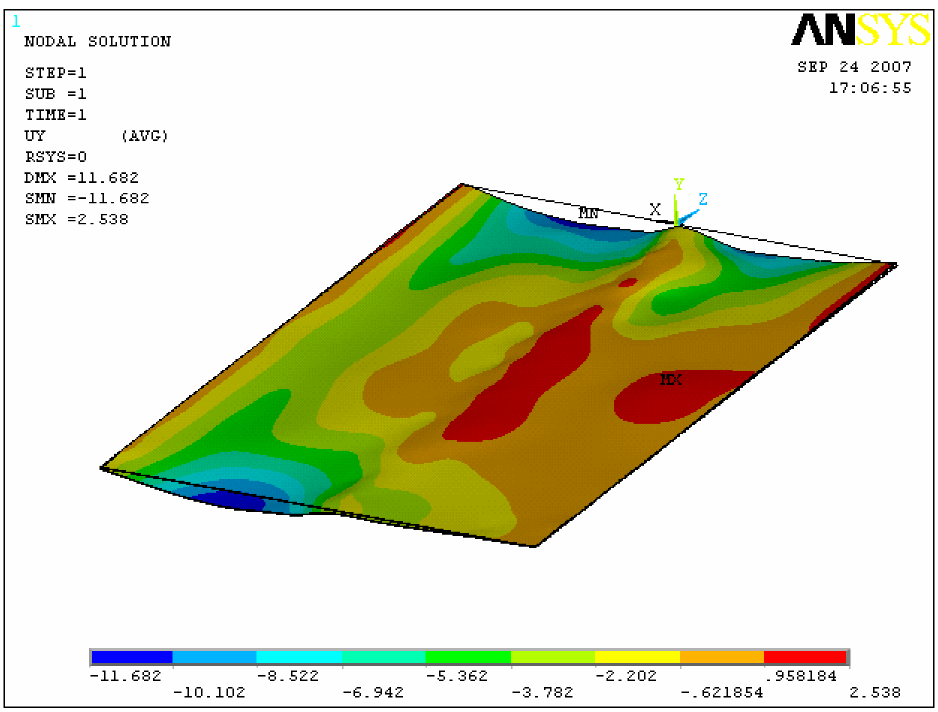


Figure 28: Plate Deformation after Welding (No Weld with Tension-Weld under Tension)

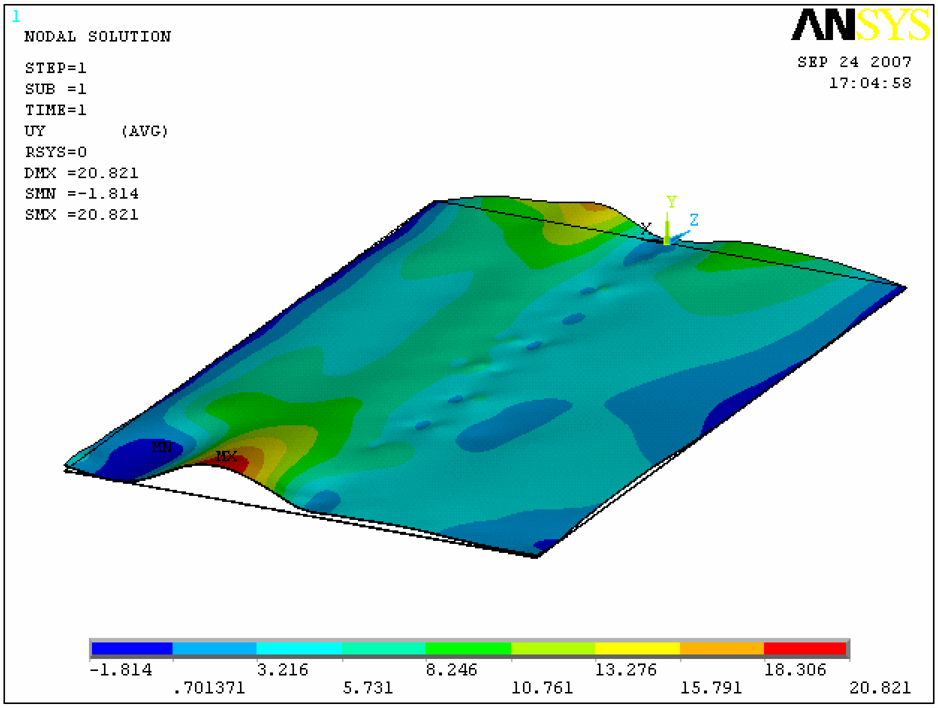


Figure 29: Plate Deformation before Welding (No Weld No Tension-No Weld with Tension)

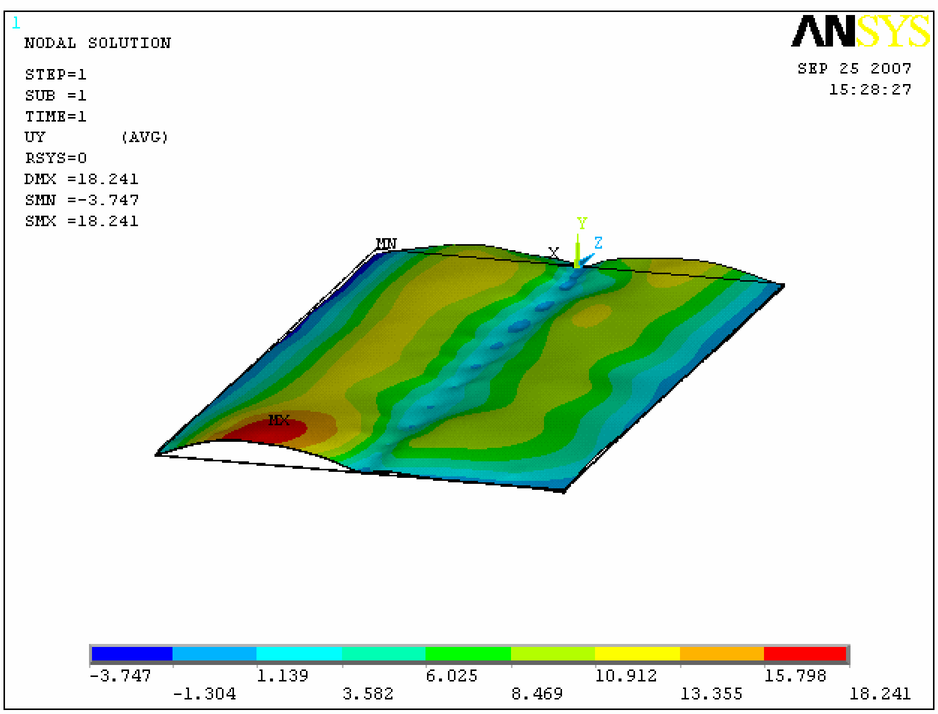


Figure 30: Plate Deformation before Welding (Base Support-No Weld with Tension)

PLATE 5 – SIDE 2

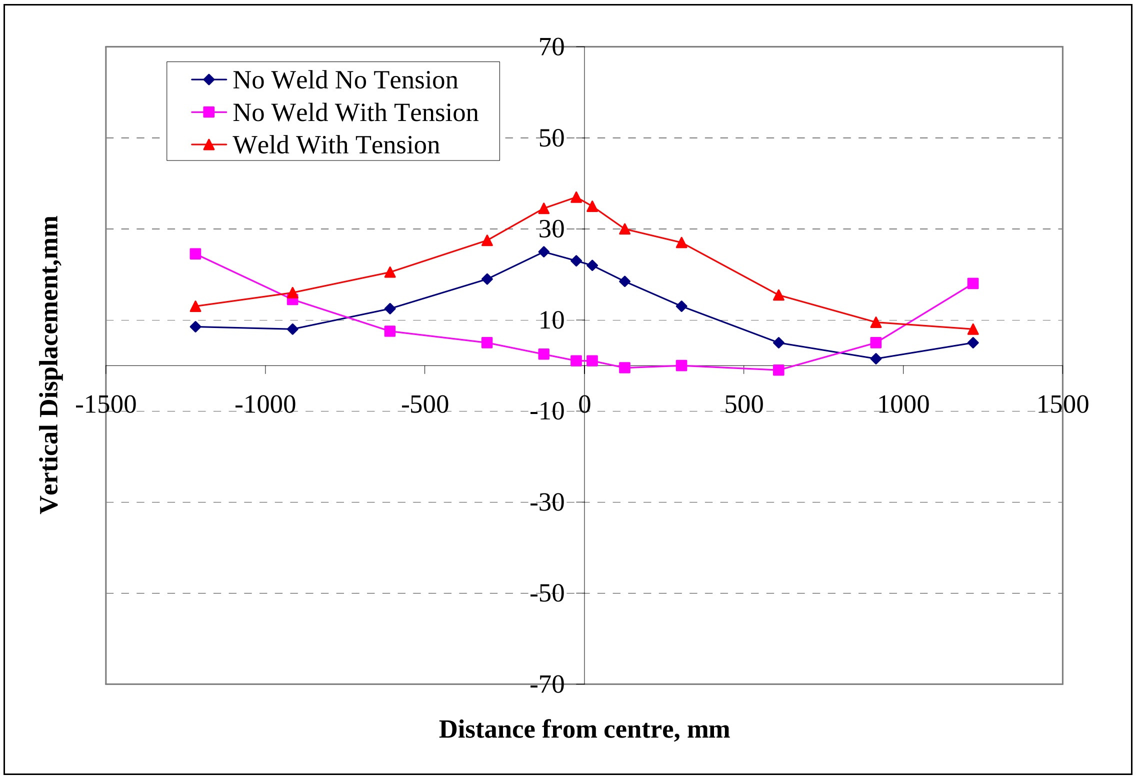


Figure 1: Transverse Section A1

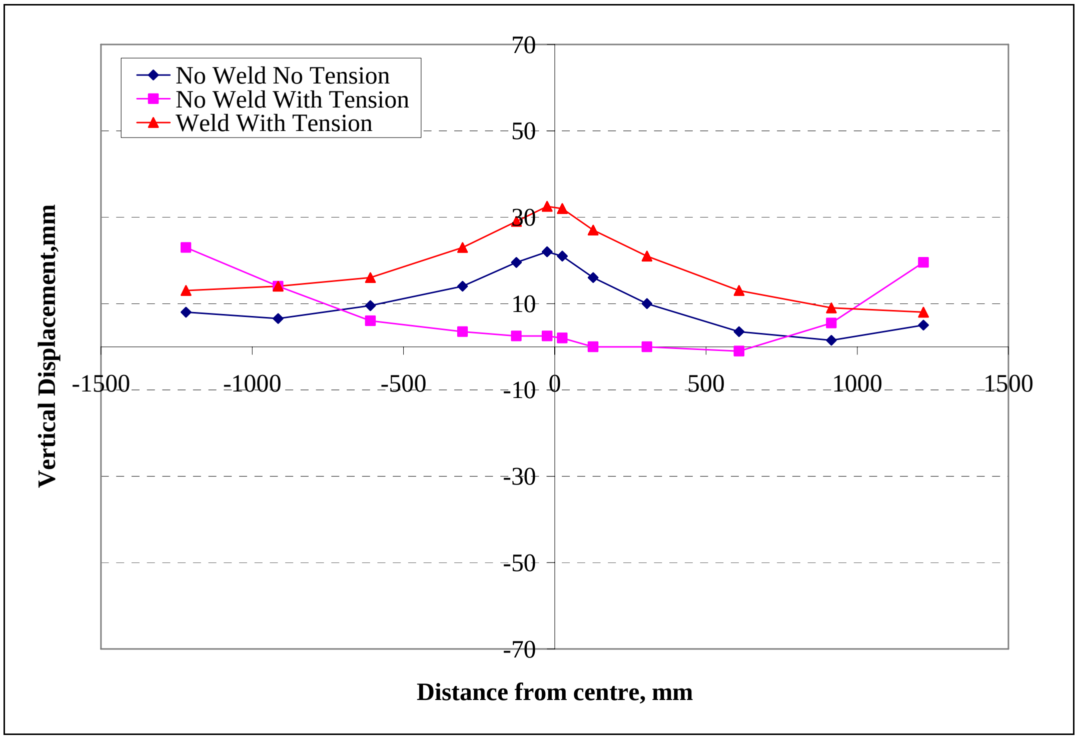


Figure 2: Transverse Section A2

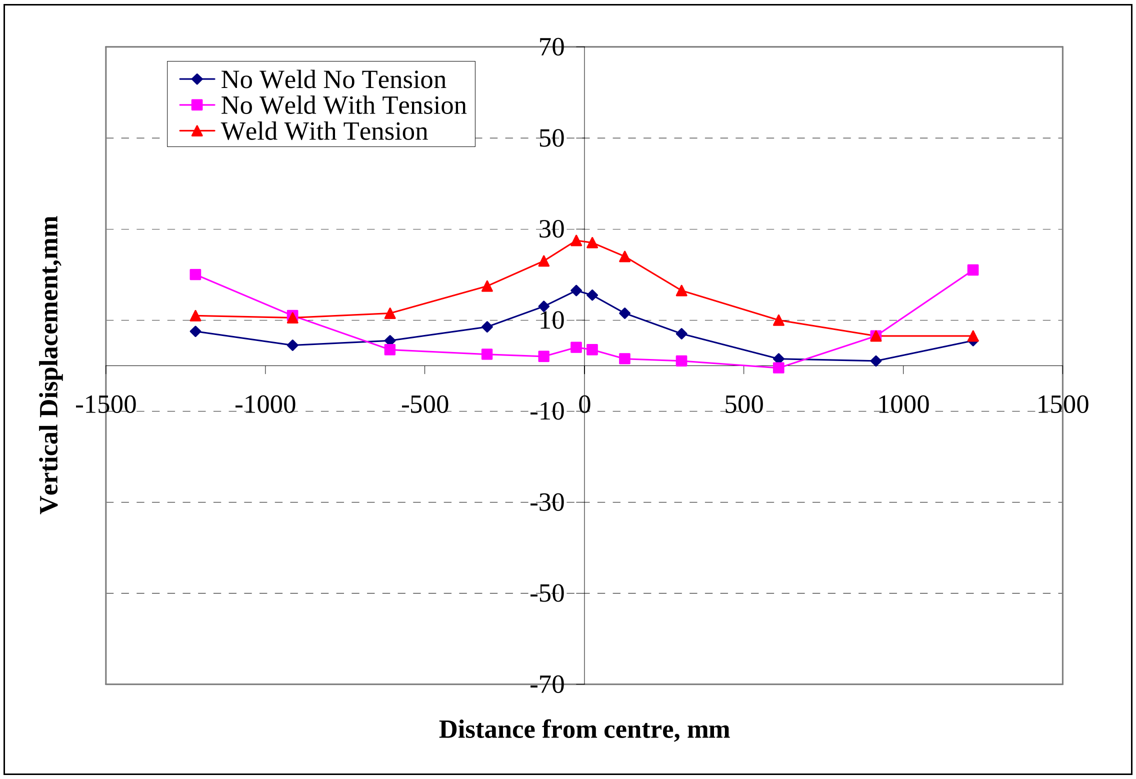


Figure 3: Transverse Section A3

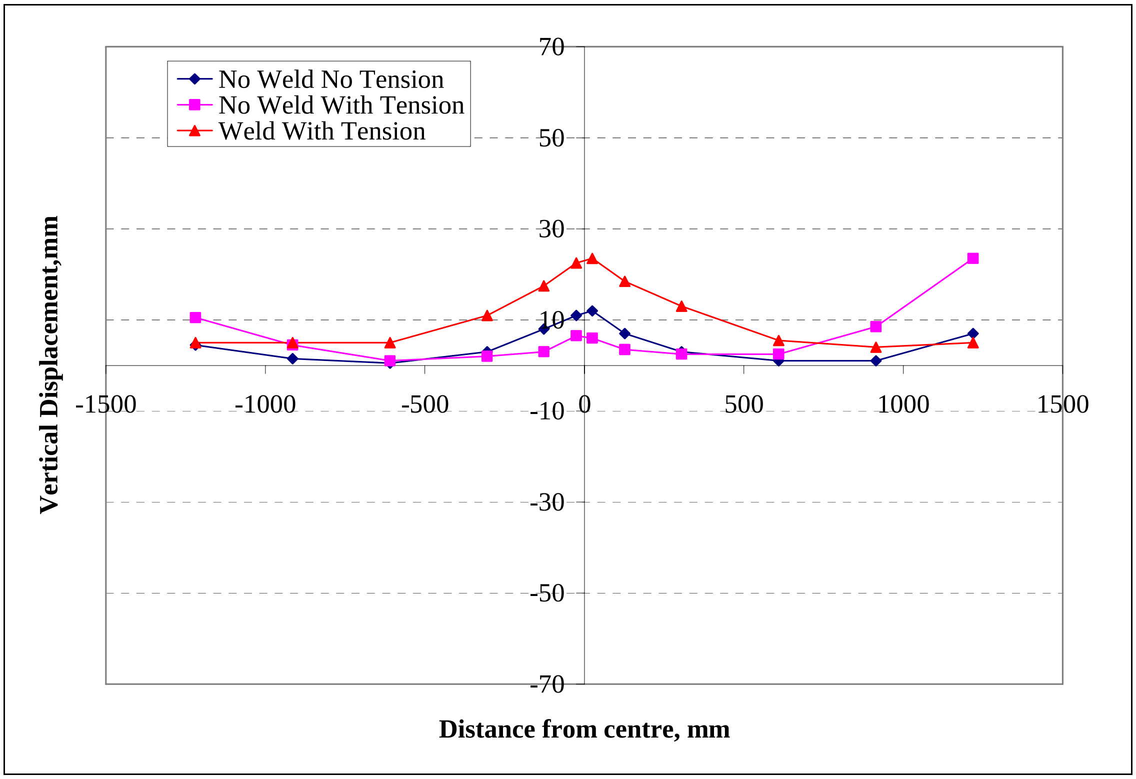


Figure 4: Transverse Section A5

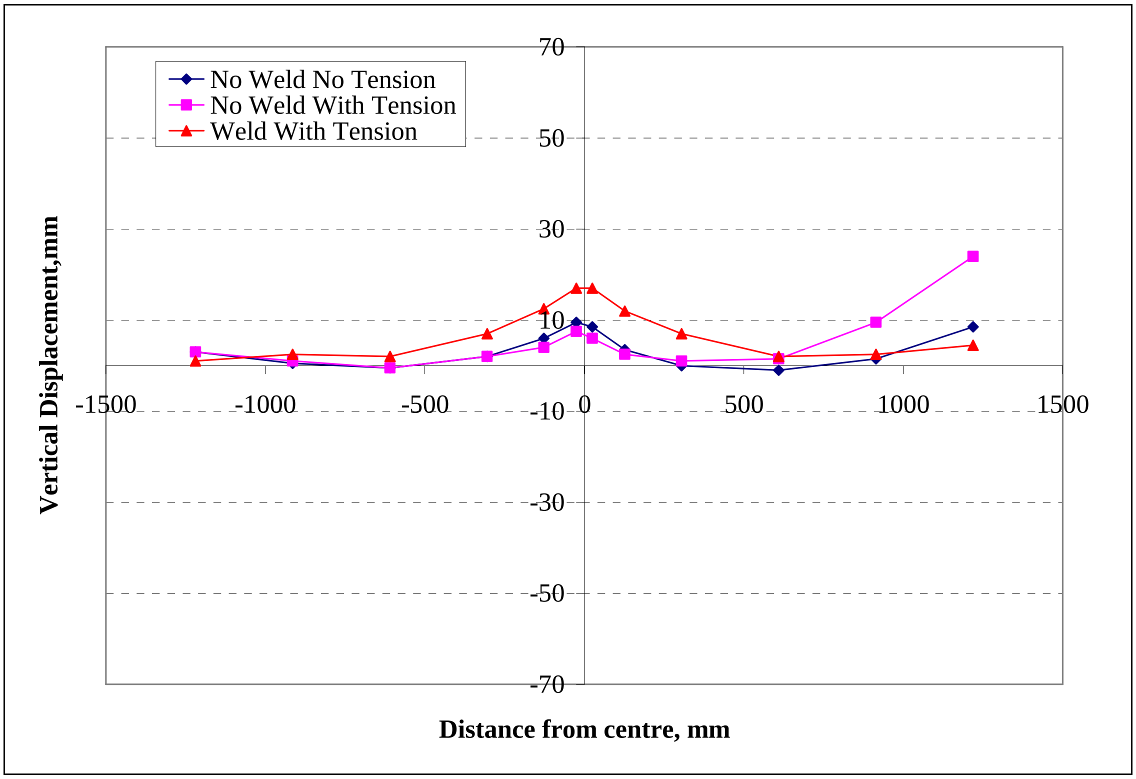


Figure 5: Transverse Section A7

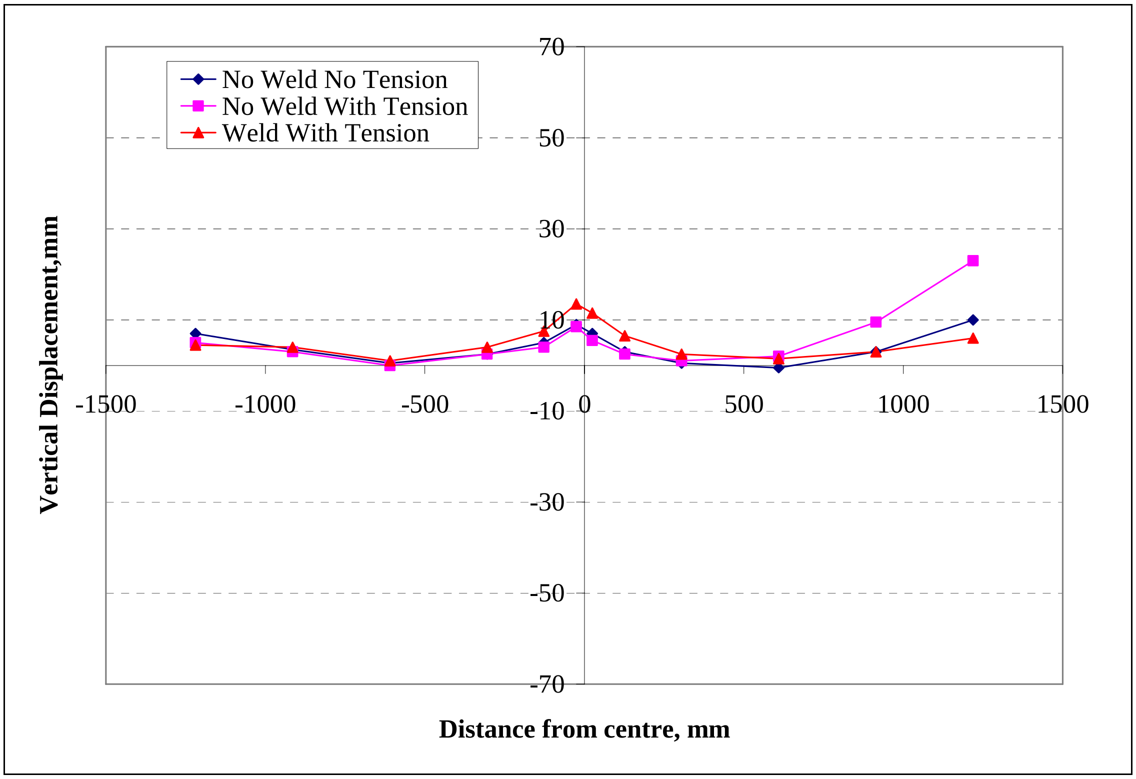


Figure 6: Transverse Section A9

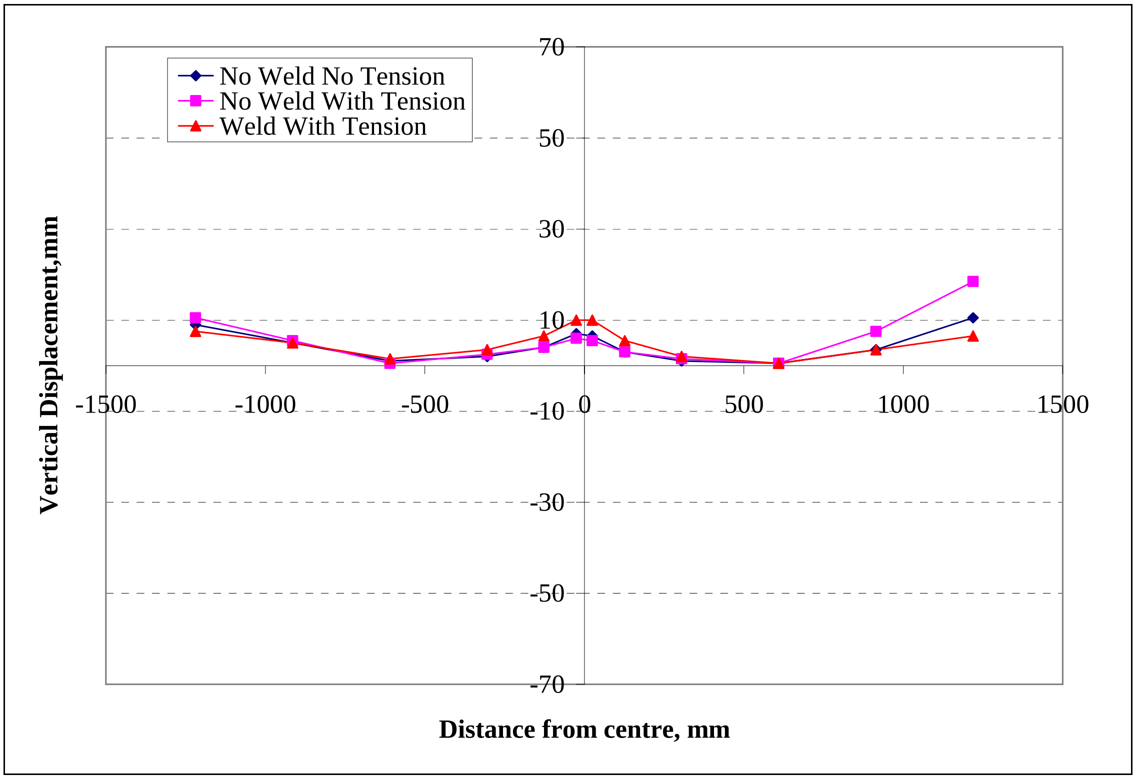


Figure 7: Transverse Section A11

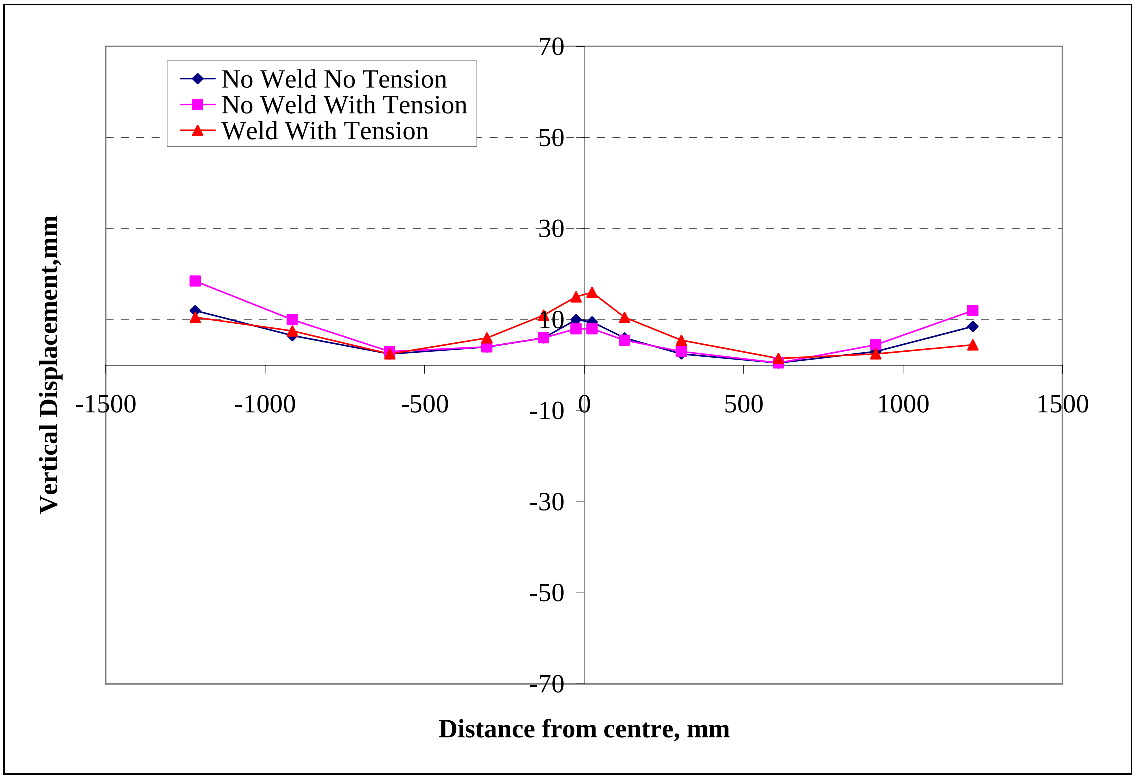


Figure 8: Transverse Section A13

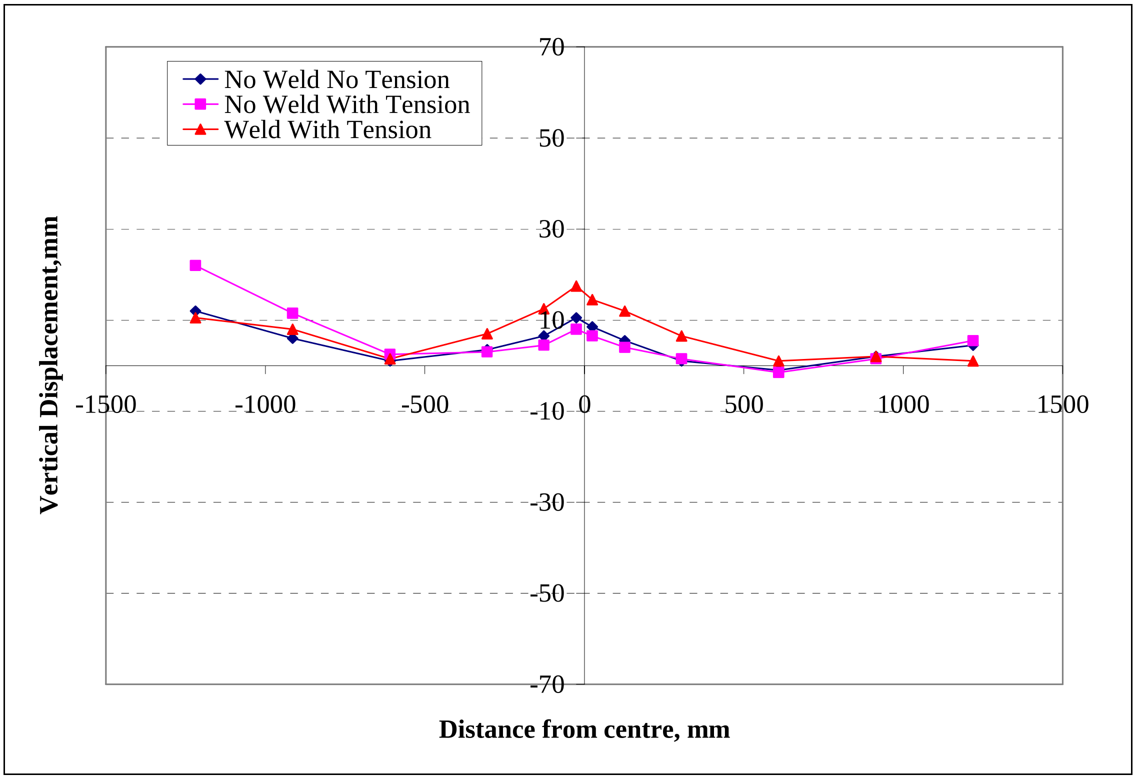


Figure 9: Transverse Section A15

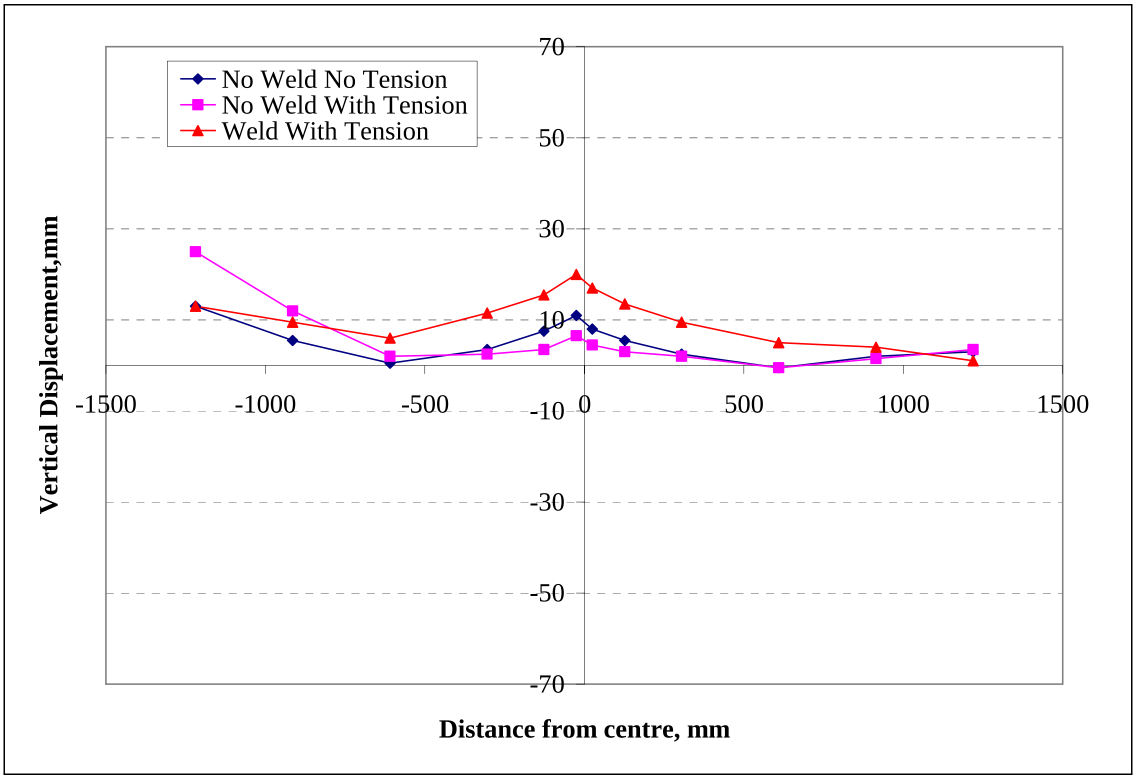


Figure 10: Transverse Section A17

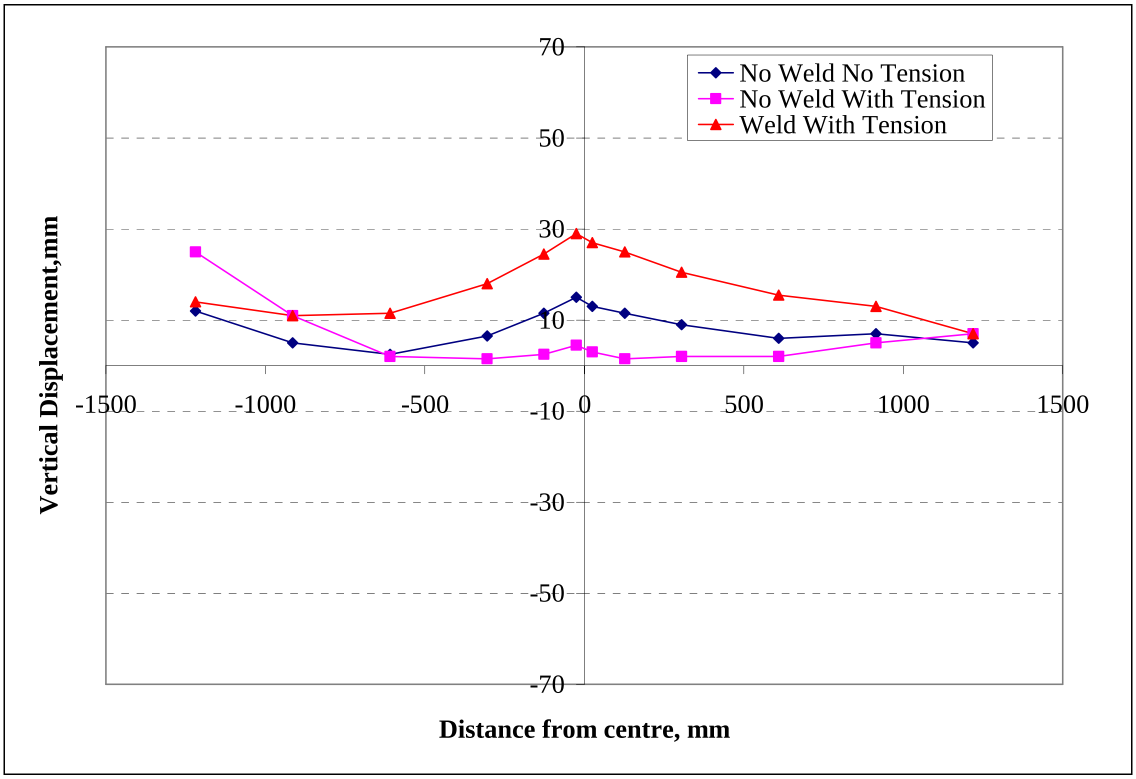


Figure 11: Transverse Section A19

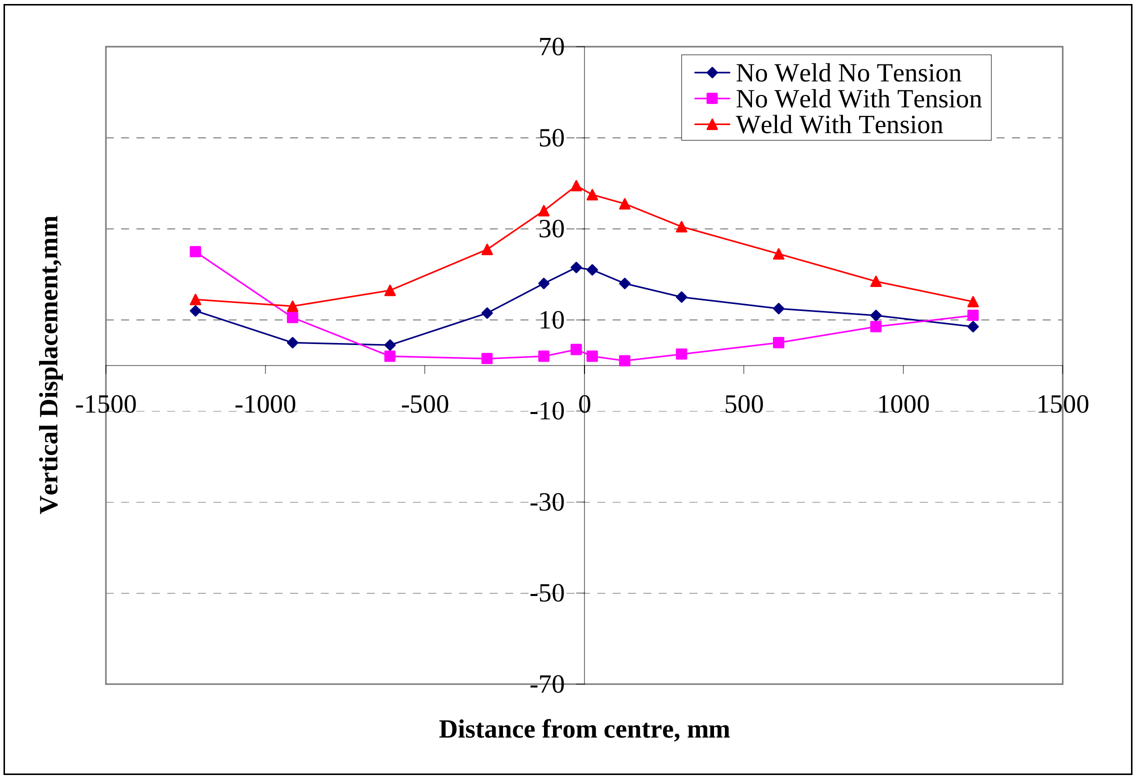


Figure 12: Transverse Section A20

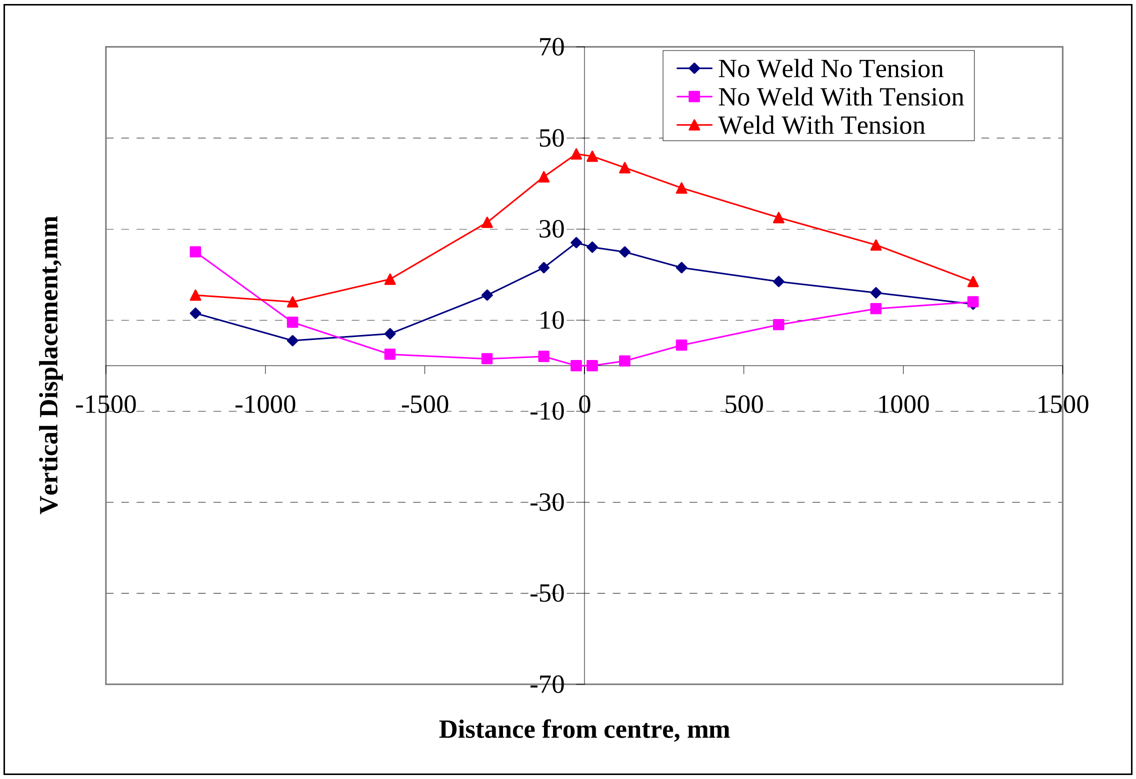


Figure 13: Transverse Section A21

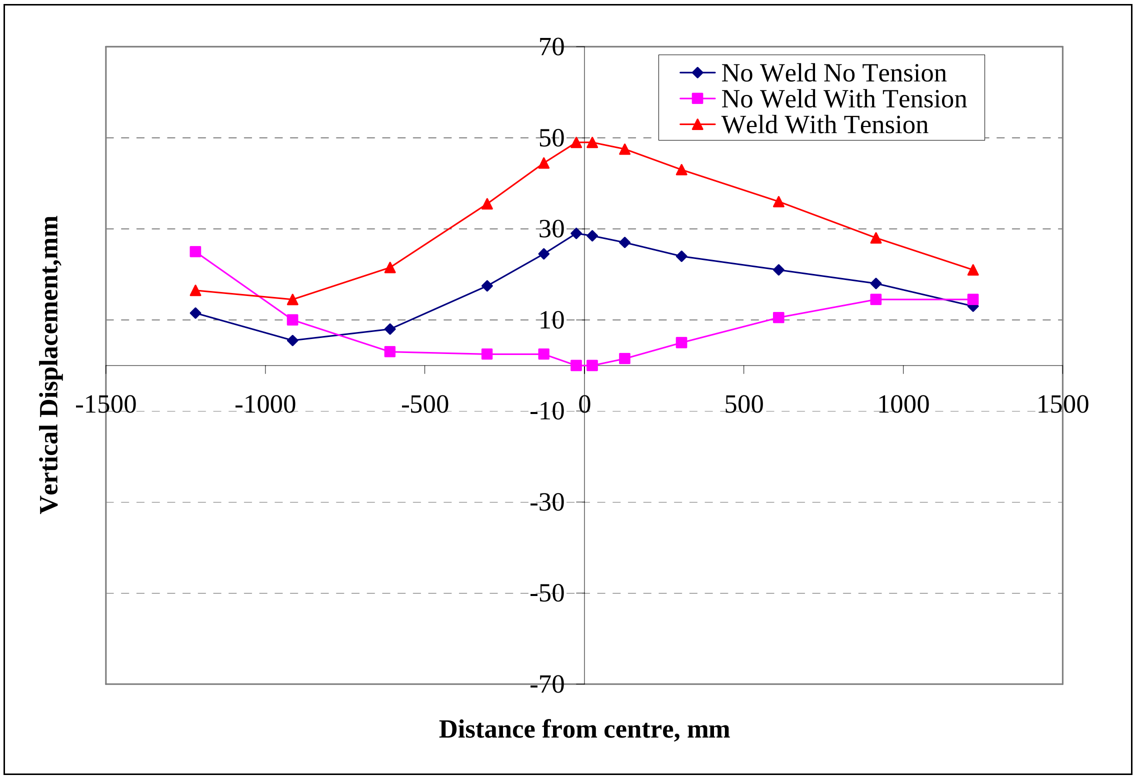


Figure 14: Transverse Section A22

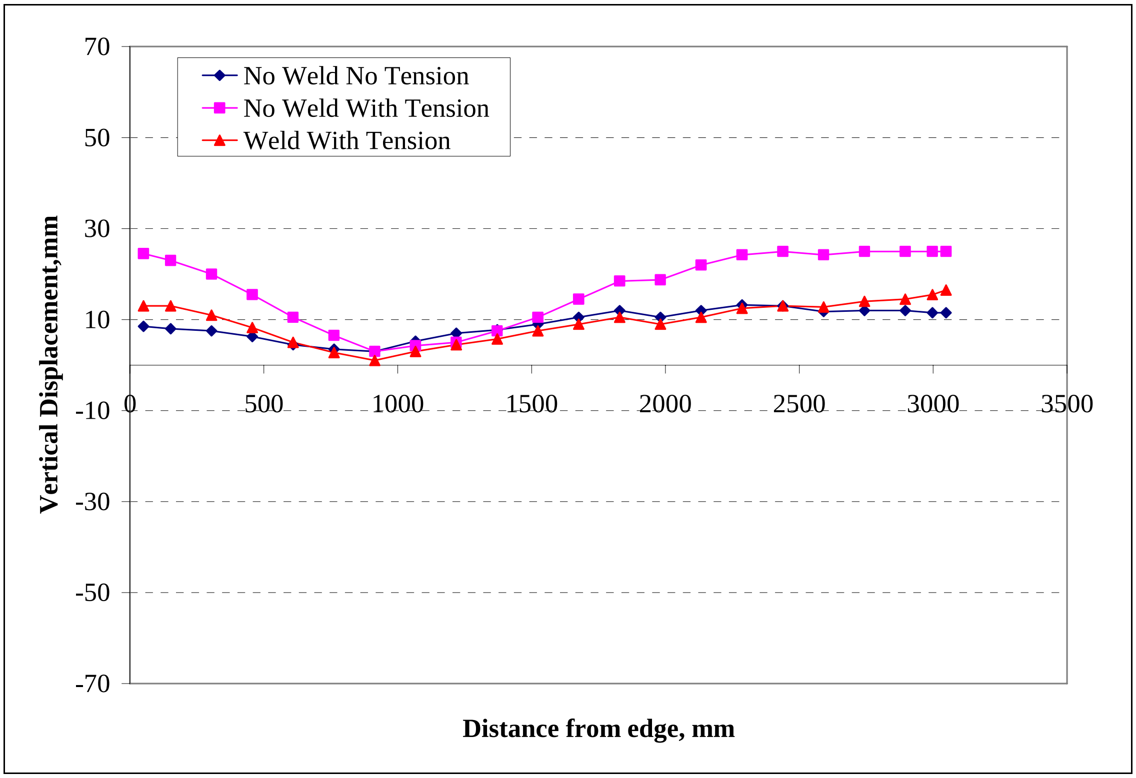


Figure 15: Longitudinal Section A

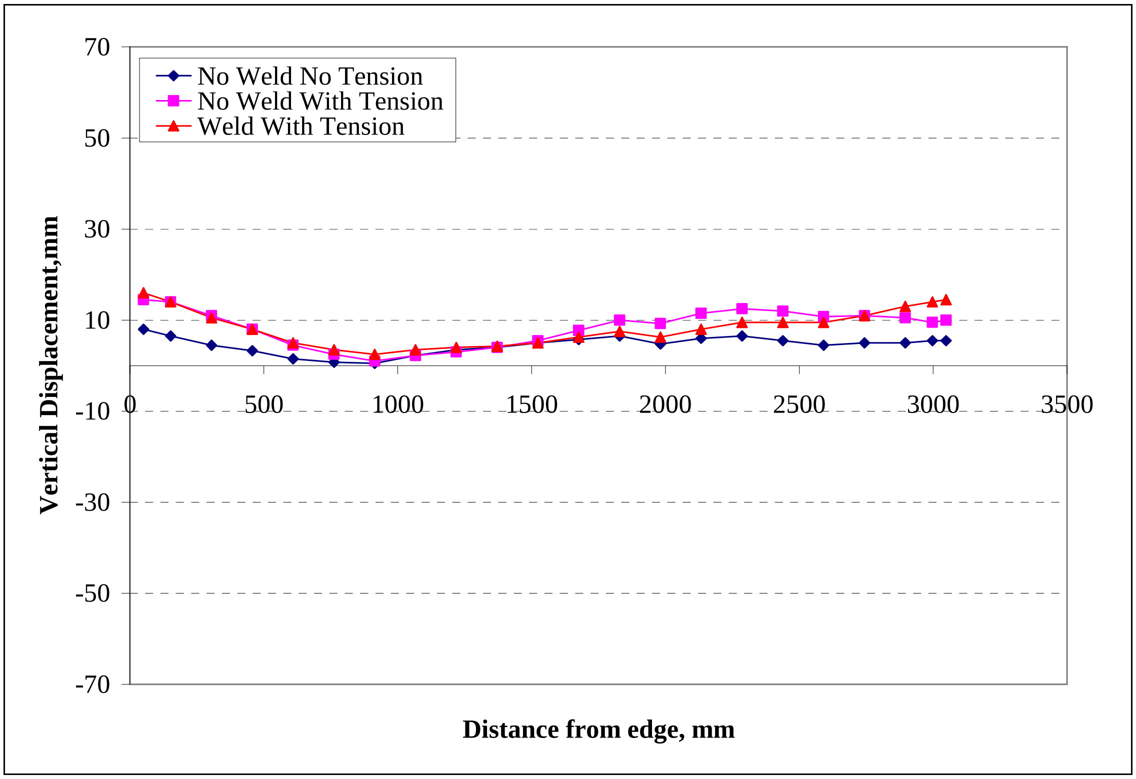


Figure 16: Longitudinal Section B

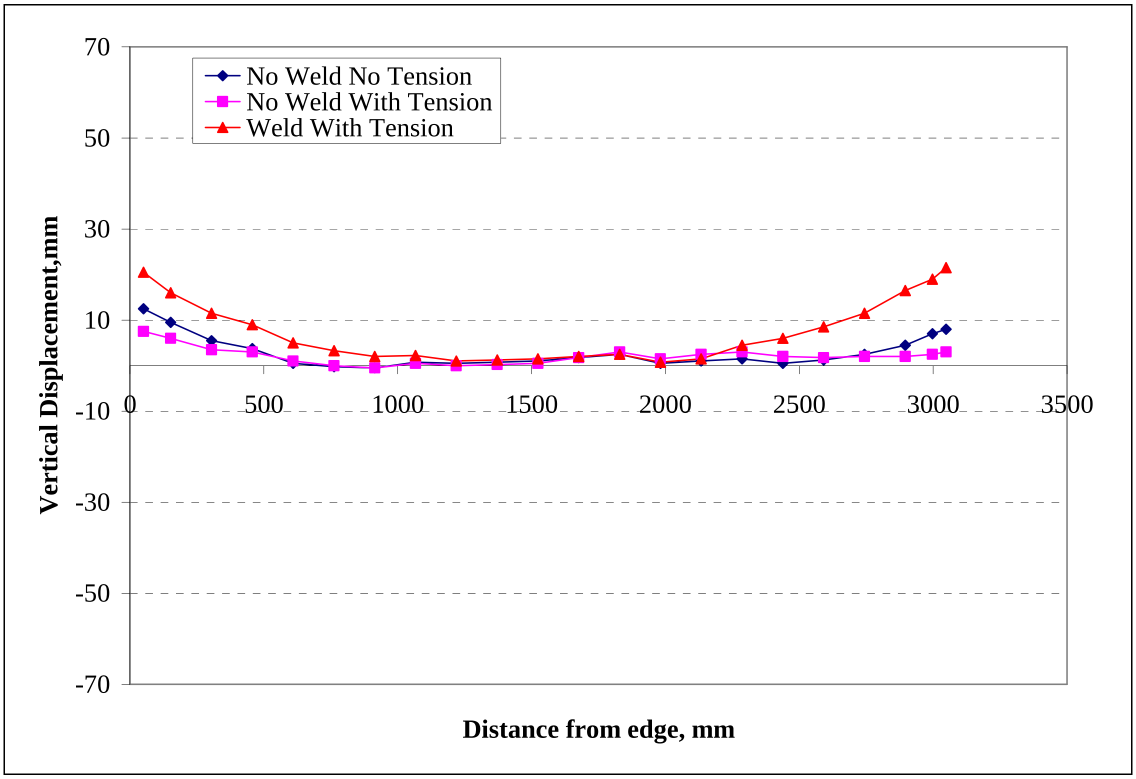


Figure 17: Longitudinal Section C

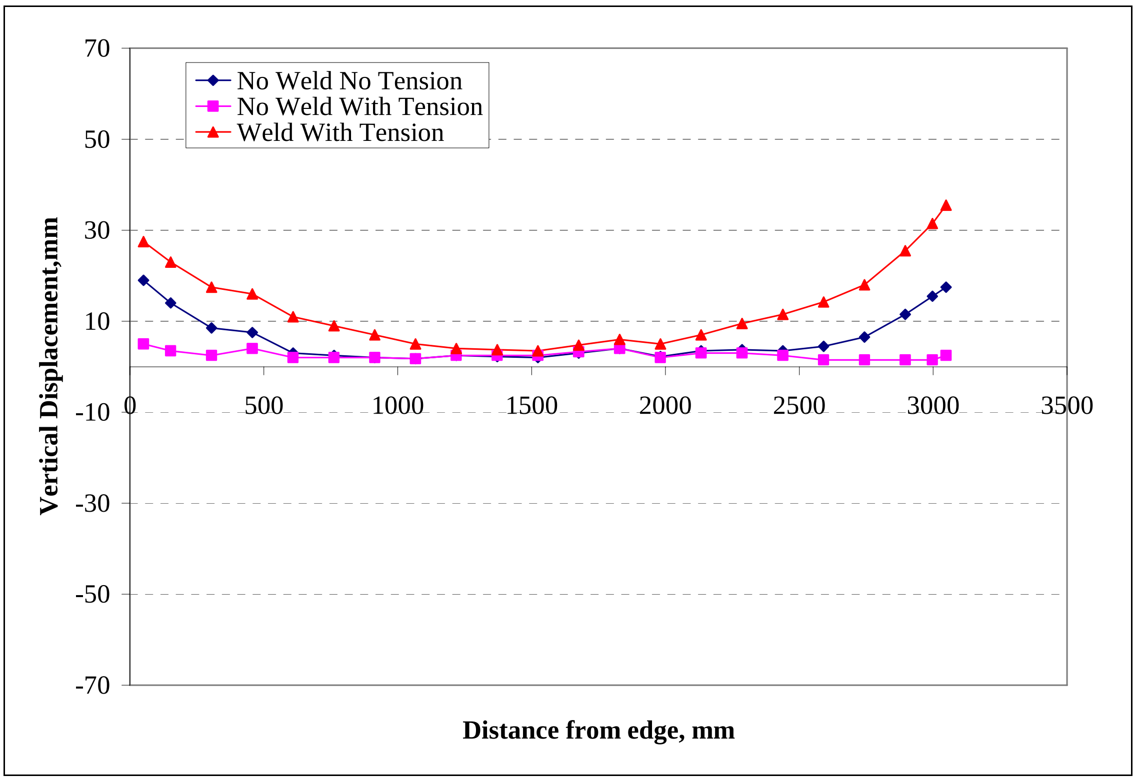


Figure 18: Longitudinal Section D

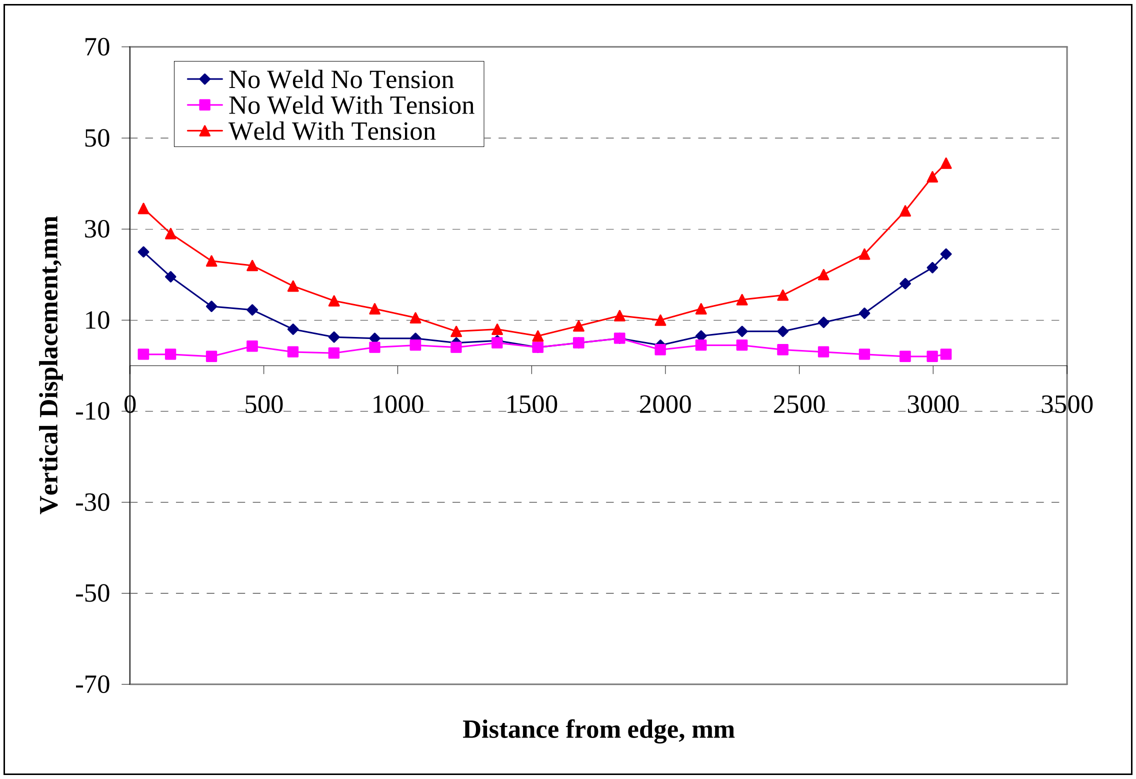


Figure 19: Longitudinal Section E

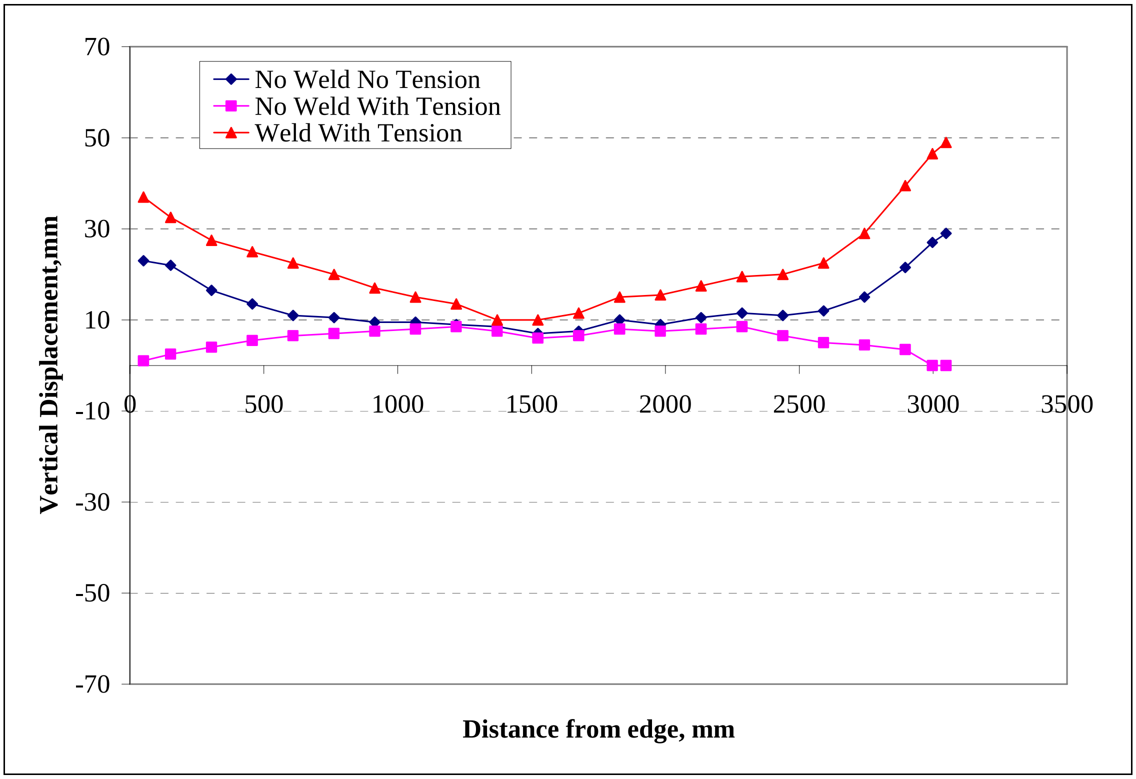


Figure 20: Longitudinal Section F

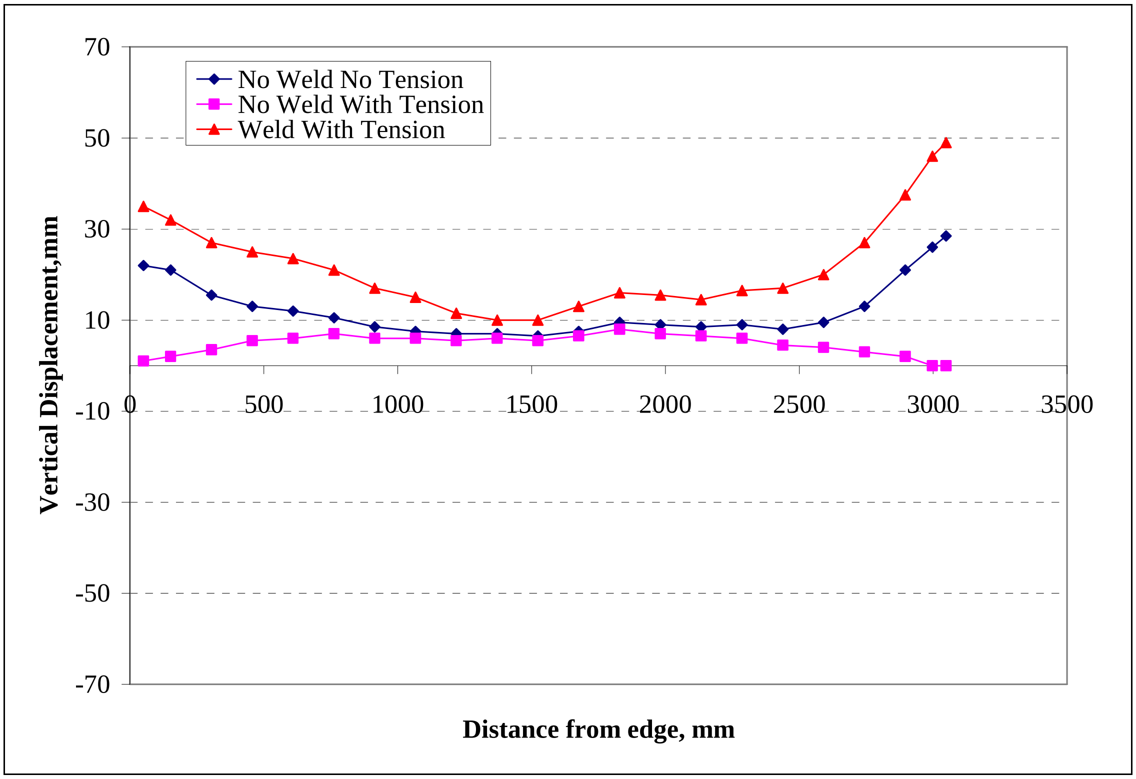


Figure 21: Longitudinal Section G

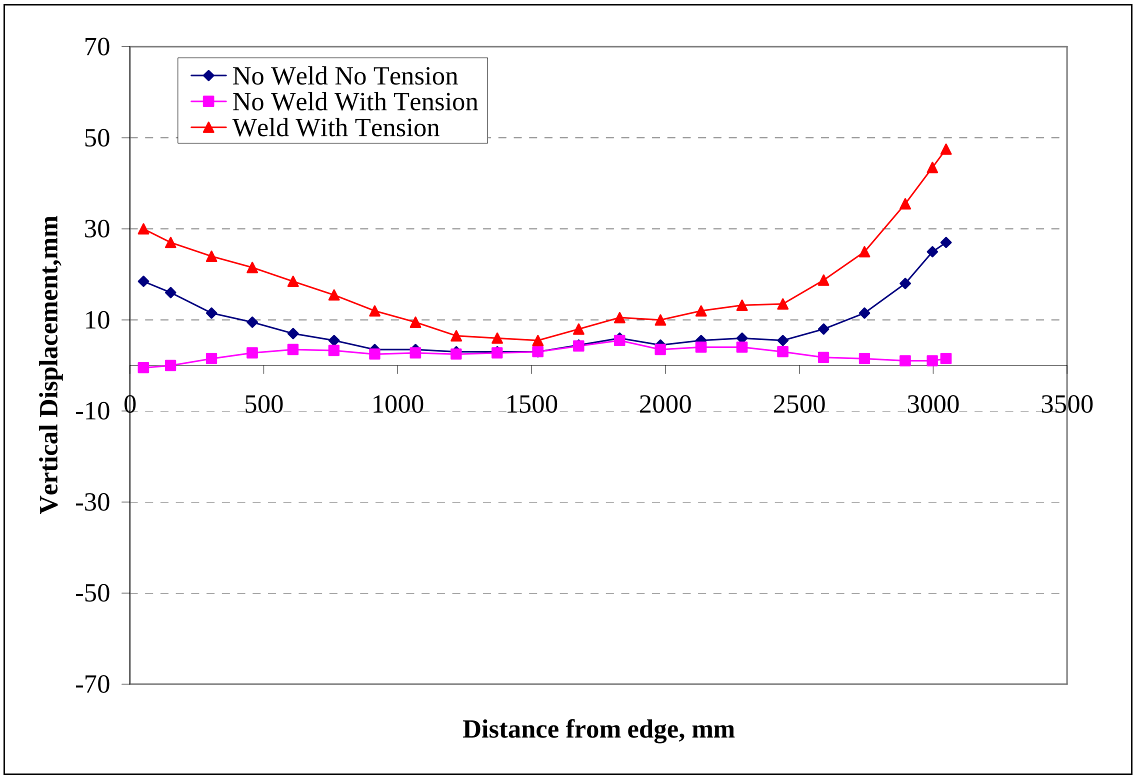


Figure 22: Longitudinal Section H

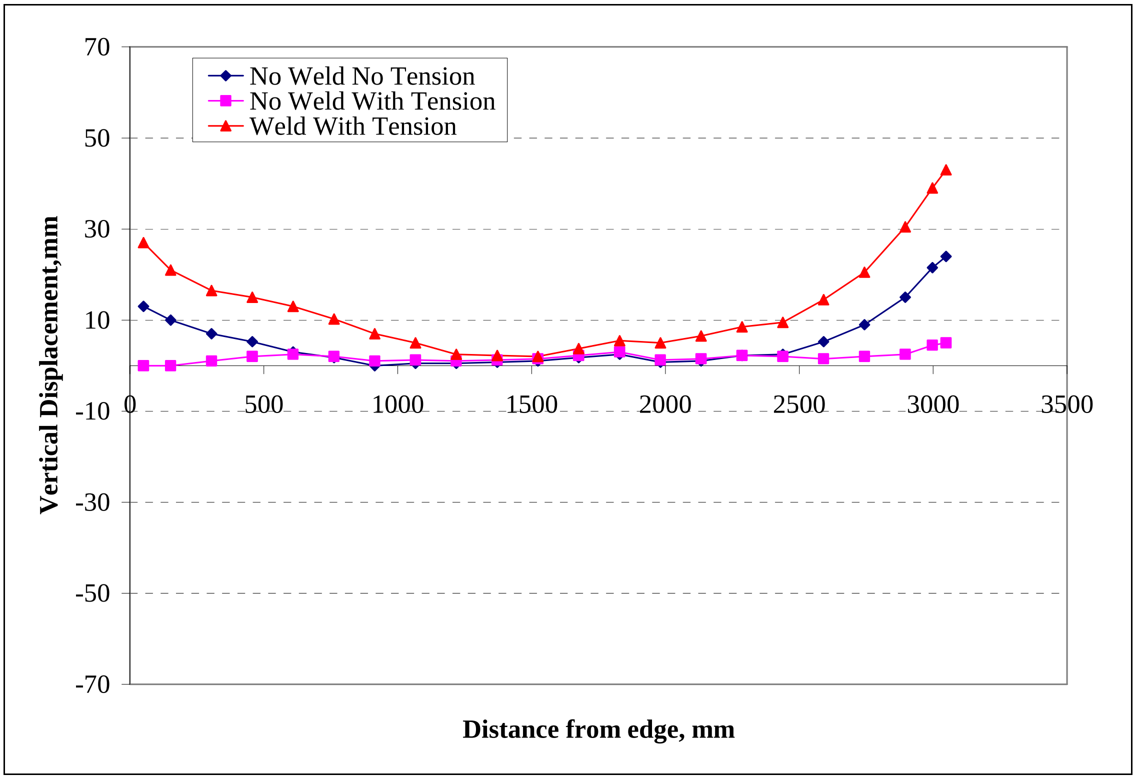


Figure 23: Longitudinal Section I

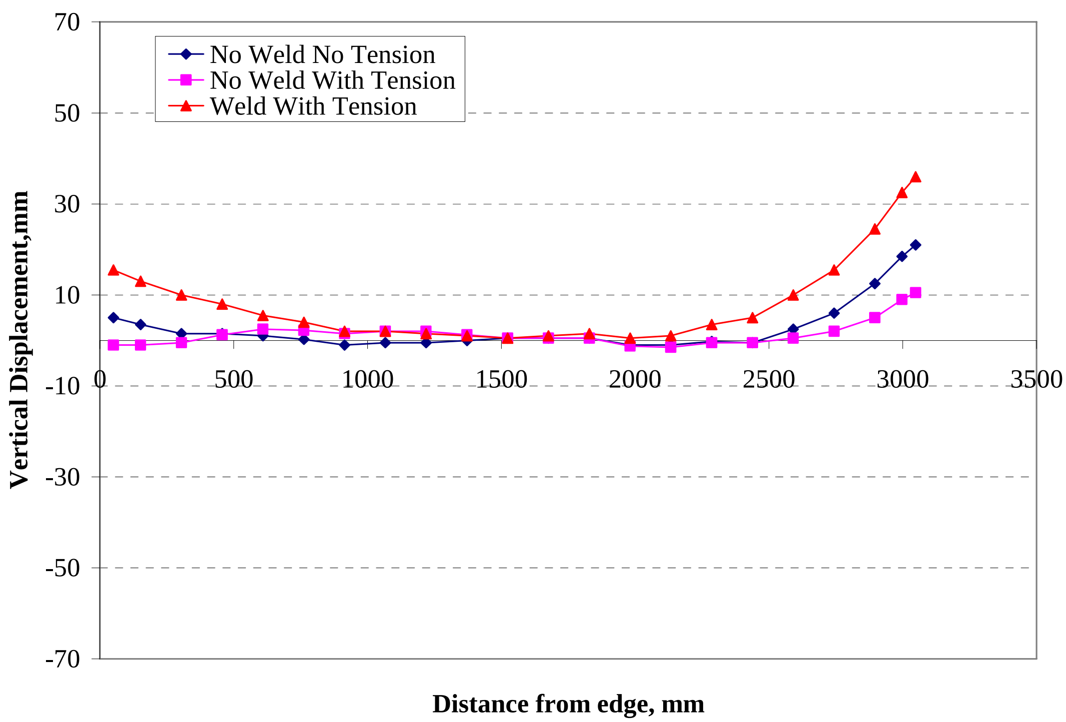


Figure 24: Longitudinal Section J

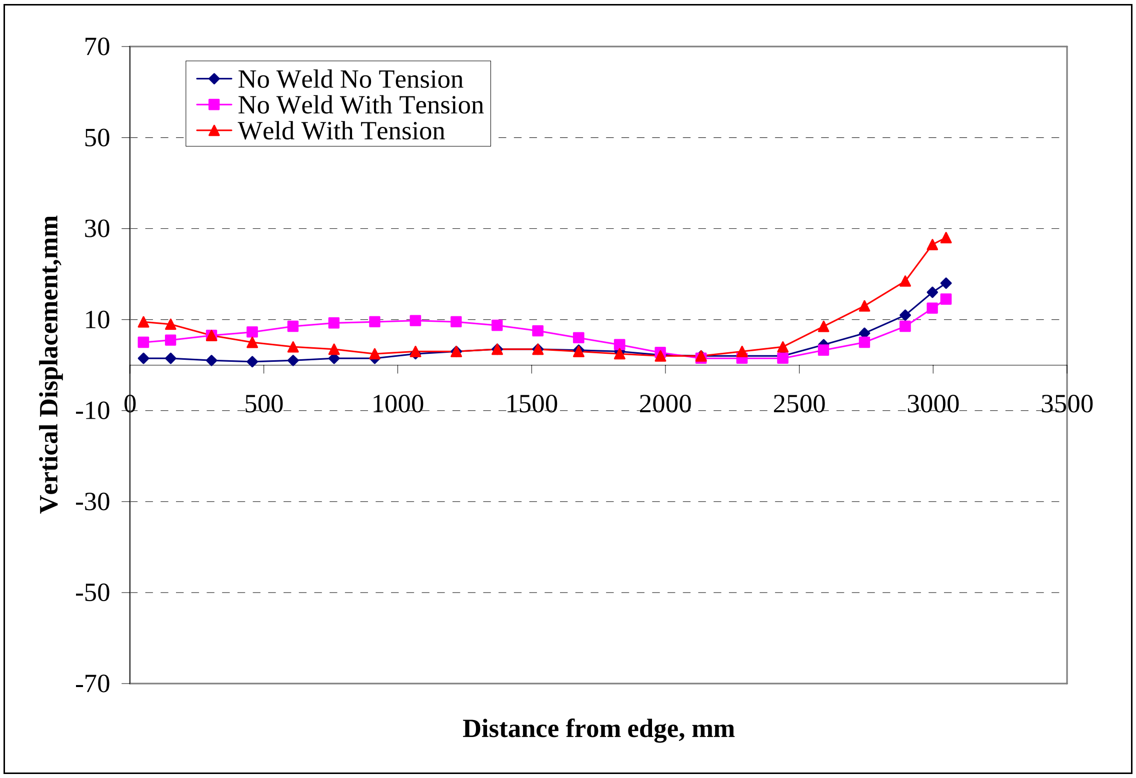


Figure 25: Longitudinal Section K

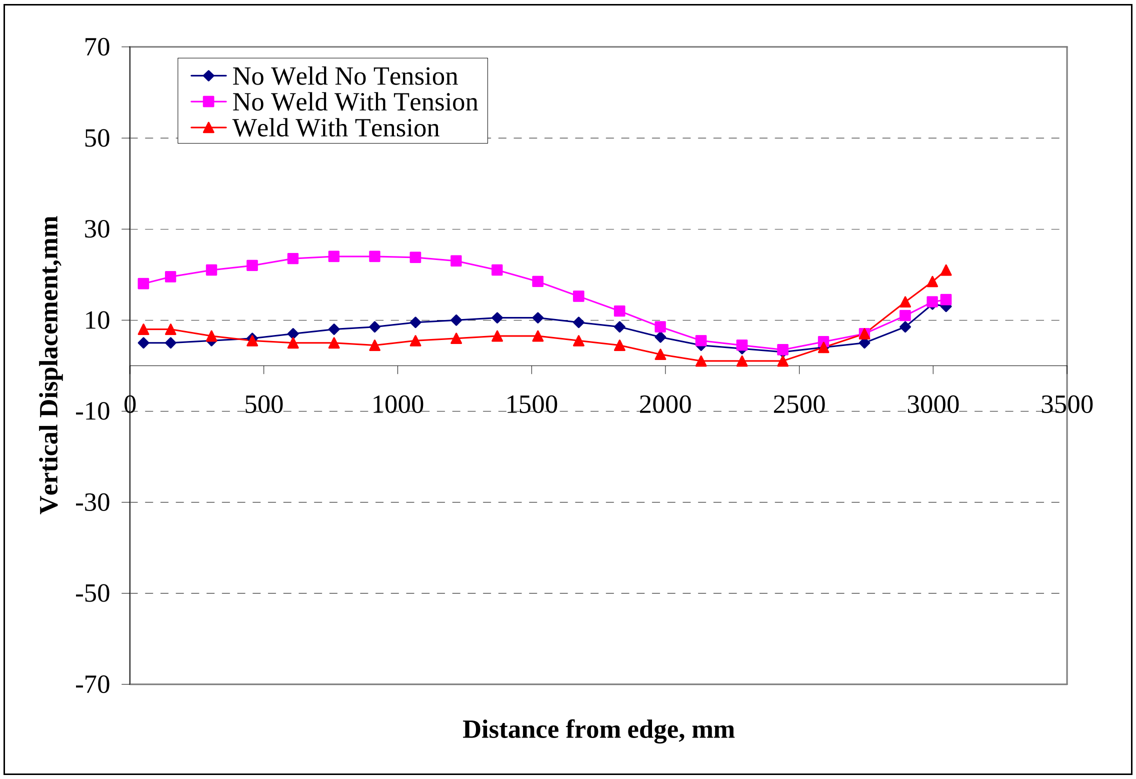


Figure 26: Longitudinal Section L

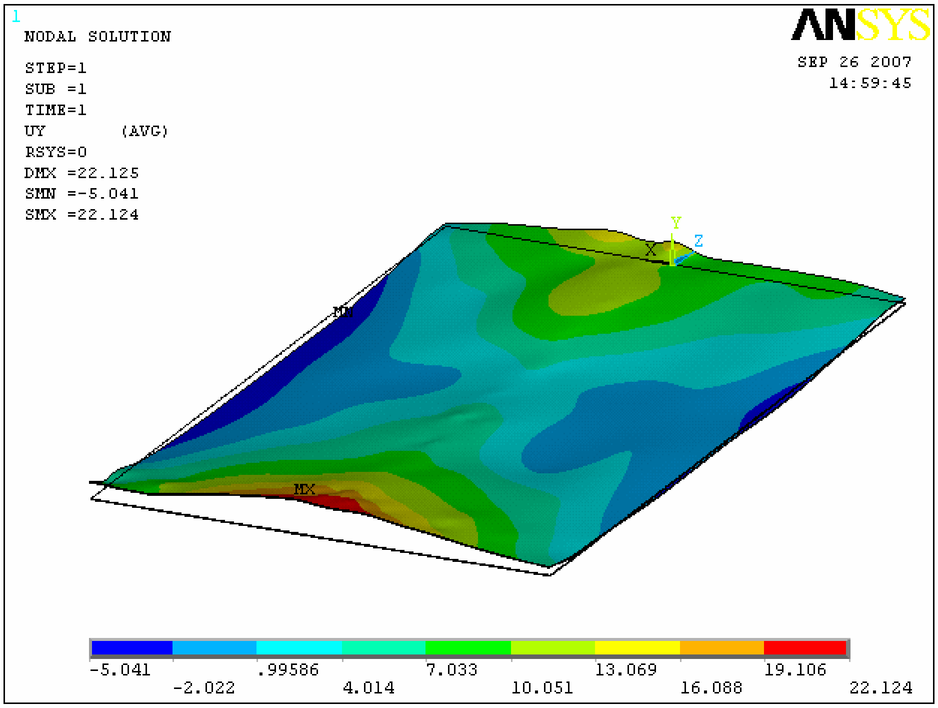


Figure 27: Net Plate Deformation (No Weld No Tension -Weld under Tension)

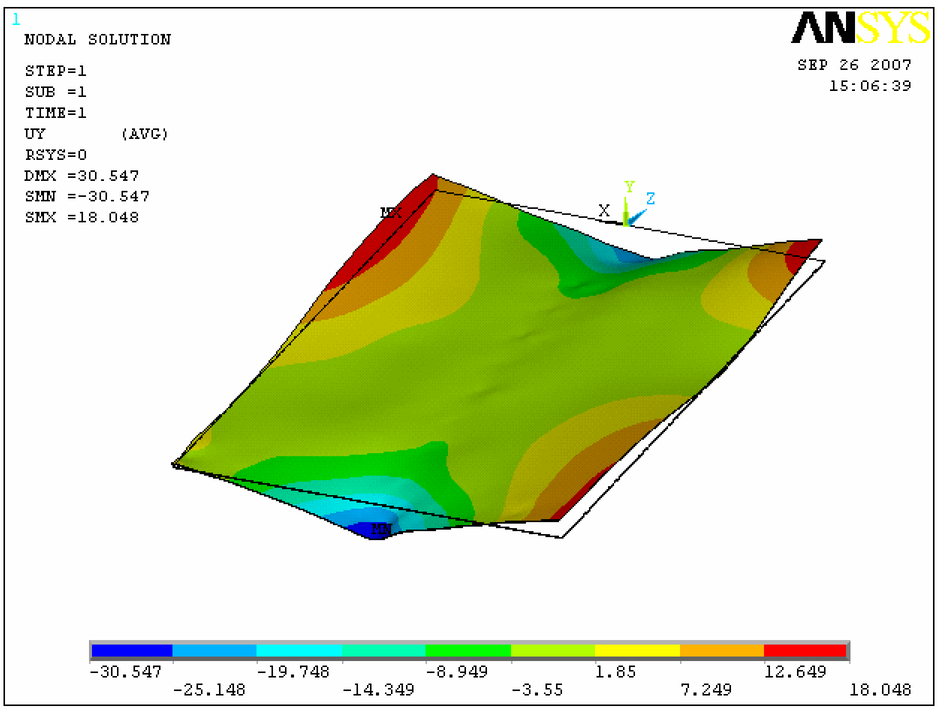


Figure 28: Plate Deformation under Tension
(No Weld with Tension-Weld under Tension)

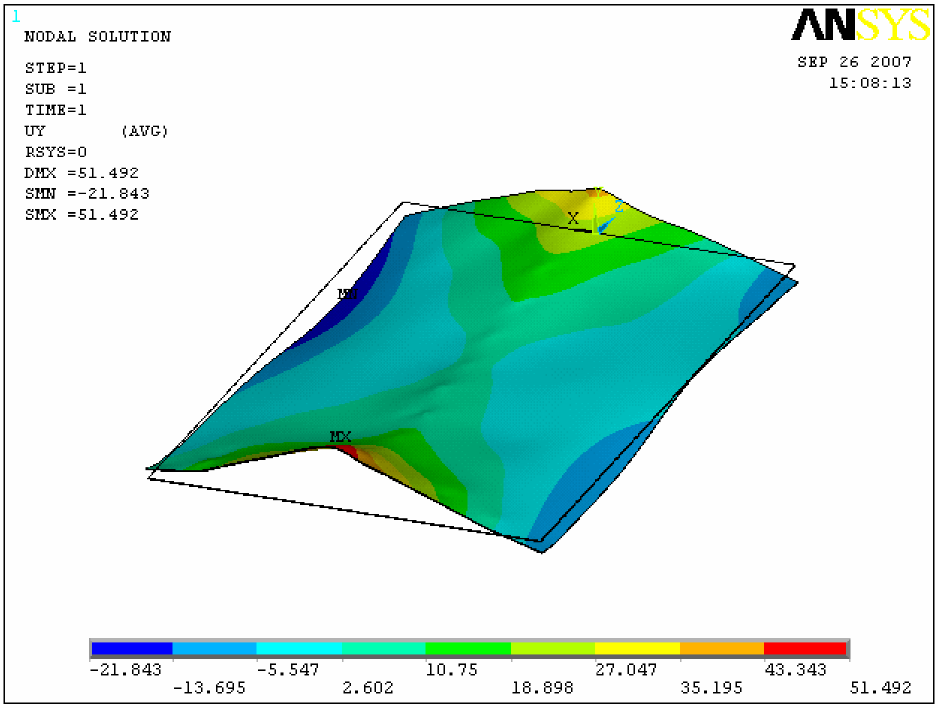


Figure 29: Plate Deformation before Welding (No Weld No Tension-No Weld with Tension)

PLATE 6 – SIDE 1

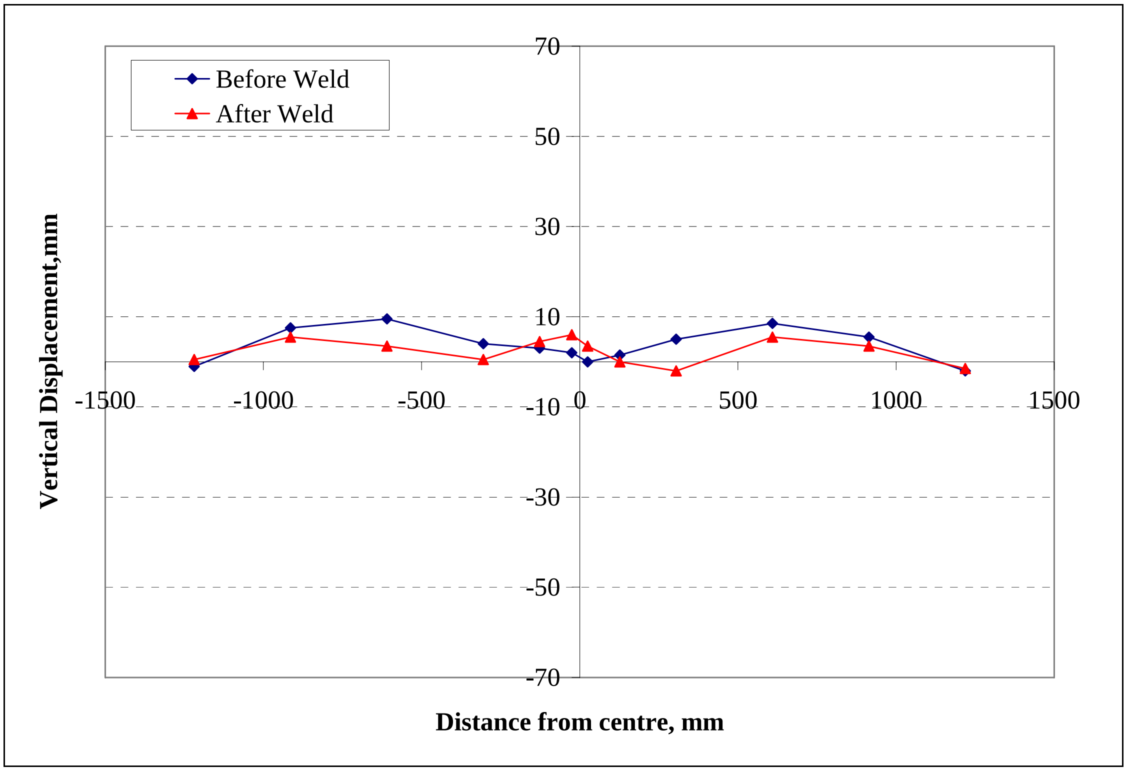


Figure 1: Transverse Section A1

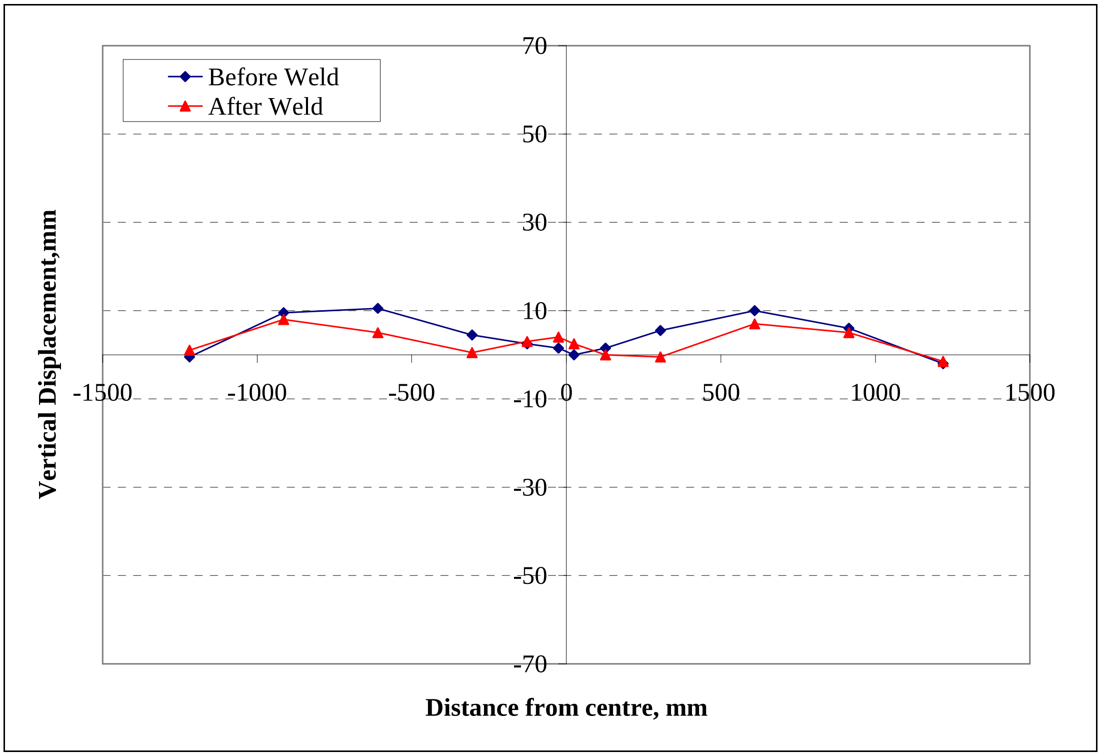


Figure 2: Transverse Section A2

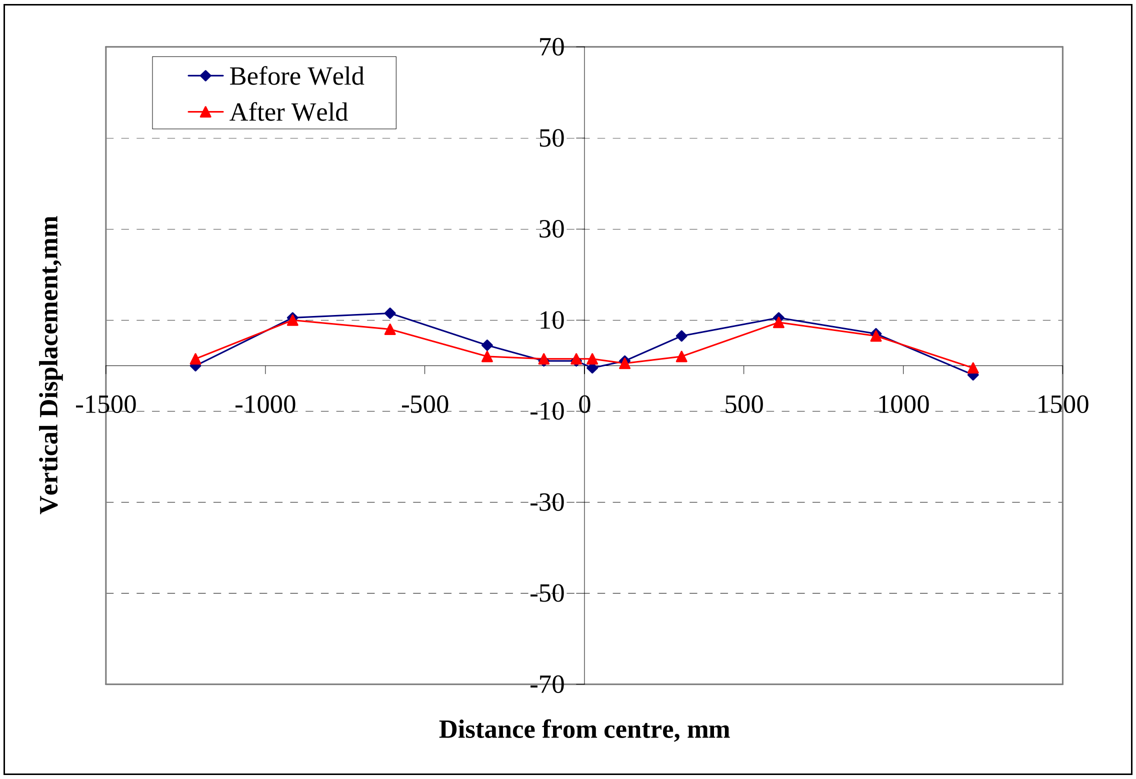


Figure 3: Transverse Section A3

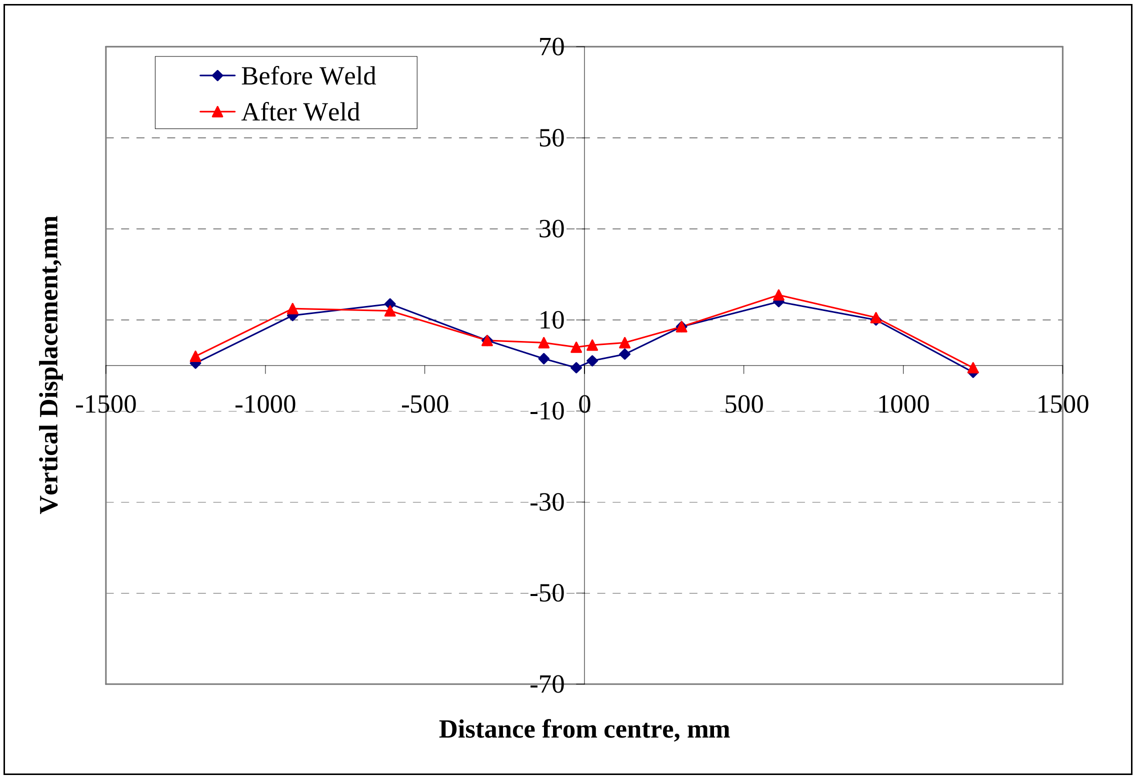


Figure 4: Transverse Section A5

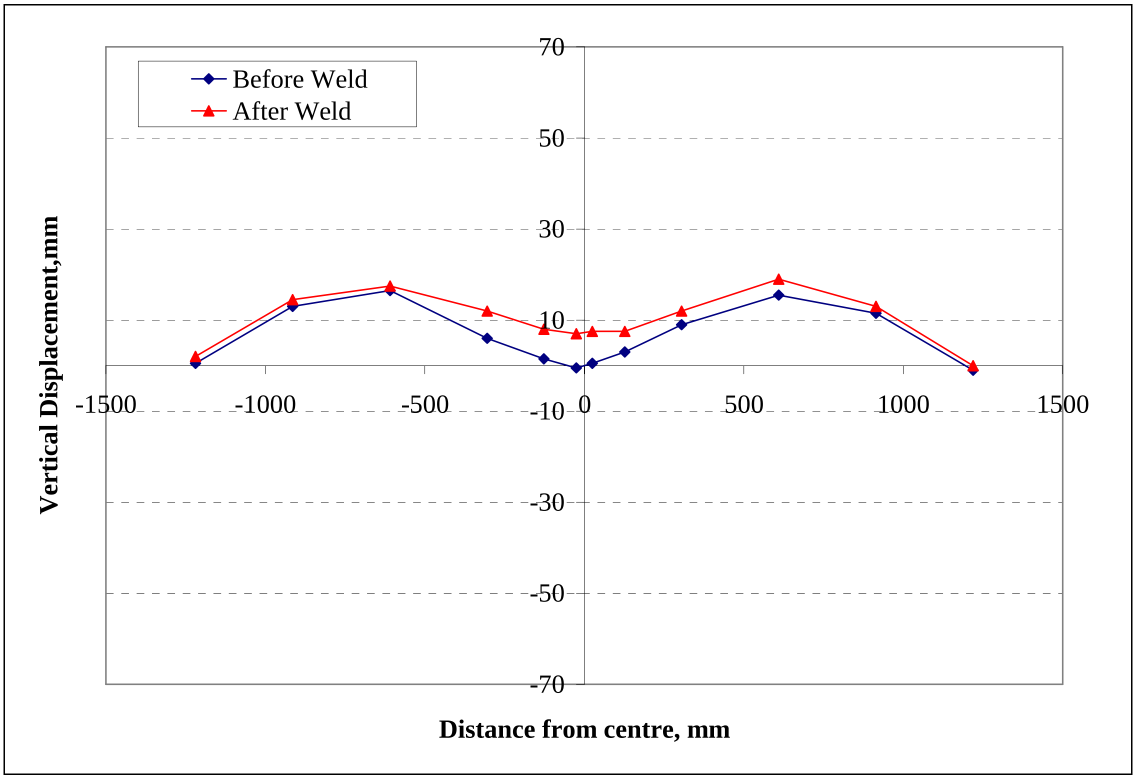


Figure 5: Transverse Section A7

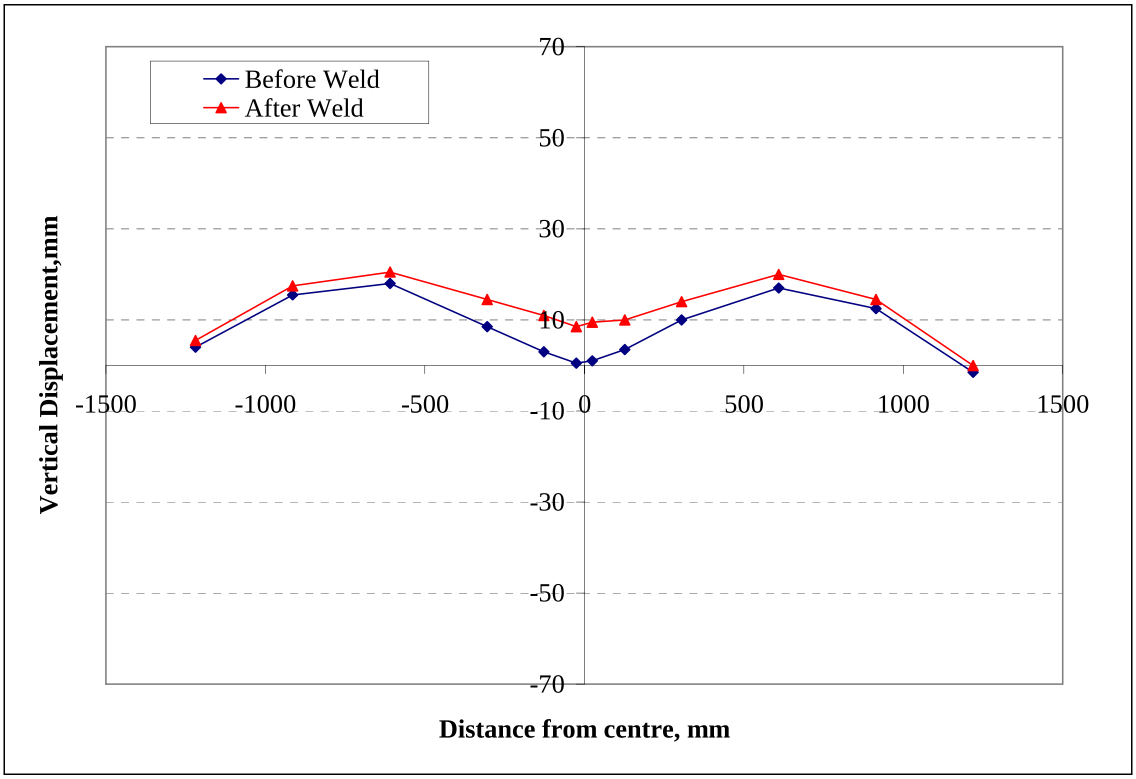


Figure 6: Transverse Section A9

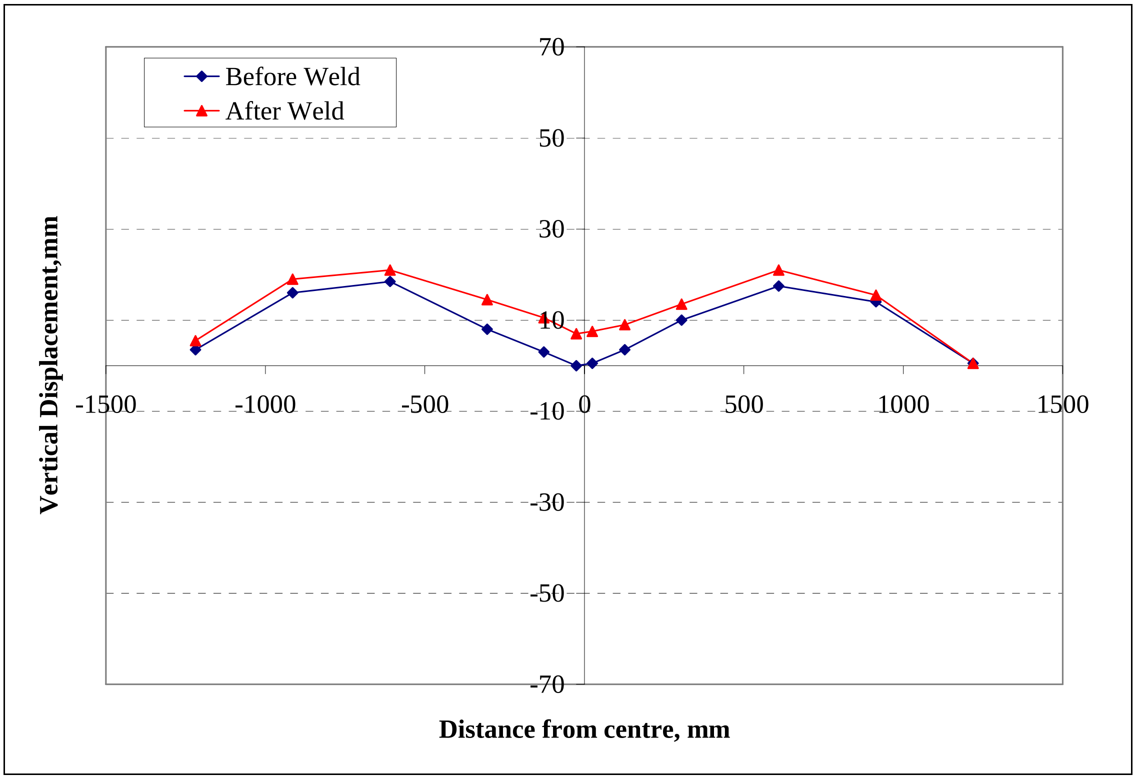


Figure 7: Transverse Section A11

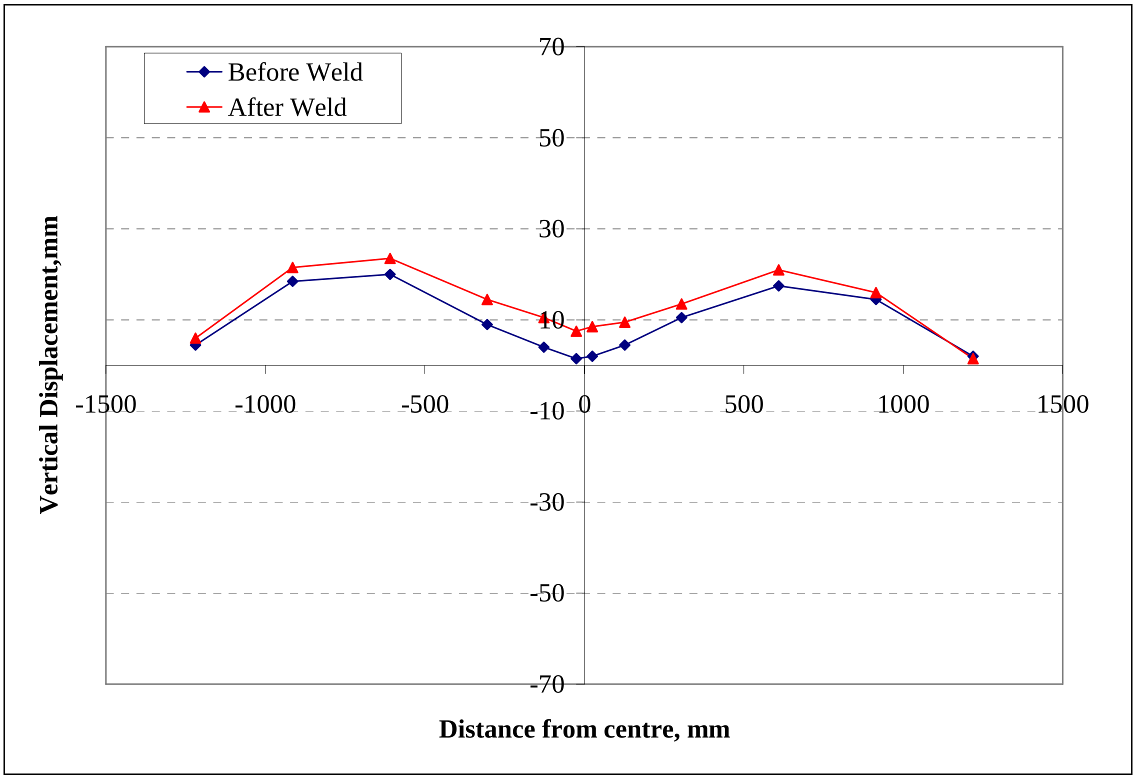


Figure 8: Transverse Section A13

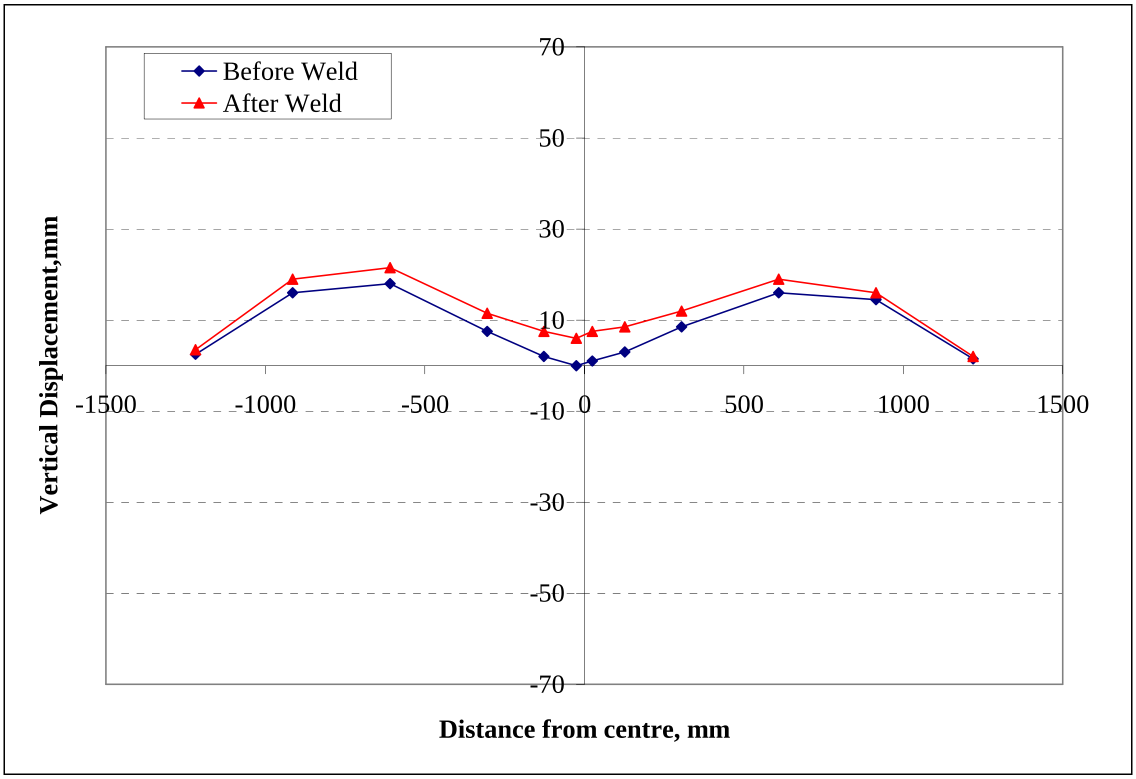


Figure 9: Transverse Section A15

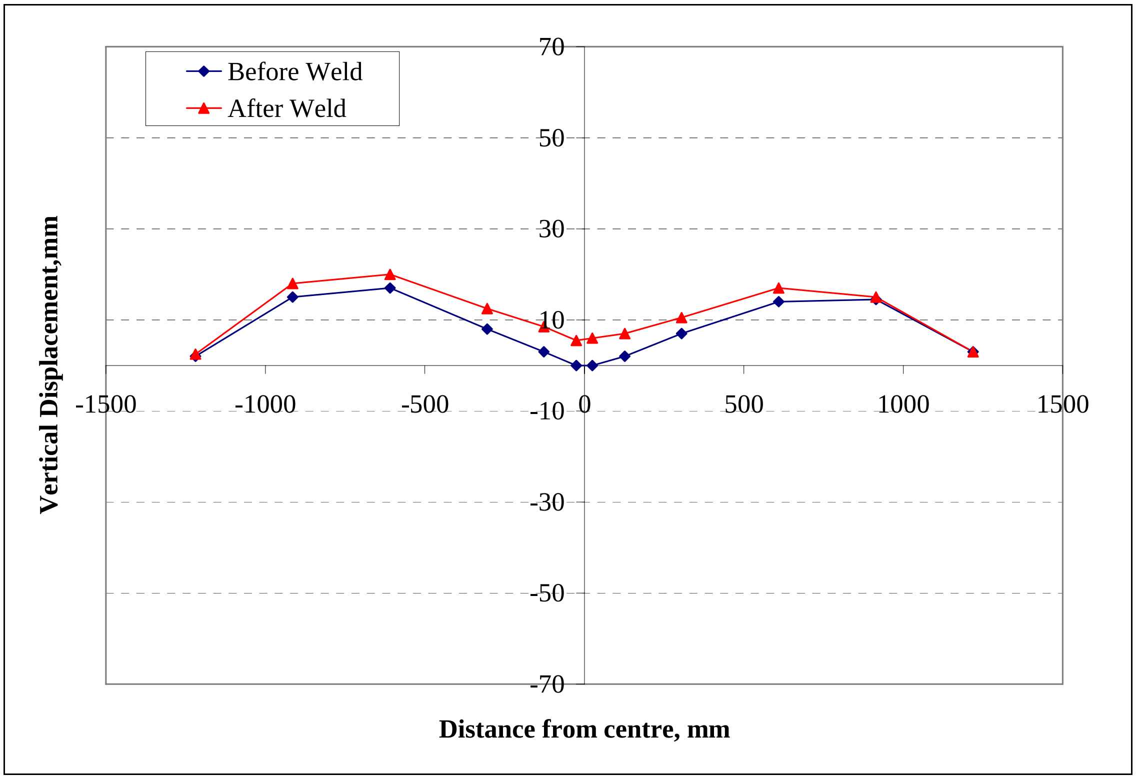


Figure 10: Transverse Section A17

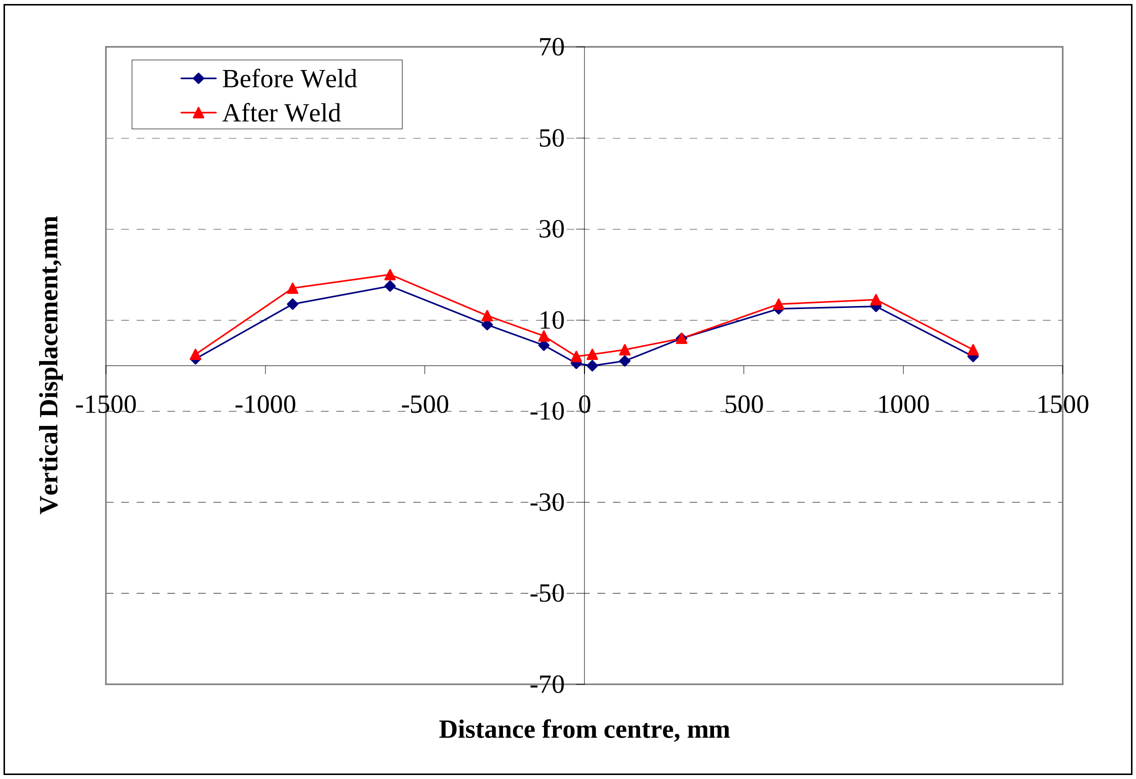


Figure 11: Transverse Section A19

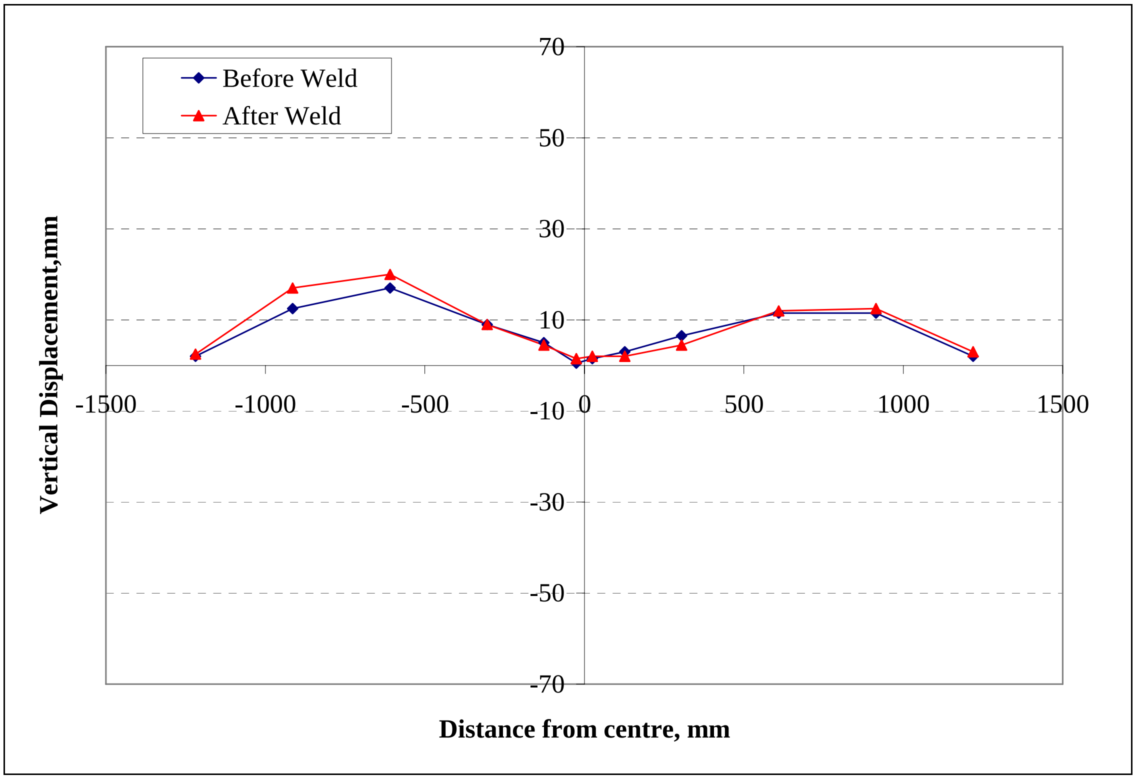


Figure 12: Transverse Section A20

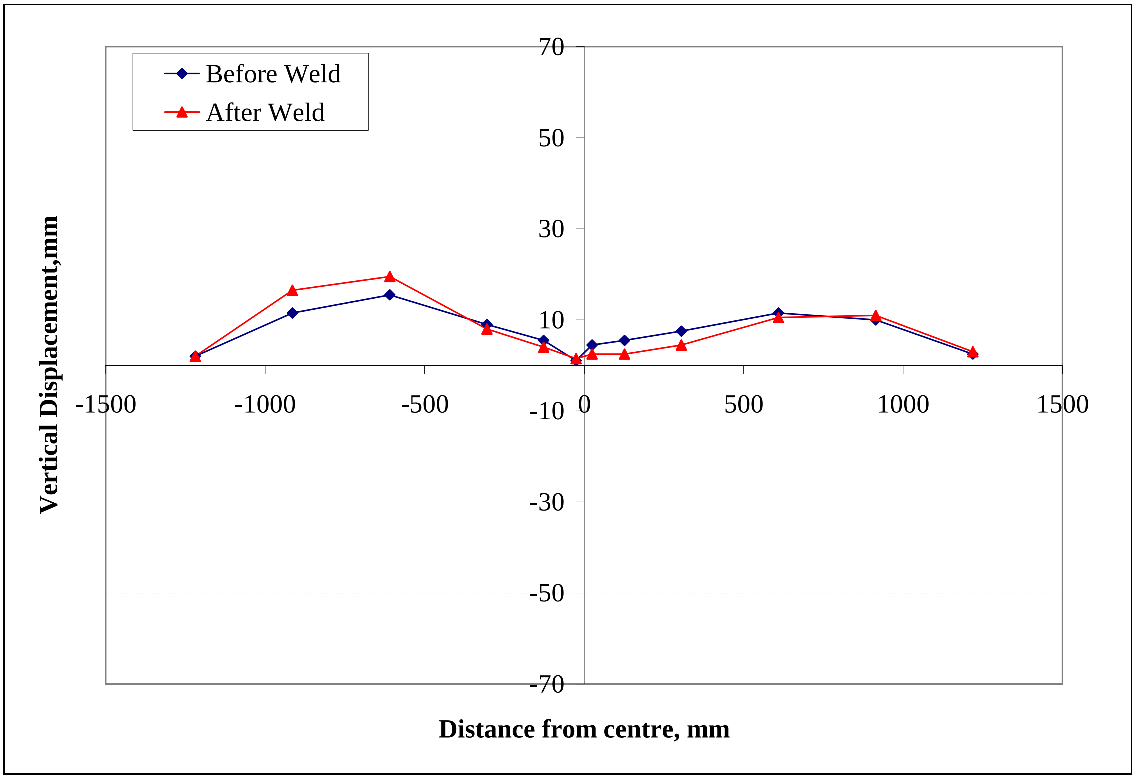


Figure 13: Transverse Section A21

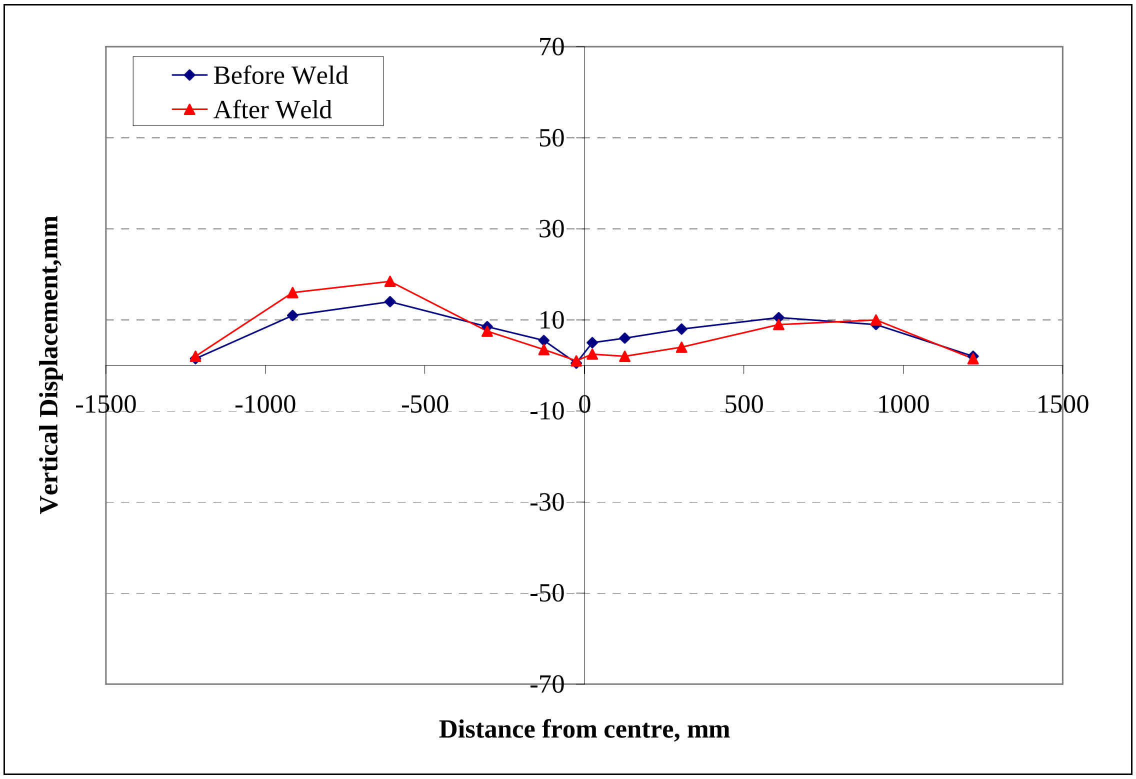


Figure 14: Transverse Section A22

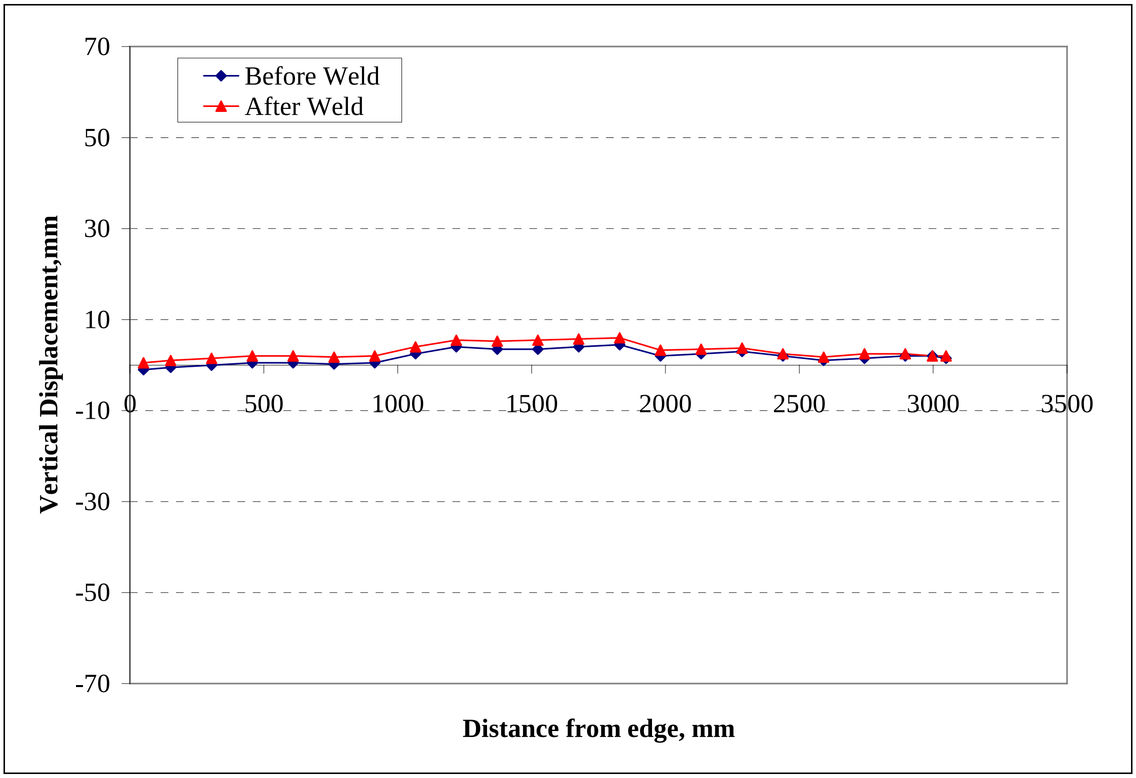


Figure 15: Longitudinal Section A

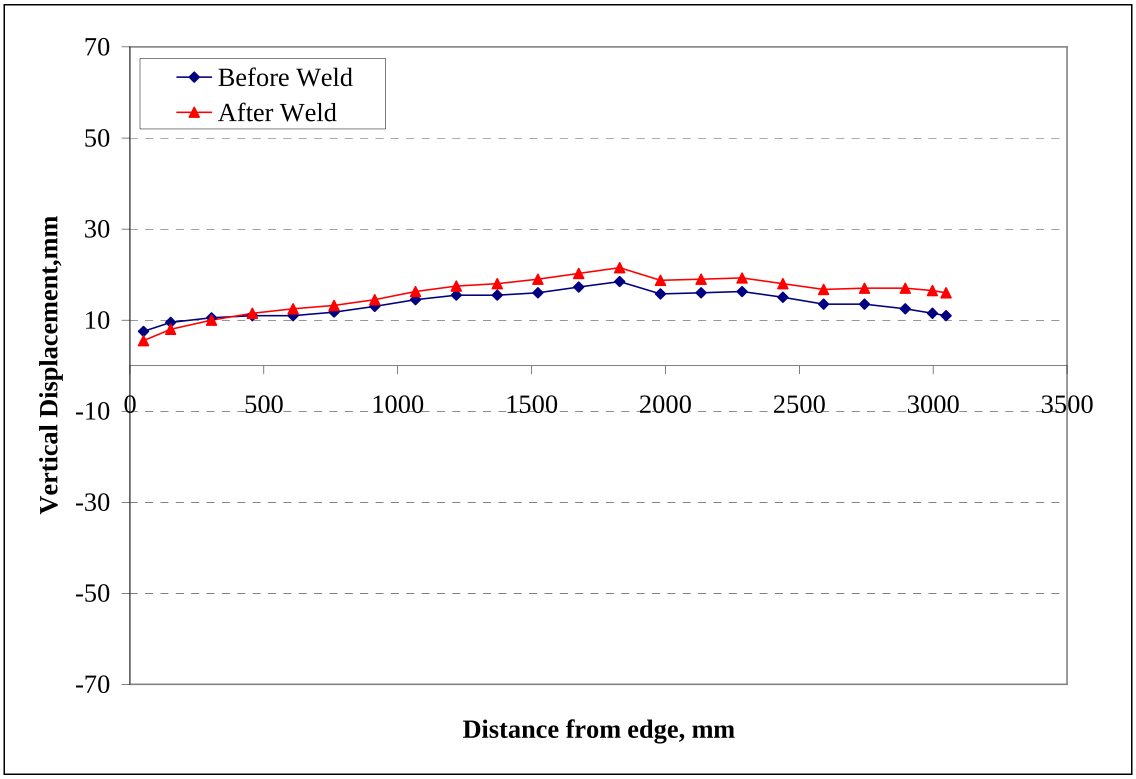


Figure 16: Longitudinal Section B

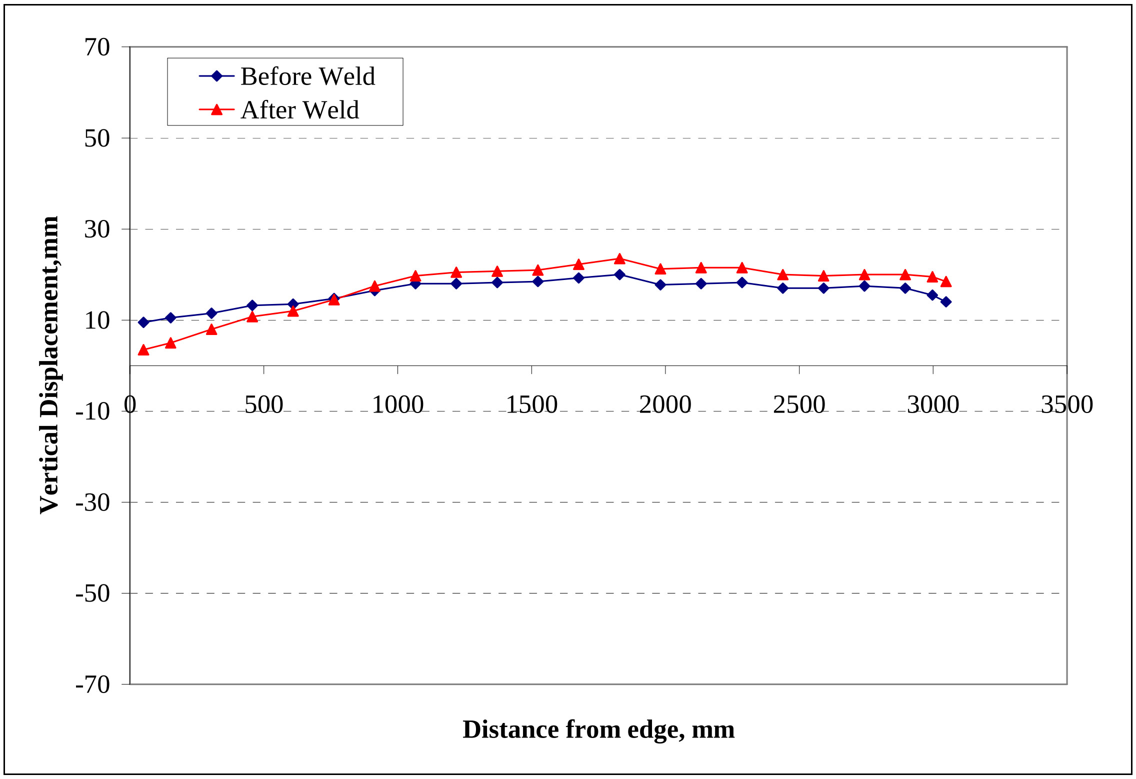


Figure 17: Longitudinal Section C

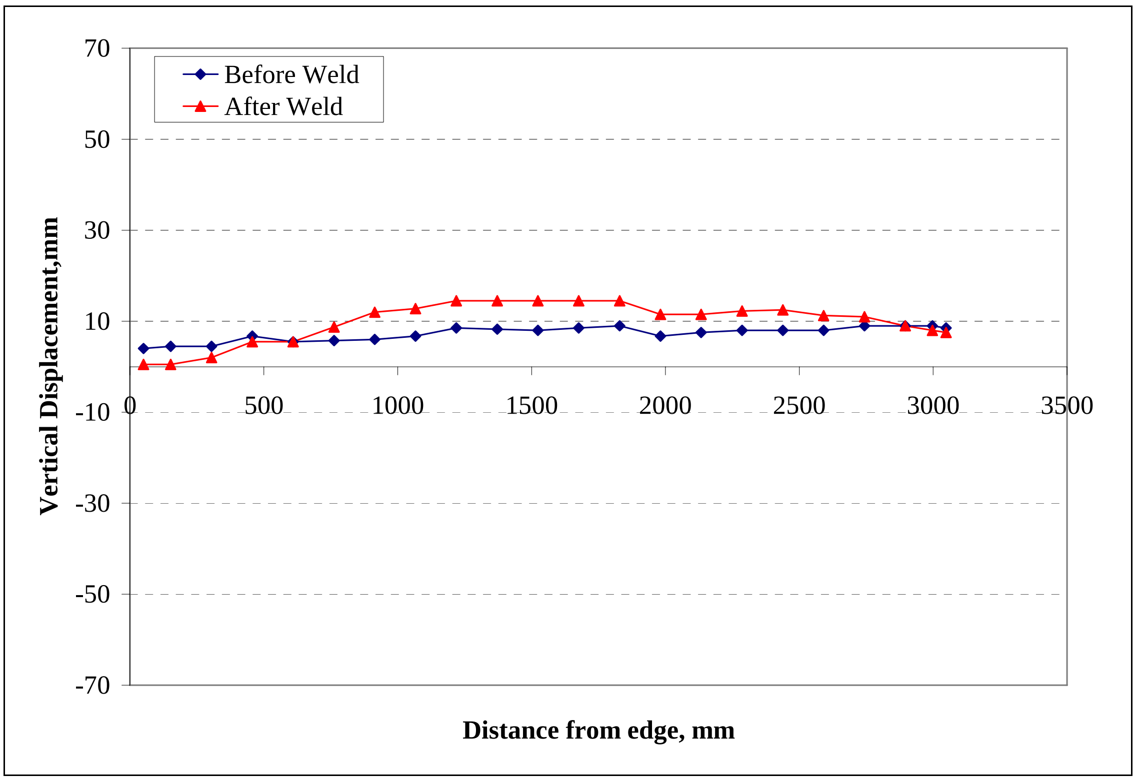


Figure 18: Longitudinal Section D

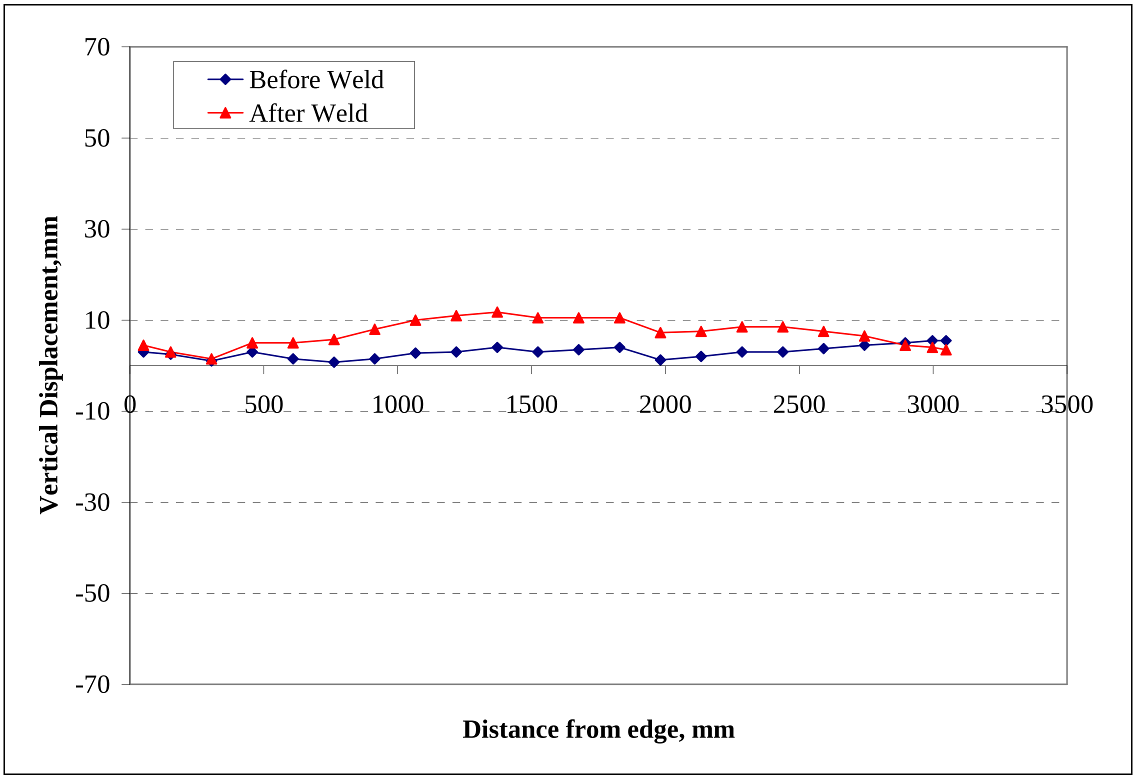


Figure 19: Longitudinal Section E

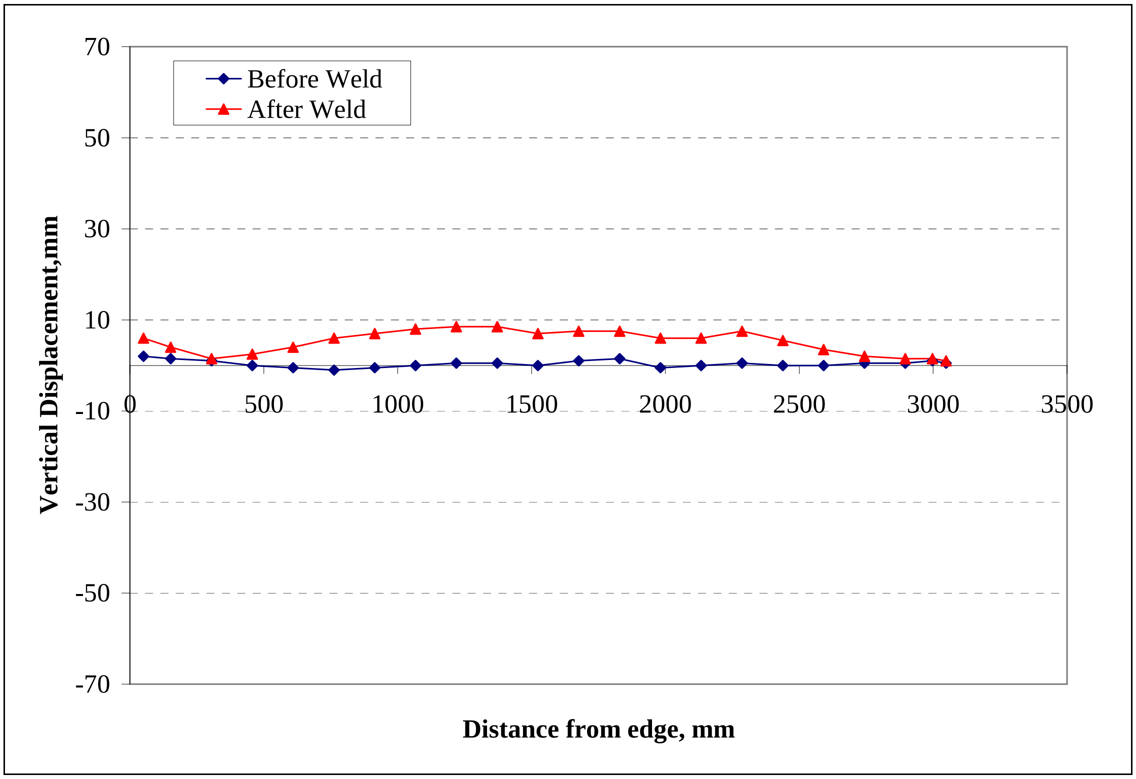


Figure 20: Longitudinal Section F

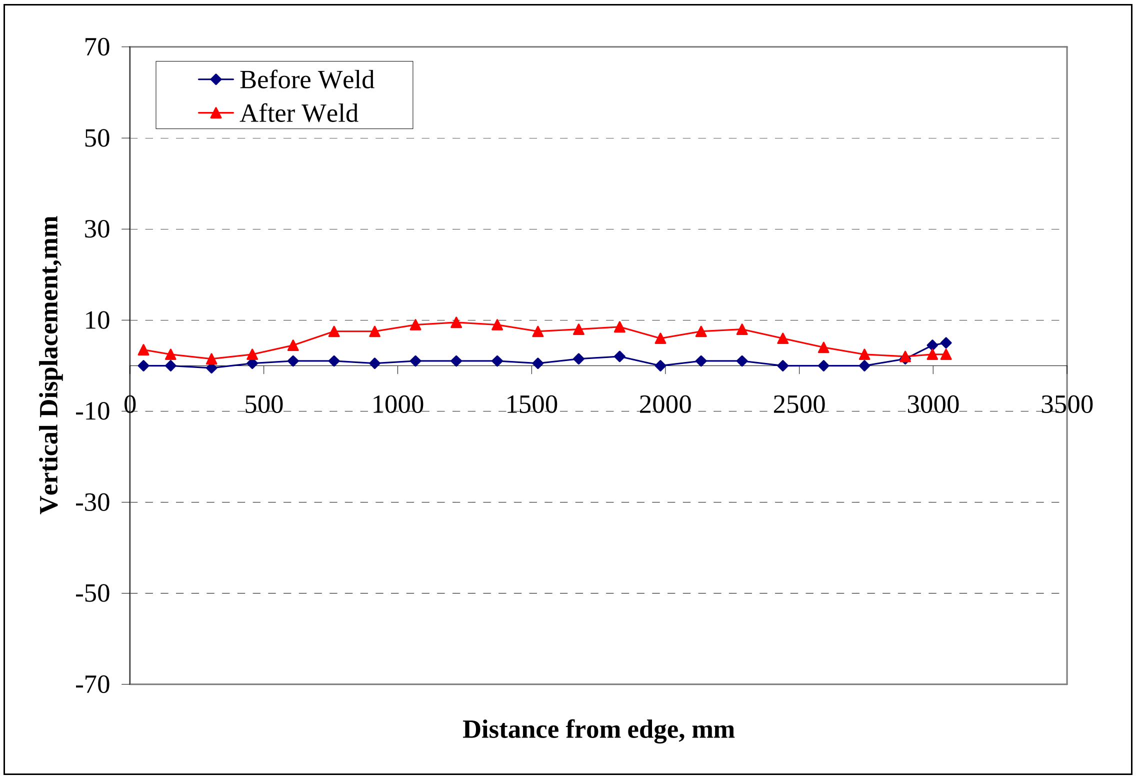


Figure 21: Longitudinal Section G

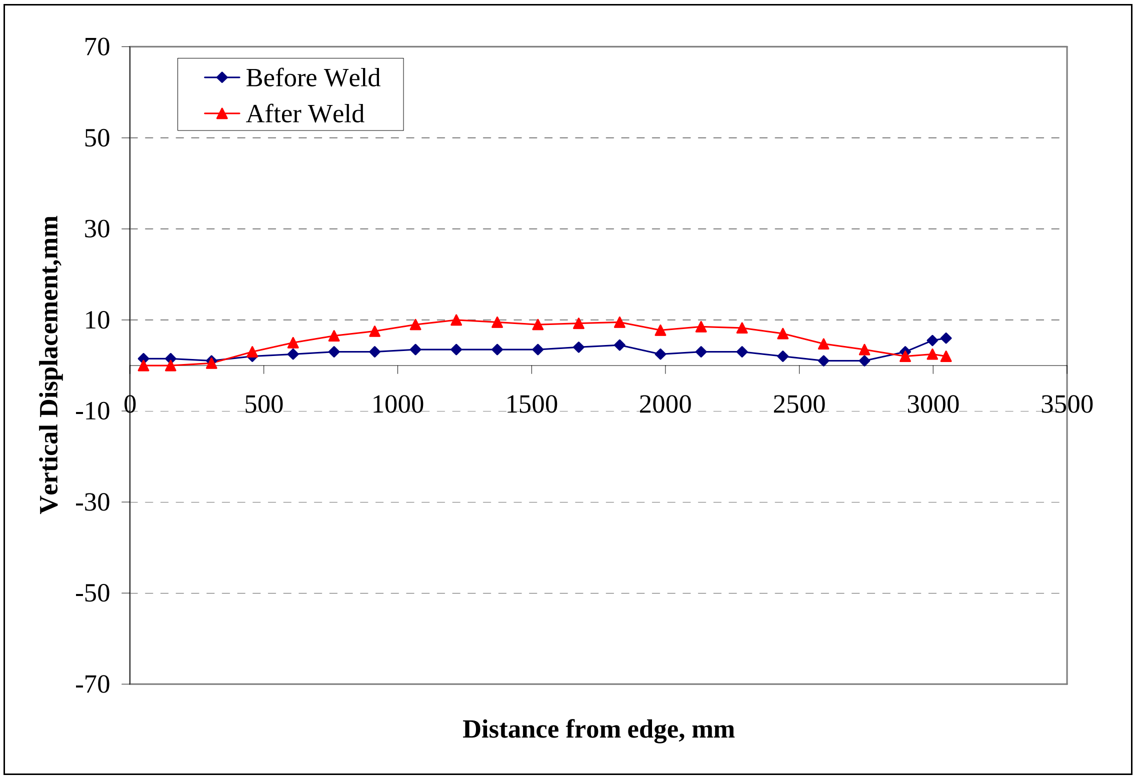


Figure 22: Longitudinal Section H

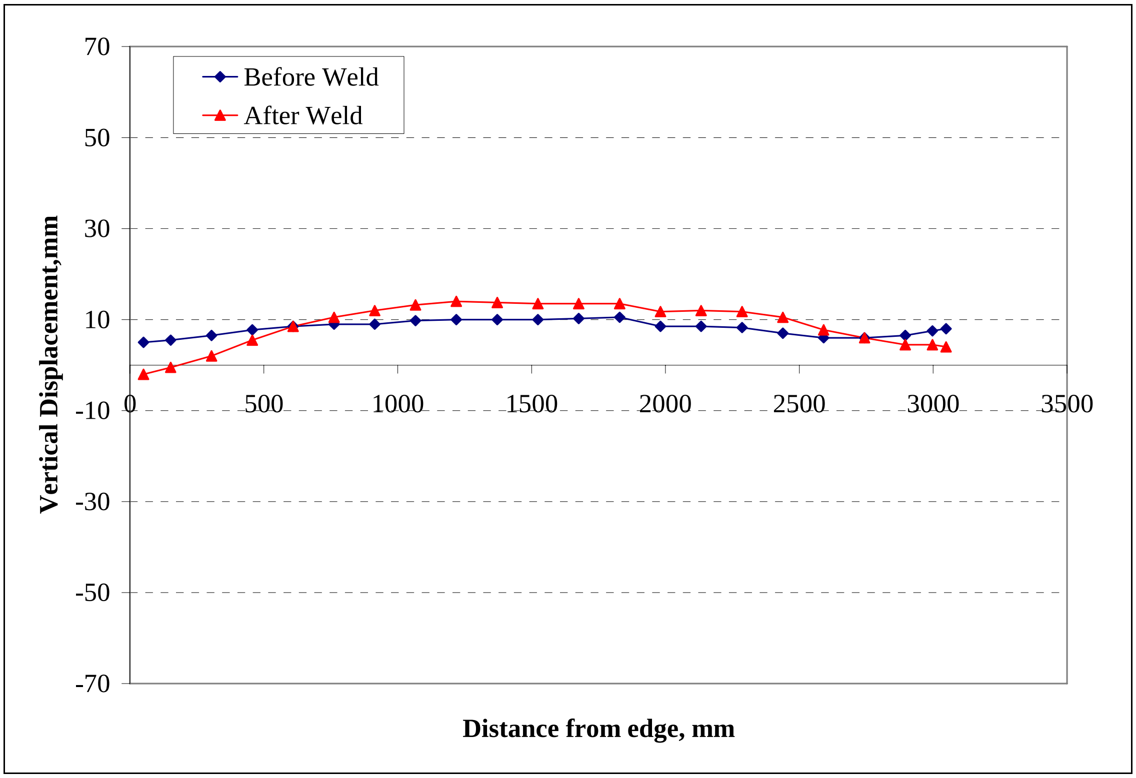


Figure 23: Longitudinal Section I

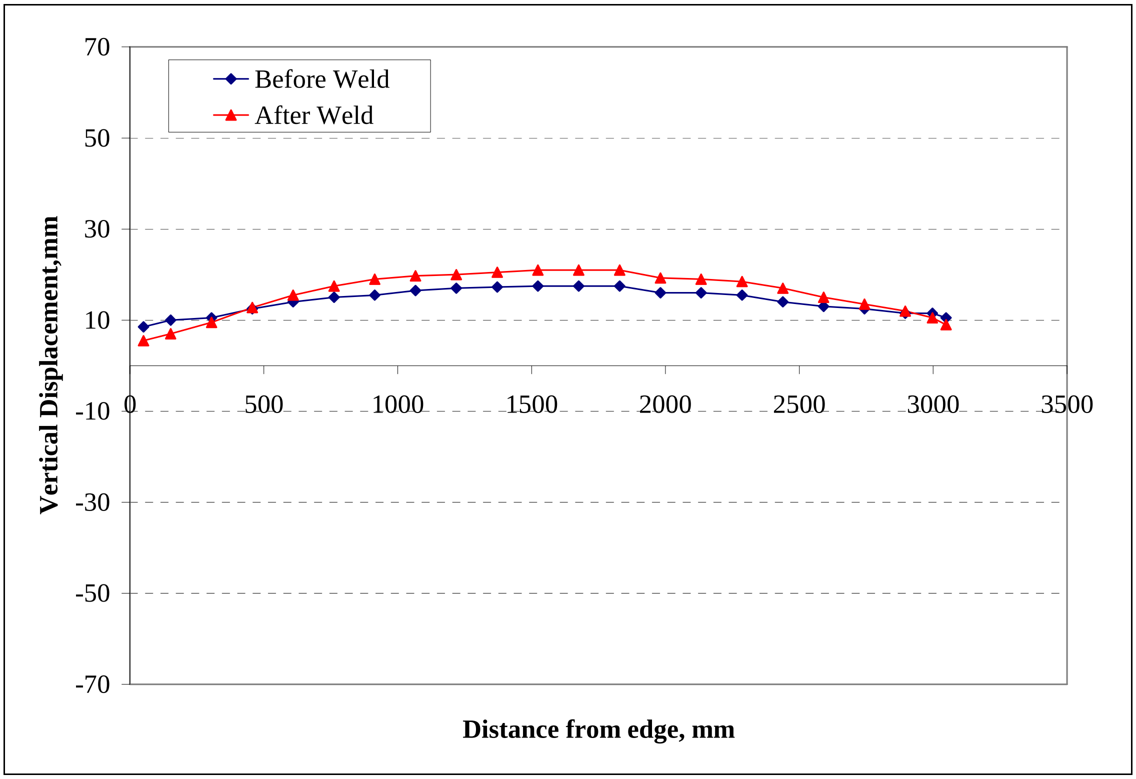


Figure 24: Longitudinal Section J

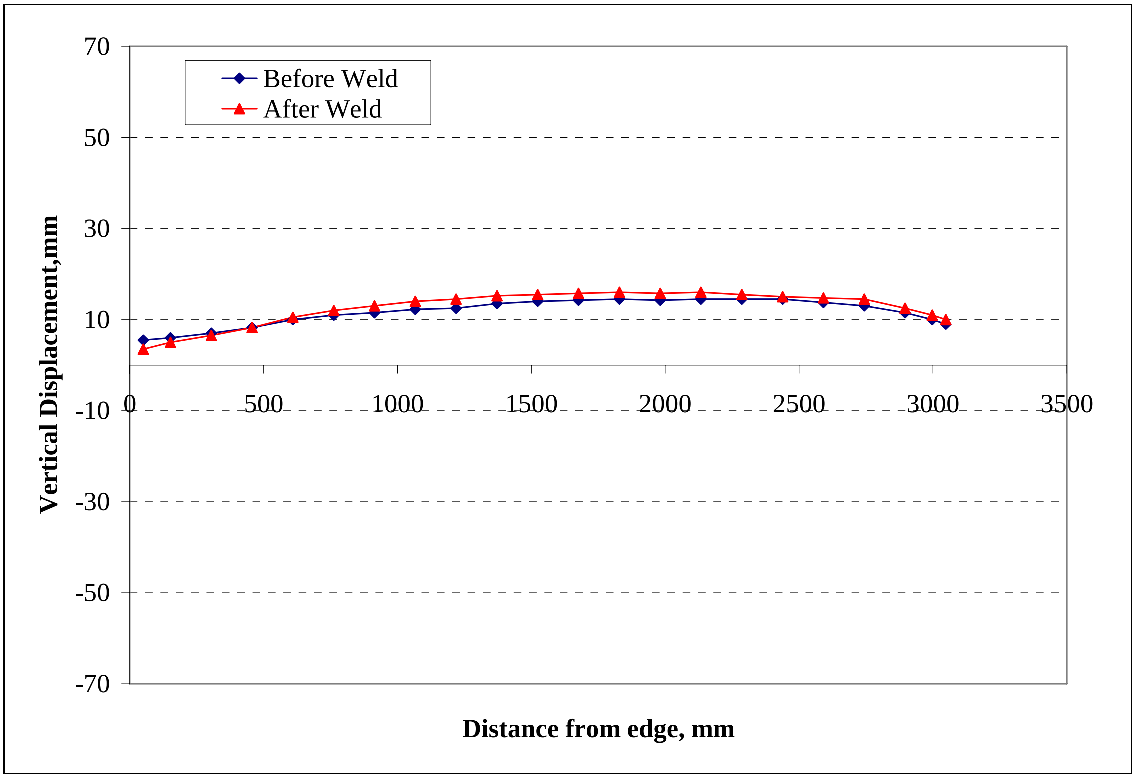


Figure 25: Longitudinal Section K

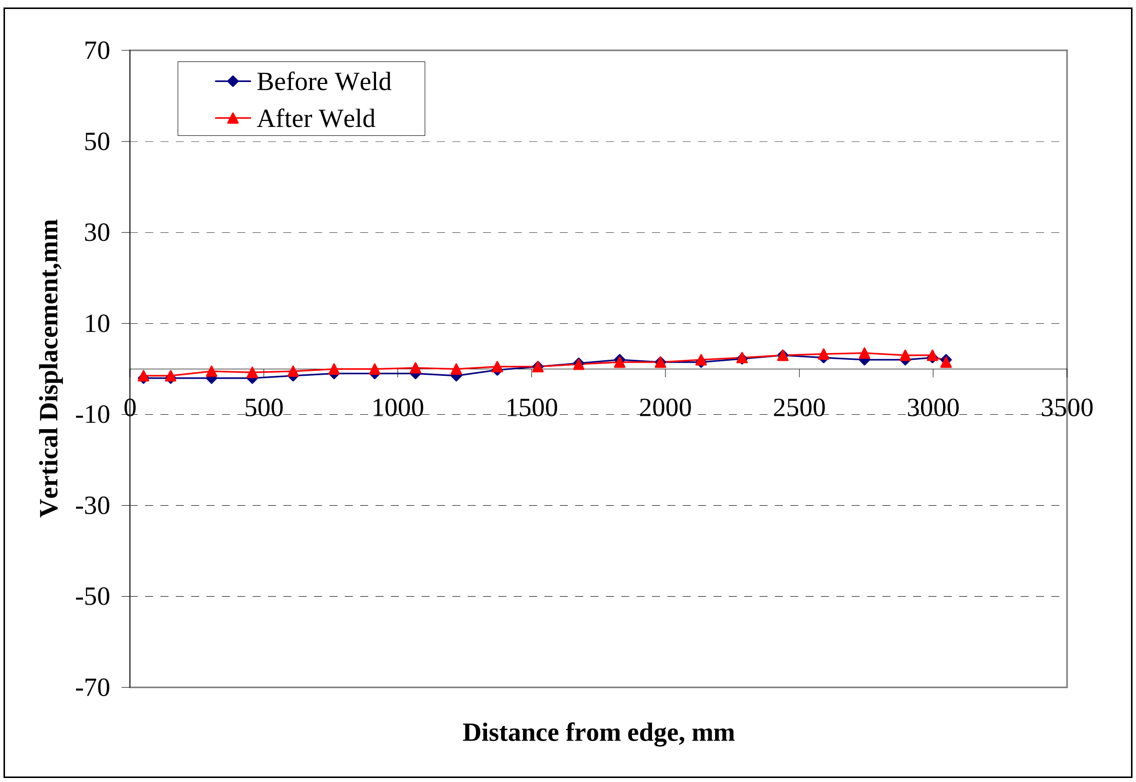


Figure 26: Longitudinal Section L

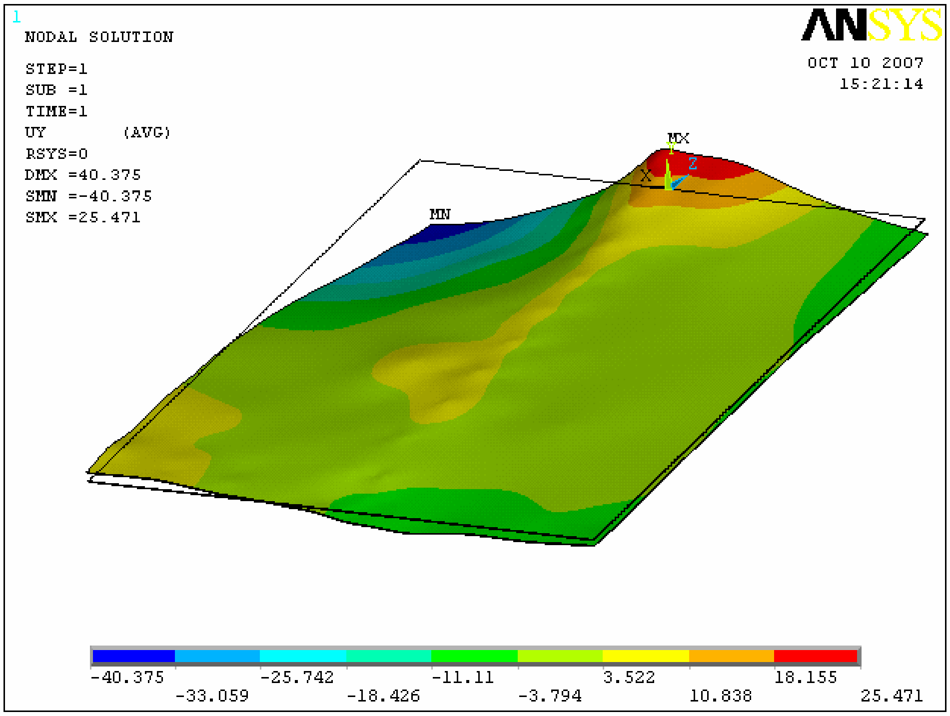


Figure 27: Net Plate Deformation after Welding

PLATE 6 – SIDE 2A

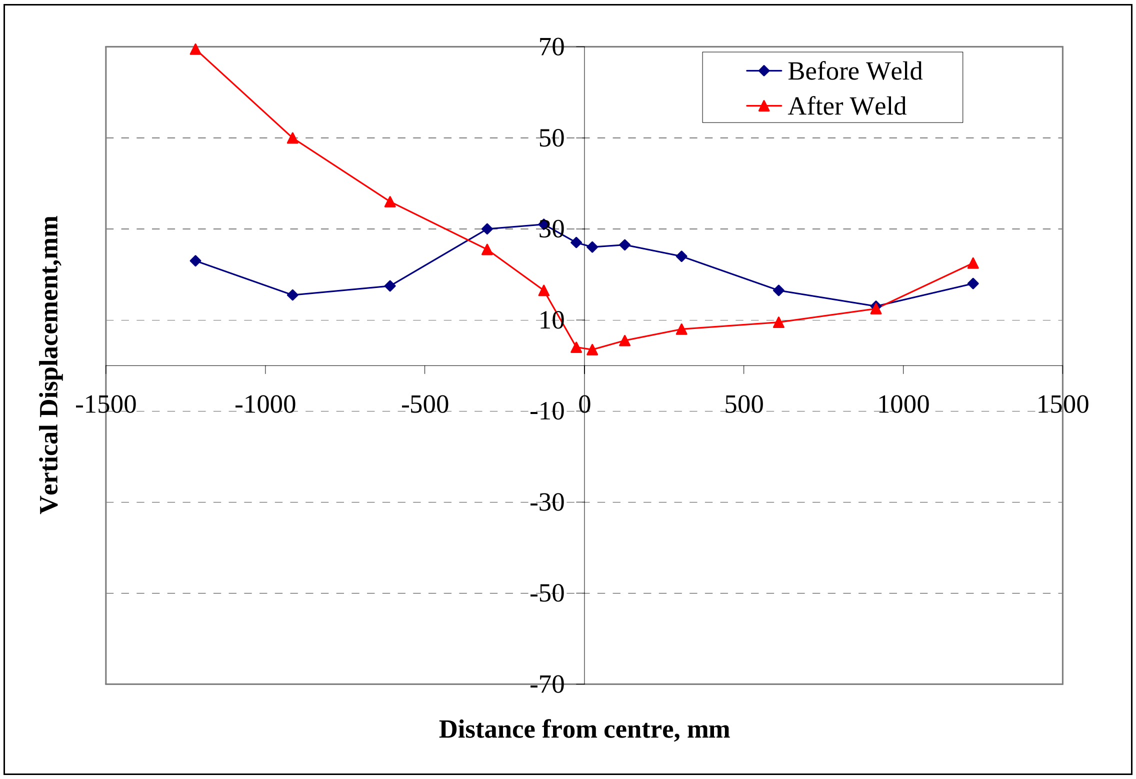


Figure 1: Transverse Section A1

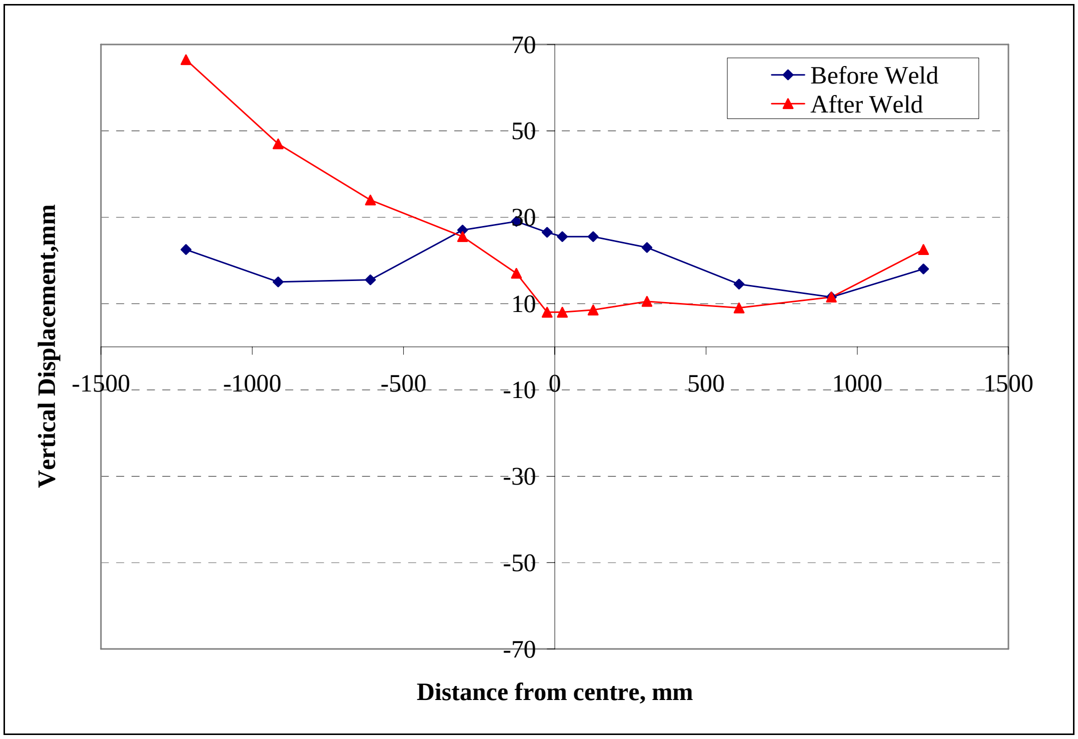


Figure 2: Transverse Section A2

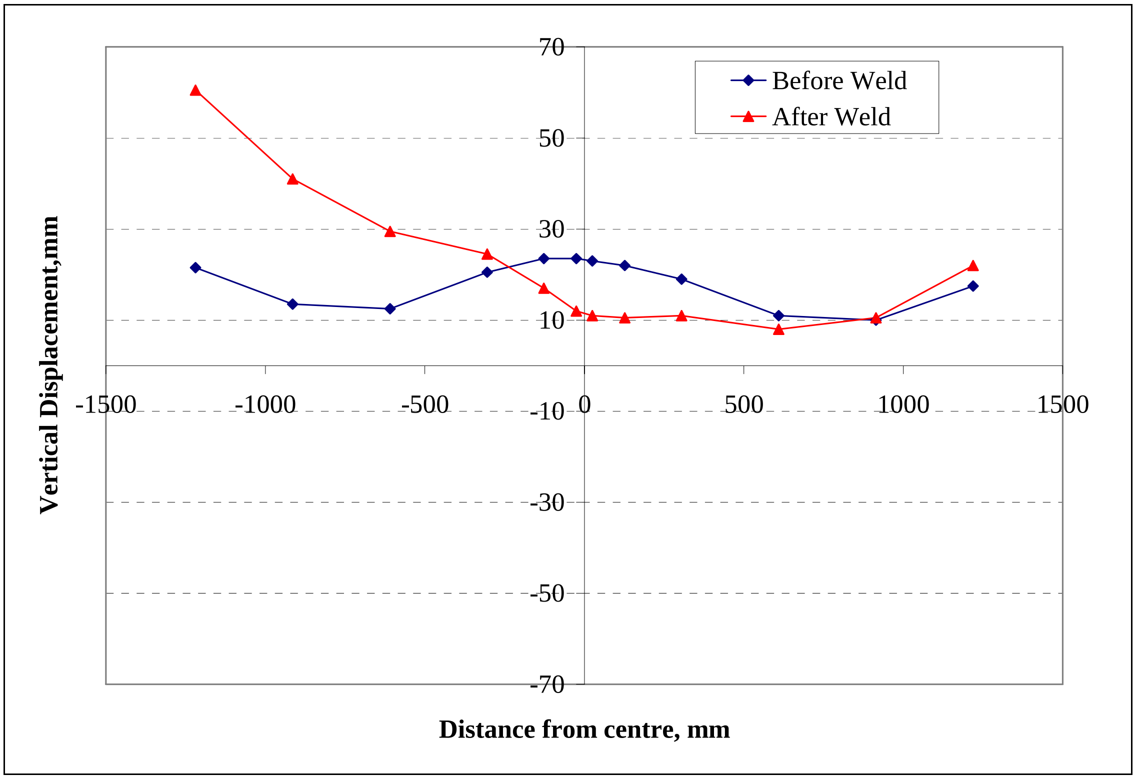


Figure 3: Transverse Section A3

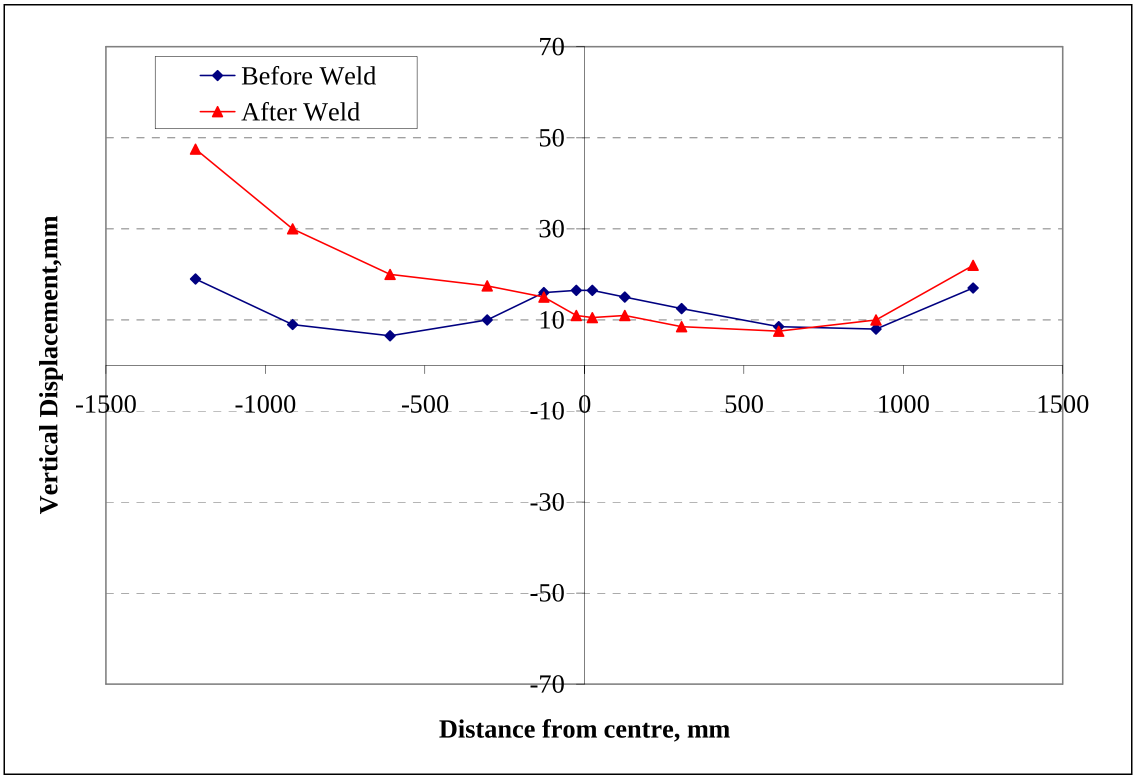


Figure 4: Transverse Section A5

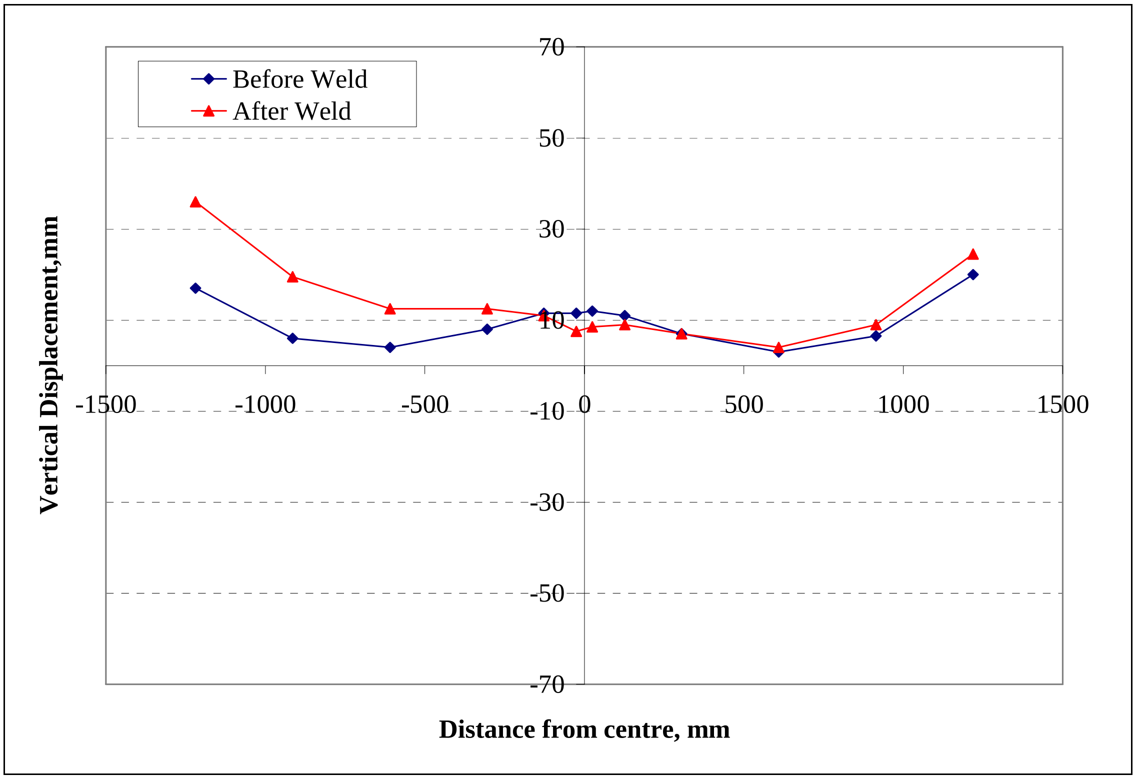


Figure 5: Transverse Section A7

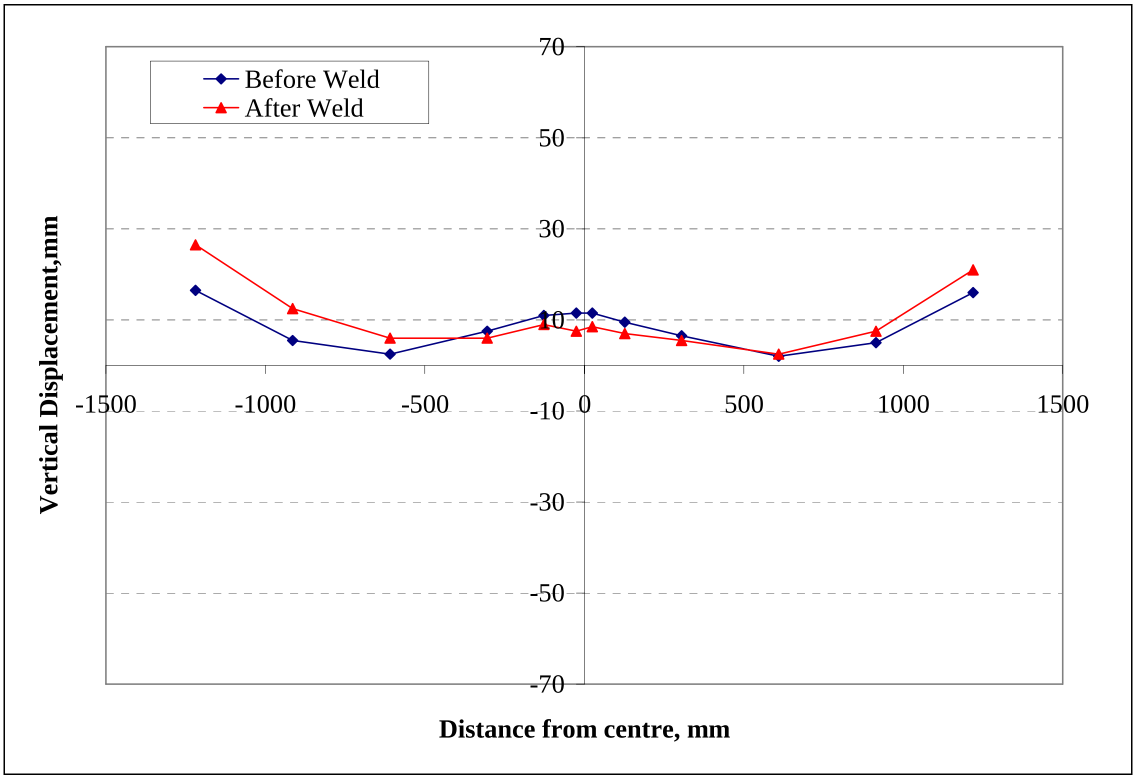


Figure 6: Transverse Section A9

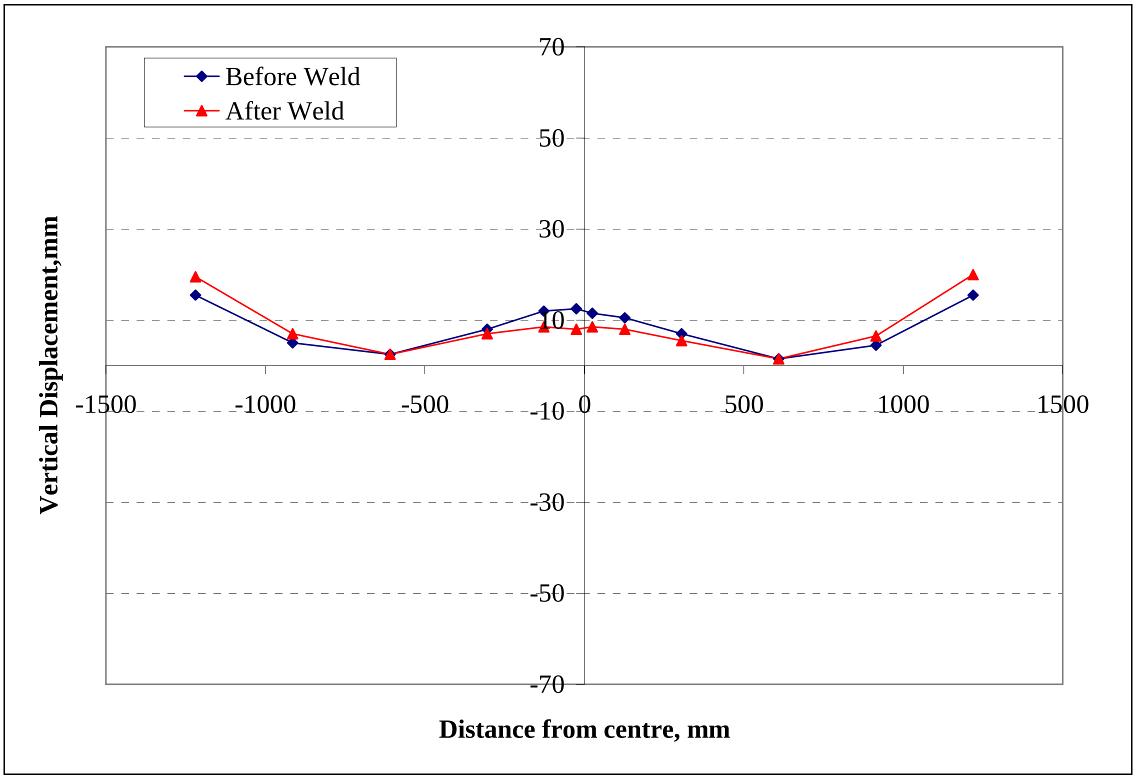


Figure 7: Transverse Section A11

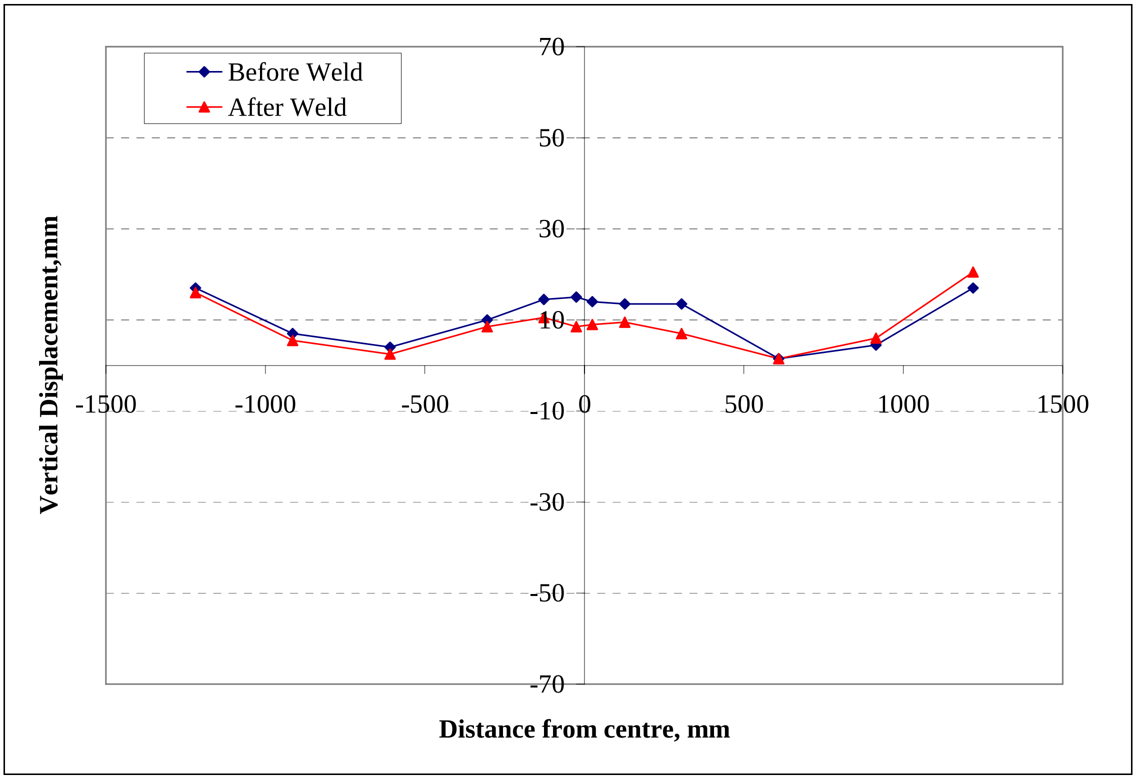


Figure 8: Transverse Section A13

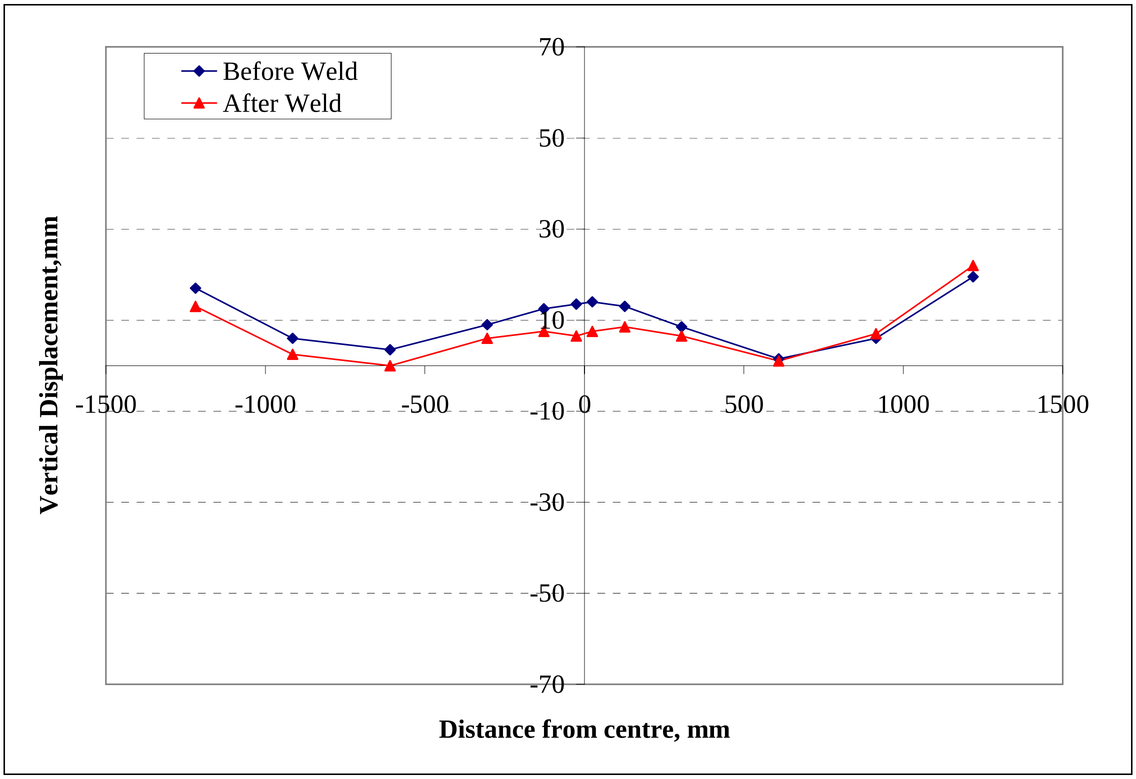


Figure 9: Transverse Section A15

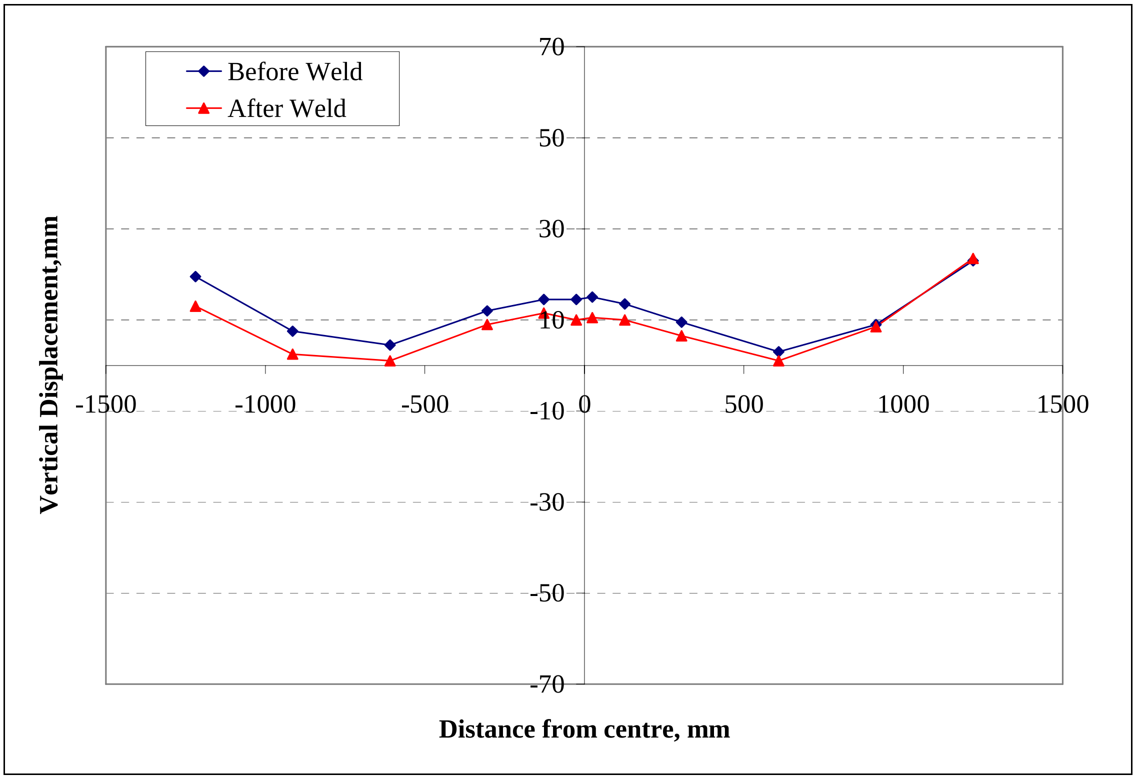


Figure 10: Transverse Section A17

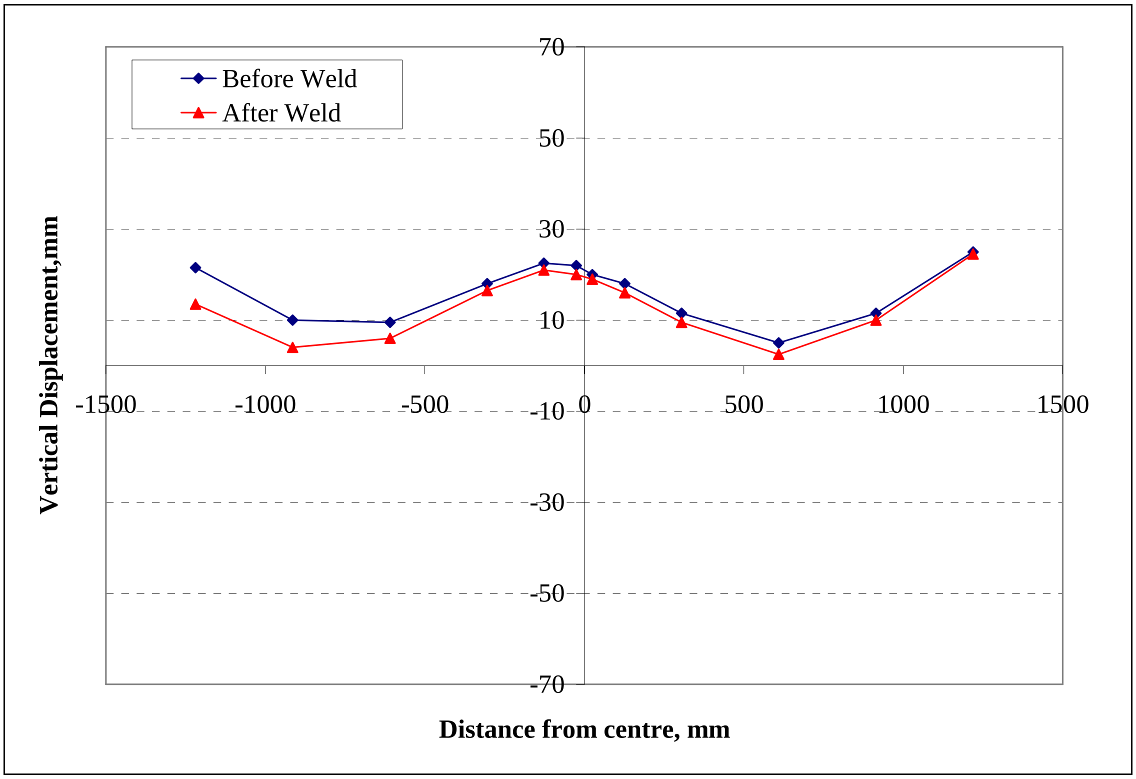


Figure 11: Transverse Section A19

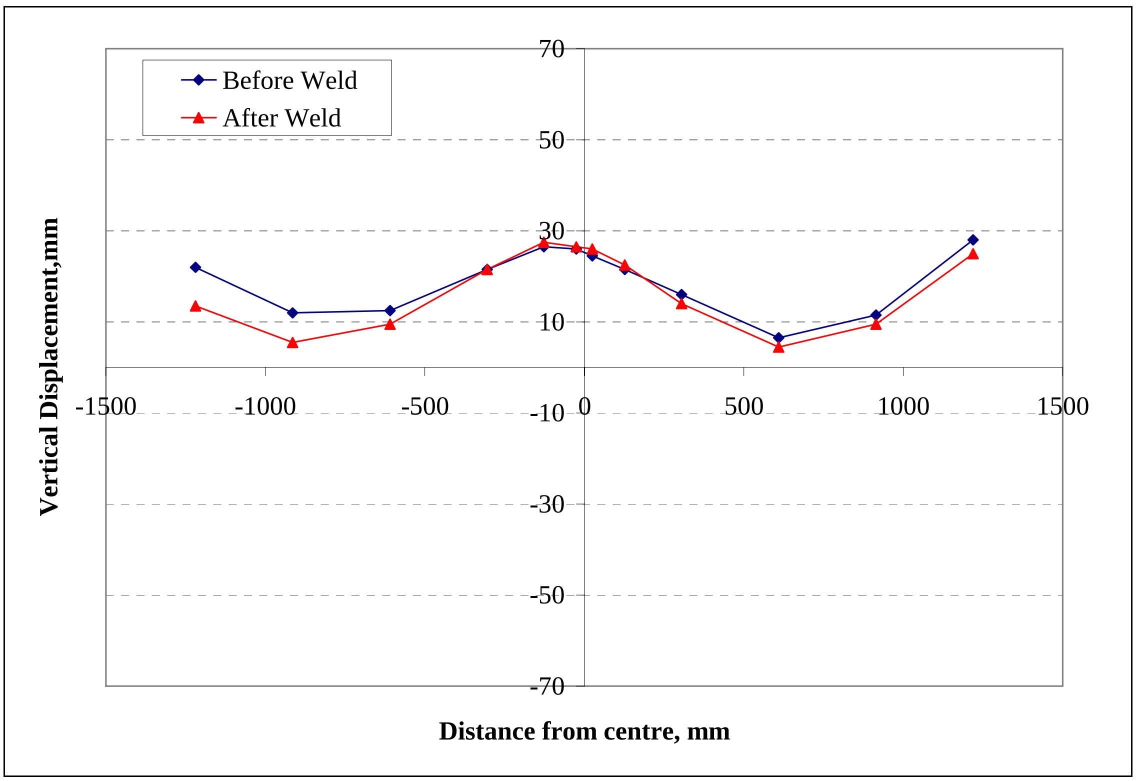


Figure 12: Transverse Section A20

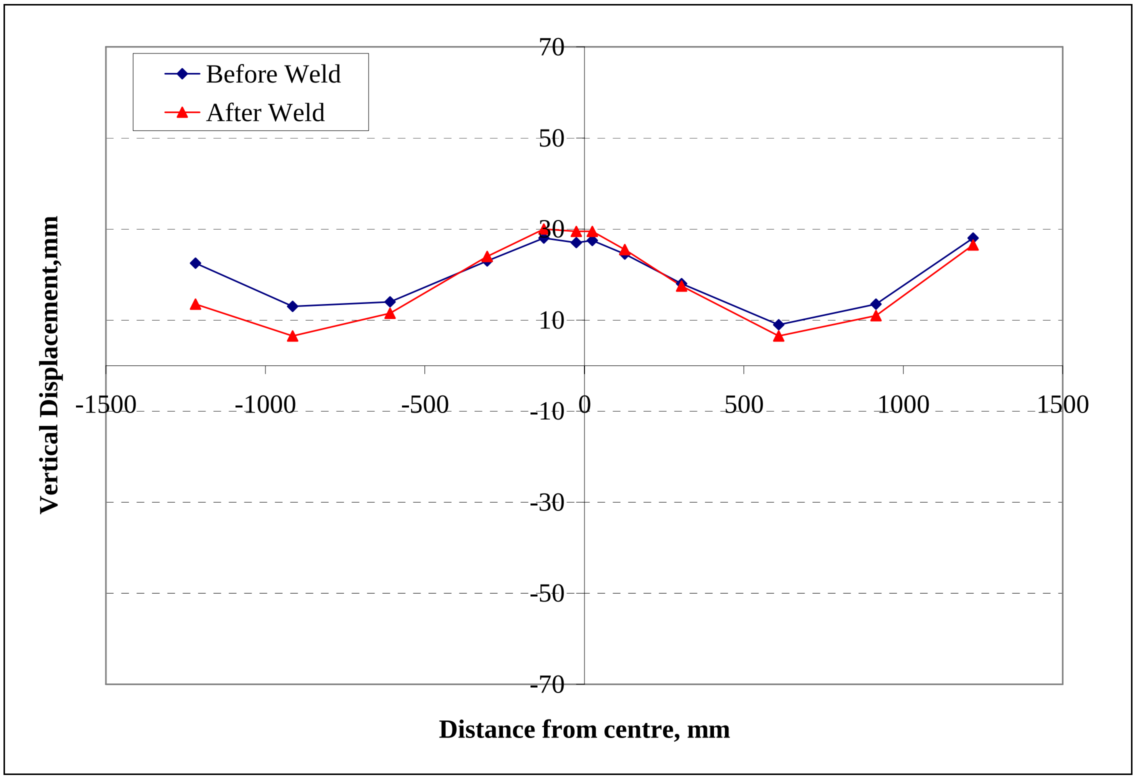


Figure 13: Transverse Section A21

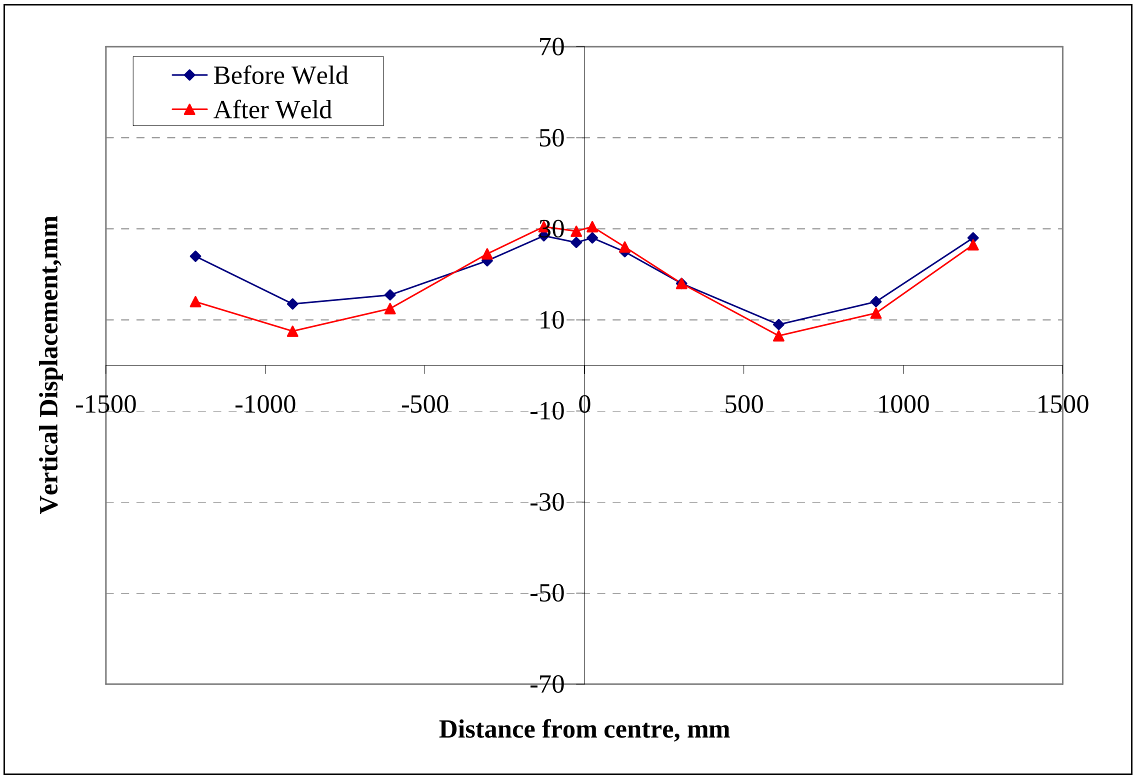


Figure 14: Transverse Section A22

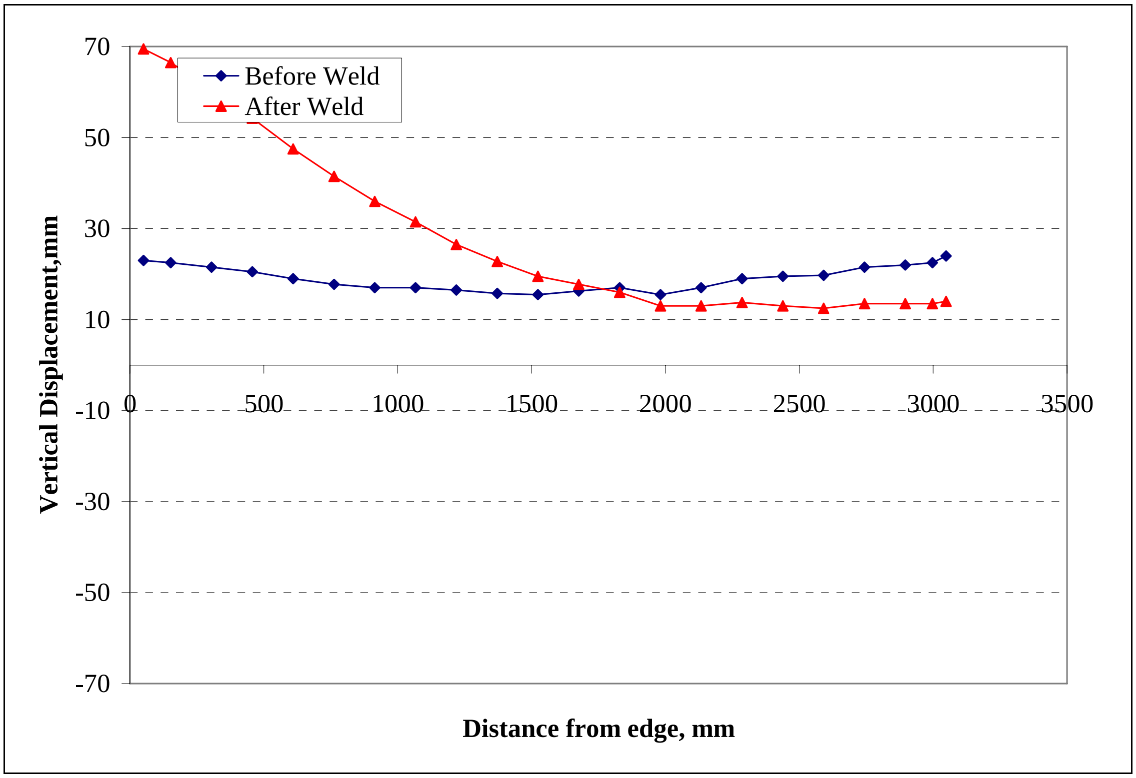


Figure 15: Longitudinal Section A

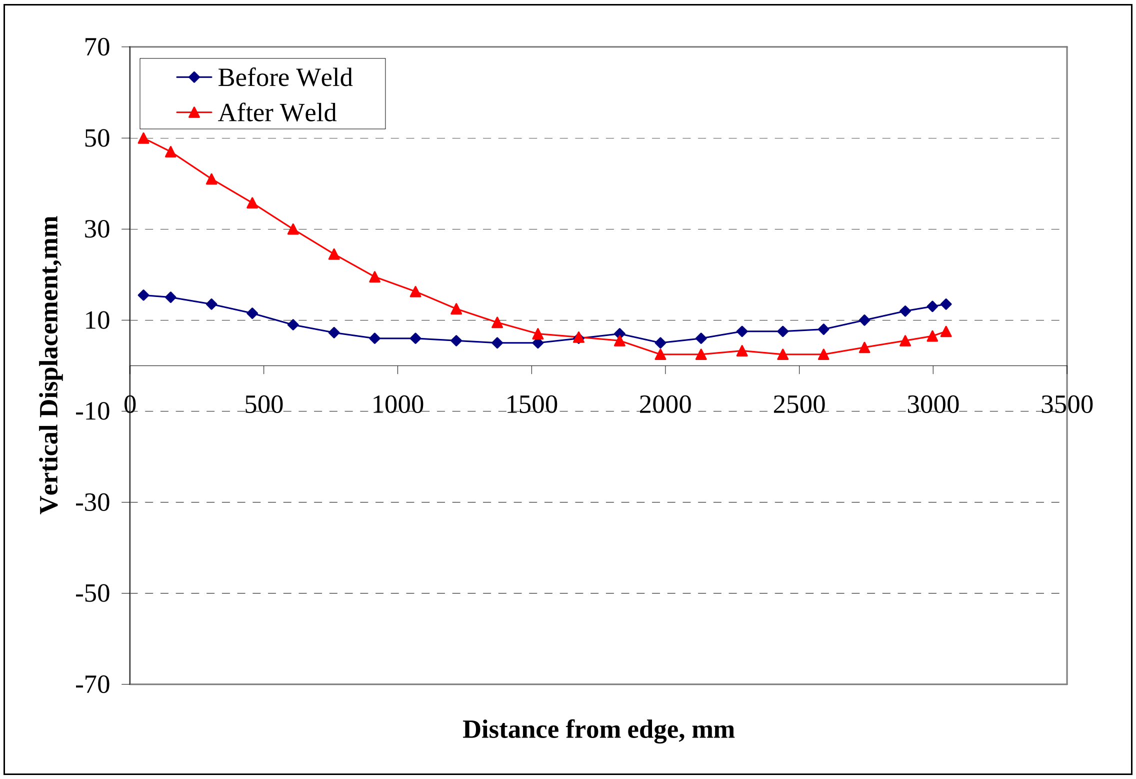


Figure 16: Longitudinal Section B

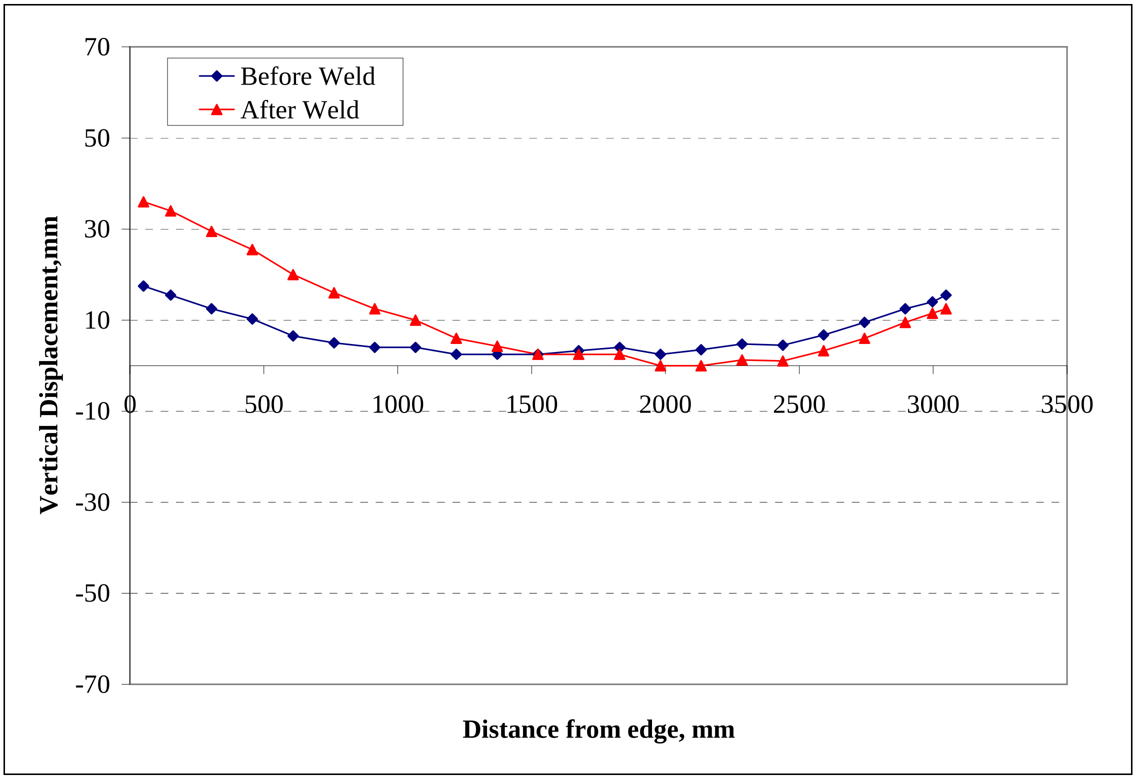


Figure 17: Longitudinal Section C

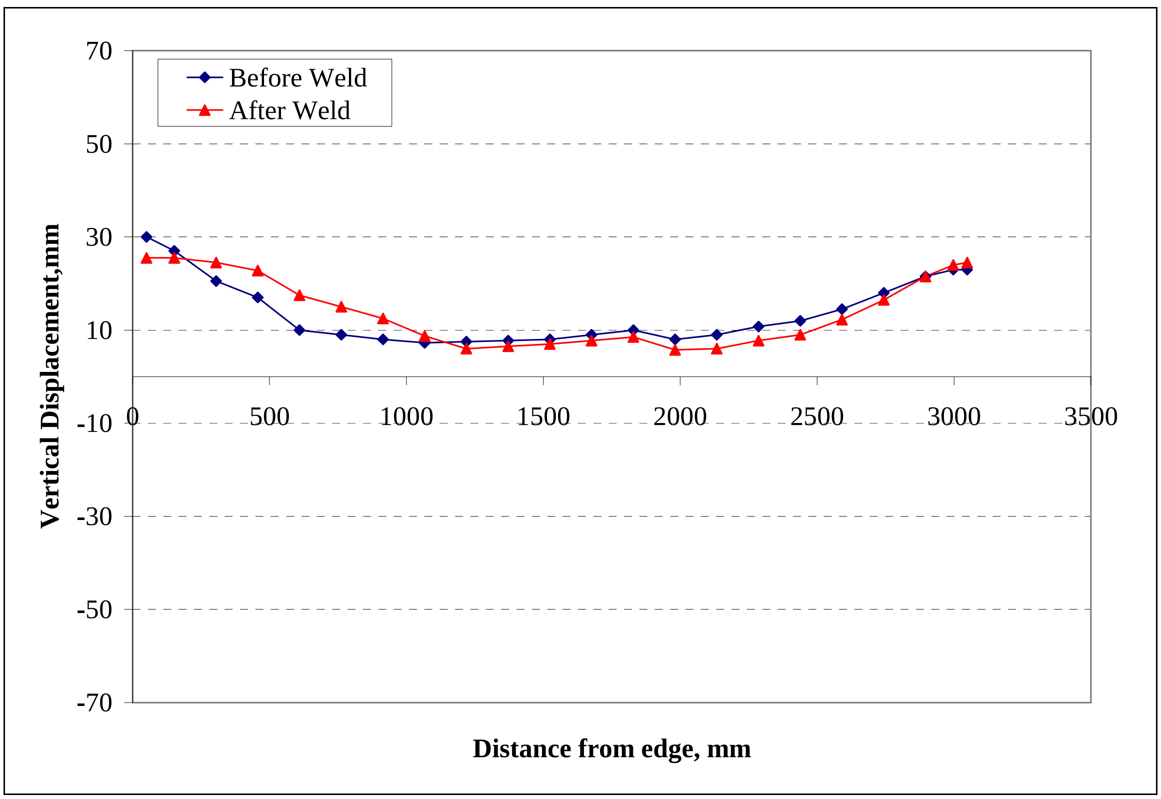


Figure 18: Longitudinal Section D

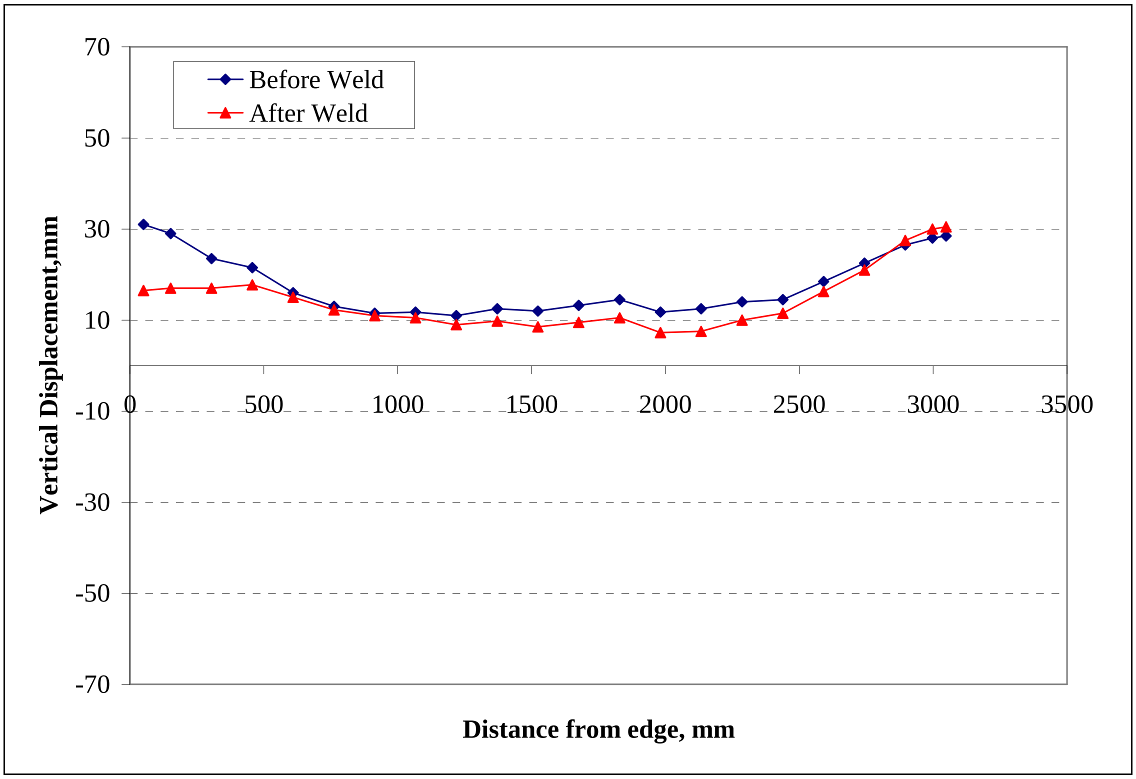


Figure 19: Longitudinal Section E

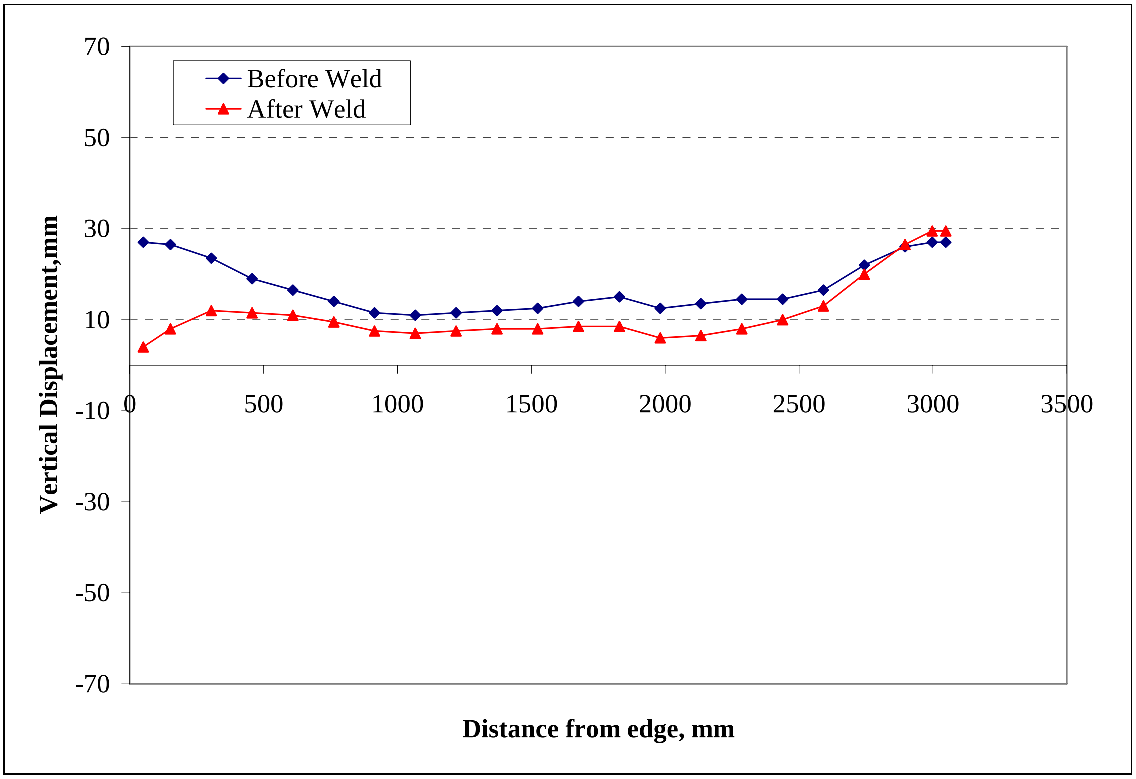


Figure 20: Longitudinal Section F

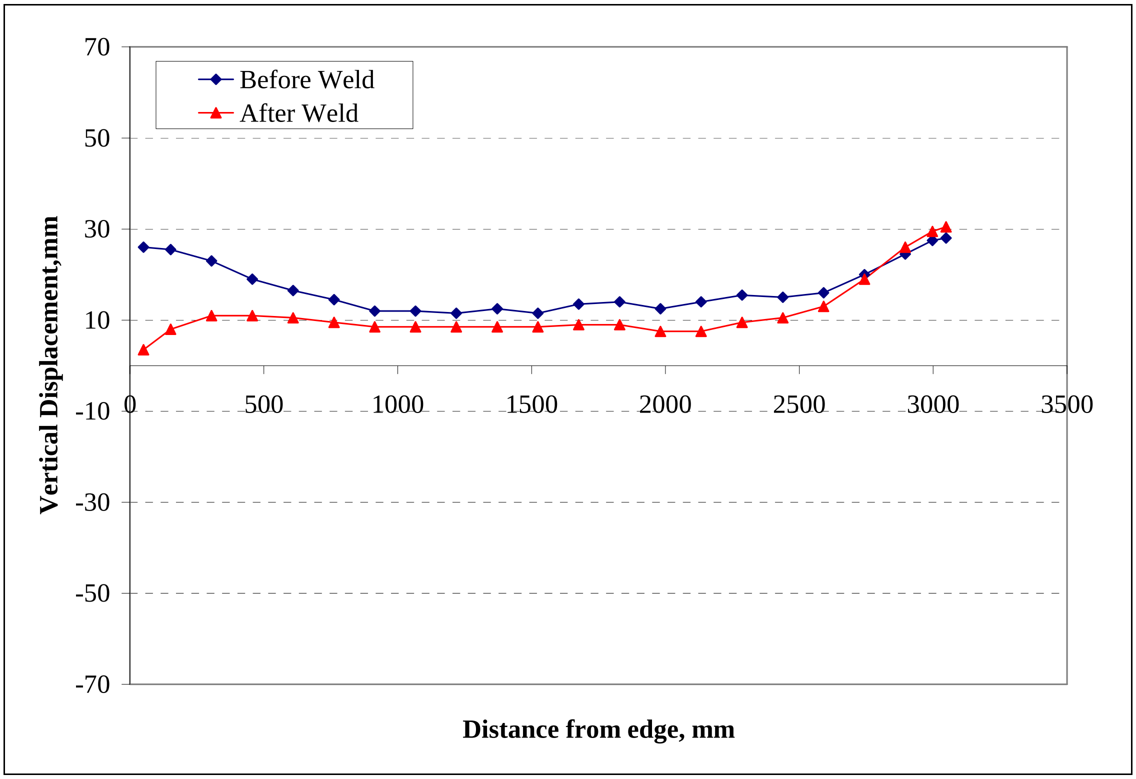


Figure 21: Longitudinal Section G

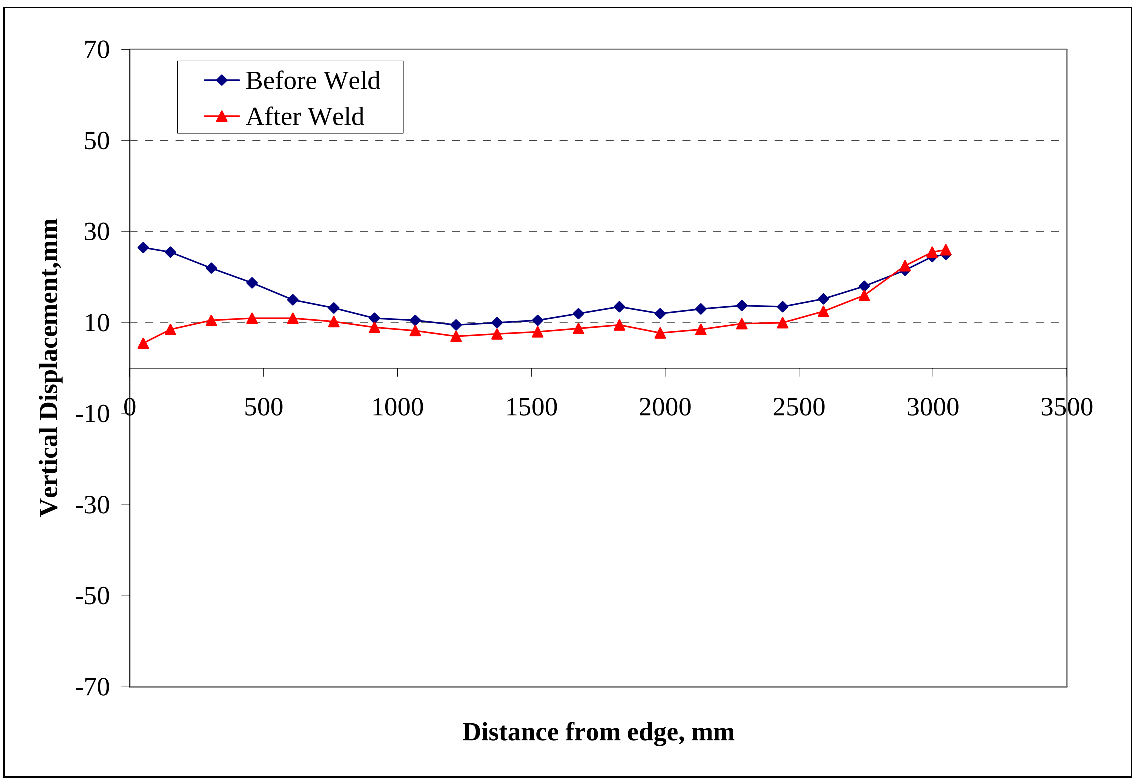


Figure 22: Longitudinal Section H

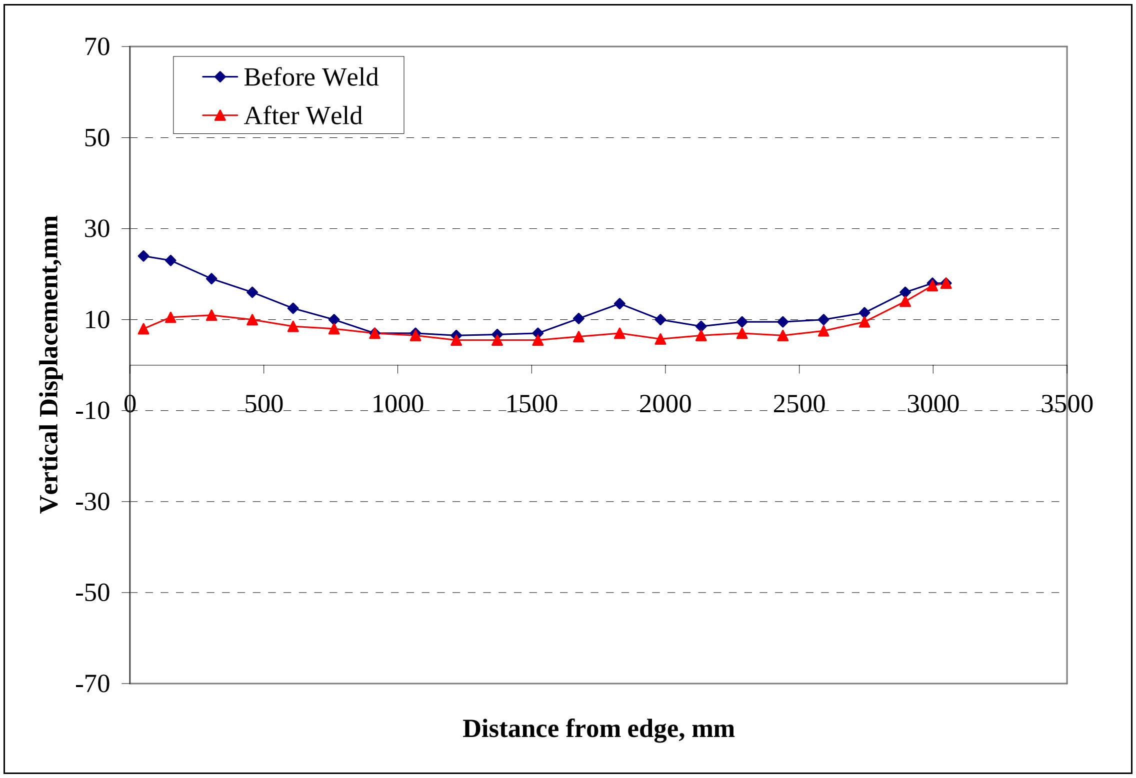


Figure 23: Longitudinal Section I

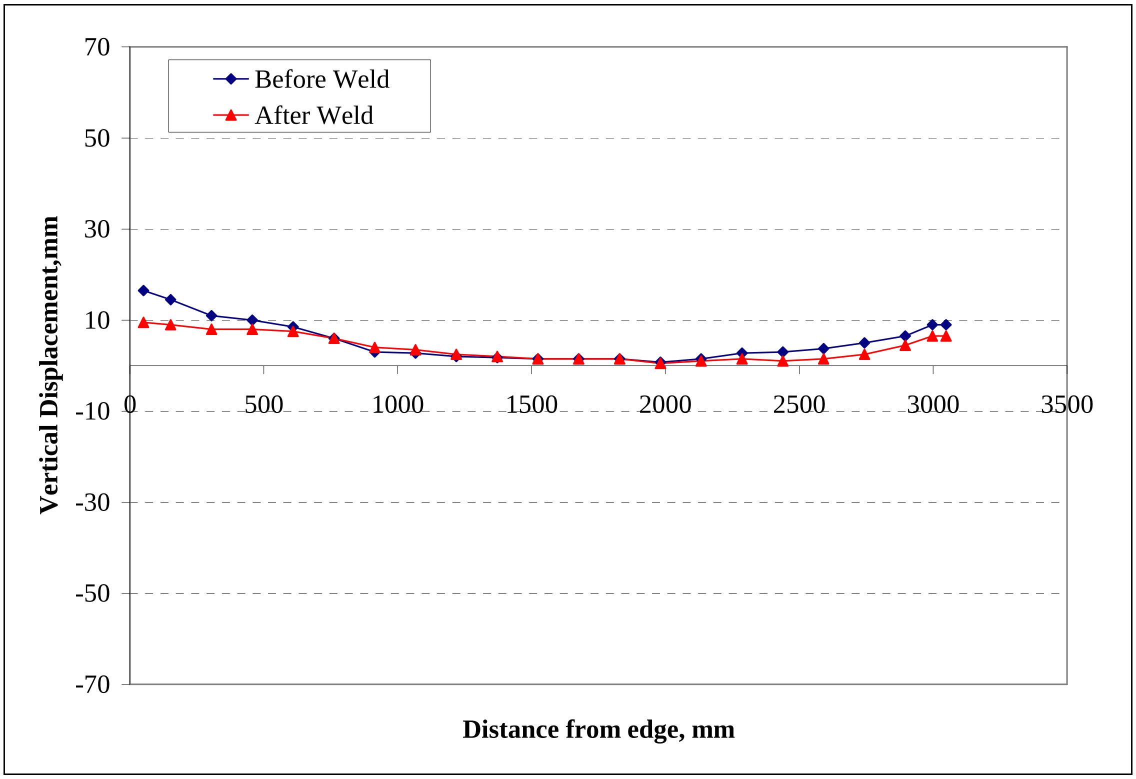


Figure 24: Longitudinal Section J

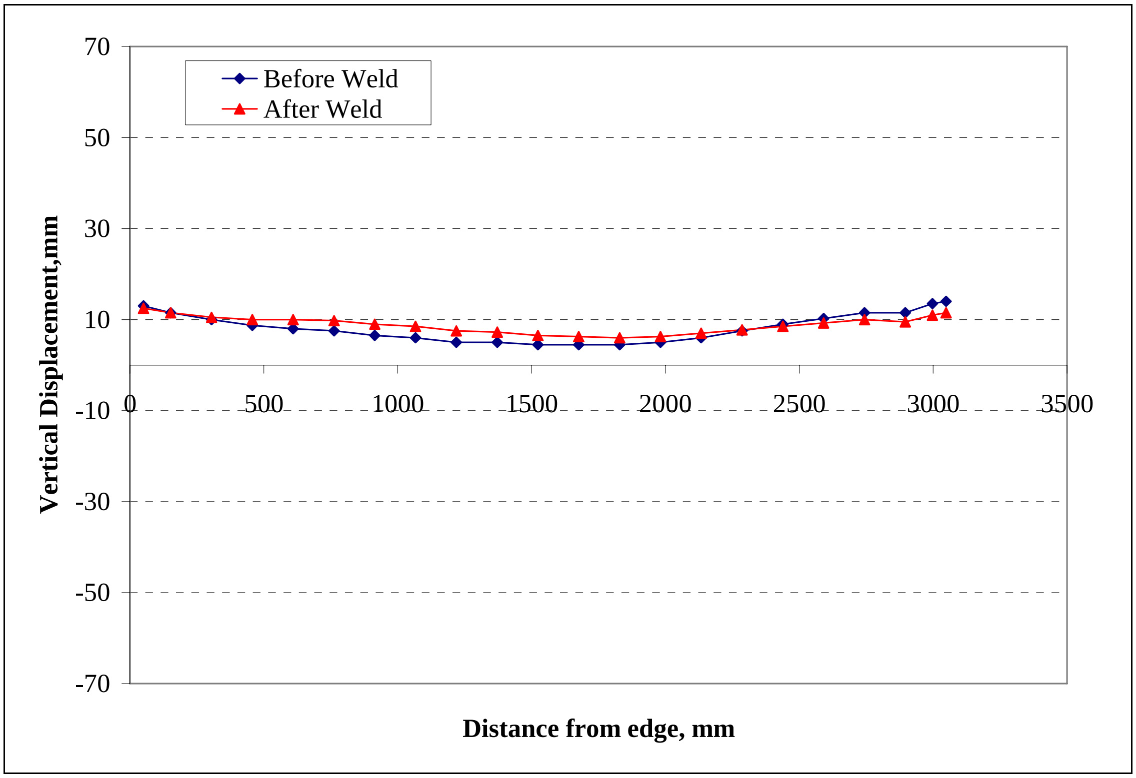


Figure 25: Longitudinal Section K

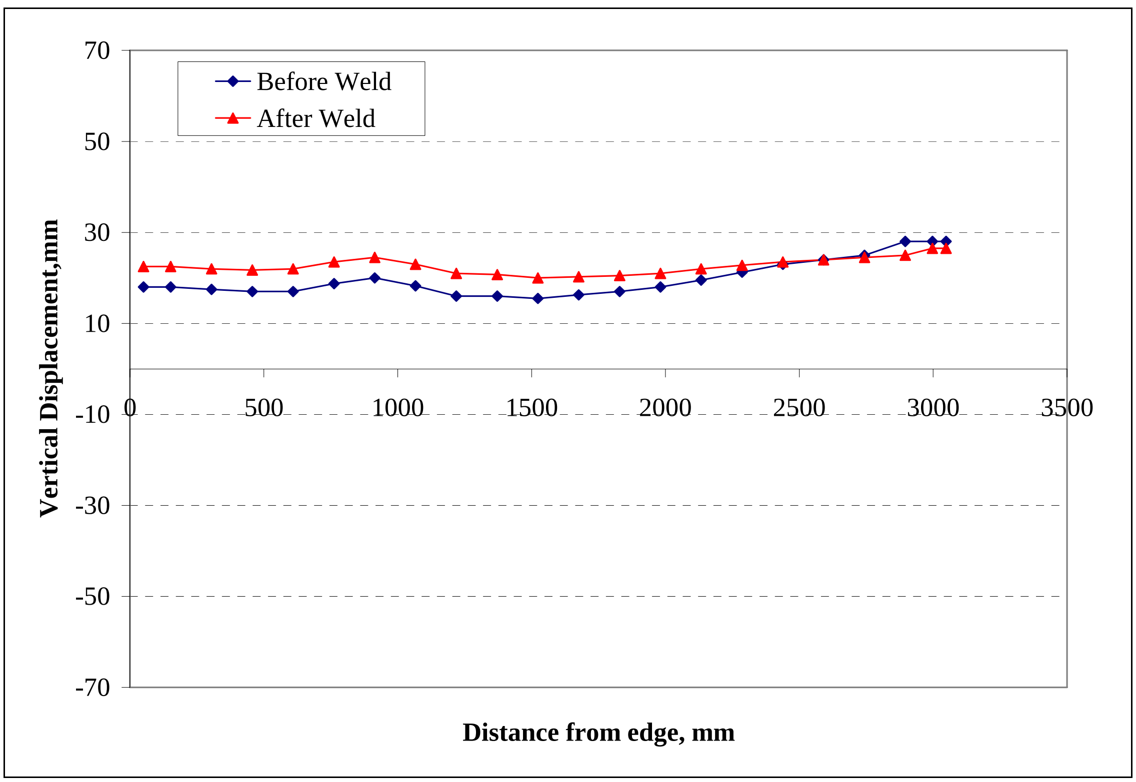


Figure 26: Longitudinal Section L

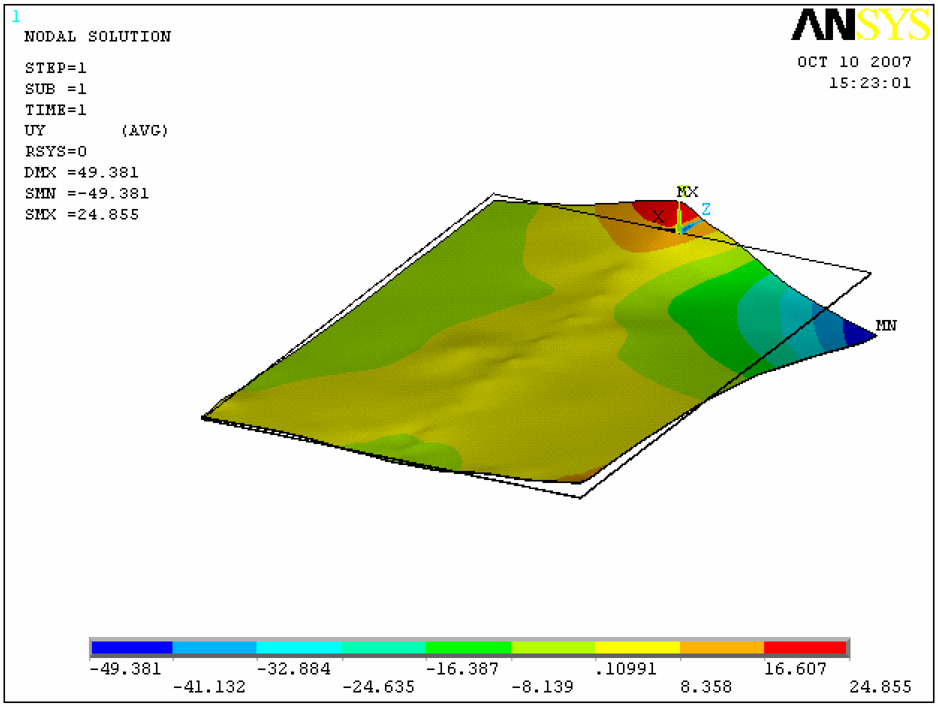


Figure 27: Net Plate Deformation after Welding

PLATE 6 – SIDE 2B

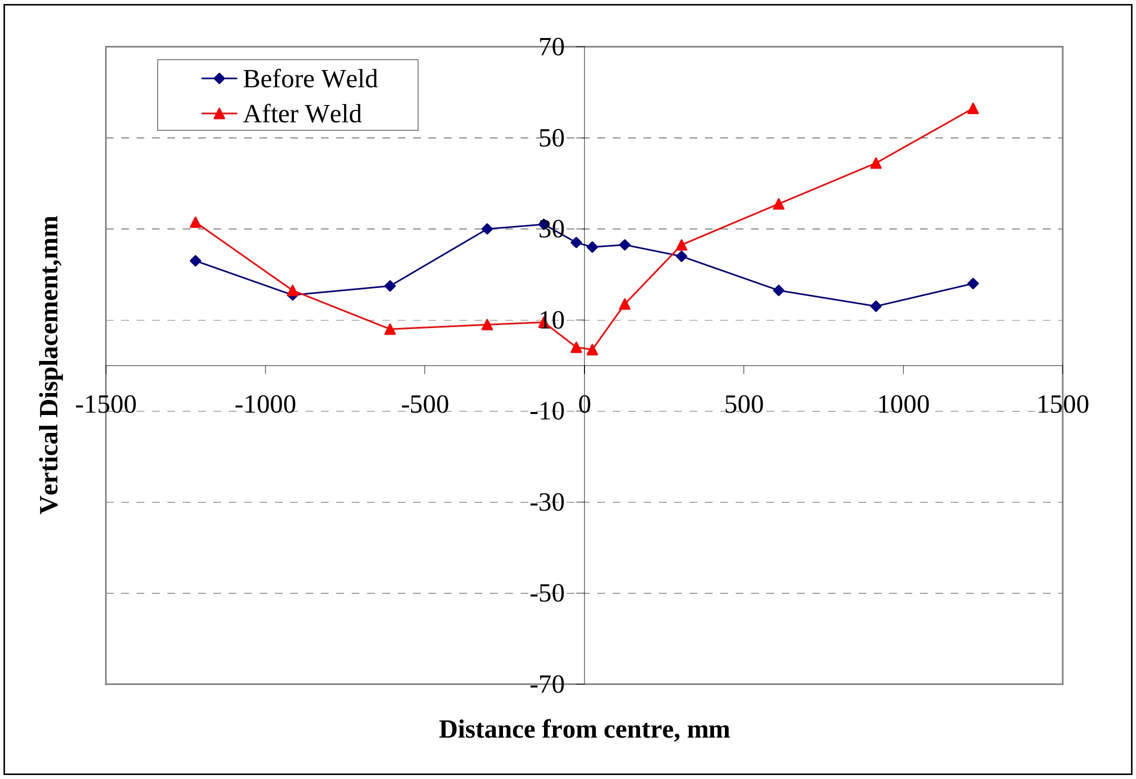


Figure 1: Transverse Section A1

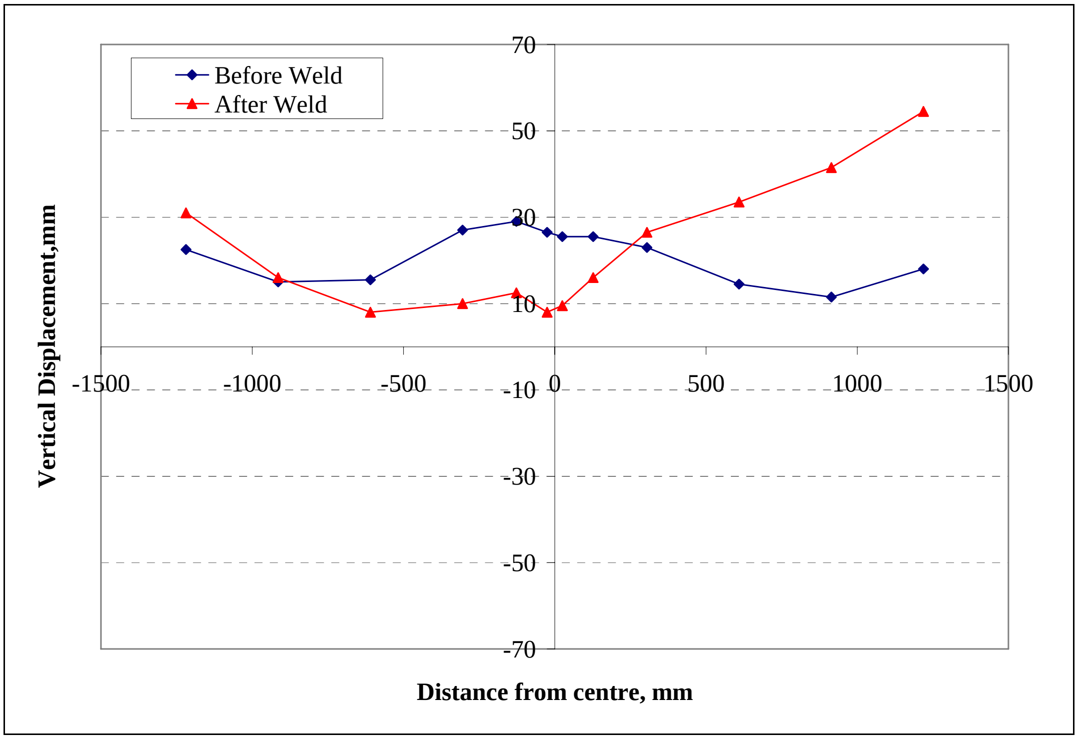


Figure 2: Transverse Section A2

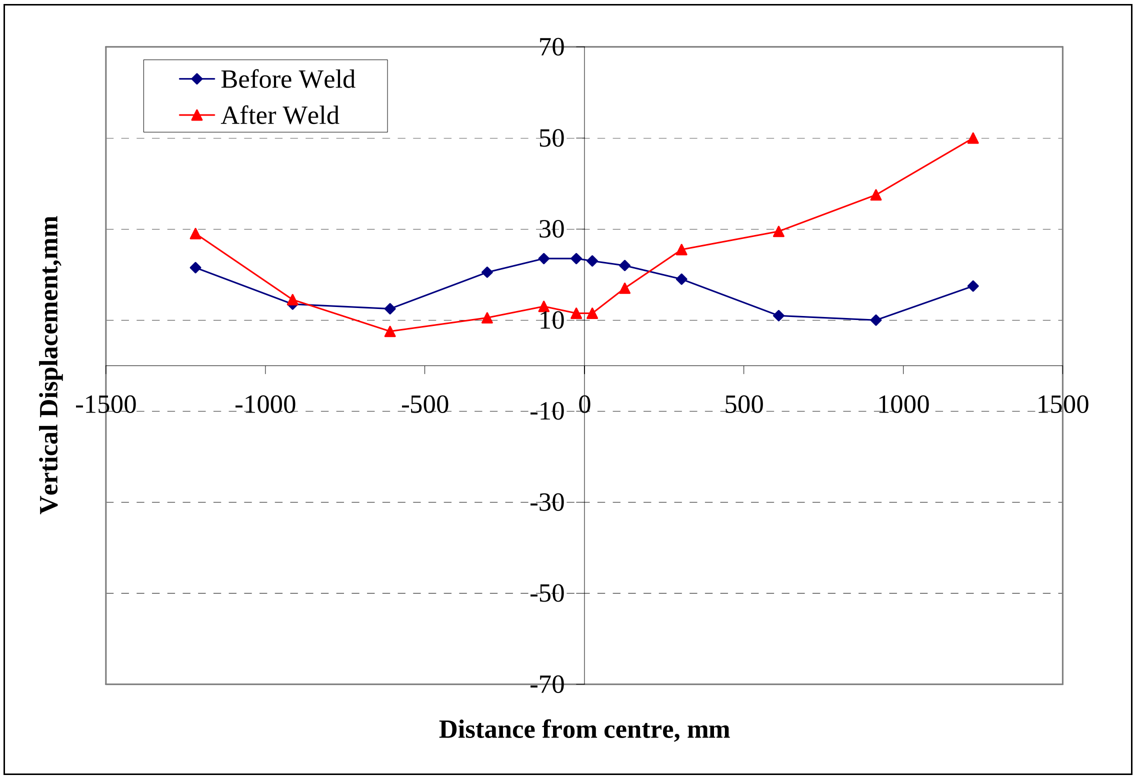


Figure 3: Transverse Section A3

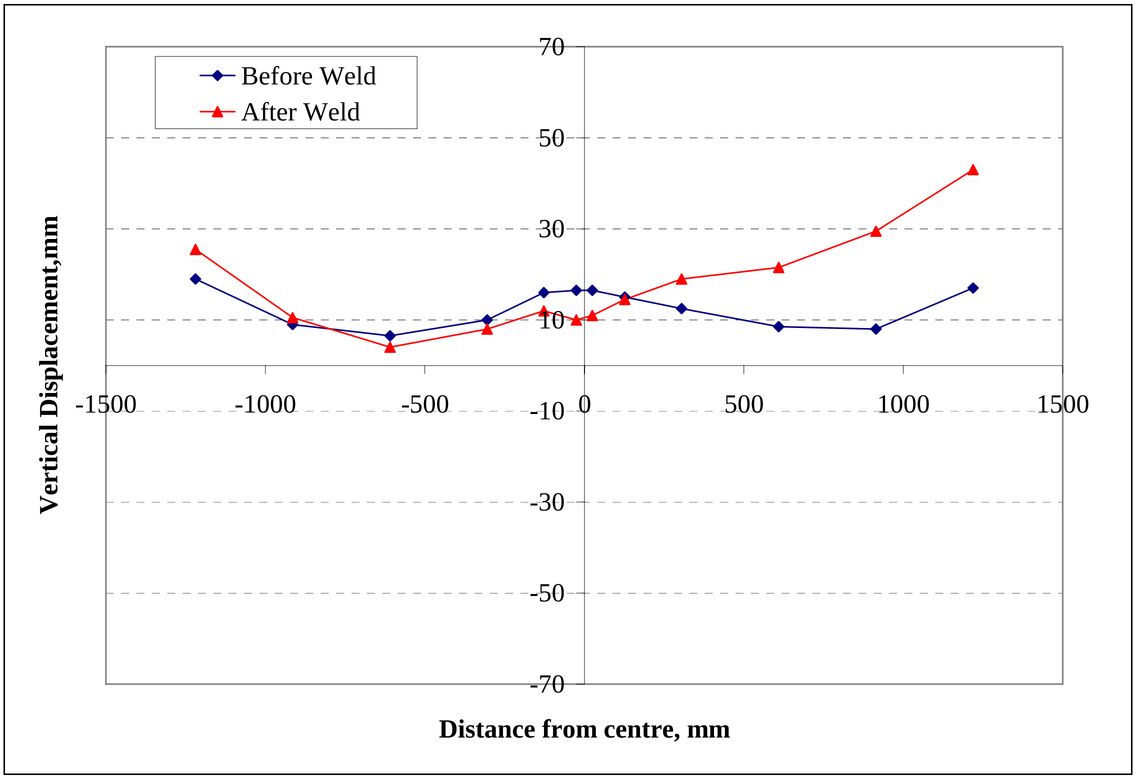


Figure 4: Transverse Section A5

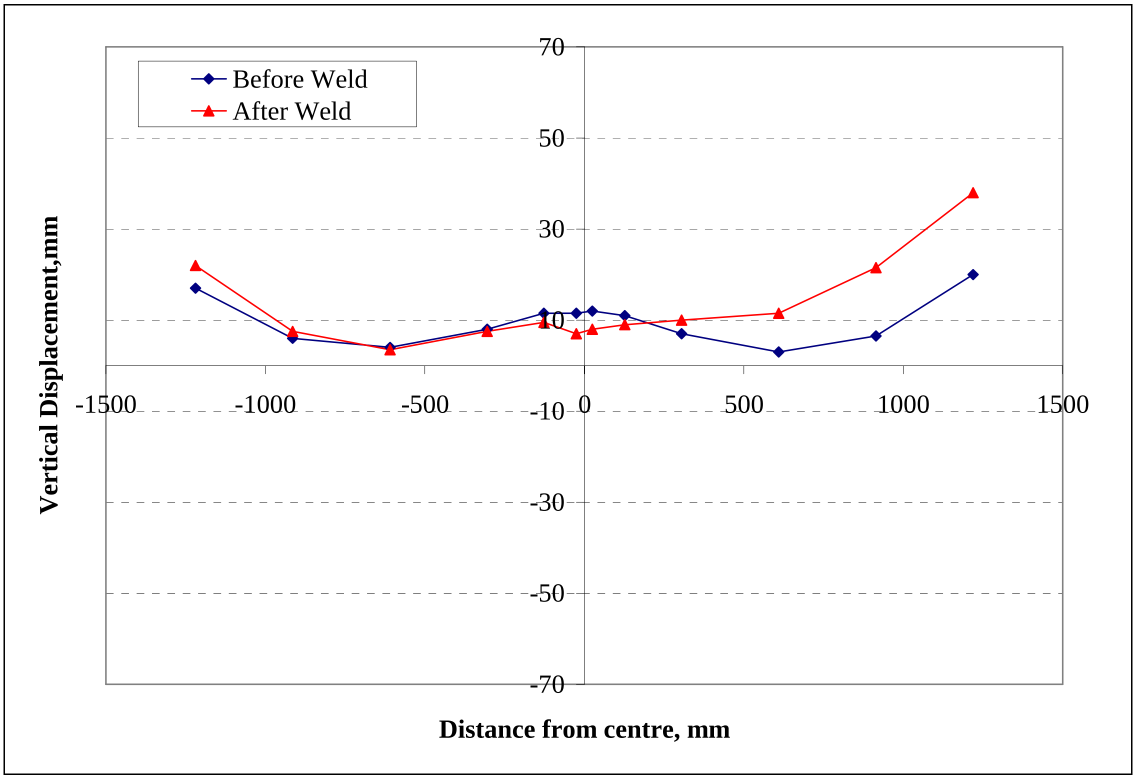


Figure 5: Transverse Section A7

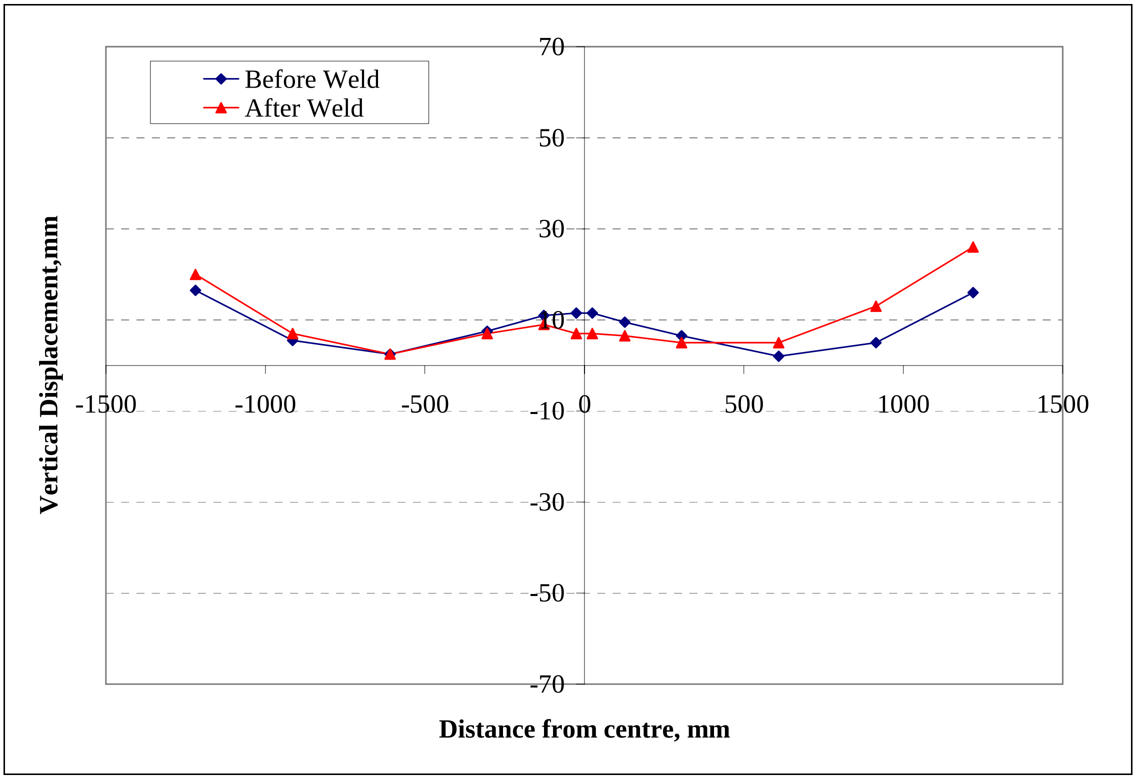


Figure 6: Transverse Section A9

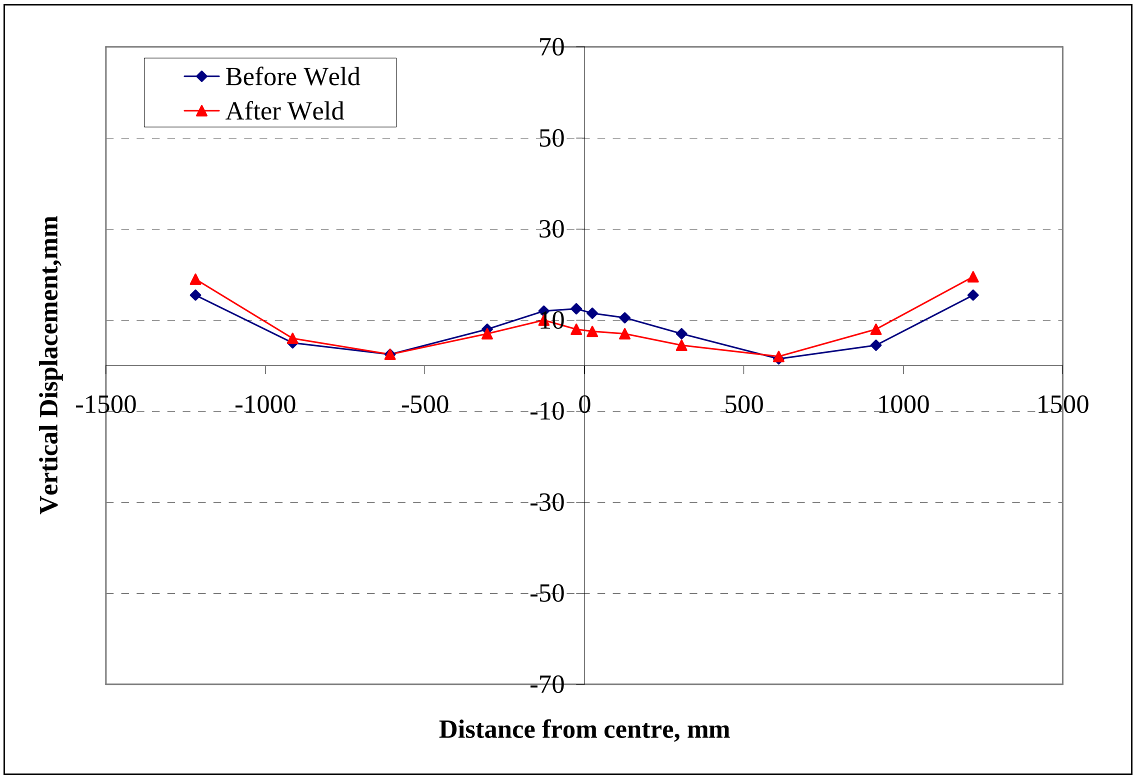


Figure 7: Transverse Section A11

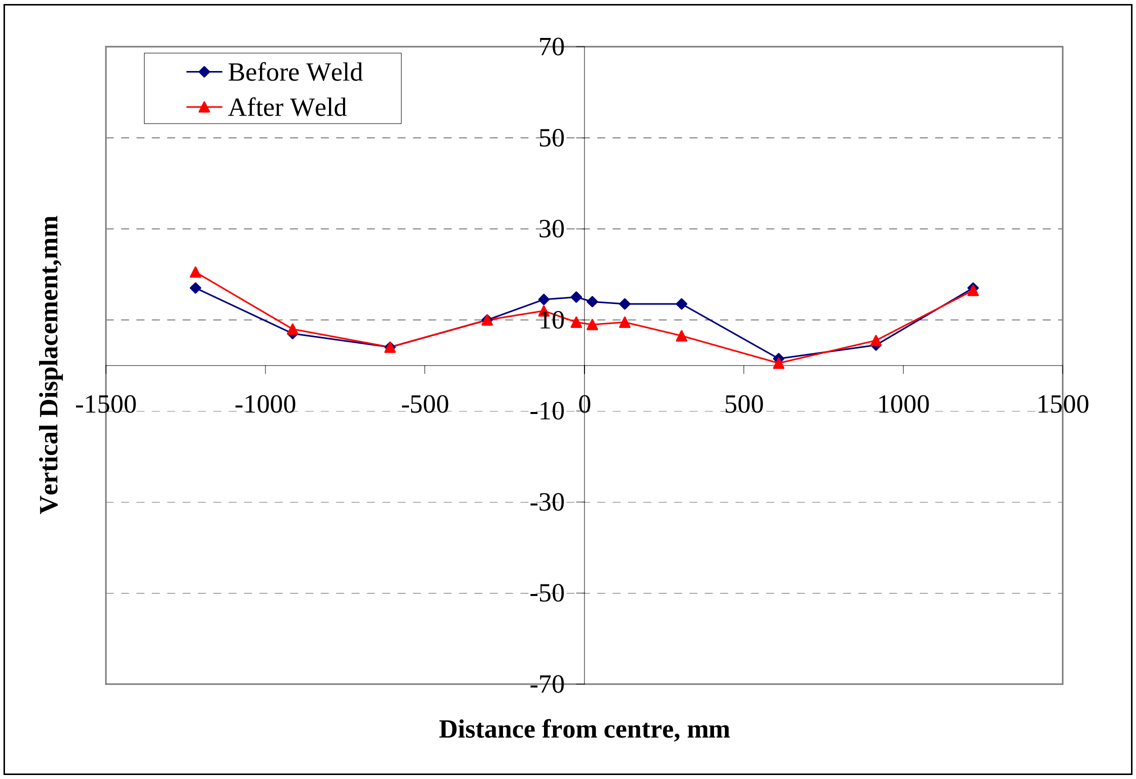


Figure 8: Transverse Section A13

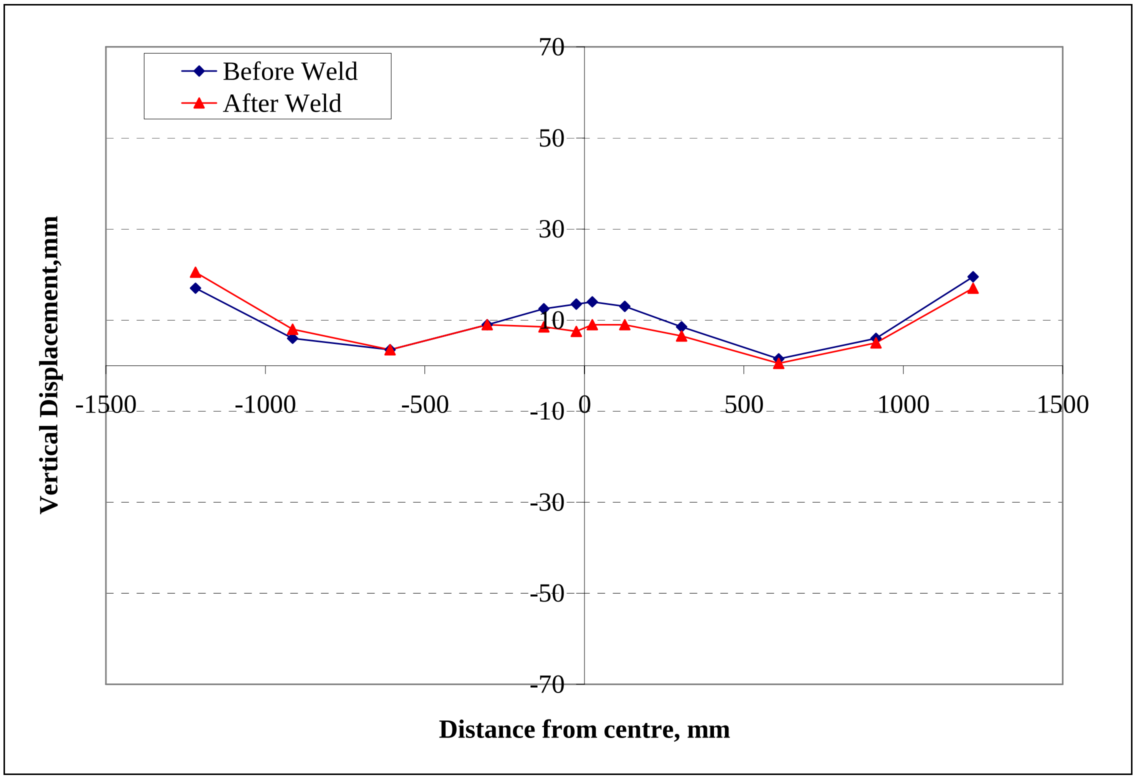


Figure 9: Transverse Section A15

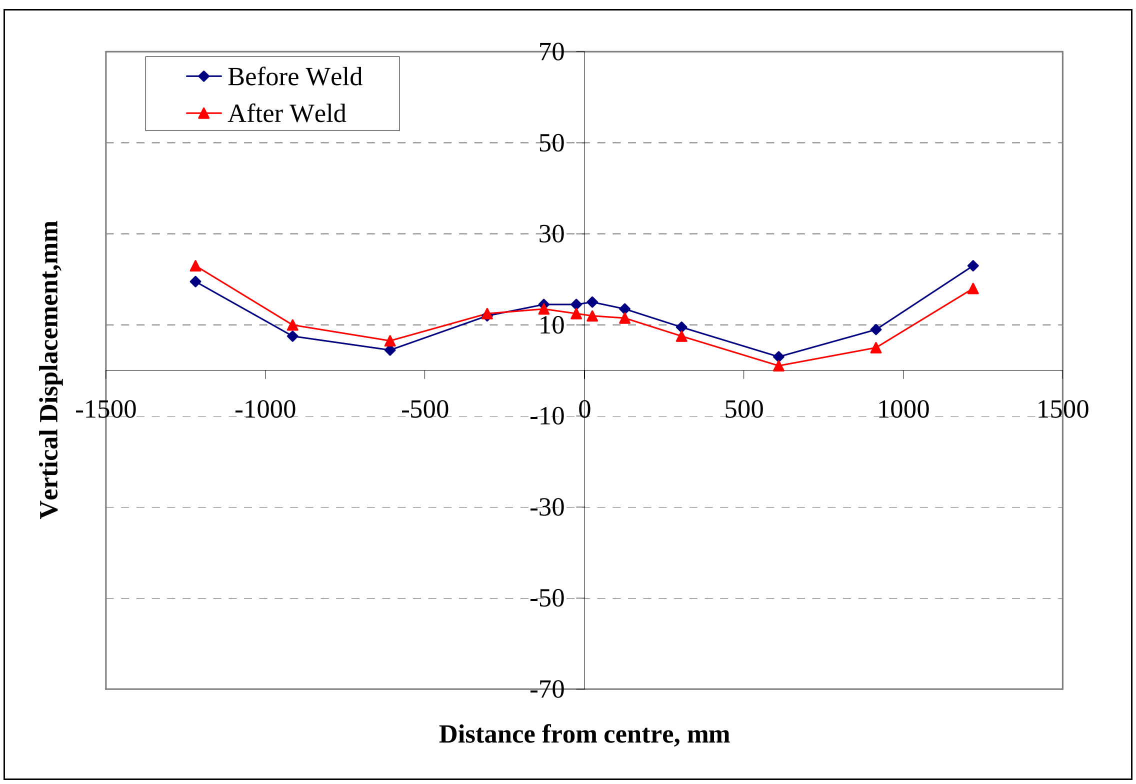


Figure 10: Transverse Section A17

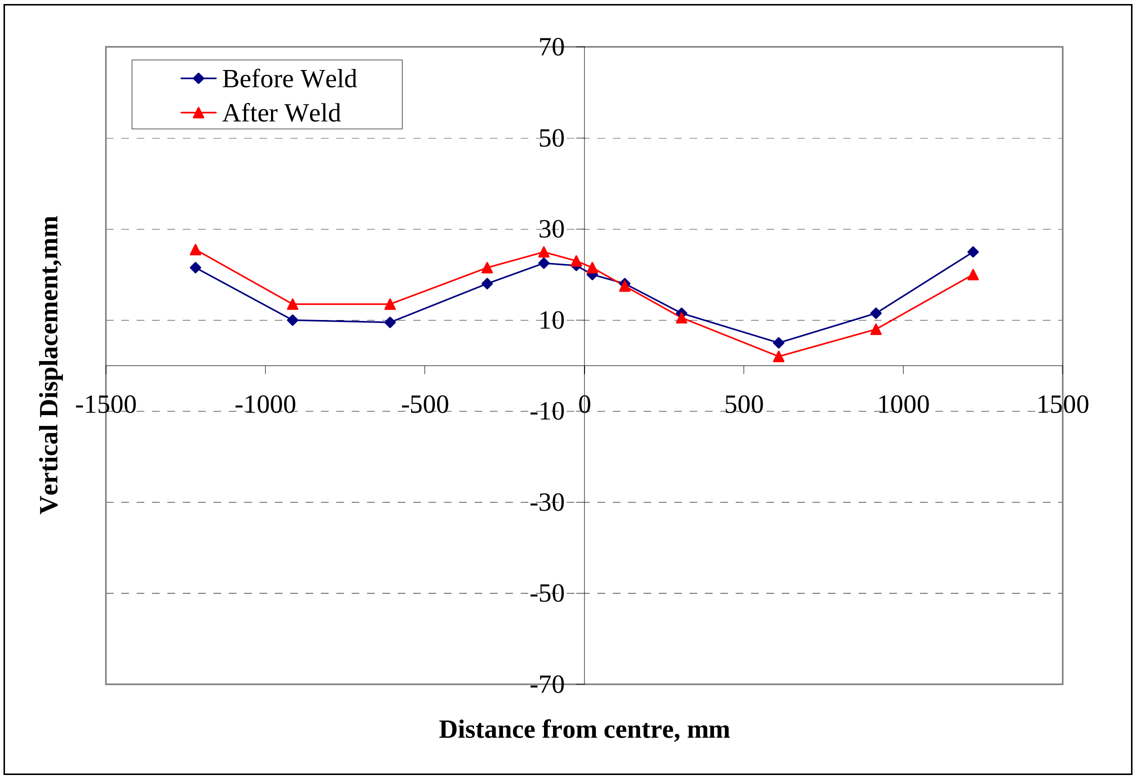


Figure 11: Transverse Section A19

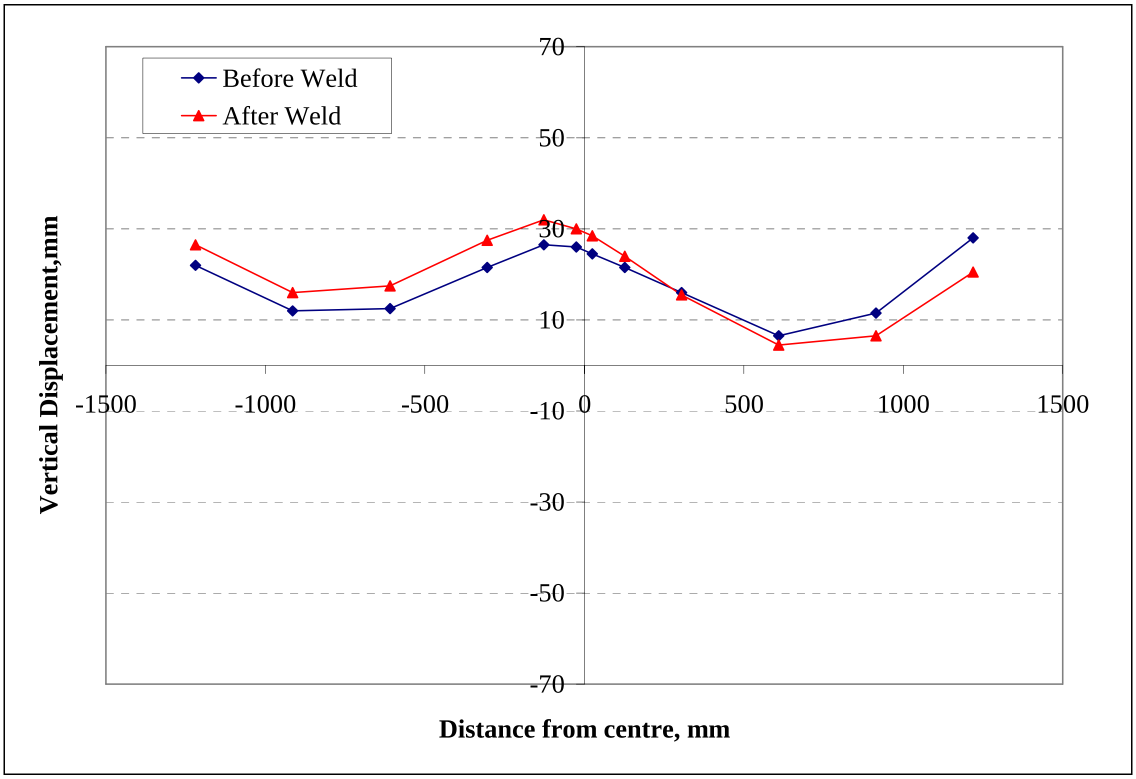


Figure 12: Transverse Section A20

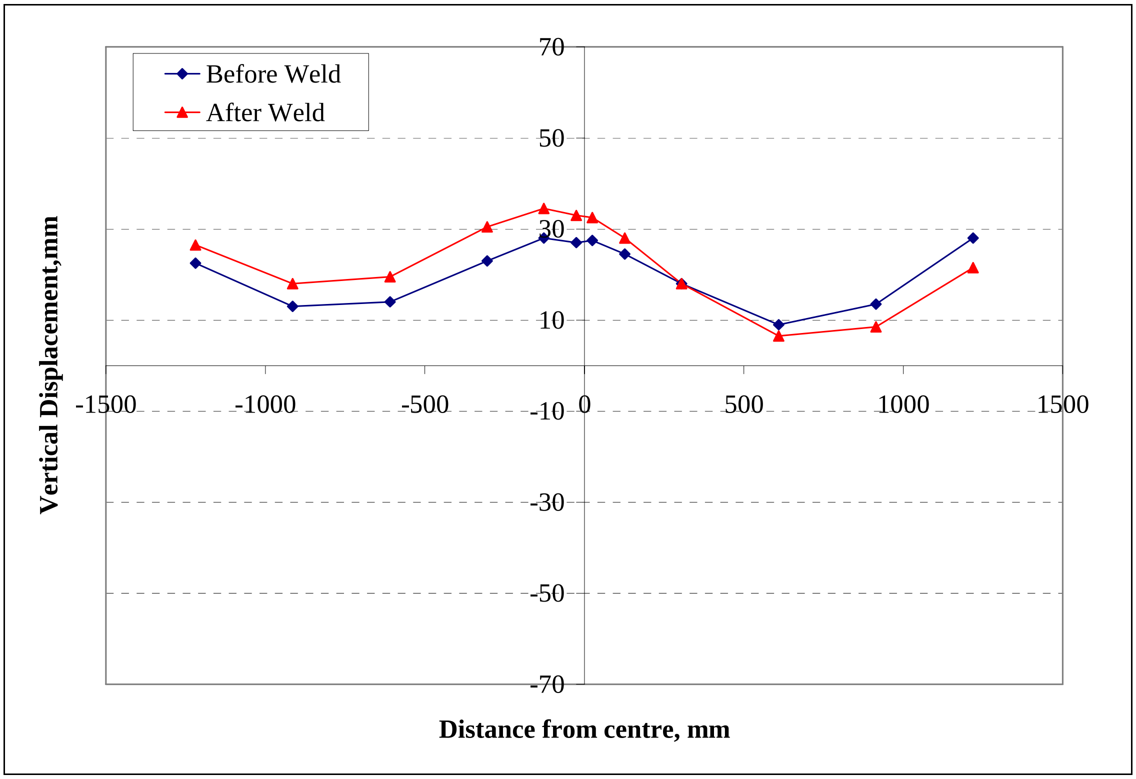


Figure 13: Transverse Section A21

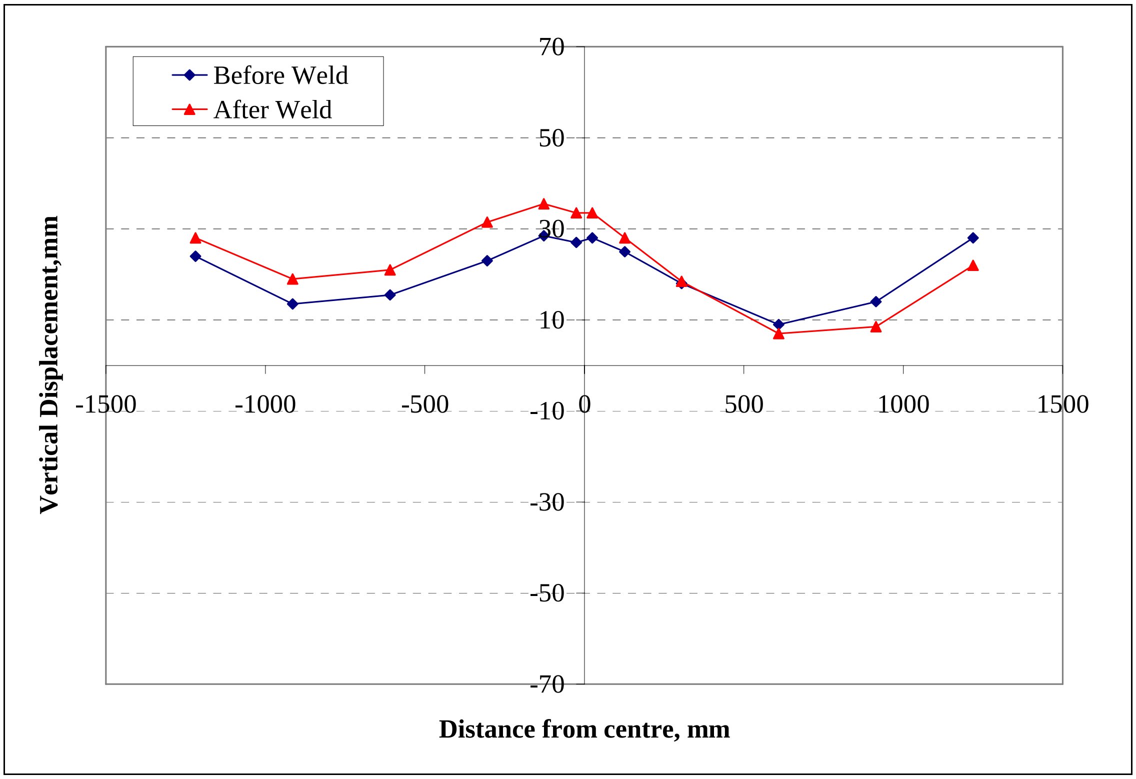


Figure 14: Transverse Section A22

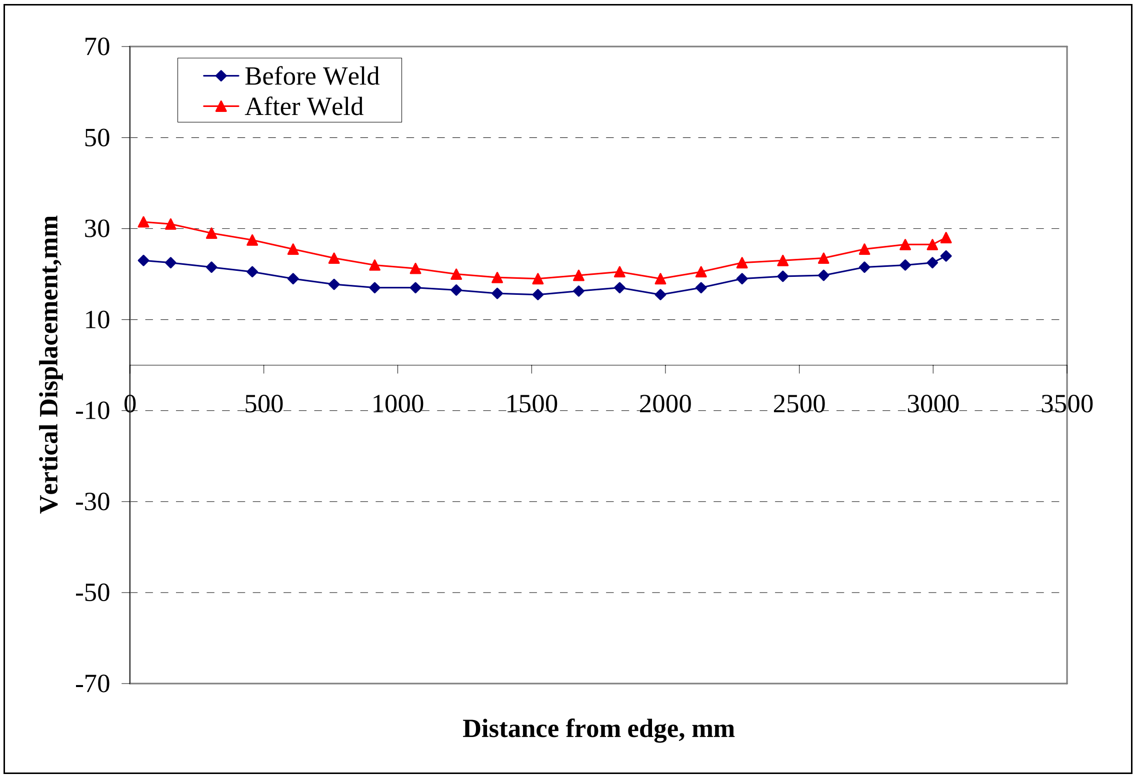


Figure 15: Longitudinal Section A

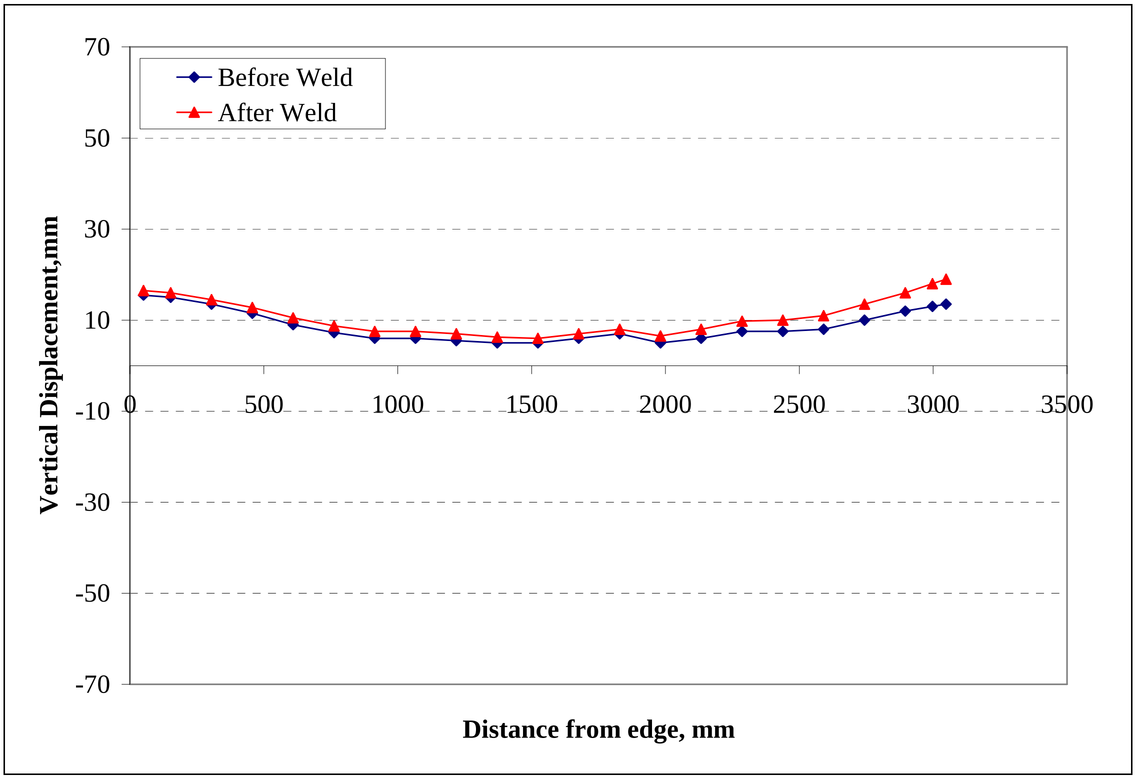


Figure 16: Longitudinal Section B

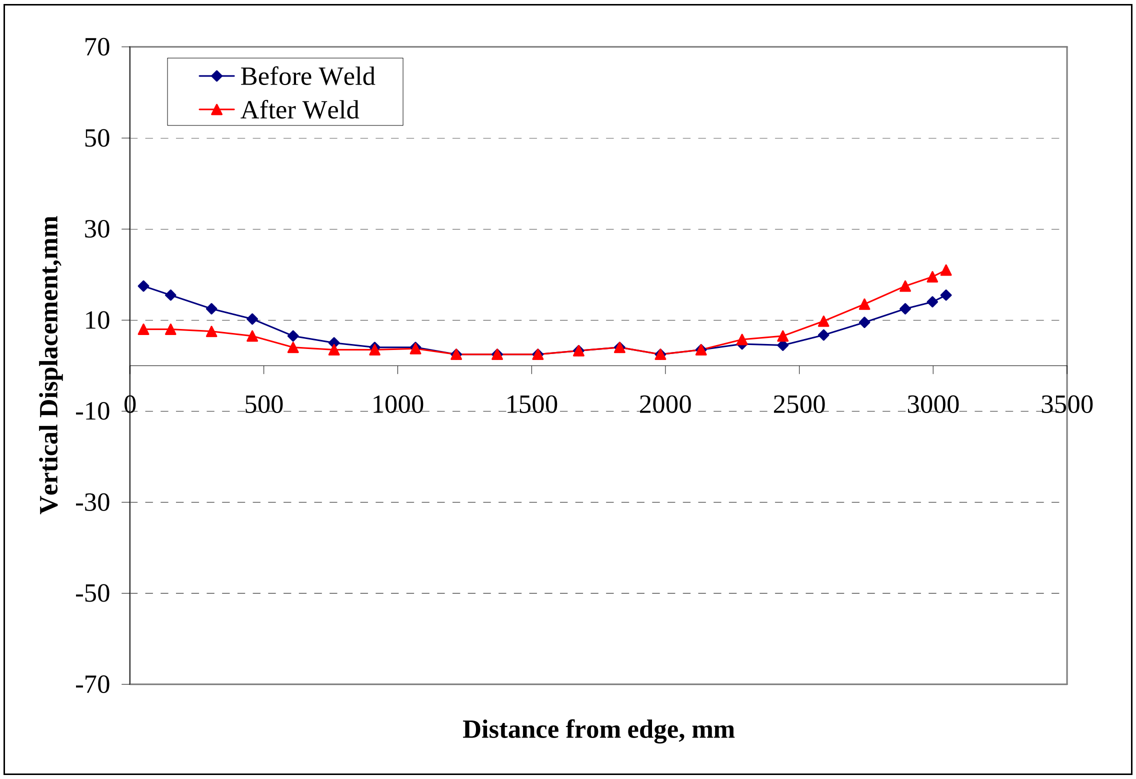


Figure 17: Longitudinal Section C

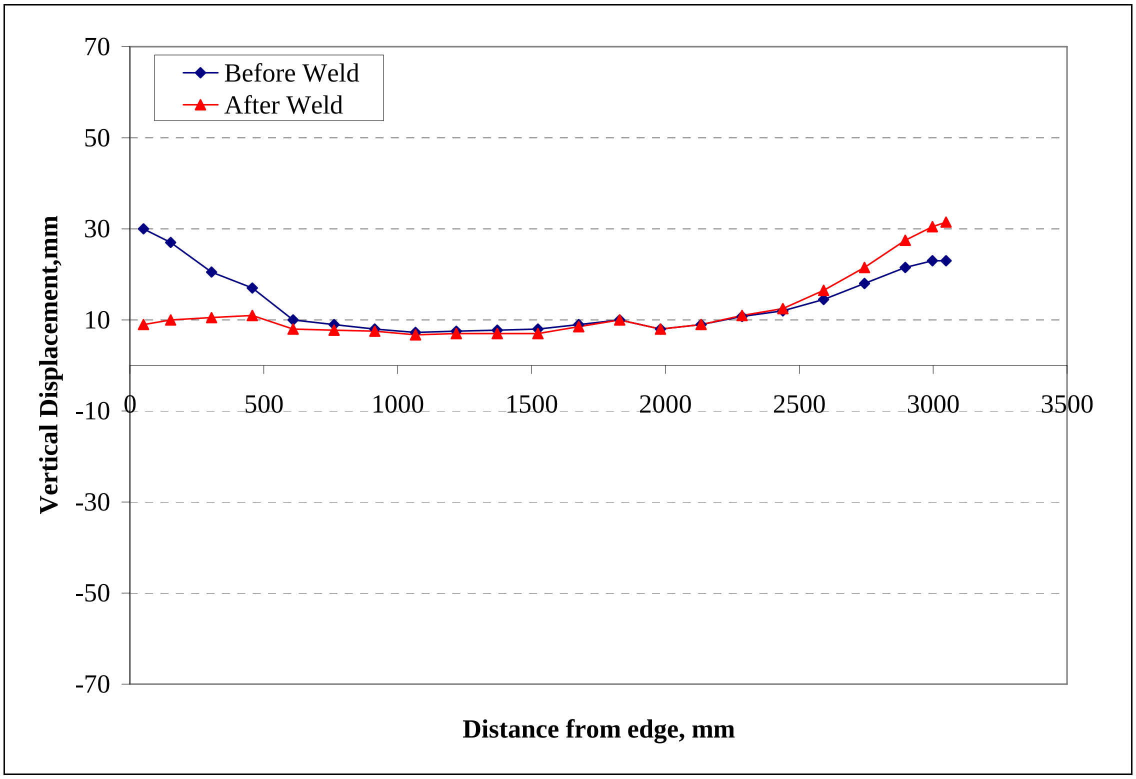


Figure 18: Longitudinal Section D

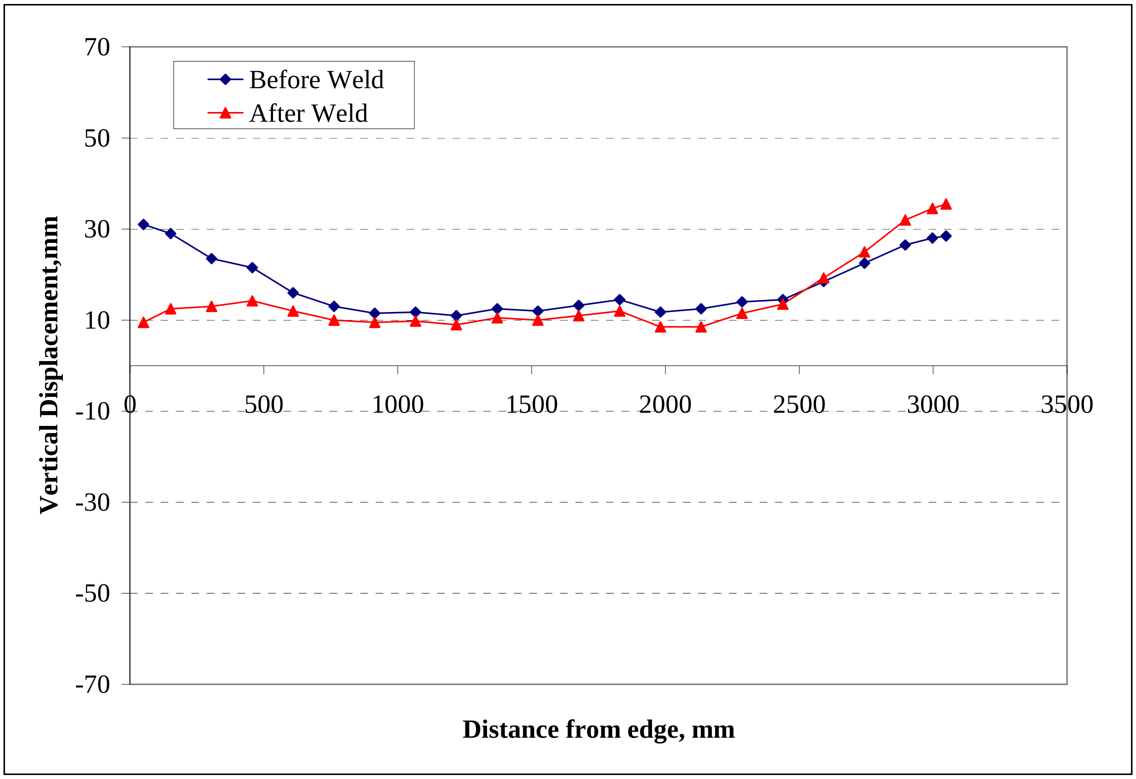


Figure 19: Longitudinal Section E

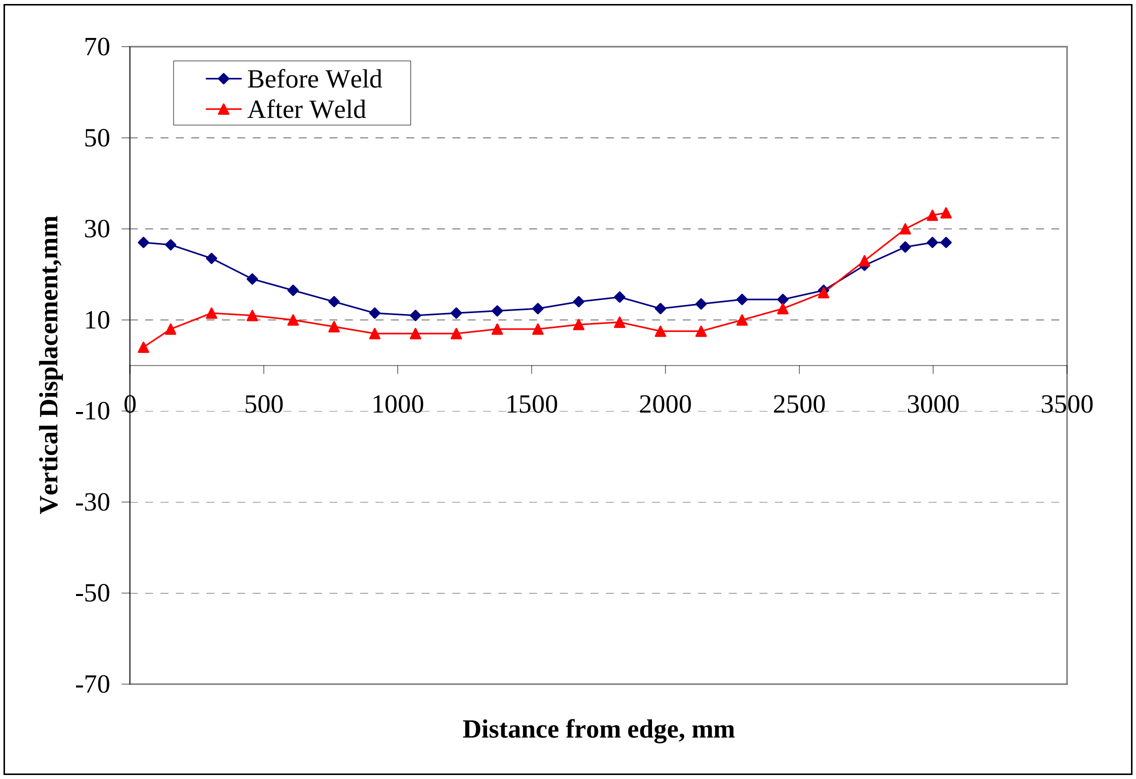


Figure 20: Longitudinal Section F

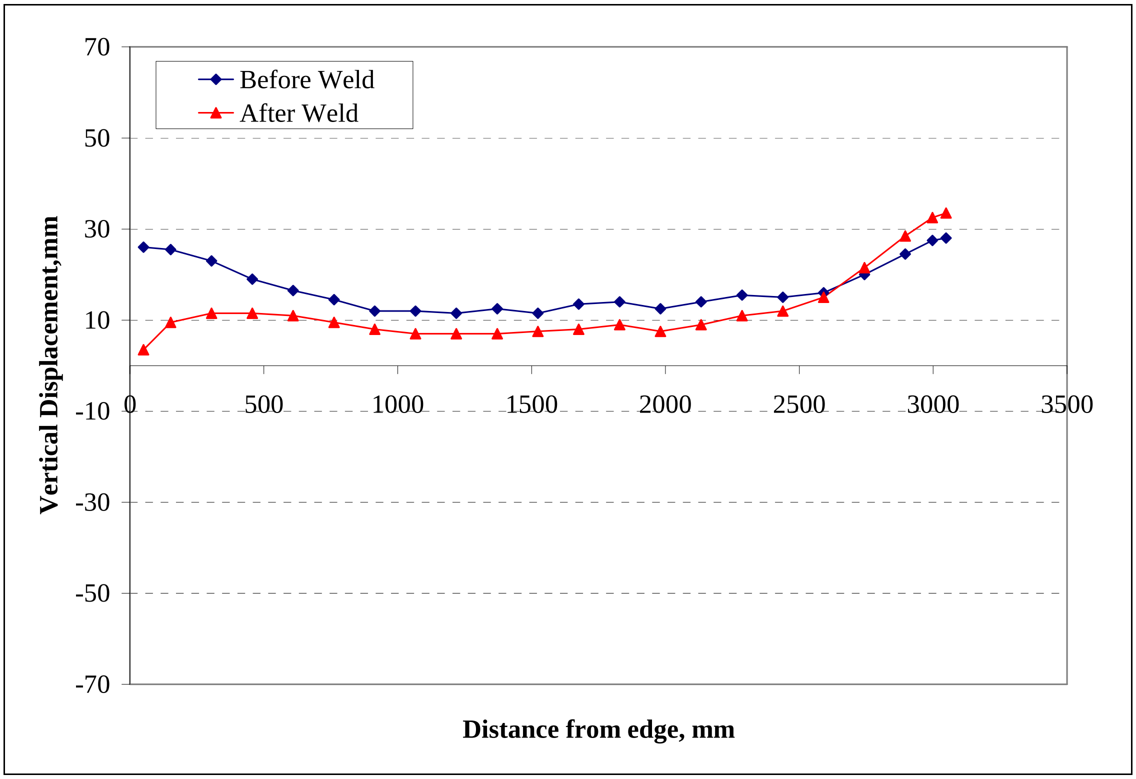


Figure 21: Longitudinal Section G

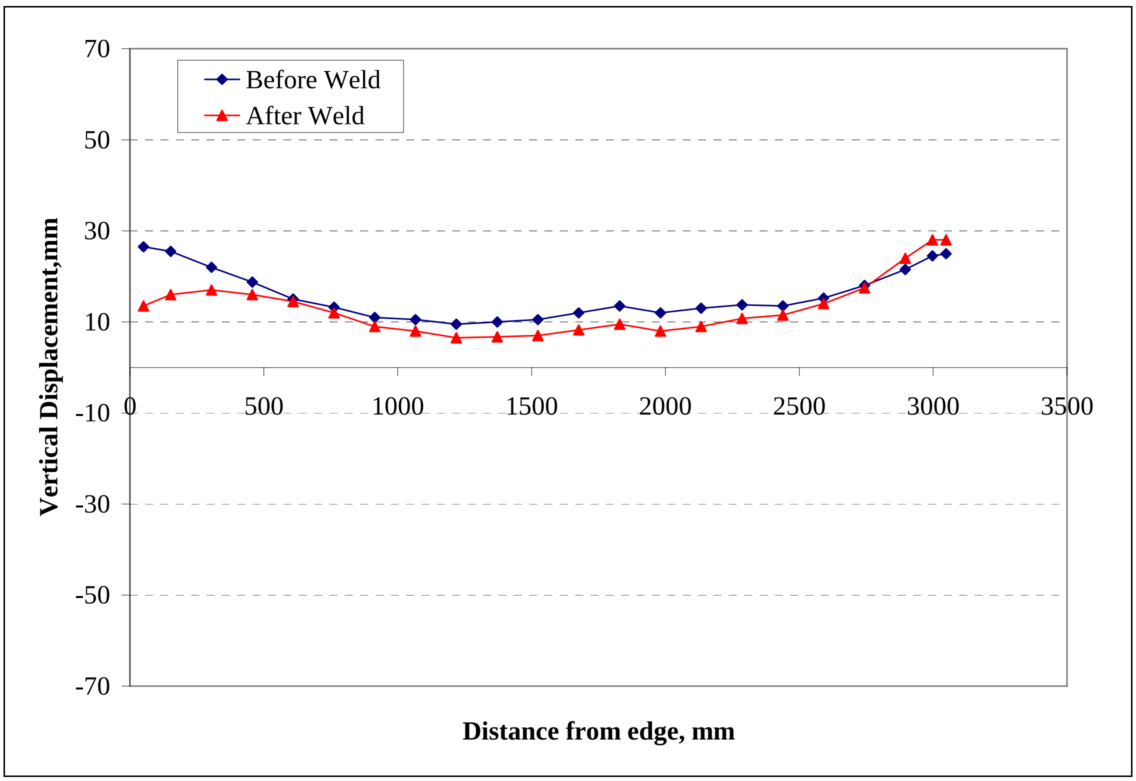


Figure 22: Longitudinal Section H

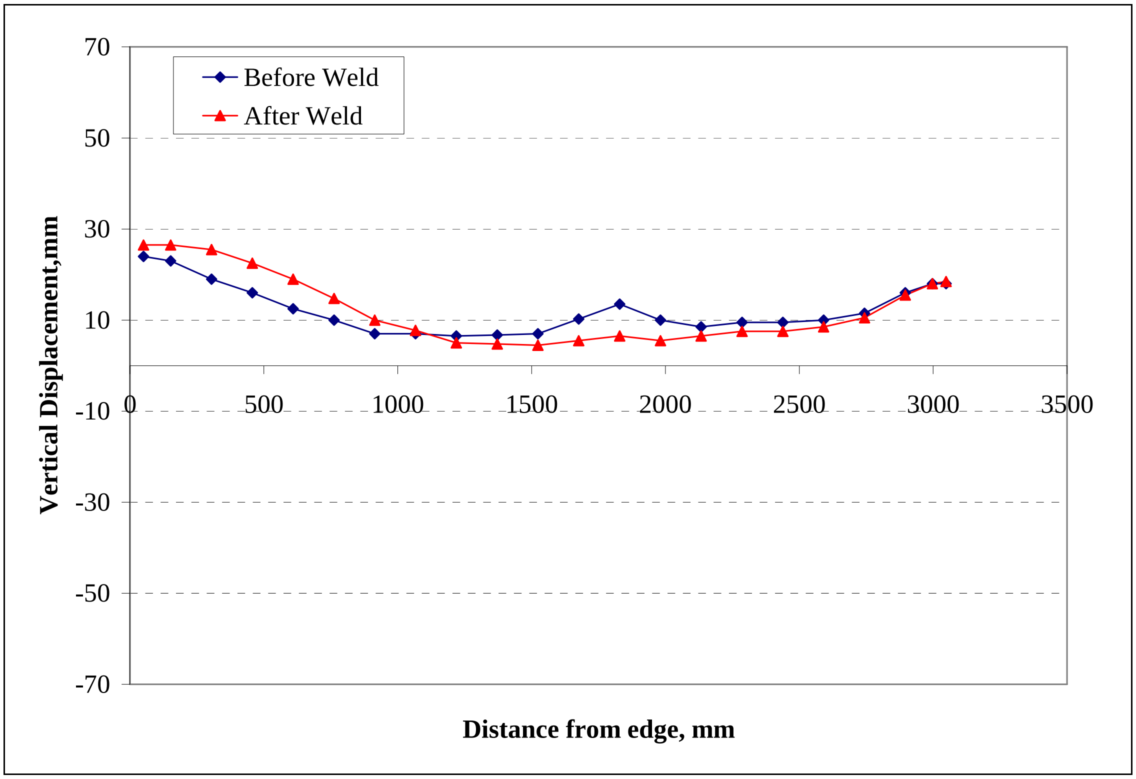


Figure 23: Longitudinal Section I

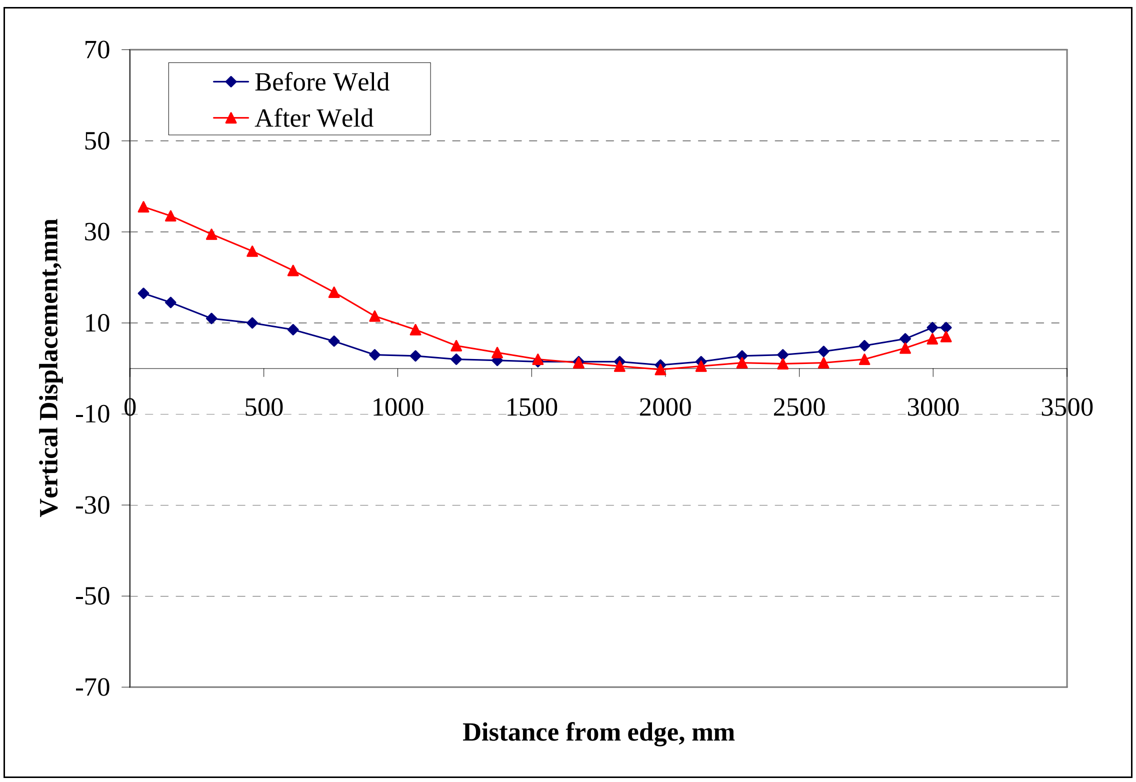


Figure 24: Longitudinal Section J

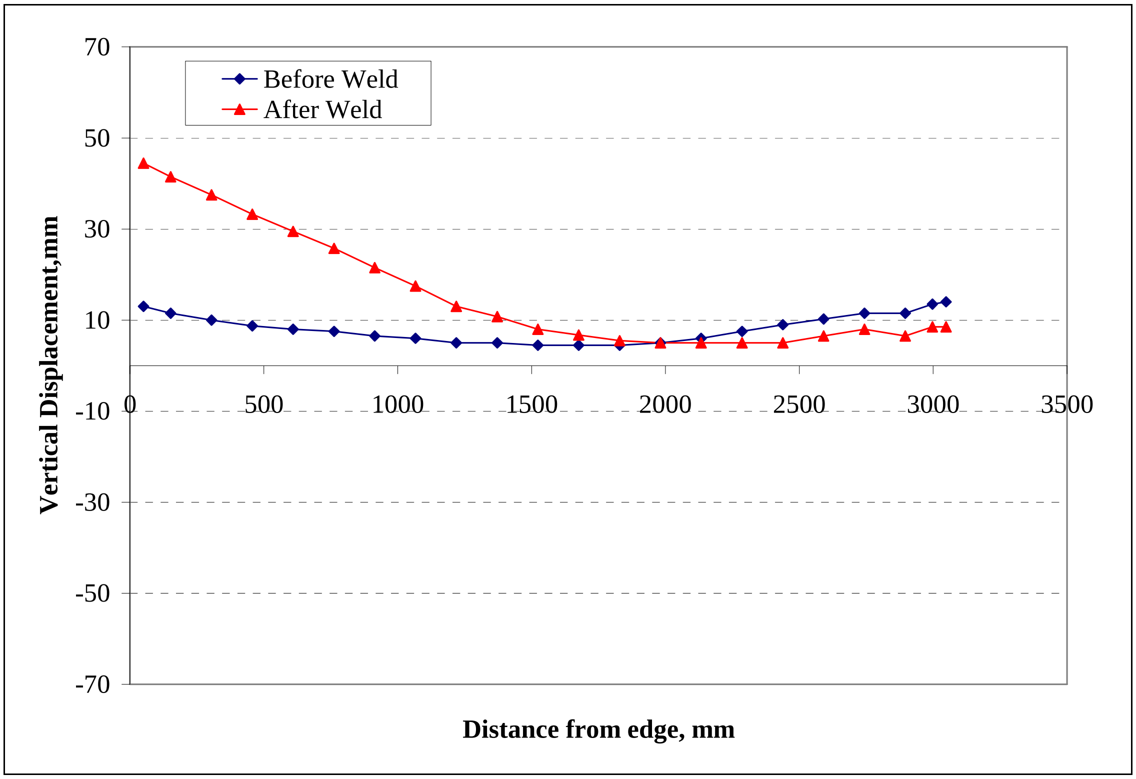


Figure 25: Longitudinal Section K

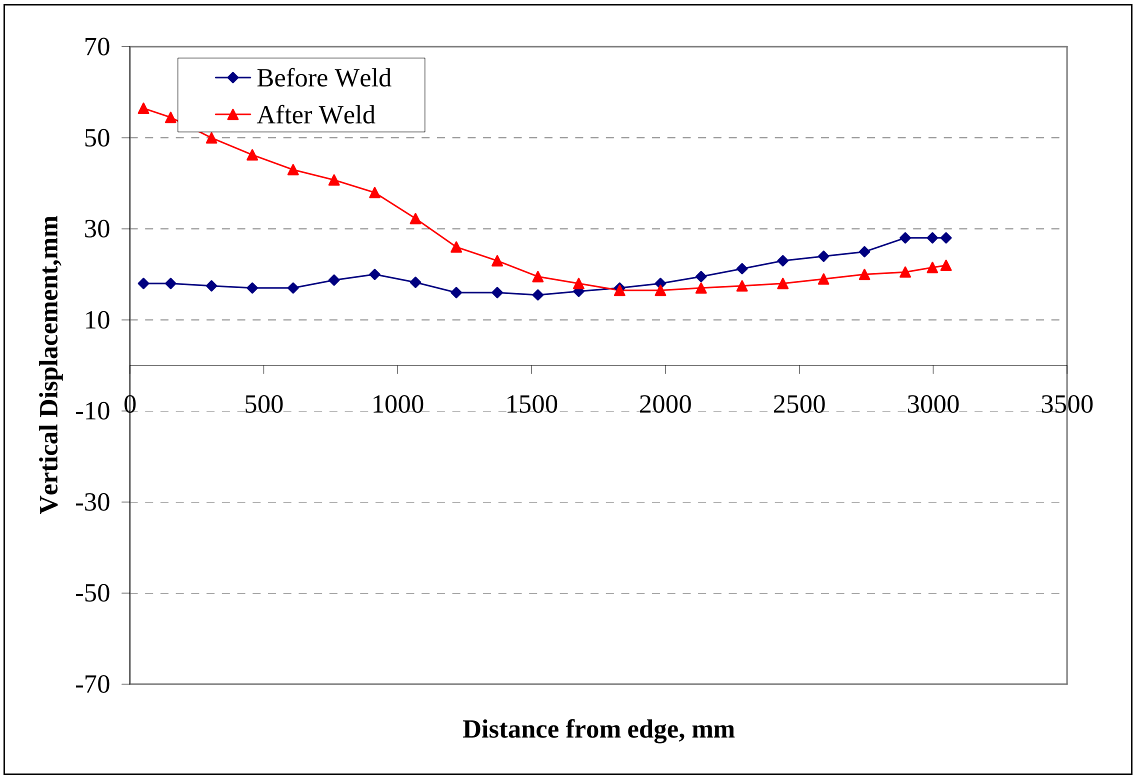


Figure 26: Longitudinal Section L

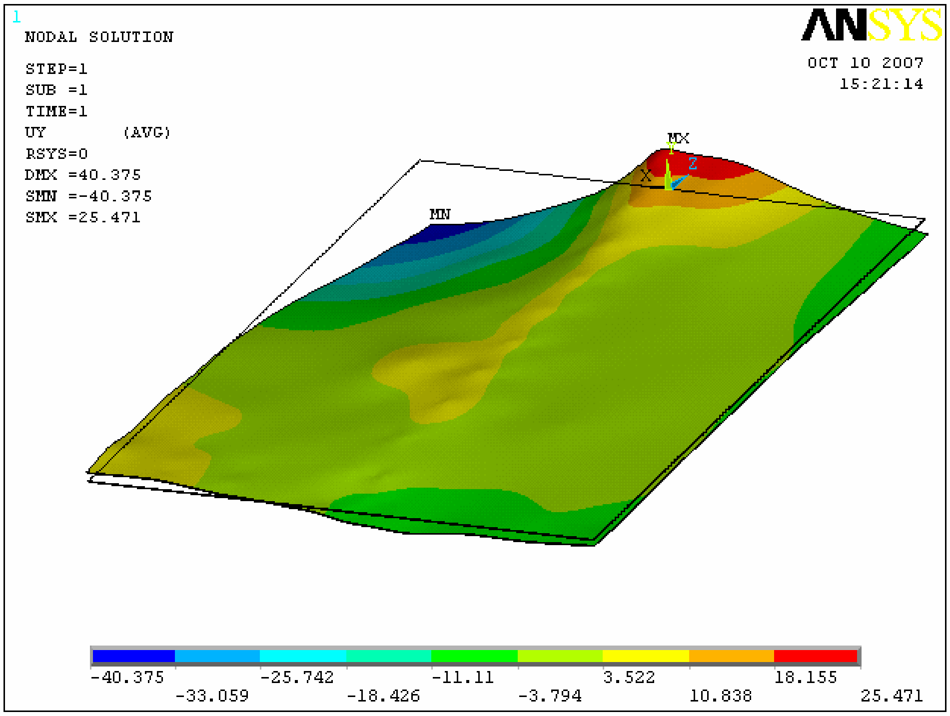


Figure 27: Net Plate Deformation after Welding

APPENDIX B

DISTORTION PLOTS FOR FILLET WELDS (STT and FCAW Processes)

Table B1: STT_Stiff_1_Benchmark Distortion Data

Before Weld					After Weld				
Displacement w.r.t to Frame, mm					Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff		A	T	B	Abs Diff
1	9	67	6.5	2.5	1	6.5	65.5	5	1.5
2	8.5	66.5	6	2.5	2	6.5	65	5	1.5
3	6.5	65	4.5	2	3	5.5	64	3.5	2
4	6	63.5	4	2	4	5.5	63	4	1.5
5	5	62	3	2	5	5	61.25	3.5	1.5
6	3.5	60.5	1.5	2	6	3.5	59.5	2.5	1
7	2.5	59.25	0.5	2	7	3	58.5	2	1
8	2	58	0.5	1.5	8	2.5	57.5	1.5	1
9	1.5	56.75	0.5	1	9	2	56.5	2	0
10	0	55.5	0	0	10	1.5	55.5	1.5	0
11	1	55.25	0	1	11	2	55.5	1.5	0.5
12	1	55	0.5	0.5	12	2.5	55.5	2	0.5
13	1.5	54.5	0.5	1	13	2.5	55	2	0.5
14	1	54	0.5	0.5	14	2	54.5	2	0
15	1.5	54.25	0.5	1	15	2.5	54.75	2.5	0
16	2.5	54.5	1.5	1	16	3.5	55	3	0.5
17	3	55	1.5	1.5	17	4	55.25	3	1
18	3.5	55.5	2.5	1	18	4.5	55.5	4	0.5
19	5.5	56.5	3.5	2	19	5.5	56.25	5	0.5
20	6.5	57.5	5	1.5	20	6.5	57	6	0.5
21	8	58.5	6	2	21	6.5	57.5	6	0.5
22	9	59	7	2	22	6.5	58	6.5	0
23	10	59.5	8	2	23	7.5	58.5	7.5	0

Table B2: FCAW_Stiff_1_Benchmark Distortion Data

Before Weld					After Weld				
Displacement w.r.t to Frame, mm					Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff		A	T	B	Abs Diff
1	7	55	9.5	2.5	1	3.5	53	9	5.5
2	6.5	55	9	2.5	2	3	53	8.5	5.5
3	5	54	7.5	2.5	3	2.5	52.25	7	4.5
4	4.5	53	6.5	2	4	2	51.5	6.5	4.5
5	3.5	51.75	5.5	2	5	2	50.5	5.5	3.5
6	2.5	50.5	3.5	1	6	2	49.5	4	2
7	2	50	3	1	7	2	49.25	3.5	1.5
8	1.5	49.5	2	0.5	8	2	49	3	1
9	1.5	49	1.5	0	9	2	48.75	2.5	0.5
10	0.5	48.5	0.5	0	10	2	48.5	2	0
11	1	49	1	0	11	2.5	49	2	0.5
12	1.5	49.5	1.5	0	12	3	49.5	2.5	0.5
13	1.5	49.5	1.5	0	13	3	49.5	2.5	0.5
14	1	49.5	1.5	0.5	14	2.5	49.5	2	0.5
15	2	50.5	2	0	15	3	50.25	2.5	0.5
16	2.5	51.5	3	0.5	16	3	51	3	0
17	3	52.5	3.5	0.5	17	3	51.5	3.5	0.5
18	3.5	53.5	5	1.5	18	3.5	52	4.5	1
19	5	55	6	1	19	4.5	53	5	0.5
20	6.5	56.5	7.5	1	20	4.5	54	6	1.5
21	7.5	58	8.5	1	21	3.5	54.5	5	1.5
22	8	58.75	9	1	22	4.5	55	5	0.5
23	8.5	59.5	9.5	1	23	5	55.5	5.5	0.5

Table B3: FCAW_Stiff_2 Distortion Data

	Before Weld				Tension No Weld				After Weld			
	Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff	A	T	B	Abs Diff	A	T	B	Abs Diff
1	10	57.5	10	0	5	54.5	4	1	3	52.5	2.5	0.5
2	9	57	8	1	5	54.5	4	1	3	52.5	2.5	0.5
3	7	56.25	6.5	0.5	4	53.5	3	1	2	51.5	1.5	0.5
4	6.5	55.5	5.5	1	4.5	52.5	3	1.5	3	50.5	2.5	0.5
5	5	54	4.5	0.5	3.5	51.25	2	1.5	2.5	49.75	2	0.5
6	4	52.5	3	1	2	50	0.5	1.5	1.5	49	1	0.5
7	3	51.5	2	1	1	49.5	0	1	1.5	48.75	1	0.5
8	2	50.5	1.5	0.5	0.5	49	0	0.5	1.5	48.5	1	0.5
9	1.5	50	1	0.5	0	48.5	0	0	1.5	48.5	1	0.5
10	1	49.5	0.5	0.5	0	48	0	0	1.5	48.5	1	0.5
11	1.5	50	0.5	1	0.5	48.75	0	0.5	1.5	49	1	0.5
12	1.5	50.5	0.5	1	0.5	49.5	0	0.5	2	49.5	1.5	0.5
13	2	50.5	1	1	1	49.25	0	1	2	49.75	1.5	0.5
14	1.5	50.5	1	0.5	0.5	49	0	0.5	2	50	1	1
15	2	51.25	1	1	1	50.25	0	1	2.5	50.5	2	0.5
16	2	52	1.5	0.5	1	51.5	0	1	2.5	51	2	0.5
17	2.5	52.75	1.5	1	1	51.75	0.5	0.5	2.5	51.5	2	0.5
18	4	53.5	2.5	1.5	2.5	52	1.5	1	3.5	52	2.5	1
19	5.5	54.75	3	2.5	3.5	53.75	2.5	1	5	53	3.5	1.5
20	7	56	4.5	2.5	4.5	55.5	3.5	1	5	54	3.5	1.5
21	8	58	4.5	3.5	2.5	56	2	0.5	3	56	1.5	1.5
22	8.5	58.5	6	2.5	2.5	57	2	0.5	3	56.25	1.5	1.5
23	9.5	59	7	2.5	2.5	58	2	0.5	3	56.5	1.5	1.5

Table B4: FCAW_Stiff_3 Distortion Data

	Before Weld				Tension No Weld				After Weld			
	Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff	A	T	B	Abs Diff	A	T	B	Abs Diff
1	10	57	9.5	0.5	3	54	4	1	0.5	53.5	2.5	2
2	9	56.5	8	1	3	53.5	4	1	1	53.5	3.5	2.5
3	6.5	55.25	6	0.5	2	52.75	3	1	1	52.5	3	2
4	6	54	5	1	3	52	3.5	0.5	1.5	51.5	3	1.5
5	5	52.5	3.5	1.5	2	51	2.5	0.5	1	50.5	2.5	1.5
6	3.5	51	2	1.5	1	50	1	0	0.5	49.5	1.5	1
7	2	50.25	1	1	0.5	49.25	0	0.5	1	49	1	0
8	1.5	49.5	0.5	1	0.5	48.5	0	0.5	1	48.5	0.5	0.5
9	1	48.75	0	1	0	47.75	0	0	1	48.25	0	1
10	0	48	0	0	0	47	0.5	0.5	0.5	48	0.5	0
11	0.5	48.25	0	0.5	0.5	47.5	0	0.5	1	48.5	1.5	0.5
12	1	48.5	0	1	0.5	48	0	0.5	1	49	1.5	0.5
13	1	48.5	0.5	0.5	0.5	47.75	0	0.5	1	49	2	1
14	0.5	48.5	0	0.5	0	47.5	0	0	0.5	49	1.5	1
15	1	49.25	0.5	0.5	0	48.25	0	0	0.5	49.5	2	1.5
16	2	50	1.5	0.5	0.5	49	0	0.5	1	50	2.5	1.5
17	2.5	51	2.5	0	0.5	49.5	1	0.5	0.5	50.5	3	2.5
18	4	52	4	0	1.5	50	1.5	0	1.5	51	3.5	2
19	5.5	53.75	5.5	0	2	51	3	1	3	52	4.5	1.5
20	7	55.5	7.5	0.5	3.5	52	4.5	1	4	53	5	1
21	8.5	57	9	0.5	3.5	53.5	4	0.5	3	54	5.5	2.5
22	9.5	58	10.5	1	3.5	54.25	4	0.5	3.5	54.5	5.5	2
23	11	59	11	0	3.5	55	4	0.5	4	55	5.5	1.5

Table B5: FCAW_Stiff_4 Distortion Data

Before Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	2.5	54.5	4.5	2
2	2.5	54.5	3.5	1
3	1	54	2	1
4	1.5	53.5	2	0.5
5	1	53	2	1
6	0	52.5	1	1
7	0	52.5	0.5	0.5
8	0	52.5	0.5	0.5
9	0	52.5	0	0
10	0	52.5	0	0
11	0	53	0	0
12	0	53.5	0	0
13	0.5	53.5	0.5	0
14	0	53.5	0	0
15	0.5	54	0	0.5
16	1	54.5	0	1
17	0.5	54.75	0.5	0
18	1.5	55	1.5	0
19	2	56	1	1
20	2.5	57	1.5	1
21	2.5	57	1.5	1
22	3.5	57.25	2.5	1
23	4	57.5	3	1

Tension No Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	3	54.5	2	1
2	3	54.5	2	1
3	2	54	1	1
4	2	53.5	1.5	0.5
5	1.5	53.25	1	0.5
6	0.5	53	0	0.5
7	0.5	53	0	0.5
8	0.5	53	0	0.5
9	0	52.75	0	0
10	0	52.5	0	0
11	0	53	0	0
12	0.5	53.5	0.5	0
13	0.5	53.25	0.5	0
14	0	53	0	0
15	0.5	53.5	0	0.5
16	0.5	54	0	0.5
17	0.5	54.5	0	0.5
18	1	55	0	1
19	1.5	55.5	0.5	1
20	2	56	0.5	1.5
21	2	56	0	2
22	2	56.5	0	2
23	2	57	0	2

After Weld				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	0.5	52	0.5	0
2	0.5	52	0.5	0
3	0	52.25	0	0
4	0.5	52.5	0.5	0
5	0.5	52.5	0.5	0
6	0	52.5	0	0
7	0.5	52.75	0.5	0
8	0.5	53	1	0.5
9	0.5	53	1.5	1
10	0	53	1.5	1.5
11	0.5	53.75	2	1.5
12	1	54.5	3	2
13	1	54.5	3	2
14	0.5	54.5	2	1.5
15	1	54.75	2	1
16	1	55	2.5	1.5
17	1	55	2	1
18	1	55	2	1
19	1.5	55.25	1.5	0
20	1.5	55.5	1.5	0
21	0.5	55.5	0.5	0
22	0.5	55.75	1	0.5
23	1	56	1	0

Table 6: FCAW_Stiff_2 Net Displacement

Net Displacement, mm				
Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff
1	-7	-5	-7.5	0.5
2	-6	-4.5	-5.5	0.5
3	-5	-4.75	-5	0
4	-3.5	-5	-3	0.5
5	-2.5	-4.25	-2.5	0
6	-2.5	-3.5	-2	0.5
7	-1.5	-2.75	-1	0.5
8	-0.5	-2	-0.5	0
9	0	-1.5	0	0
10	0.5	-1	0.5	0
11	0	-1	0.5	0.5
12	0.5	-1	1	0.5
13	0	-0.75	0.5	0.5
14	0.5	-0.5	0	0.5
15	0.5	-0.75	1	0.5
16	0.5	-1	0.5	0
17	0	-1.25	0.5	0.5
18	-0.5	-1.5	0	0.5
19	-0.5	-1.75	0.5	1
20	-2	-2	-1	1
21	-5	-2	-3	2
22	-5.5	-2.25	-4.5	1
23	-6.5	-2.5	-5.5	1

Net Displacement, mm				
Benchmark				
	A	T	B	Abs Diff
1	-3.5	-2	-0.5	3
2	-3.5	-2	-0.5	3
3	-2.5	-1.75	-0.5	2
4	-2.5	-1.5	0	2.5
5	-1.5	-1.25	0	1.5
6	-0.5	-1	0.5	1
7	0	-0.75	0.5	0.5
8	0.5	-0.5	1	0.5
9	0.5	-0.25	1	0.5
10	1.5	0	1.5	0
11	1.5	0	1	0.5
12	1.5	0	1	0.5
13	1.5	0	1	0.5
14	1.5	0	0.5	1
15	1	-0.25	0.5	0.5
16	0.5	-0.5	0	0.5
17	0	-1	0	0
18	0	-1.5	-0.5	0.5
19	-0.5	-2	-1	0.5
20	-2	-2.5	-1.5	0.5
21	-4	-3.5	-3.5	0.5
22	-3.5	-3.75	-4	0.5
23	-3.5	-4	-4	0.5

Net Improvement, mm		
Benchmark		
-3.5	-3	-7
-2.5	-2.5	-5
-2.5	-3	-4.5
-1	-3.5	-3
-1	-3	-2.5
-2	-2.5	-2.5
-1.5	-2	-1.5
-1	-1.5	-1.5
-0.5	-1.25	-1
-1	-1	-1
-1.5	-1	-0.5
-1	-1	0
-1.5	-0.75	-0.5
-1	-0.5	-0.5
-0.5	-0.5	0.5
0	-0.5	0.5
0	-0.25	0.5
-0.5	0	0.5
0	0.25	1.5
0	0.5	0.5
-1	1.5	0.5
-2	1.5	-0.5
-3	1.5	-1.5

Table B3: FCAW_Stiff_3 Net Improvement

Net Displacement, mm						Net Displacement, mm						Net Improvement, mm		
Displacement w.r.t to Frame, mm						Benchmark						Benchmark		
	A	T	B	Abs Diff			A	T	B	Abs Diff				
1	-9.5	-3.5	-7	2.5		1	-3.5	-2	-0.5	3		-6	-1.5	-6.5
2	-8	-3	-4.5	3.5		2	-3.5	-2	-0.5	3		-4.5	-1	-4
3	-5.5	-2.75	-3	2.5		3	-2.5	-1.75	-0.5	2		-3	-1	-2.5
4	-4.5	-2.5	-2	2.5		4	-2.5	-1.5	0	2.5		-2	-1	-2
5	-4	-2	-1	3		5	-1.5	-1.25	0	1.5		-2.5	-0.75	-1
6	-3	-1.5	-0.5	2.5		6	-0.5	-1	0.5	1		-2.5	-0.5	-1
7	-1	-1.25	0	1		7	0	-0.75	0.5	0.5		-1	-0.5	-0.5
8	-0.5	-1	0	0.5		8	0.5	-0.5	1	0.5		-1	-0.5	-1
9	0	-0.5	0	0		9	0.5	-0.25	1	0.5		-0.5	-0.25	-1
10	0.5	0	0.5	0		10	1.5	0	1.5	0		-1	0	-1
11	0.5	0.25	1.5	1		11	1.5	0	1	0.5		-1	0.25	0.5
12	0	0.5	1.5	1.5		12	1.5	0	1	0.5		-1.5	0.5	0.5
13	0	0.5	1.5	1.5		13	1.5	0	1	0.5		-1.5	0.5	0.5
14	0	0.5	1.5	1.5		14	1.5	0	0.5	1		-1.5	0.5	1
15	-0.5	0.25	1.5	2		15	1	-0.25	0.5	0.5		-1.5	0.5	1
16	-1	0	1	2		16	0.5	-0.5	0	0.5		-1.5	0.5	1
17	-2	-0.5	0.5	2.5		17	0	-1	0	0		-2	0.5	0.5
18	-2.5	-1	-0.5	2		18	0	-1.5	-0.5	0.5		-2.5	0.5	0
19	-2.5	-1.75	-1	1.5		19	-0.5	-2	-1	0.5		-2	0.25	0
20	-3	-2.5	-2.5	0.5		20	-2	-2.5	-1.5	0.5		-1	0	-1
21	-5.5	-3	-3.5	2		21	-4	-3.5	-3.5	0.5		-1.5	0.5	0
22	-6	-3.5	-5	1		22	-3.5	-3.75	-4	0.5		-2.5	0.25	-1
23	-7	-4	-5.5	1.5		23	-3.5	-4	-4	0.5		-3.5	0	-1.5

Table B4: FCAW_Stiff_4 Net Improvement

Net Displacement, mm						Net Displacement, mm						Net Improvement, mm		
Displacement w.r.t to Frame, mm						Benchmark						Benchmark		
	A	T	B	Abs Diff			A	T	B	Abs Diff				
1	-2	-2.5	-4	2		1	-3.5	-2	-0.5	3		1.5	-0.5	-3.5
2	-2	-2.5	-3	1		2	-3.5	-2	-0.5	3		1.5	-0.5	-2.5
3	-1	-1.75	-2	1		3	-2.5	-1.75	-0.5	2		1.5	0	-1.5
4	-1	-1	-1.5	0.5		4	-2.5	-1.5	0	2.5		1.5	0.5	-1.5
5	-0.5	-0.5	-1.5	1		5	-1.5	-1.25	0	1.5		1	0.75	-1.5
6	0	0	-1	1		6	-0.5	-1	0.5	1		0.5	1	-1.5
7	0.5	0.25	0	0.5		7	0	-0.75	0.5	0.5		0.5	1	-0.5
8	0.5	0.5	0.5	0		8	0.5	-0.5	1	0.5		0	1	-0.5
9	0.5	0.5	1.5	1		9	0.5	-0.25	1	0.5		0	0.75	0.5
10	0	0.5	1.5	1.5		10	1.5	0	1.5	0		-1.5	0.5	0
11	0.5	0.75	2	1.5		11	1.5	0	1	0.5		-1	0.75	1
12	1	1	3	2		12	1.5	0	1	0.5		-0.5	1	2
13	0.5	1	2.5	2		13	1.5	0	1	0.5		-1	1	1.5
14	0.5	1	2	1.5		14	1.5	0	0.5	1		-1	1	1.5
15	0.5	0.75	2	1.5		15	1	-0.25	0.5	0.5		-0.5	1	1.5
16	0	0.5	2.5	2.5		16	0.5	-0.5	0	0.5		-0.5	1	2.5
17	0.5	0.25	1.5	1		17	0	-1	0	0		0.5	1.25	1.5
18	-0.5	0	0.5	1		18	0	-1.5	-0.5	0.5		-0.5	1.5	1
19	-0.5	-0.75	0.5	1		19	-0.5	-2	-1	0.5		0	1.25	1.5
20	-1	-1.5	0	1		20	-2	-2.5	-1.5	0.5		1	1	1.5
21	-2	-1.5	-1	1		21	-4	-3.5	-3.5	0.5		2	2	2.5
22	-3	-1.5	-1.5	1.5		22	-3.5	-3.75	-4	0.5		0.5	2.25	2.5
23	-3	-1.5	-2	1		23	-3.5	-4	-4	0.5		0.5	2.5	2

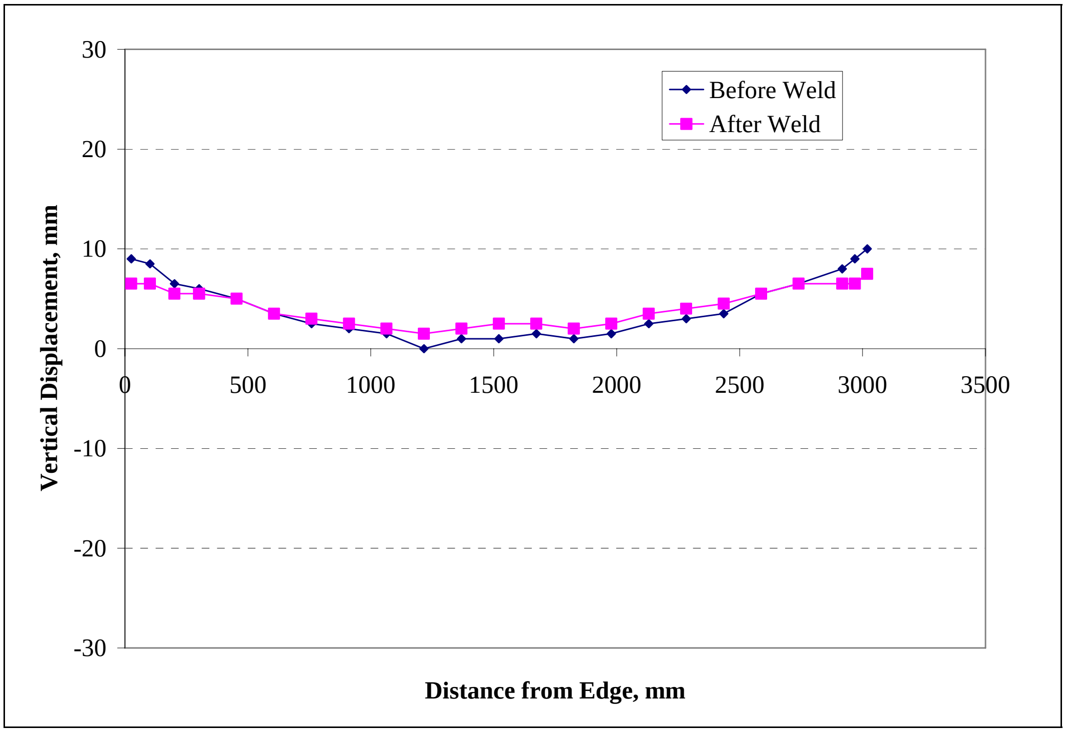


Figure B1: Net Displacement along Longitudinal Section A for STT Stiffener Benchmark Assembly

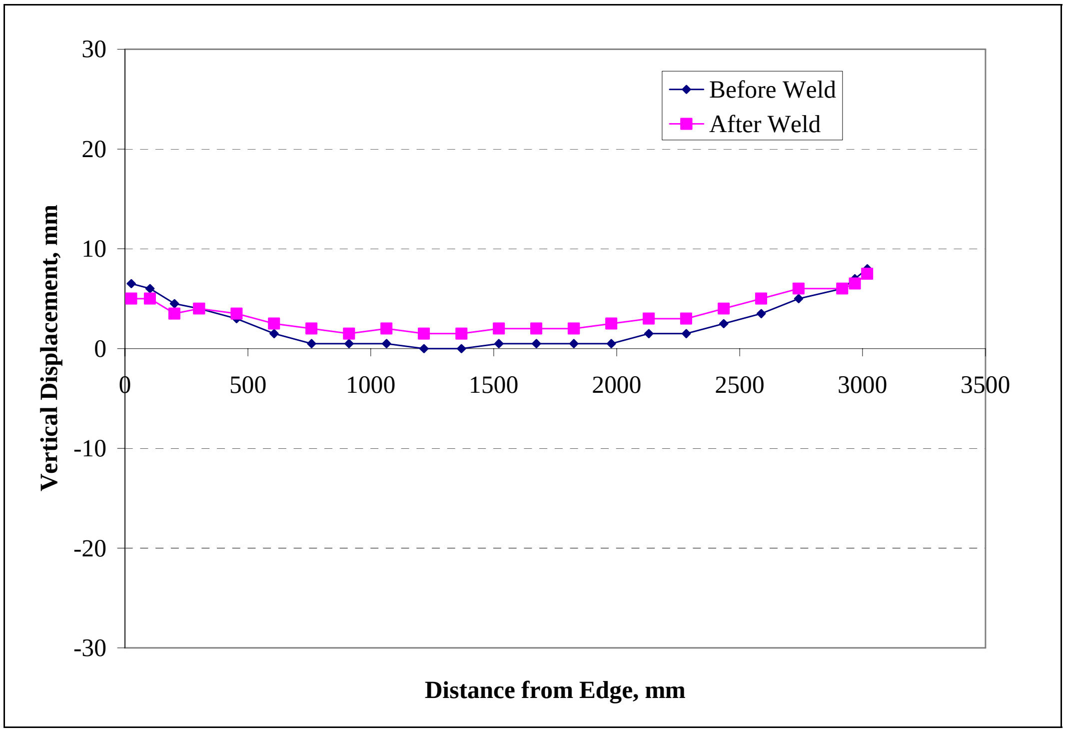


Figure B2: Net Displacement along Longitudinal Section B for STT Stiffener Benchmark Assembly

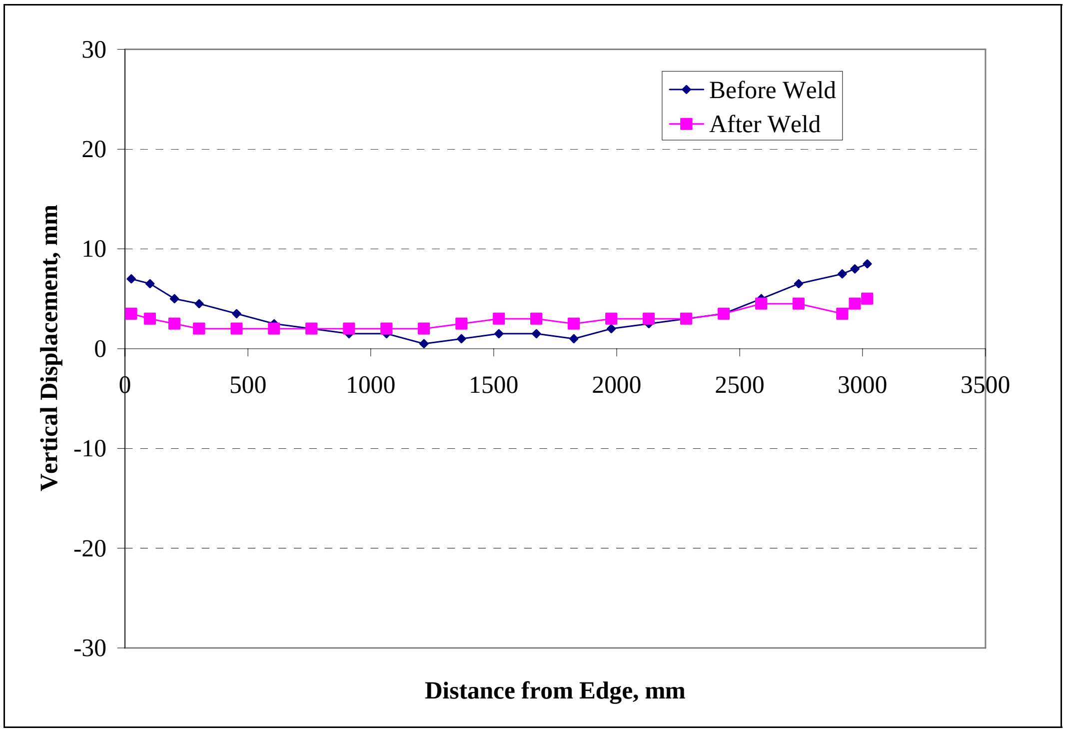


Figure B3: Net Displacement along Longitudinal Section A for FCAW Stiffener Benchmark Assembly

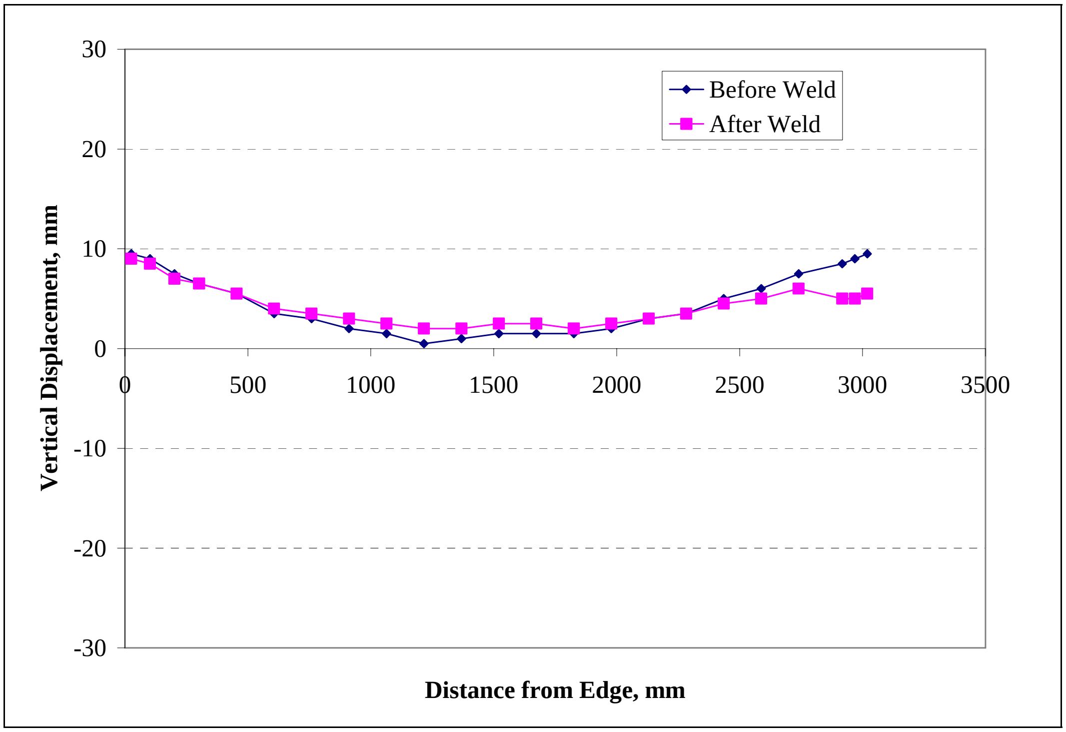
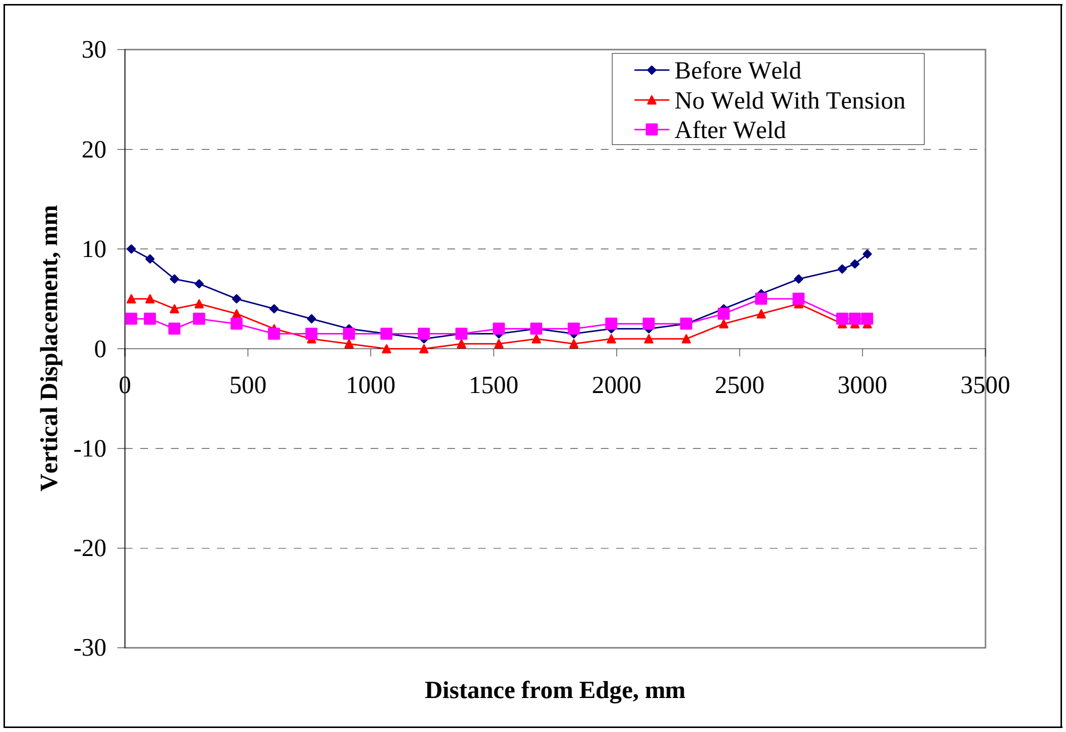


Figure B4: Net Displacement along Longitudinal Section B for FCAW Stiffener Benchmark Assembly



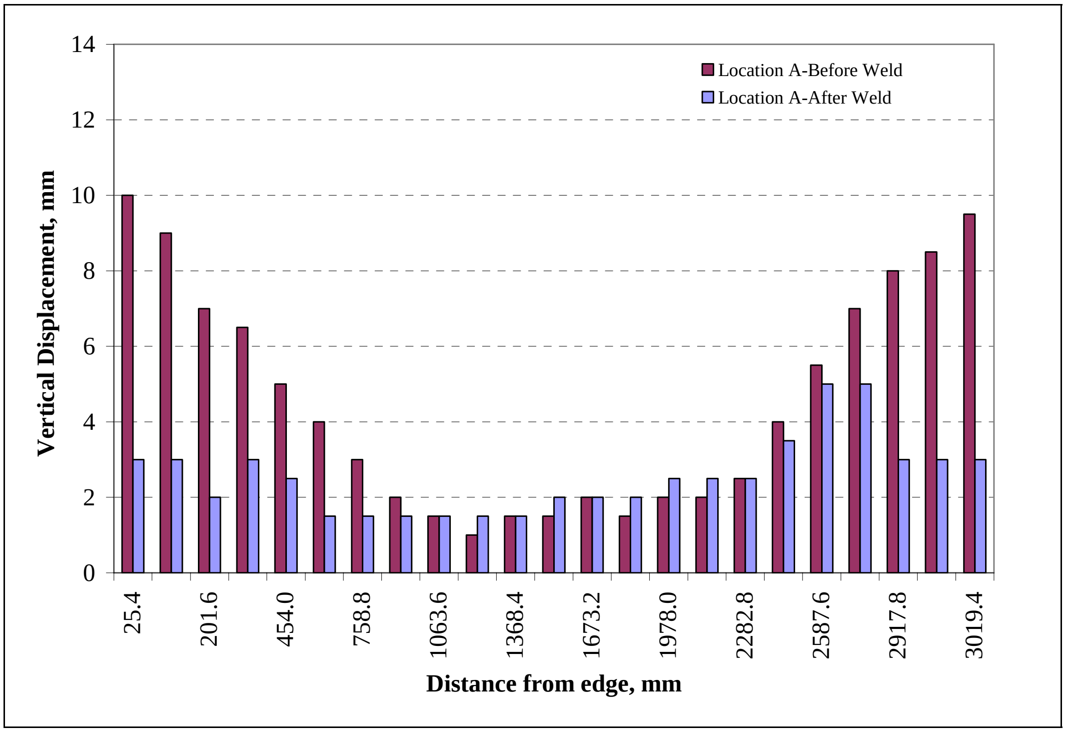
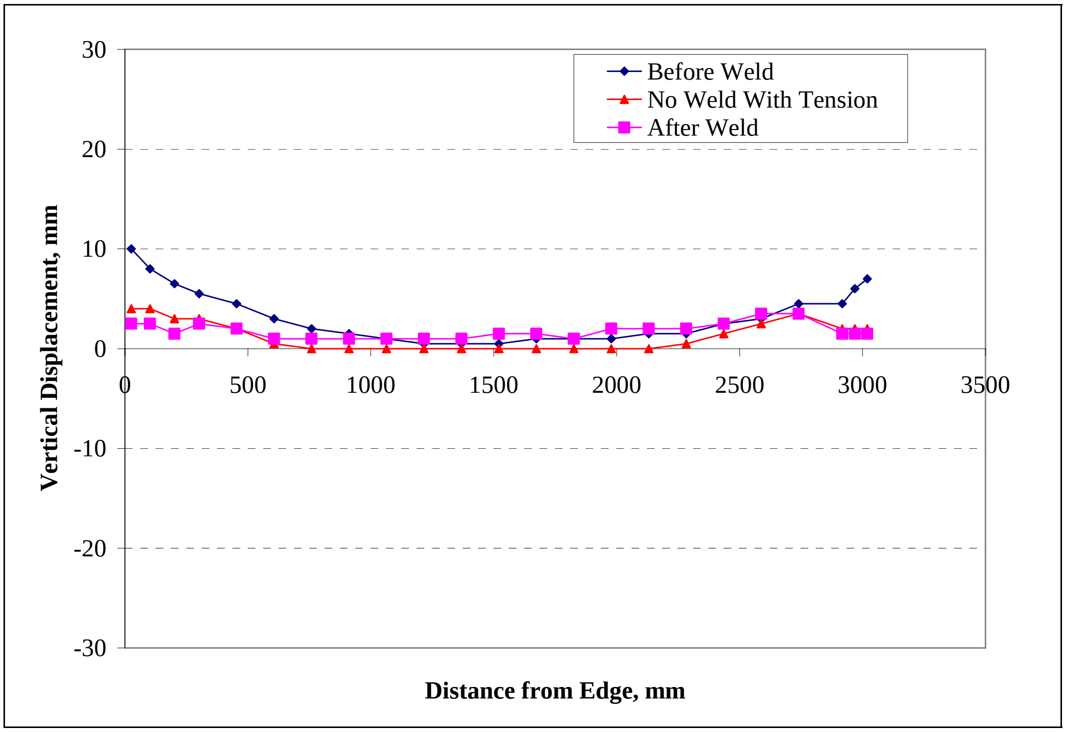


Figure B5: Net Displacement along Longitudinal Section A for FCAW Stiffener Assembly 2



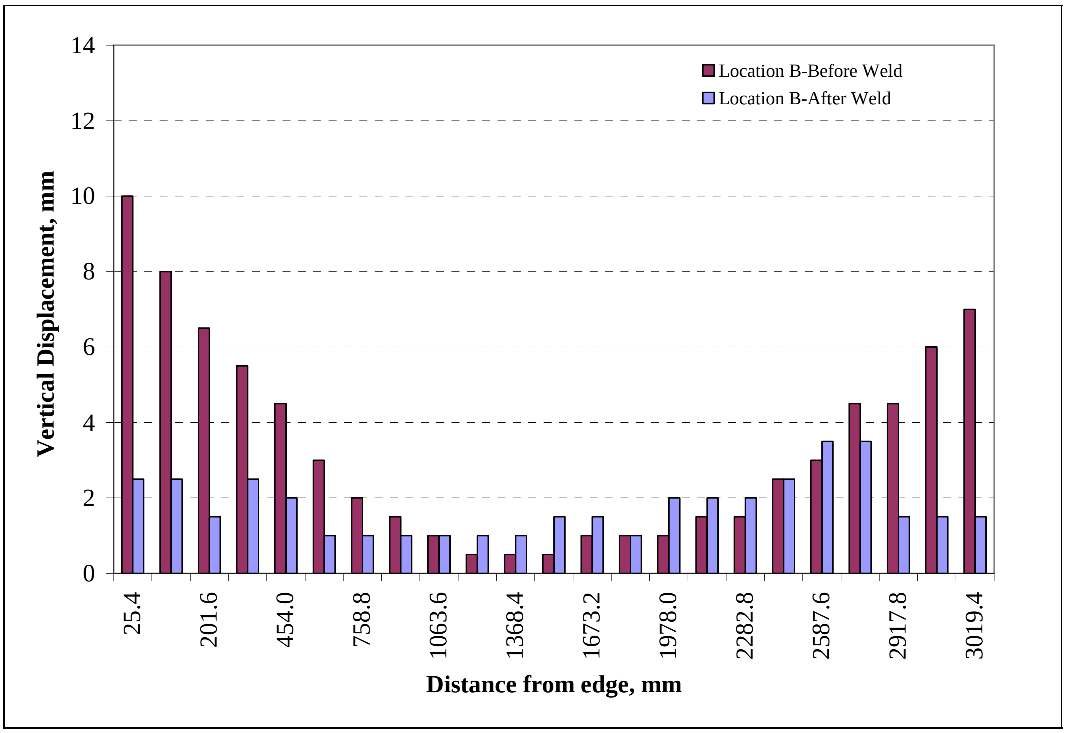
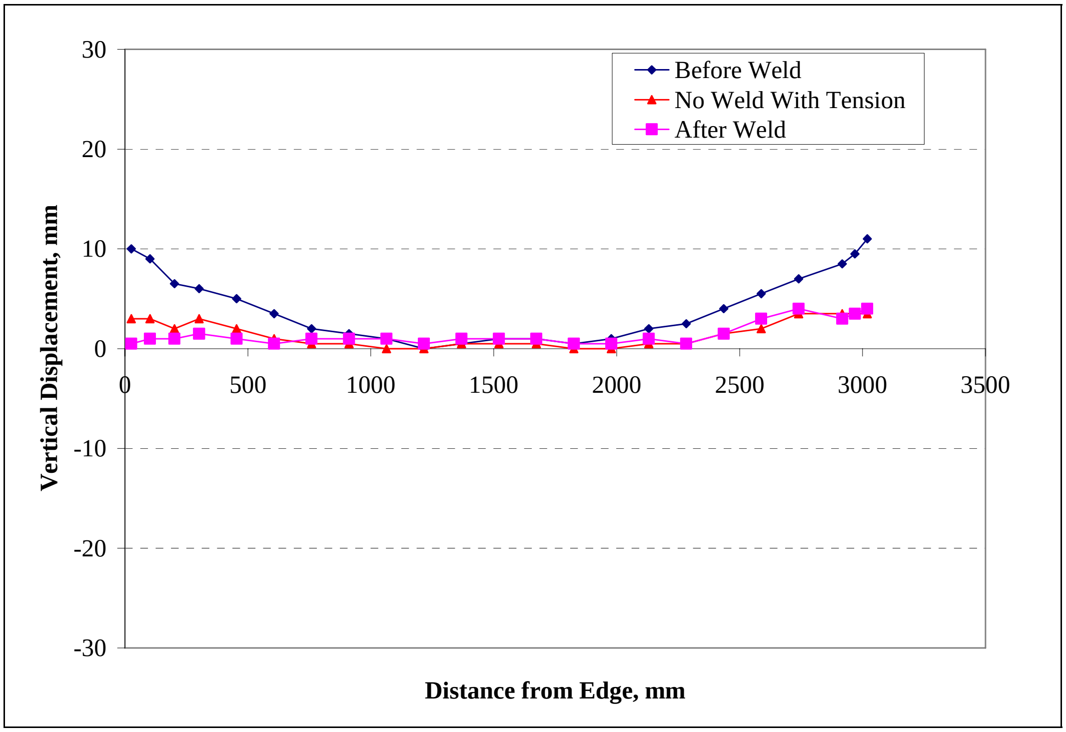


Figure B6: Net Displacement along Longitudinal Section B for FCAW Stiffener Assembly 2



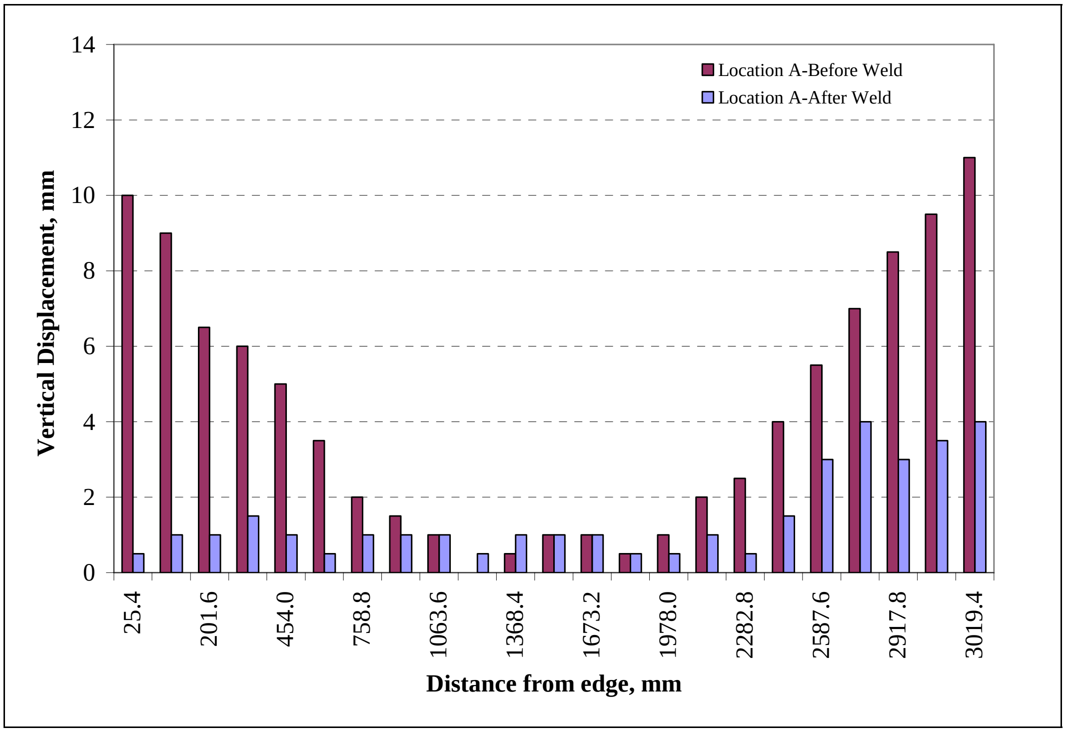
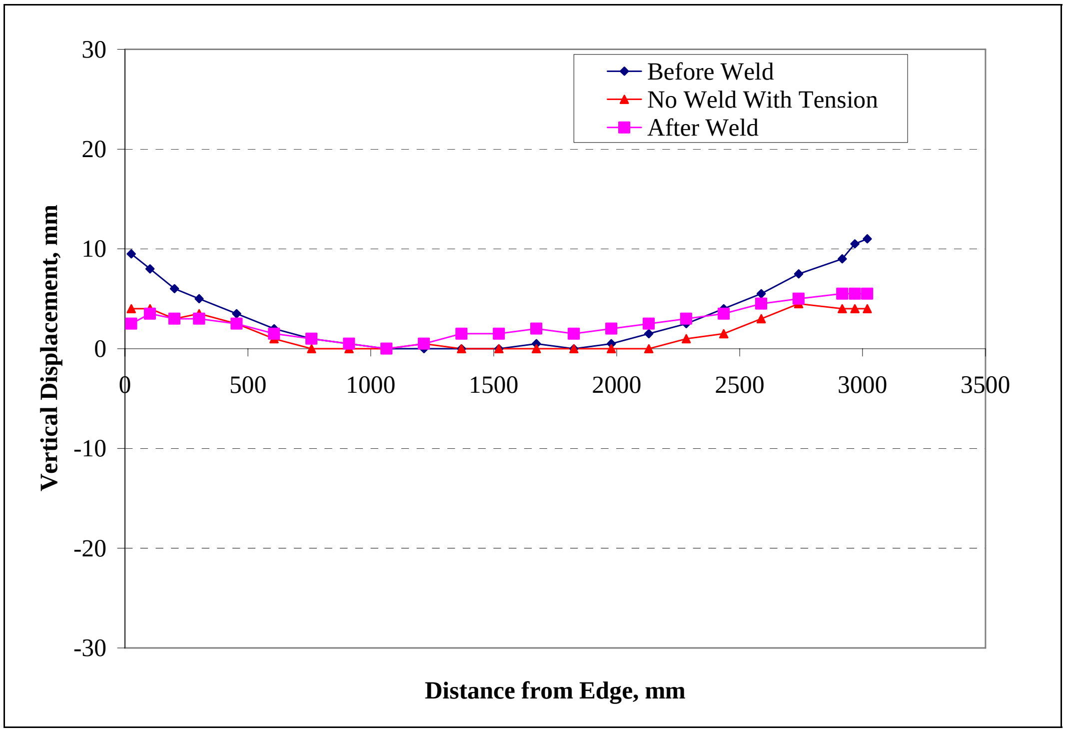


Figure B7: Net Displacement along Longitudinal Section A for FCAW Stiffener Assembly 3



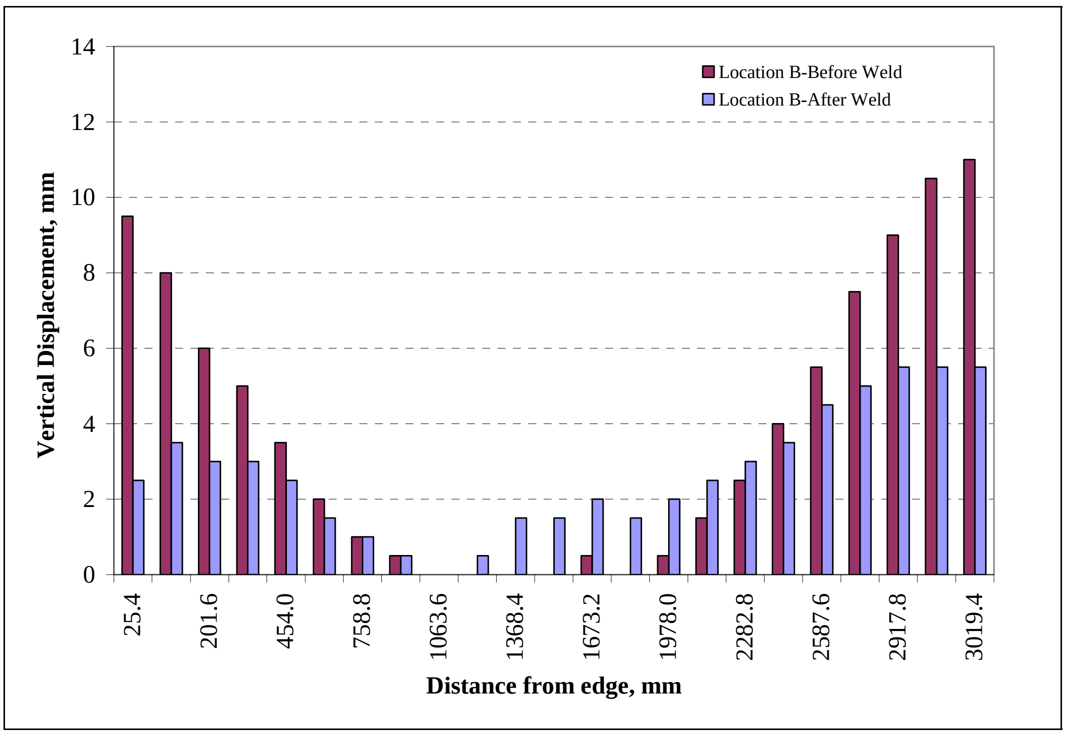


Figure B8: Net Displacement along Longitudinal Section B for FCAW Stiffener Benchmark Assembly 3

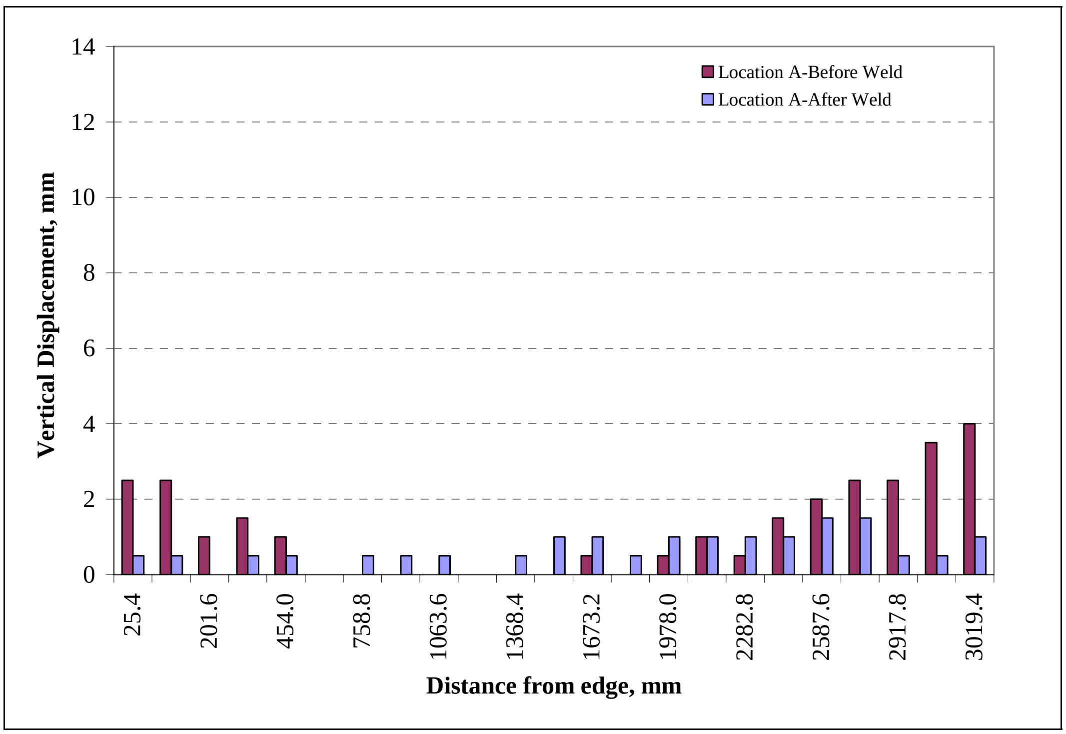


Figure B9: Net Displacement along Longitudinal Section A for FCAW Stiffener Assembly 4

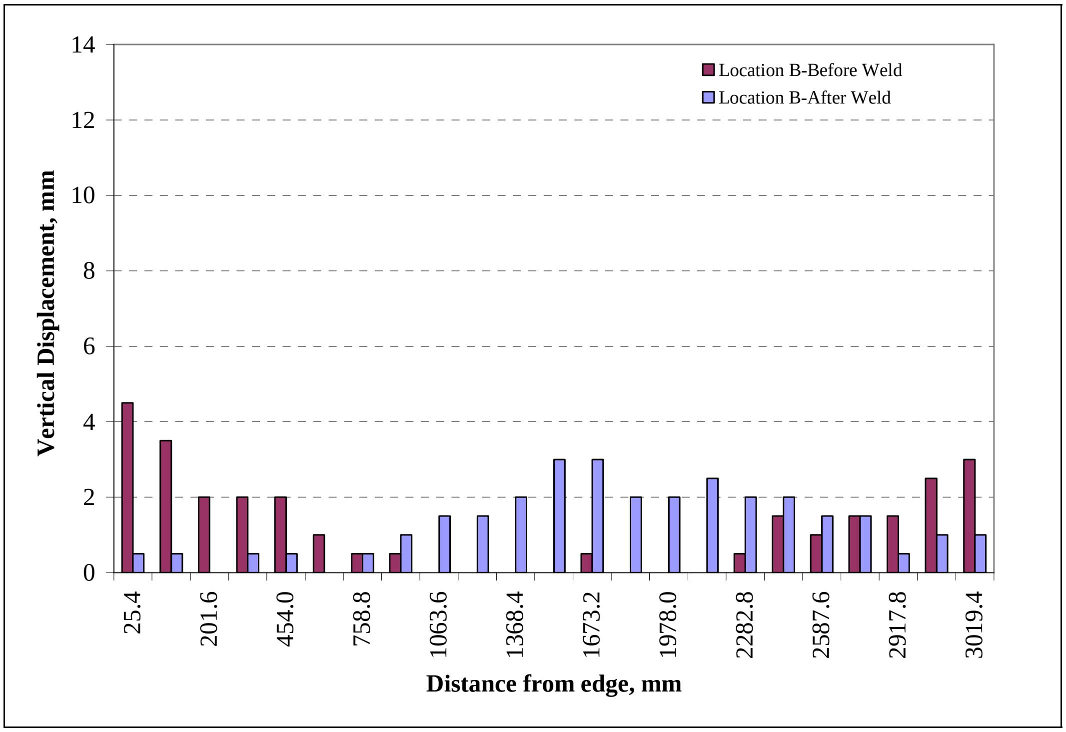


Figure B10: Net Displacement along Longitudinal Section B for FCAW Stiffener Benchmark Assembly 4

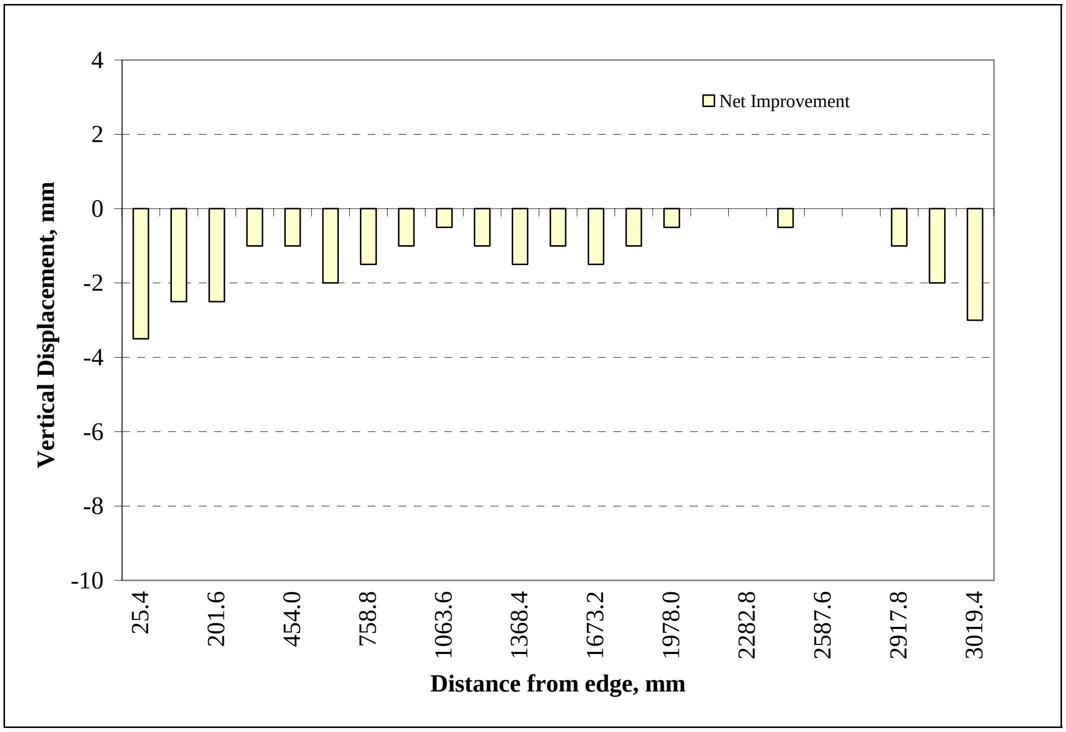


Figure B11: FCAW_Stiff_2 -Net Improvement at Location A.

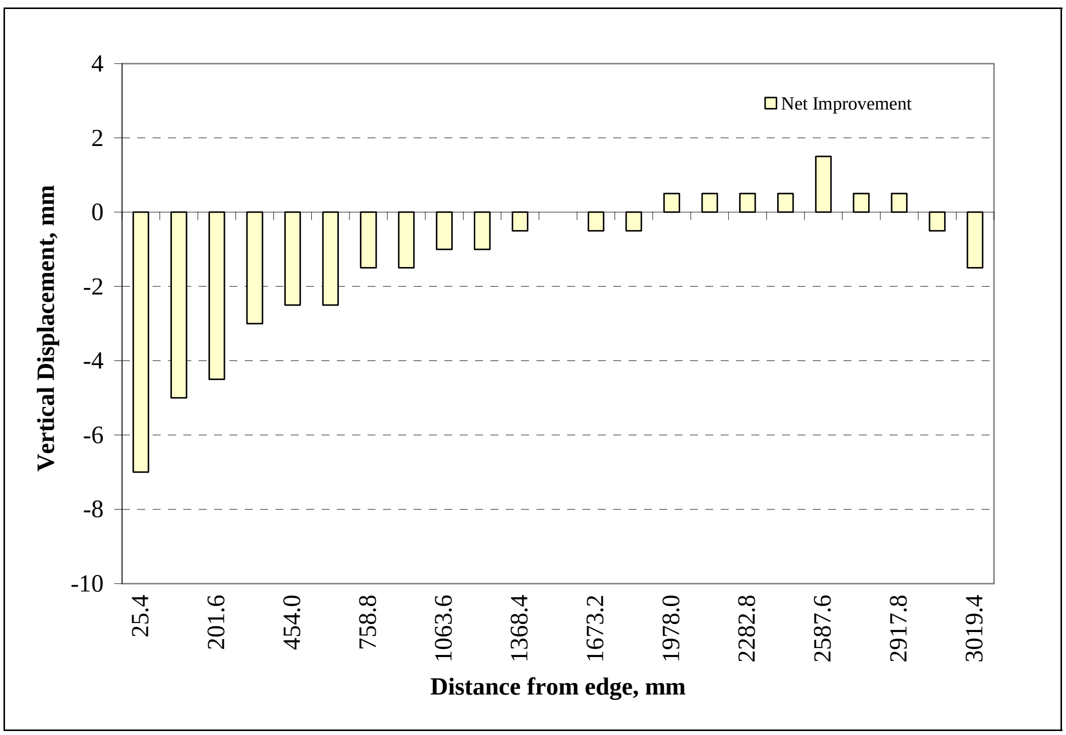


Figure B12: FCAW_Stiff_2 -Net Improvement at Location B.

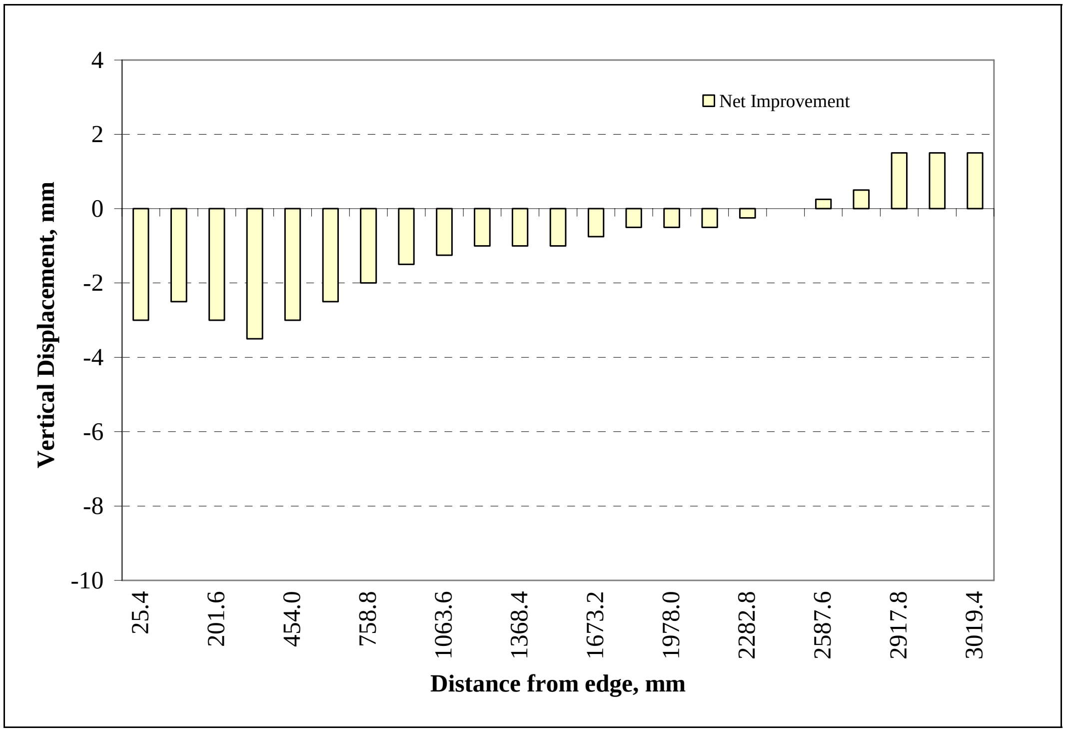


Figure B13: FCAW_Stiff_2 -Net Improvement at Location T.

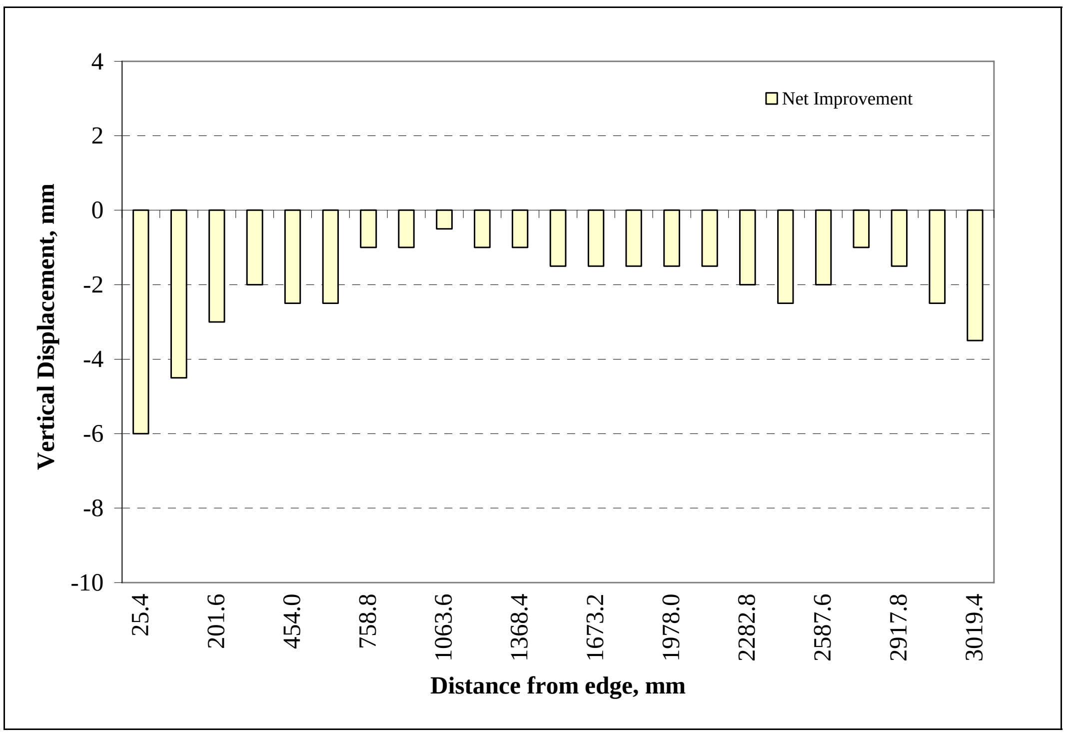


Figure B14: FCAW_Stiff_3 -Net Improvement at Location A.

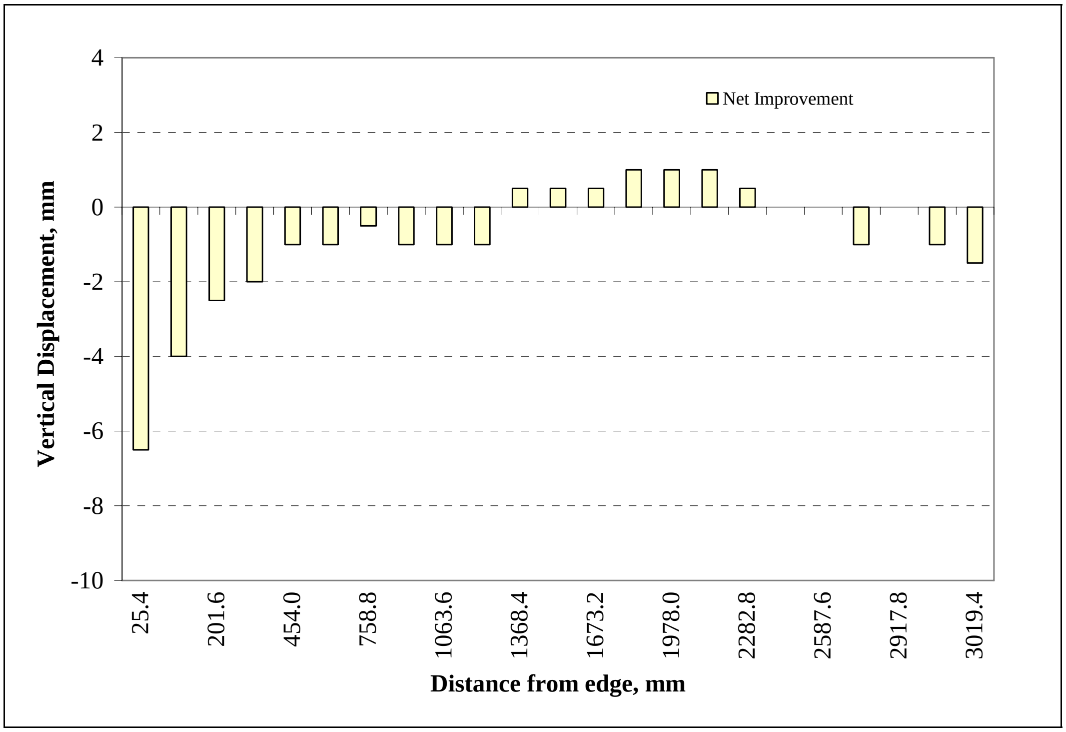


Figure B15: FCAW_Stiff_3 -Net Improvement at Location B.

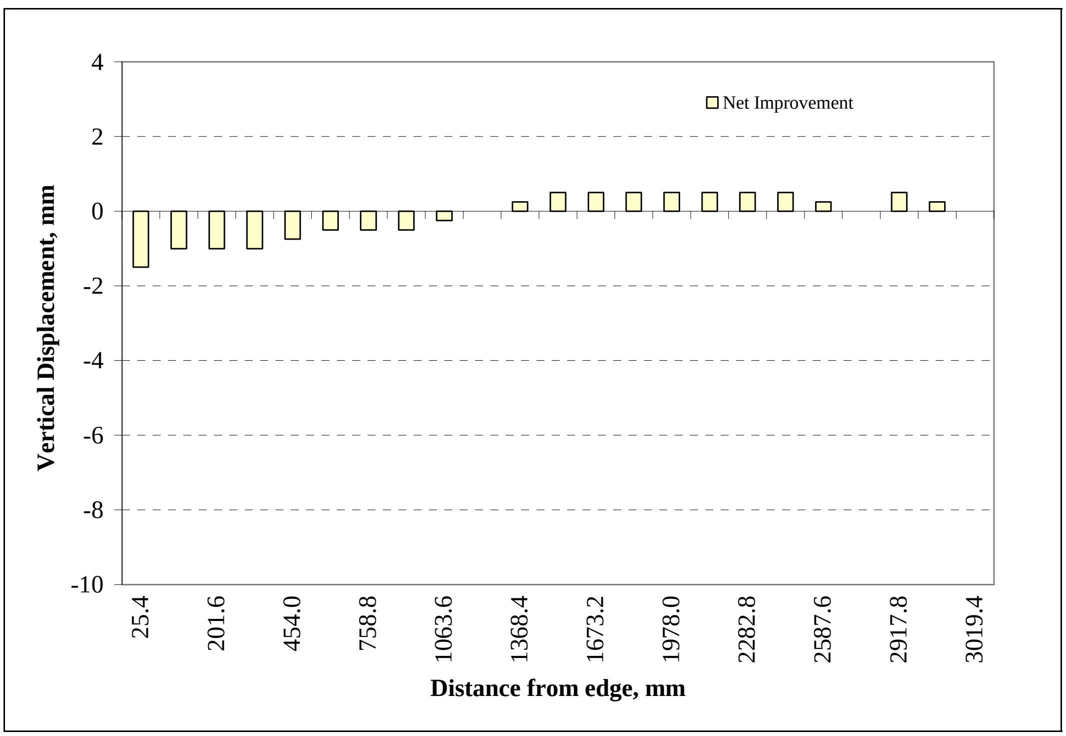


Figure B16: FCAW_Stiff_3 -Net Improvement at Location T.

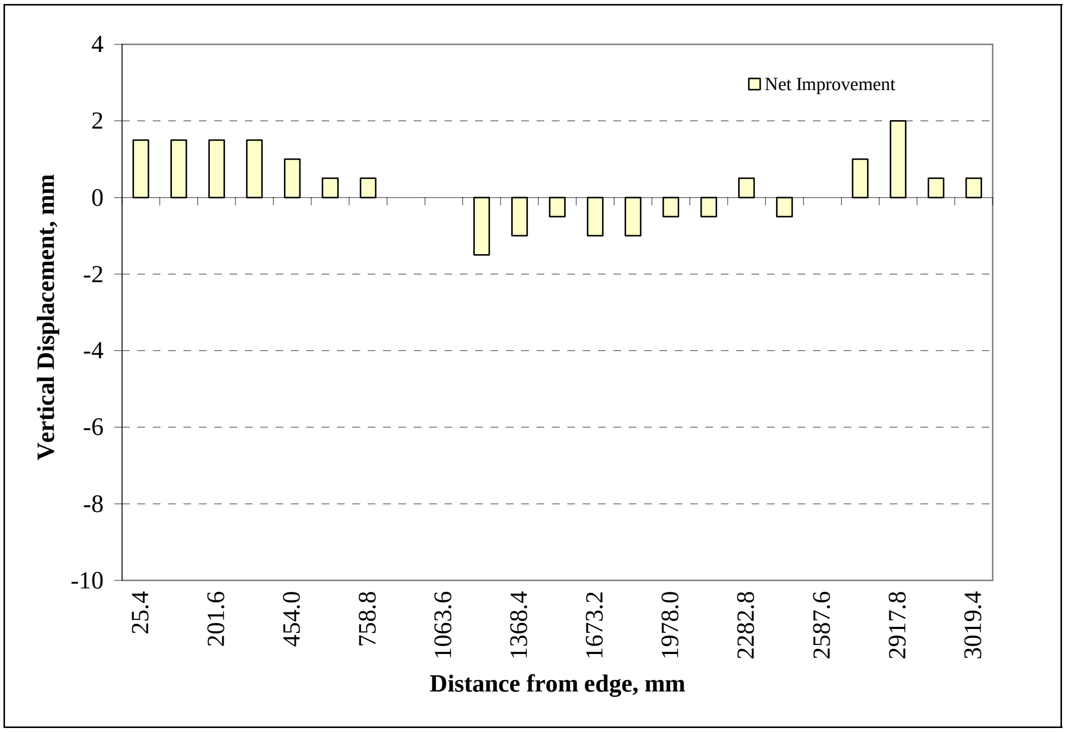


Figure B17: FCAW_Stiff_4 -Net Improvement at Location A.

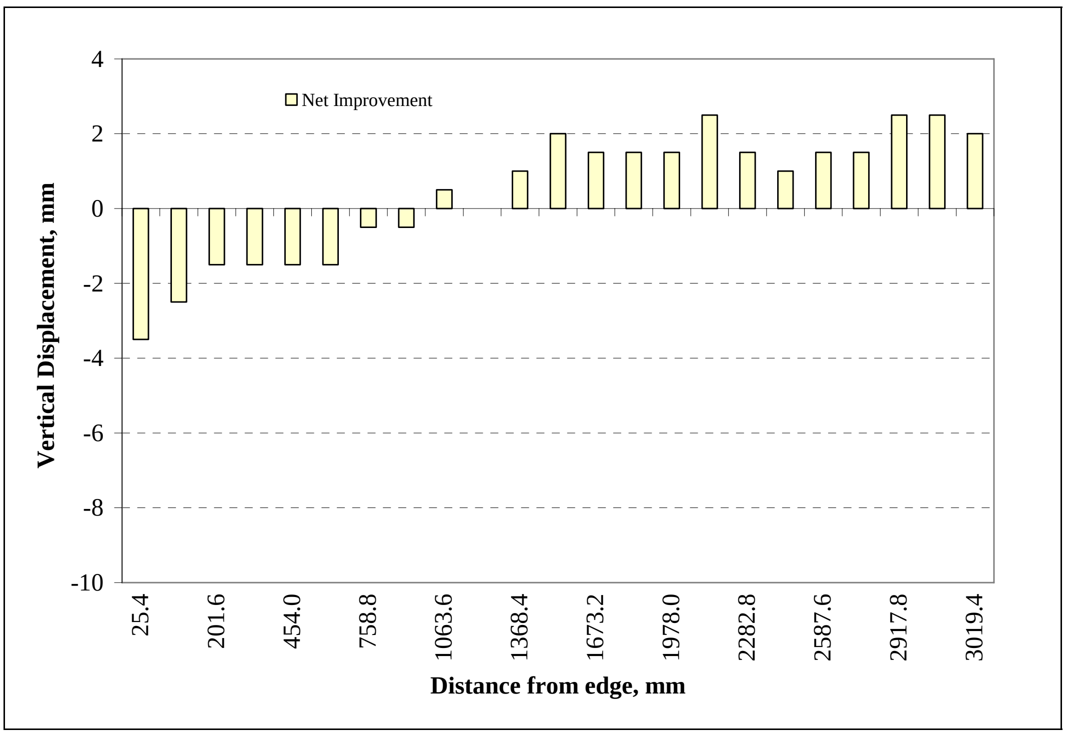


Figure B18: FCAW_Stiff_4 -Net Improvement at Location B.

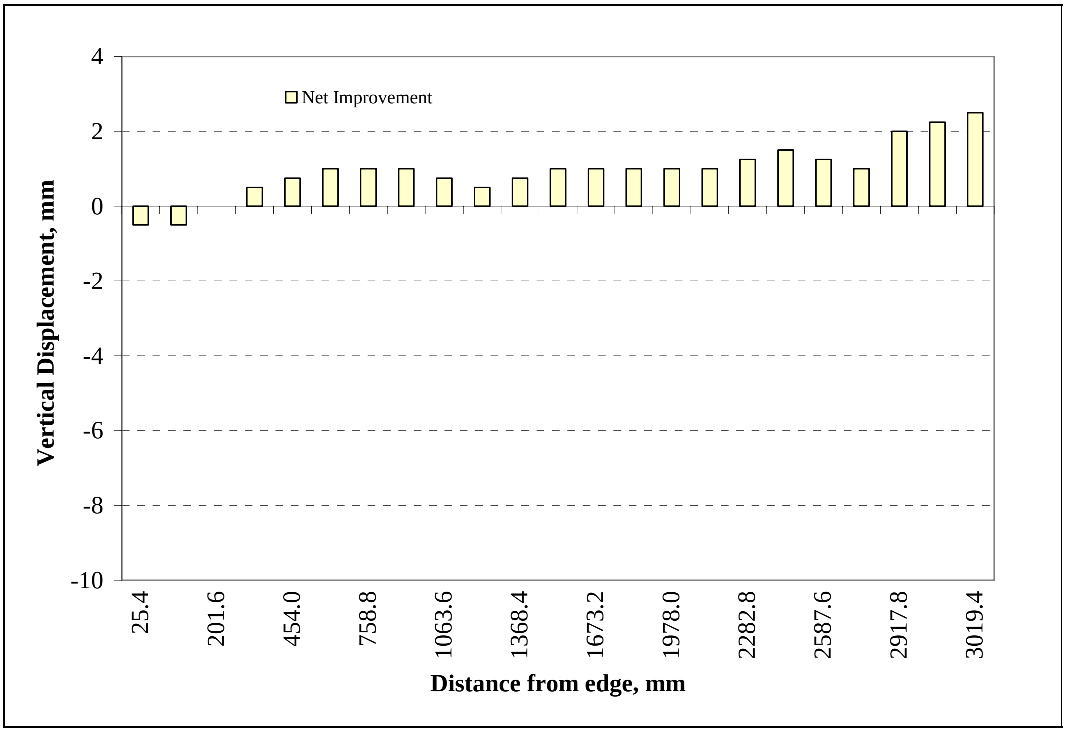


Figure B19: FCAW_Stiff_4 -Net Improvement at Location T.

APPENDIX C

STT PROCESS RECOMMENDATIONS

STT USER GUIDELINES

1. Always refer to approved welding procedure data sheet when setting up the STT process for critical applications such as the welding of stiffener plates to panels. Welding procedure data sheets shall be approved specifically for the Lincoln STT equipment being used as software and synergic control settings may not be the same for different STT equipment.
2. Limit material thickness of any member welded with the STT process to 5mm. The range of material thickness using WPDS's herein shall be limited between 3mm and 5mm.
3. Maintain a short contact tip to work (CTTW) distance similar to GMAW short arc. A 10mm (3/8") CTTW distance is suitable. Set contact tip to be only slightly recessed in the gas nozzle to achieve the desired CTTW distance.
4. An air cooled gun is adequate for welding with STT because of the low welding current.
5. A travel angle between 0 degrees and 15 degrees push is recommended for achieving desired weld bead profile when making fillet welds.

BMT Fleet Technology — **WELDING PROCEDURE DATA SHEET**

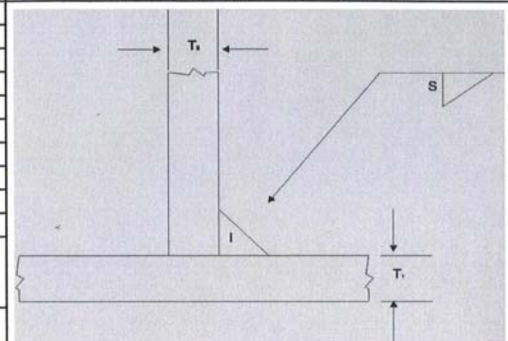
WPDS NO.: STT-035-C02-2F
DATE: 12/19/2007 Rev.:

Company Name:	BMT Fleet Technology	Ref. Standards:	
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8	Ref. WPS:	

Welding Processes:	1	GMAW-STT	Pulsed: ☐ Yes ☑ No
Shielding Gas Type:		100% CO2	
	2		Pulsed: ☐ Yes ☐ No

Positions:	Horizontal (2F)
Process Mode:	☐ Manual ☑ Semi-Auto ☑ Machine ☐ Auto
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet
Backing:	Material: N/A Thickness: N/A
Backgouging:	☐ Yes Method: N/A
	☐ No Depth: N/A
Electrode Extension:	contact tip to work distance = 3/8"
Nozzle Diameter(s):	1/2" to 5/8"
Flux Classification:	N/A
Tungsten Electrode:	Type: N/A Dia.: N/A
Cleaning Procedures	Wiire wheel
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	HSLA 80	3mm to 5mm	
II	HSLA 80	3mm to 5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-STT	ESAB Spoolarc 95	ER100S-1		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Program number	Gas Flow Rate (CFH	Heat Input (kJ/in)
T	3.0	1	1	STT	.035	210	115	16	DCEP	13	131	30	8.5
T	4.8	1	1	STT	.035	210	115	16	DCEP	10	131	30	11.0

Heat treatment :

Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Power Source: Lincoln Powerwave 455
Arc Control: 8.0, Trim: 1.0
Run-in: 100ipm, burnback: 0.03sec, preflow: 0.5sec
Work angle: 40 degrees, Travel angle: 0 degrees

5mm plate is the limitation of this process. Use of STT transfer on plate above 5mm in thickness may result in lack of fusion or lack of penetration. Contact tip to work distance of 3/8" must be maintained to achieve acceptable weld profile and penetration profile.

Acceptance

Company Authorization

Date:

Figure C1: Procedure for STT 0.035" diameter wire with C02 Shielding Gas

BMT Fleet Technology

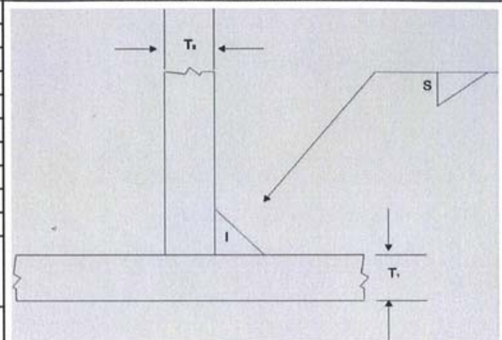
WELDING PROCEDURE DATA SHEET

WPDS NO.: STT-035-C25-2F
DATE: 12/19/2007 Rev.:

Company Name: BMT Fleet Technology
Address: 311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:
Ref. WPS:

Welding Processes:	1 GMAW-STT Pulsed: ☐ Yes ☑ No	2 Pulsed: ☐ Yes ☐ No
Shielding Gas Type:	75 Ar / 25 CO2	
Positions:	Horizontal (2F)	
Process Mode:	☐ Manual ☑ Semi-Auto ☑ Machine ☐ Auto	
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge	
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet	
Backing:	Material: N/A Thickness: N/A	
Backgouging:	☐ Yes Method: N/A; ☐ No Depth: N/A	
Electrode Extension:	contact tip to work distance = 3/8"	
Nozzle Diameter(s):	1/2" to 5/8"	
Flux Classification:	N/A	
Tungsten Electrode:	Type: N/A Dia.: N/A	
Cleaning Procedures	Wiire wheel	
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only	

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	HSLA 80	3mm to 5mm	
II	HSLA 80	3mm to 5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-STT	ESAB Spoolarc 95	ER100S-1		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Program number	Gas Flow Rate (CFH	Heat Input (kJ/in)
T	3.0	1	1	STT	.035	210	118	16	DCEP	11	127	30	10.3
T	4.8	1	1	STT	.035	210	118	16	DCEP	8	127	30	14.2

Heat treatment :

Preheat min: Ambient | Interpasstemp.max.: N/A | Interpasstemp.min.: N/A

Power Source: Lincoln Powerwave 455
Arc Control: 9.5, Trim: 1.5
Run-in: 100ipm, burnback: 0.03sec, preflow: 0.5sec
Work angle: 40 degrees, Travel angle: 0 degrees

5mm plate is the limitation of this process. Use of STT transfer on plate above 5mm in thickness may result in lack of fusion or lack of penetration. Contact tip to work distance of 3/8" must be maintained to achieve acceptable weld profile and penetration profile.

Acceptance

Company Authorization

Date:

Figure C2: Procedure for STT 0.035" diameter wire with C25 Shielding Gas

BMT Fleet Technology

WELDING PROCEDURE DATA SHEET

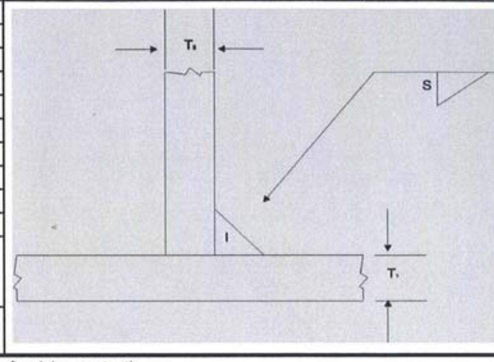
WPDS NO.: STT-045-C02-2F
DATE: 12/19/2007 Rev.:

Company Name:	BMT Fleet Technology	Ref. Standards:
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8	Ref. WPS:

Welding Processes:	1	GMAW-STT	Pulsed: ☐ Yes ☑ No
Shielding Gas Type:		100% CO2	
	2		Pulsed: ☐ Yes ☐ No

Positions:	Horizontal (2F)
Process Mode:	☐ Manual ☑ Semi-Auto ☑ Machine ☐ Auto
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet
Backing:	Material: N/A Thickness: N/A
Backgouging:	☐ Yes Method: N/A
	☐ No Depth: N/A
Electrode Extension:	contact tip to work distance = 3/8"
Nozzle Diameter(s):	1/2" to 5/8"
Flux Classification:	N/A
Tungsten Electrode:	Type: N/A Dia.: N/A
Cleaning Procedures	Wiire wheel
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	HSLA 80	3mm to 5mm	
II	HSLA 80	3mm to 5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-STT	ESAB Spoolarc 95	ER100S-1		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Program number	Gas Flow Rate (CFH)	Heat Input (kJ/in)
T	3.0	1	1	STT	.045	125	135	16	DCEP	14	117	30	9.3
T	4.8	1	1	STT	.045	125	135	16	DCEP	11	117	30	11.8

Heat treatment :

Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Power Source: Lincoln Powerwave 455
Arc Control: 7.5, Trim: 1.4
Run-in: 60ipm, burnback: 0.03sec, preflow: 0.5sec
Work angle: 40 degrees, Travel angle: 0 degrees

5mm plate is the limitation of this process. Use of STT transfer on plate above 5mm in thickness may result in lack of fusion or lack of penetration. Contact tip to work distance of 3/8" must be maintained to achieve acceptable weld profile and penetration profile.

Acceptance

Company Authorization

Date:

Figure C3: Procedure for STT 0.045" diameter wire with C02 Shielding Gas

BMT Fleet Technology

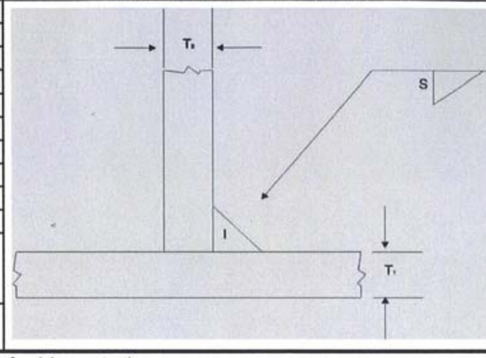
WELDING PROCEDURE DATA SHEET

WPDS NO.: STT-045-C25-2F
DATE: 12/19/2007 Rev.:

Company Name:	BMT Fleet Technology	Ref. Standards:	
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8	Ref. WPS:	

Welding Processes:	1	GMAW-STT	Pulsed: ☐ Yes ☑ No
Shielding Gas Type:		75Ar / 25CO2	
Welding Processes:	2		Pulsed: ☐ Yes ☐ No
Positions:	Horizontal (2F)		
Process Mode:	☐ Manual ☑ Semi-Auto ☑ Machine ☐ Auto		
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge		
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet		
Backing:	Material: N/A	Thickness: N/A	
Backgouging:	☐ Yes Method: N/A		
	☐ No Depth: N/A		
Electrode Extension:	contact tip to work distance = 3/8"		
Nozzle Diameter(s):	1/2" to 5/8"		
Flux Classification:	N/A		
Tungsten Electrode:	Type: N/A	Dia.: N/A	
Cleaning Procedures	Wiire wheel		
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only		

Joint Configuration & Pass/Layer Sequence



Identification of Base Material (for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	HSLA 80	3mm to 5mm	
II	HSLA 80	3mm to 5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-STT	ESAB Spoolarc 95	ER100S-1		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (in.)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Program number	Gas Flow Rate (CFH)	Heat Input (kJ/in)
T	3.0	1	1	STT	.045	125	135	16	DCEP	14	118	30	9.3
T	4.8	1	1	STT	.045	150	150	16	DCEP	14	118	30	10.3

Heat treatment :		**Acceptance**	**Company Authorization**
Preheat min: Ambient	Interpasstemp.max.: N/A		
	Interpasstemp.min.: N/A		Date:

Power Source: Lincoln Powerwave 455
Arc Control: 7.5, Trim: 1.4
Run-in: 60ipm, burnback: 0.03sec, preflow: 0.5sec
Work angle: 40 degrees, Travel angle: 0 degrees

5mm plate is the limitation of this process. Use of STT transfer on plate above 5mm in thickness may result in lack of fusion or lack of penetration. Contact tip to work distance of 3/8" must be maintained to achieve acceptable weld profile and penetration profile.

Figure C4: Procedure for STT 0.045” diameter wire with C25 Shielding Gas

APPENDIX D

WELDING PROCEDURE DATA SHEETS

BMT Fleet Technology

WELDING PROCEDURE DATA SHEET

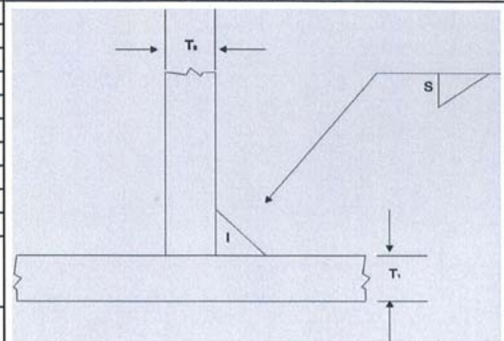
WPDS NO.: CV-Argon-2F
DATE: 02/04/2008 Rev.:

Company Name: BMT Fleet Technology
Address: 311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:
Ref. WPS:

Welding Processes:	1	GMAW	Pulsed: ☐ Yes ☑ No
Shielding Gas Type:		100% Argon	
Welding Processes:	2		Pulsed: ☐ Yes ☐ No

Positions:	Horizontal (2F)
Process Mode:	☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet
Backing:	Material: N/A Thickness: N/A
Backgouging:	☐ Yes Method: N/A; ☐ No Depth: N/A
Electrode Extension:	contact tip to work distance = 3/4"
Nozzle Diameter(s):	Tandem Torch Noxxle
Flux Classification:	N/A
Tungsten Electrode:	Type: N/A Dia.: N/A
Cleaning Procedures	Stainless wire wheel, stainless sanding disk, stainless wire brush as required
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	5086 H116	5mm	
II	5086 H116	5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW	OK Autrod 5356	ER5356		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (mm)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Data Set	Gas Flow Rate (CFH)	Heat Input (kJ/in)
T	5	1	1	GMAW	1.2	600	259	19.8	DCEP	50	5	45	6.2

Heat treatment :

Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Power Source: ESAB Aristomig 450
Drive Unit: Mech/Mek
Pendant: ESAB U8
Work Angle: 40°, Travel Angle: 0°
Program Info: Mig/Mag, Dip/Spray, Al/Mg, Ar, 1.2mm

Acceptance

Company Authorization

Date:

Figure C1: Procedure for Conventional CV Process

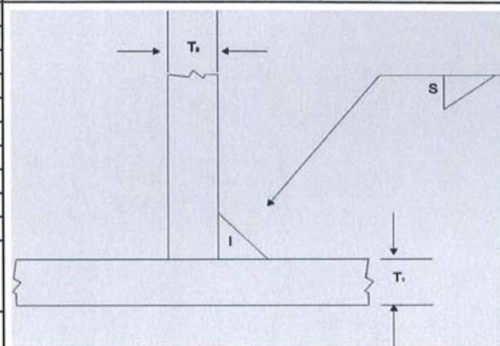
BMT Fleet Technology — **WELDING PROCEDURE DATA SHEET**

WPDS NO.: Pulse-Argon-2F
DATE: 02/04/2008 Rev.:

Company Name: BMT Fleet Technology
Address: 311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:
Ref. WPS:

Welding Processes:	1	GMAW — Pulsed: ☑ Yes ☐ No
Shielding Gas Type:		100% Argon
Welding Processes:	2	Pulsed: ☐ Yes ☐ No
Positions:	Horizontal (2F)	
Process Mode:	☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto	
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge	
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet	
Backing:	Material: N/A	Thickness: N/A
Backgouging:	☐ Yes Method: N/A	
	☐ No Depth: N/A	
Electrode Extension:	contact tip to work distance = 3/4"	
Nozzle Diameter(s):	Tandem Torch Noxxle	
Flux Classification:	N/A	
Tungsten Electrode:	Type: N/A	Dia.: N/A
Cleaning Procedures	Stainless wire wheel, stainless sanding disk, stainless wire brush as required	
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only	

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	5086 H116	5mm	
II	5086 H116	5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-P	OK Autrod 5356	ER5356		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (mm)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Data Set	Gas Flow Rate (CFH	Heat Input (kJ/in)
T	5	1	1	GMAW-P	1.2	610	250	22.0	DCEP	46	6	45	7.2

Heat treatment :

Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Power Source: ESAB Aristomig 450
Drive Unit: Mech/Mek
Pendant: ESAB U8
Work Angle: 40°, Travel Angle: 0°
Program Info: Mig/Mag, Pulse, Al/Mg, Ar, 1.2mm

Acceptance

Company Authorization

Date:

Figure C2: Procedure for Standard Pulse

BMT Fleet Technology

WELDING PROCEDURE DATA SHEET

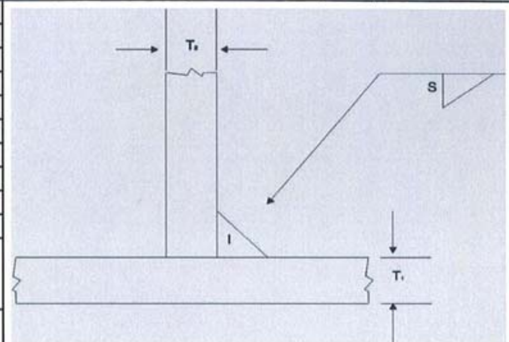
WPDS NO.: Pulse/Pulse-Argon-2F
DATE: 02/04/2008 Rev.:

Company Name: BMT Fleet Technology
Address: 311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:
Ref. WPS:

Welding Processes:	1	GMAW	Pulsed: ☑ Yes ☐ No
Shielding Gas Type:		100% Argon	
	2		Pulsed: ☐ Yes ☐ No

Positions:	Horizontal (2F)
Process Mode:	☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto
Joint Type:	☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge
Penetration:	☐ Complete ☐ Partial ETT= ☑ Fillet
Backing:	Material: N/A Thickness: N/A
Backgouging:	☐ Yes Method: N/A ☐ No Depth: N/A
Electrode Extension:	contact tip to work distance = 3/4"
Nozzle Diameter(s):	Tandem Torch Noxxle
Flux Classification:	N/A
Tungsten Electrode:	Type: N/A Dia.: N/A
Cleaning Procedures	Stainless wire wheel, stainless sanding disk, stainless wire brush as required
CSA W186 Rebar Splice Type:	☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	5086 H116	5mm	
II	5086 H116	5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-P	OK Autrod 5356	ER5356		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (mm)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Data Set	Gas Flow Rate (CFH)	Heat Input (kJ/in)
T	5	1	1	GMAW-P	1.2	504	199	24.3	DCEP	30	7, 8	45	9.1
Secondary Phase						343		23.8					

Heat treatment :

Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Acceptance

Company Authorization

Date:

Power Source: ESAB Aristomig 450
Drive Unit: Mech/Mek
Pendant: ESAB U8
Work Angle: 40°, Travel Angle: 0°
Program Info Primary Phase: Pulse, Al/Mg, Ar, 1.2mm
Program Info Secondary Phase: Pulse, Al/Mg, Ar, 1.2mm

Figure C3: Procedure for Superpulse, Pulse on Pulse

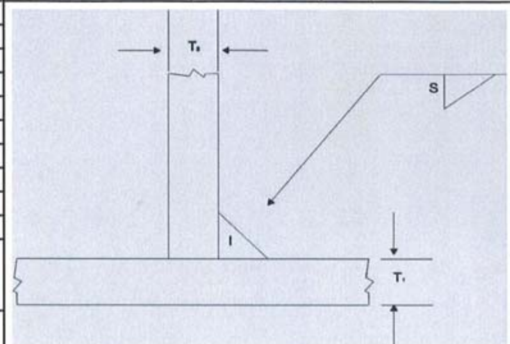
BMT Fleet Technology

WELDING PROCEDURE DATA SHEET

WPDS NO.:	Pulse/Spray-Argon-2F
DATE:	02/04/2008
Rev.:	
Company Name:	BMT Fleet Technology
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:	
Ref. WPS:	

Welding Processes:	1	GMAW — Pulsed: ☑ Yes ☐ No
Shielding Gas Type:		100% Argon
	2	Pulsed: ☐ Yes ☐ No
Positions:		Horizontal (2F)
Process Mode:		☐ Manual ☐ Semi-Auto ☑ Machine ☐ Auto
Joint Type:		☐ Butt ☑ Tee ☑ Corner ☑ Lap ☐ Edge
Penetration:		☐ Complete ☐ Partial ETT= ☑ Fillet
Backing:		Material: N/A Thickness: N/A
Backgouging:		☐ Yes Method: N/A; ☐ No Depth: N/A
Electrode Extension:		contact tip to work distance = 3/4"
Nozzle Diameter(s):		Tandem Torch Noxxle
Flux Classification:		N/A
Tungsten Electrode:		Type: N/A Dia.: N/A
Cleaning Procedures		Stainless wire wheel, stainless sanding disk, stainless wire brush as required
CSA W186 Rebar Splice Type:		☐ Direct Splice ☐ Indirect Splice ☐ Lap Splice ☐ Rebar to Structural Member Only

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	5086 H116	5mm	
II	5086 H116	5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-P	OK Autrod 5356	ER5356		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (mm)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Data Set	Gas Flow Rate (CFH)	Heat Input (kJ/in)
T	5	1	1	GMAW-P	1.2	472	215	24.3	DCEP	35	9,10	45	7.9
Secondary Phase						453		20.0					

Heat treatment :			
Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Acceptance

Company Authorization

Power Source: ESAB Aristomig 450
Drive Unit: Mech/Mek
Pendant: ESAB U8
Work Angle: 40°, Travel Angle: 0°
Program Info Primary Phase: Pulse, Al/Mg, Ar, 1.2mm
Program Info Secondary Phase: Dip/Spray, Al/Mg, Ar, 1.2mm

Date:

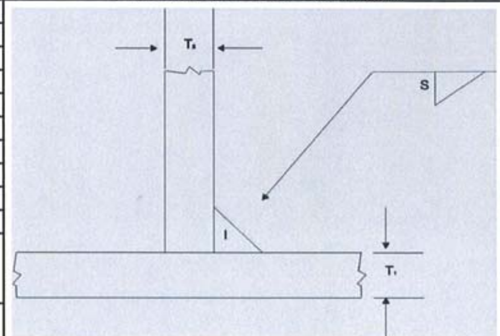
Figure C4: Procedure for Superpulse, Pulse on Spray

BMT Fleet Technology — **WELDING PROCEDURE DATA SHEET**

WPDS NO.:	Pulse/Short-Argon-2F
DATE:	02/04/2008
Rev.:	
Company Name:	BMT Fleet Technology
Address:	311 Legget Drive Kanata, Ontario K2K 1Z8
Ref. Standards:	
Ref. WPS:	

Welding Processes:	1	GMAW	Pulsed: ☑ Yes ☐ No	2 — Pulsed: ☐ Yes ☐ No
Shielding Gas Type:		100% Argon		
Positions:	Horizontal (2F)			
Process Mode:	☐ Manual	☐ Semi-Auto	☑ Machine	☐ Auto
Joint Type:	☐ Butt ☑ Tee	☑ Corner	☑ Lap	☐ Edge
Penetration:	☐ Complete	☐ Partial	ETT=	☑ Fillet
Backing:	Material: N/A		Thickness: N/A	
Backgouging:	☐ Yes	Method: N/A		
	☐ No	Depth: N/A		
Electrode Extension:	contact tip to work distance = 3/4"			
Nozzle Diameter(s):	Tandem Torch Noxxle			
Flux Classification:	N/A			
Tungsten Electrode:	Type: N/A		Dia.: N/A	
Cleaning Procedures	Stainless wire wheel, stainless sanding disk, stainless wire brush as required			
CSA W186 Rebar Splice Type:	☐ Direct Splice	☐ Indirect Splice	☐ Lap Splice	
	☐ Rebar to Structural Member Only			

Joint Configuration & Pass/Layer Sequence



Identification of Base Material(for CSA W186 indicate carbon equivalent, max. phosphorus & sulphur content)

Part	Specification & Grade	Thickness or Dia.	Special Requirements
I	5086 H116	5mm	
II	5086 H116	5mm	

Identification of Filler Material

Process	Trade Name	Classification	Group	Filler Treatment
GMAW-P	OK Autrod 5356	ER5356		

Welding Parameters

Thick-ness (mm)	Weld Size/ ETT	Layer	Pass Number	Welding Process	Dia. (mm)	Wire Feed Speed (IPM)	Current A	Volt V	Current Polarity	Welding Speed (IPM)	Data Set	Gas Flow Rate (CFH)	Heat Input (kJ/in)
T	5	1	1	GMAW-P	1.2	437	158	25.0	DCEP	25	9,10	45	7.3
	Secondary Phase					260		13.3					

Heat treatment :			
Preheat min:	Ambient	Interpasstemp.max.:	N/A
		Interpasstemp.min.:	N/A

Power Source: ESAB Aristomig 450
Drive Unit: Mech/Mek
Pendant: ESAB U8
Work Angle: 40°, Travel Angle: 0°
Program Info Primary Phase: Pulse, Al/Mg, Ar, 1.2mm
Program Info Secondary Phase: Dip/Spray, Al/Mg, Ar, 1.2mm

Acceptance	**Company Authorization**
	Date:

Figure C5: Procedure for Superpulse, Pulse on Short

APPENDIX E

DISTORTION COMPARISON BETWEEN FCAW and T-MCAW (10” WIDE BASE PLATES)

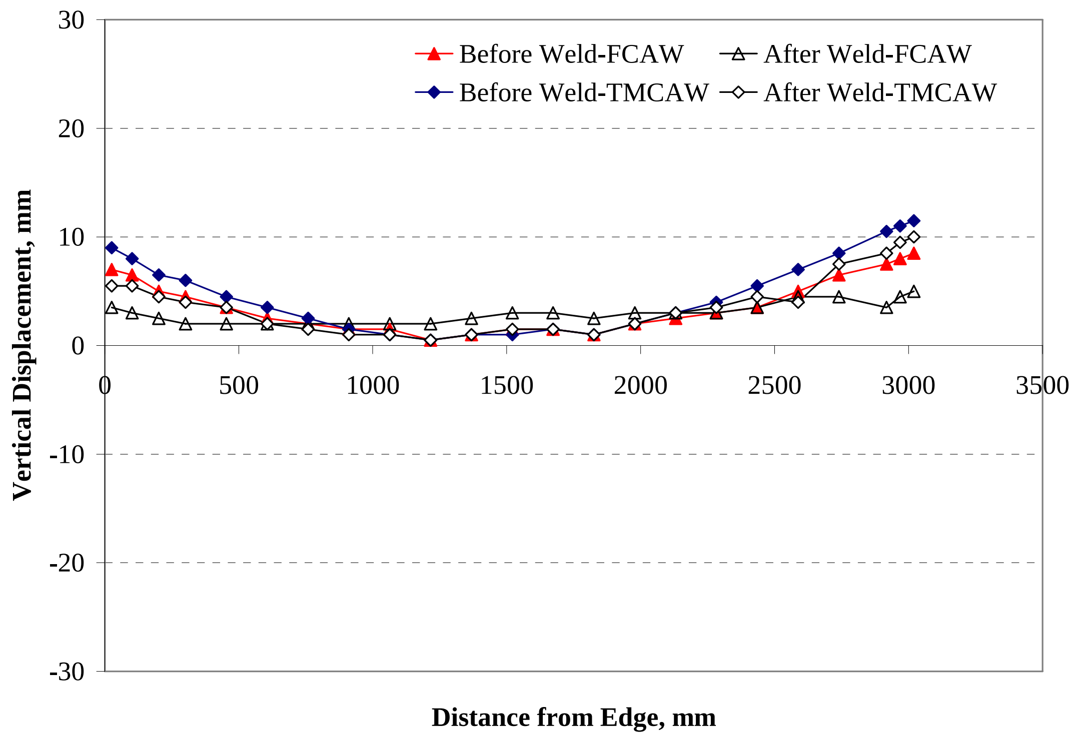


Figure E.1: Baseline Location A – Relative Displacement

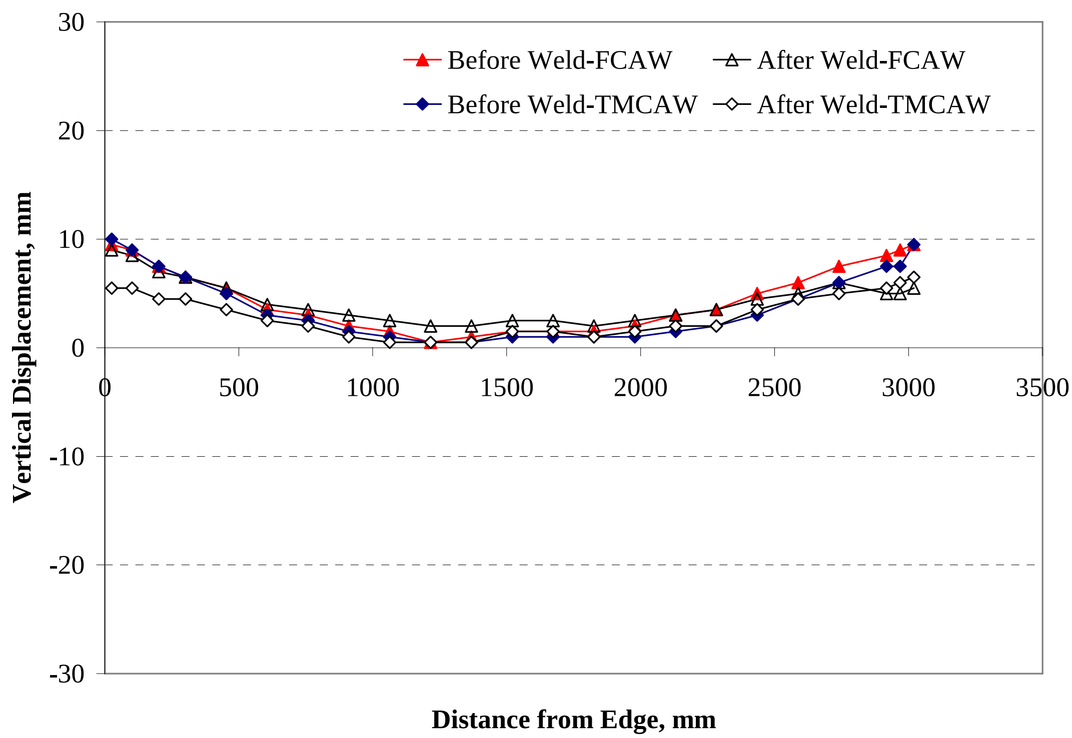


Figure E.2: Baseline Location B – Relative Displacement

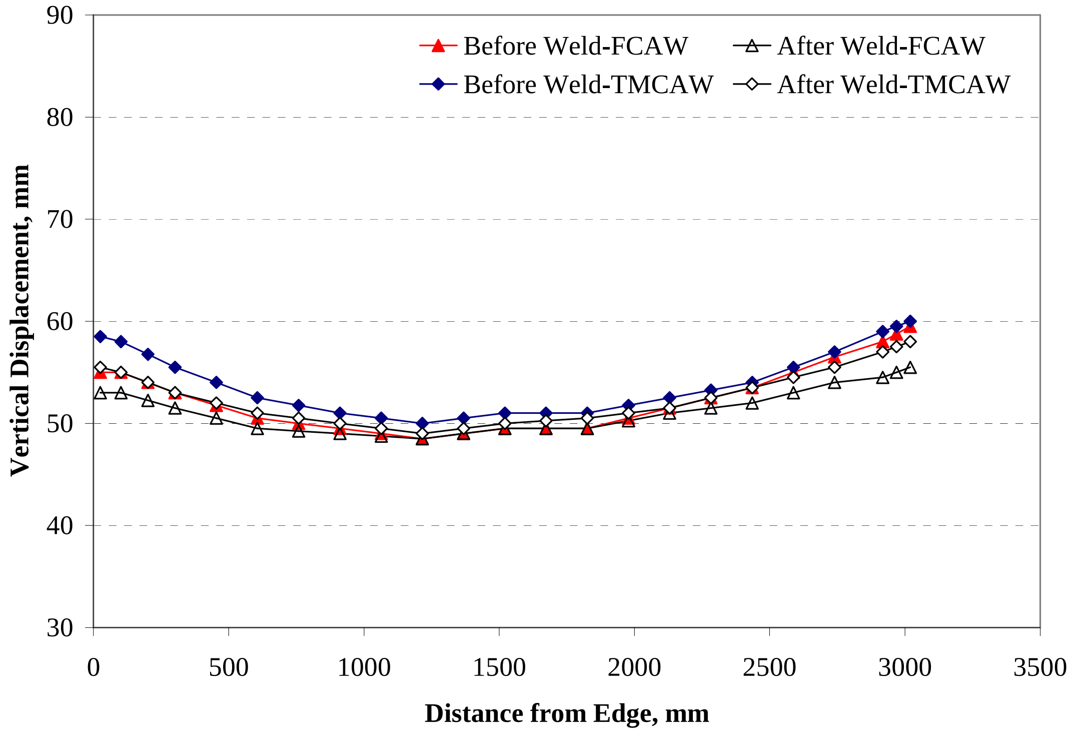


Figure E.3: Baseline At Stiffener – Relative Displacement

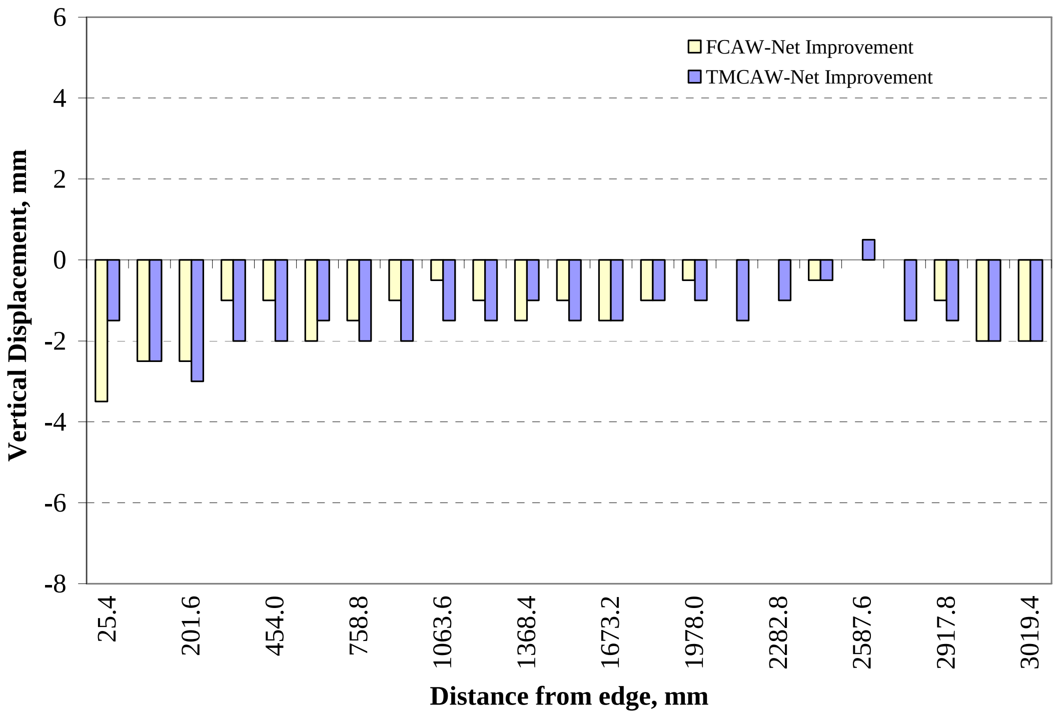


Figure FF.1: Plate 2 Location A – Net Improvement

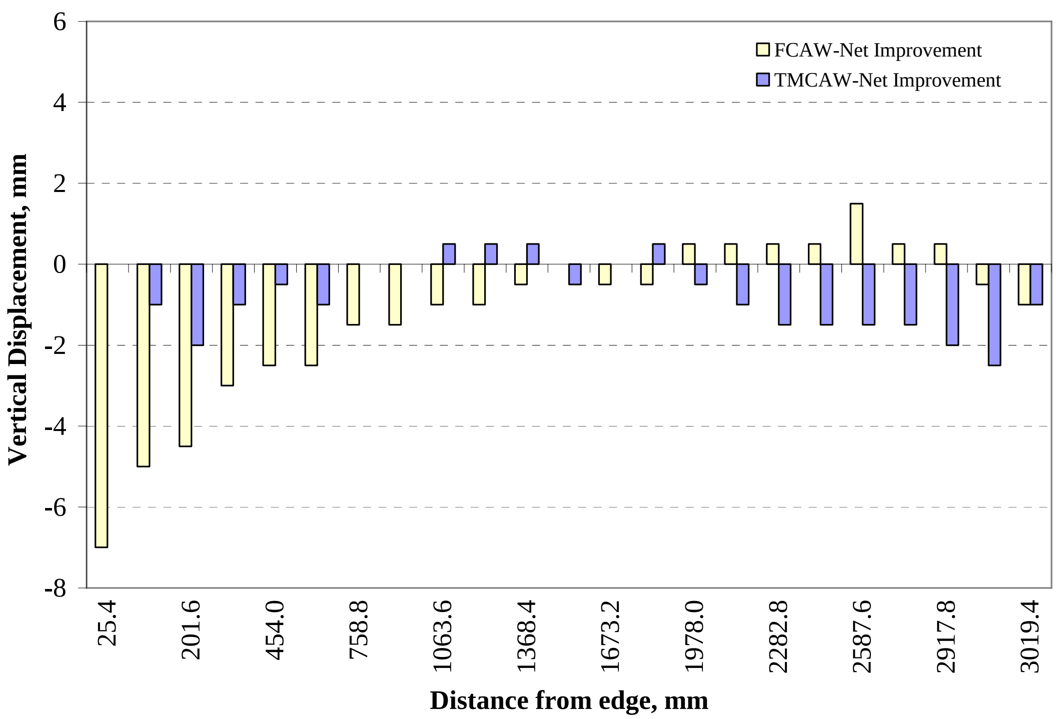


Figure F.2: Plate 2 Location B – Net Improvement

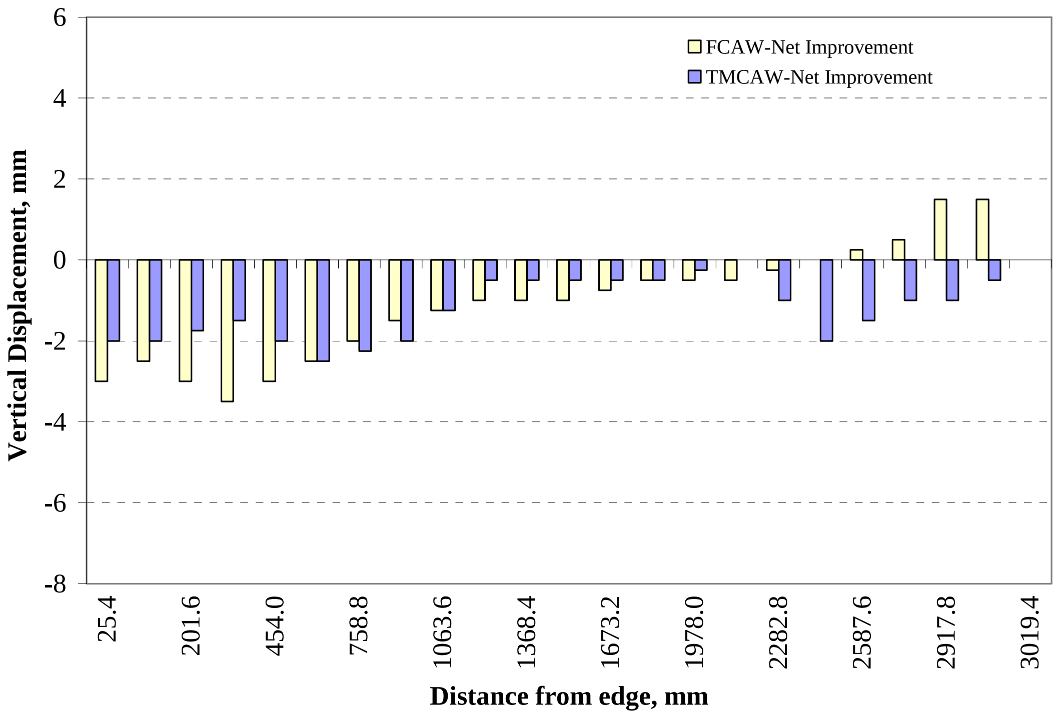


Figure F.3: Plate 2 At Stiffener – Net Improvement

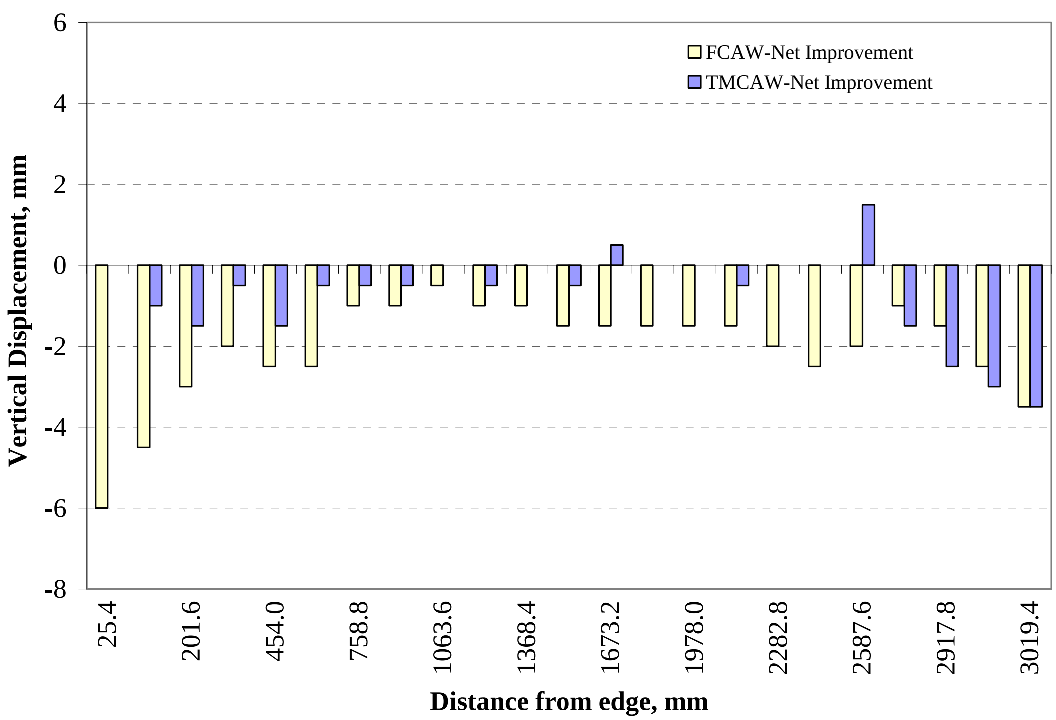


Figure F.4: Plate 3 Location A – Net Improvement

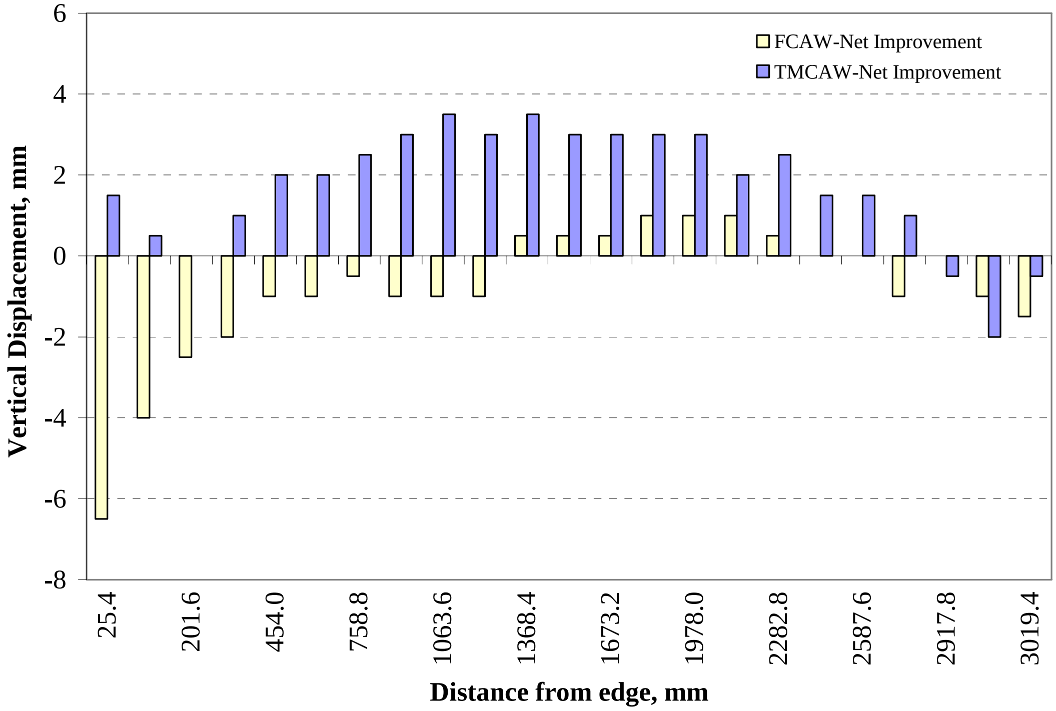


Figure F.5: Plate 3 Location B – Net Improvement

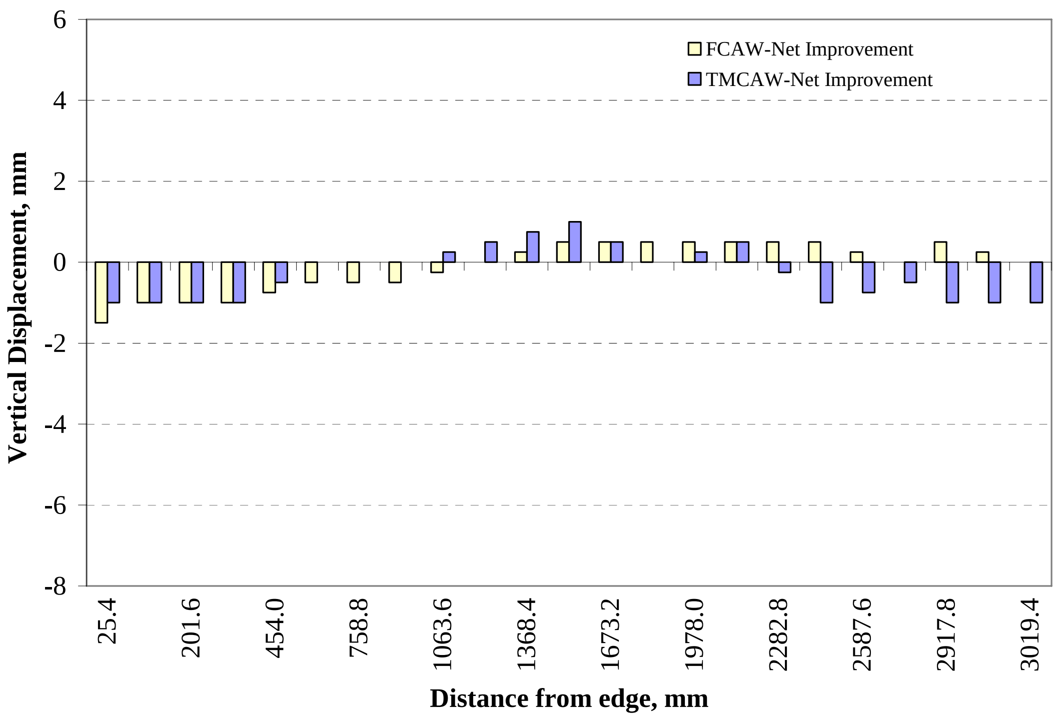


Figure F.6: Plate 3 At Stiffener – Net Improvement

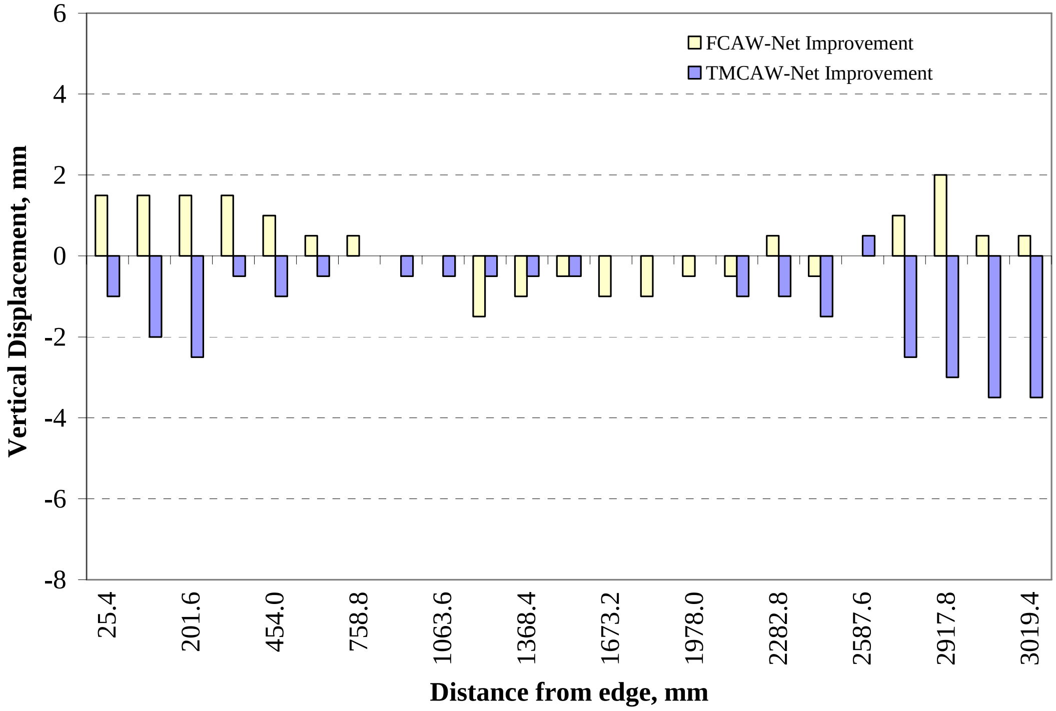


Figure F.7: Plate 4 Location A – Net Improvement

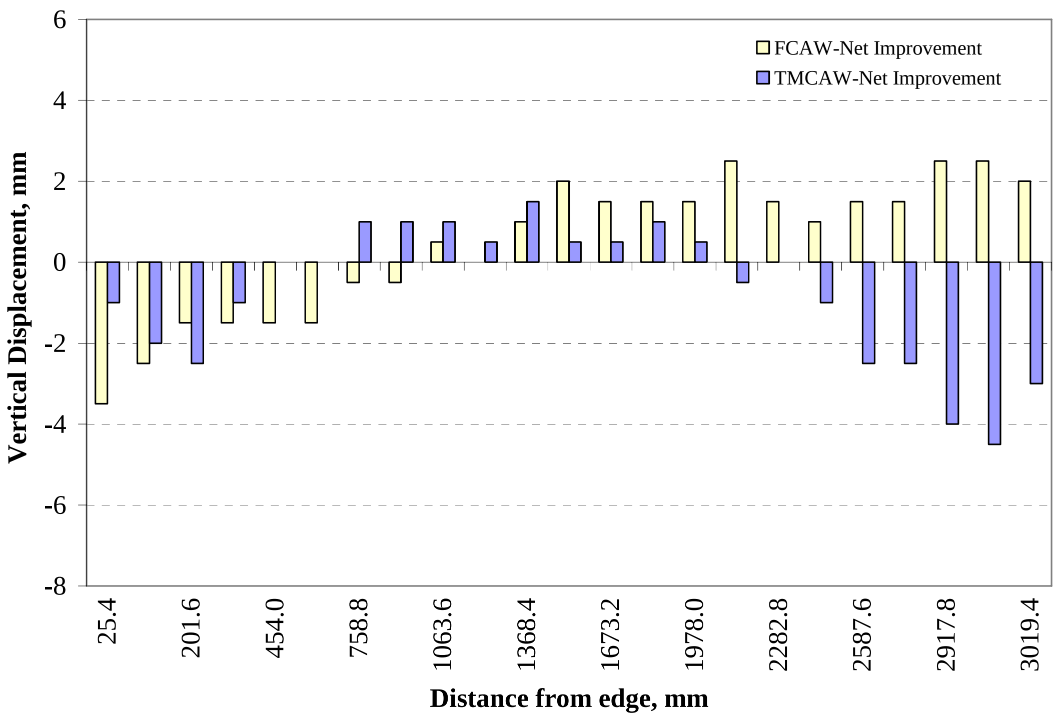


Figure F.8: Plate 4 Location B – Net Improvement

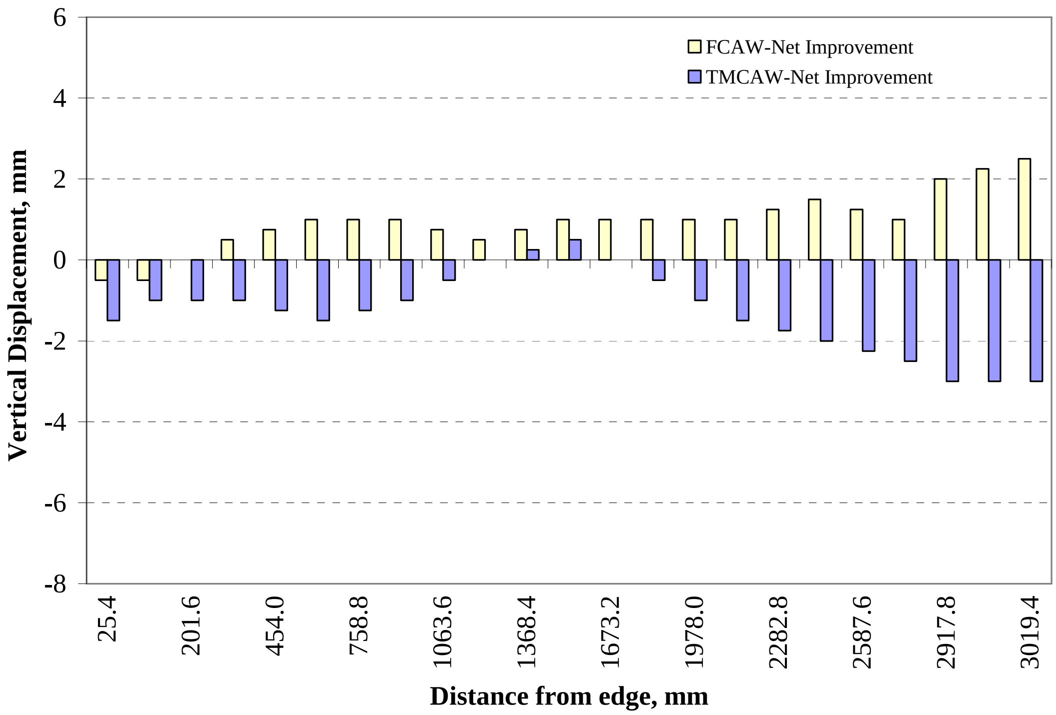


Figure F.9: Plate 4 At Stiffener – Net Improvement

APPENDIX F

DISTORTION PLOTS FOR FILLET WELDS
T-MCAW PROCESS (10" WIDE BASE PLATES)

Table F.1: T-MCAW_Stiff_1_Benchmark Distortion Data

Before Weld					After Weld				
Displacement w.r.t to Frame, mm					Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff		A	T	B	Abs Diff
1	9	58.5	10	1	1	5.5	55.5	5.5	0
2	8	58	9	1	2	5.5	55	5.5	0
3	6.5	56.75	7.5	1	3	4.5	54	4.5	0
4	6	55.5	6.5	0.5	4	4	53	4.5	0.5
5	4.5	54	5	0.5	5	3.5	52	3.5	0
6	3.5	52.5	3	0.5	6	2	51	2.5	0.5
7	2.5	51.75	2.5	0	7	1.5	50.5	2	0.5
8	1.5	51	1.5	0	8	1	50	1	0
9	1	50.5	1	0	9	1	49.5	0.5	0.5
10	0.5	50	0.5	0	10	0.5	49	0.5	0
11	1	50.5	0.5	0.5	11	1	49.5	0.5	0.5
12	1	51	1	0	12	1.5	50	1.5	0
13	1.5	51	1	0.5	13	1.5	50.25	1.5	0
14	1	51	1	0	14	1	50.5	1	0
15	2	51.75	1	1	15	2	51	1.5	0.5
16	3	52.5	1.5	1.5	16	3	51.5	2	1
17	4	53.25	2	2	17	3.5	52.5	2	1.5
18	5.5	54	3	2.5	18	4.5	53.5	3.5	1
19	7	55.5	4.5	2.5	19	4	54.5	4.5	0.5
20	8.5	57	6	2.5	20	7.5	55.5	5	2.5
21	10.5	59	7.5	3	21	8.5	57	5.5	3
22	11	59.5	7.5	3.5	22	9.5	57.5	6	3.5
23	11.5	60	9.5	2	23	10	58	6.5	3.5

Table F.2: T-MCAW_Stiff_2_92Ar/8C02 Distortion Data

Before Weld					Tension No Weld					After Weld				
Displacement w.r.t to Frame, mm					Displacement w.r.t to Frame, mm					Displacement w.r.t to Frame, mm				
	A	T	B	Abs Diff		A	T	B	Abs Diff		A	T	B	Abs Diff
1	11.5	60	11.5	0	1	6.5	55	6.5	0	1	6.5	55	7	0.5
2	11.5	59.5	11.5	0	2	6.5	54.5	6.5	0	2	6.5	54.5	7	0.5
3	10.5	58	11	0.5	3	5	53.5	5	0	3	5.5	53.5	6	0.5
4	10	56.5	10	0	4	5.5	52.5	5.5	0	4	6	52.5	7	1
5	8	55	8.5	0.5	5	4.5	51.5	4.5	0	5	5	51	6.5	1.5
6	6.5	53.5	6.5	0	6	3	50.5	3	0	6	3.5	49.5	5	1.5
7	5.5	52.5	4.5	1	7	2	49.5	2	0	7	2.5	49	4	1.5
8	4.5	51.5	4	0.5	8	1.5	48.5	1.5	0	8	2	48.5	3.5	1.5
9	3.5	50.25	3	0.5	9	1	47.75	1	0	9	2	48	3	1
10	3	49	2	1	10	0.5	47	0	0.5	10	1.5	47.5	2.5	1
11	3	49.5	2	1	11	1	47.25	0.5	0.5	11	2	48	2.5	0.5
12	3	50	2.5	0.5	12	1.5	47.5	1	0.5	12	2	48.5	2.5	0.5
13	3.5	49.75	2.5	1	13	1.5	47.5	1	0.5	13	2	48.5	3	1
14	3	49.5	2	1	14	1	47.5	0.5	0.5	14	2	48.5	2.5	0.5
15	3	50	2.5	0.5	15	1	47.75	0.5	0.5	15	2	49	2.5	0.5
16	4	50.5	3.5	0.5	16	1.5	48	1	0.5	16	2.5	49.5	3	0.5
17	4	51.25	4	0	17	1	48.25	0.5	0.5	17	2.5	49.5	2.5	0
18	4.5	52	4.5	0	18	1.5	48.5	1.5	0	18	3	49.5	3.5	0.5
19	5.5	52.75	5	0.5	19	2	49.25	1.5	0.5	19	3	50.25	3.5	0.5
20	6.5	53.5	6.5	0	20	3.5	50	2.5	1	20	4	51	4	0
21	7.5	55	8	0.5	21	3.5	51	2	1.5	21	4	52	4	0
22	7.5	55.25	8	0.5	22	3.5	51.75	2	1.5	22	4	52.75	4	0
23	7.5	55.5	8	0.5	23	3.5	52.5	2	1.5	23	4	53.5	4	0

Table F.3: T-MCAW_Stiff_3_85Ar/15C02 Distortion Data

	Before Weld				Tension No Weld				After Weld			
	Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff	A	T	B	Abs Diff	A	T	B	Abs Diff
1	9.5	52.5	10.5	1	5.5	49	6.5	1	6	48.5	7.5	1.5
2	9.5	52	10.5	1	5.5	48.5	6.5	1	6	48	7.5	1.5
3	8.5	50.75	9.5	1	4.5	47.5	5.5	1	5	47	6.5	1.5
4	8	49.5	8.5	0.5	5	46.5	5.5	0.5	5.5	46	7.5	2
5	6.5	47.75	7	0.5	4	45.25	5	1	4	45.25	7.5	3.5
6	5	46	5	0	2.5	44	3.5	1	3	44.5	6.5	3.5
7	4	45.25	4.5	0.5	1.5	43.5	2.5	1	2.5	44	6.5	4
8	2.5	44.5	3	0.5	1	43	1.5	0.5	1.5	43.5	5.5	4
9	2	43.75	2	0	1	42.5	1	0	2	43	5	3
10	1.5	43	1	0.5	0.5	42	0.5	0	1	42.5	4	3
11	1.5	43.5	1	0.5	1	42.5	1	0	1.5	43.25	4.5	3
12	2	44	1.5	0.5	1.5	43	1	0.5	2	44	5	3
13	2	44	2	0	1.5	43	1.5	0	2.5	43.75	5.5	3
14	2	44	2	0	1	43	1	0	2	43.5	5	3
15	2.5	44.75	2	0.5	1	43.25	1	0	2.5	44.25	5.5	3
16	3	45.5	3	0	1.5	43.5	1.5	0	2.5	45	5.5	3
17	3.5	46.5	3.5	0	1.5	44.25	2	0.5	3	45.5	6	3
18	5	47.5	5	0	2	45	3	1	4	46	7	3
19	6	49	6	0	3	46	4	1	4.5	47.25	7.5	3
20	7.5	50.5	7.5	0	4	47	5.5	1.5	5	48.5	7.5	2.5
21	9	52	9	0	3	48.5	5	2	4.5	49	6.5	2
22	9	52.75	9	0	3	49.25	5	2	4.5	49.75	5.5	1
23	9	53.5	9	0	3	50	5	2	4	50.5	5.5	1.5

Table F.4: T-MCAW_Stiff_4_75Ar/25C02 Distortion Data

	Before Weld				Tension No Weld				After Weld			
	Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm				Displacement w.r.t to Frame, mm			
	A	T	B	Abs Diff	A	T	B	Abs Diff	A	T	B	Abs Diff
1	9.5	68	10	0.5	6	65	4	2	5	63.5	4.5	0.5
2	9.5	67.5	10	0.5	6	64.5	4	2	5	63.5	4.5	0.5
3	8.5	66	9	0.5	5	63.25	3	2	4	62.25	3.5	0.5
4	7.5	64.5	8	0.5	6	62	4	2	5	61	5	0
5	6	62.75	6.5	0.5	5	60.5	3.5	1.5	4	59.5	5	1
6	4.5	61	4.5	0	3	59	2	1	2.5	58	4	1.5
7	3	60	3	0	2	58.25	1.5	0.5	2	57.5	3.5	1.5
8	2.5	59	2.5	0	1.5	57.5	1	0.5	1.5	57	3	1.5
9	2	58.25	2	0	1	57	1	0	1.5	56.75	2.5	1
10	1.5	57.5	1	0.5	0.5	56.5	0.5	0	1	56.5	1.5	0.5
11	2	58	1	1	1	57	0.5	0.5	1.5	57.25	2.5	1
12	2	58.5	1.5	0.5	1	57.5	1	0	2	58	2.5	0.5
13	2	58.5	1.5	0.5	1.5	57.5	1	0.5	2	57.75	2.5	0.5
14	2	58.5	1	1	1	57.5	1	0	2	57.5	2	0
15	2.5	59.25	1.5	1	1.5	58	1	0.5	2.5	57.5	2.5	0
16	4	60	3	1	2	58.5	1	1	3	57.5	3	0
17	4.5	61	3	1.5	2	58.75	1.5	0.5	3	58.5	3	0
18	6	62	4	2	2.5	59	2.5	0	3.5	59.5	3.5	0
19	7.5	63.75	6	1.5	3	60.25	3.5	0.5	5	60.5	3.5	1.5
20	9.5	65.5	7.5	2	4.5	61.5	5	0.5	6	61.5	4	2
21	11.5	68	9.5	2	4	63	5	1	6.5	63	3.5	3
22	11.5	68.5	9.5	2	4	63.75	5	1	6.5	63.5	3.5	3
23	11.5	69	9.5	2	4	64.5	5	1	6.5	64	3.5	3

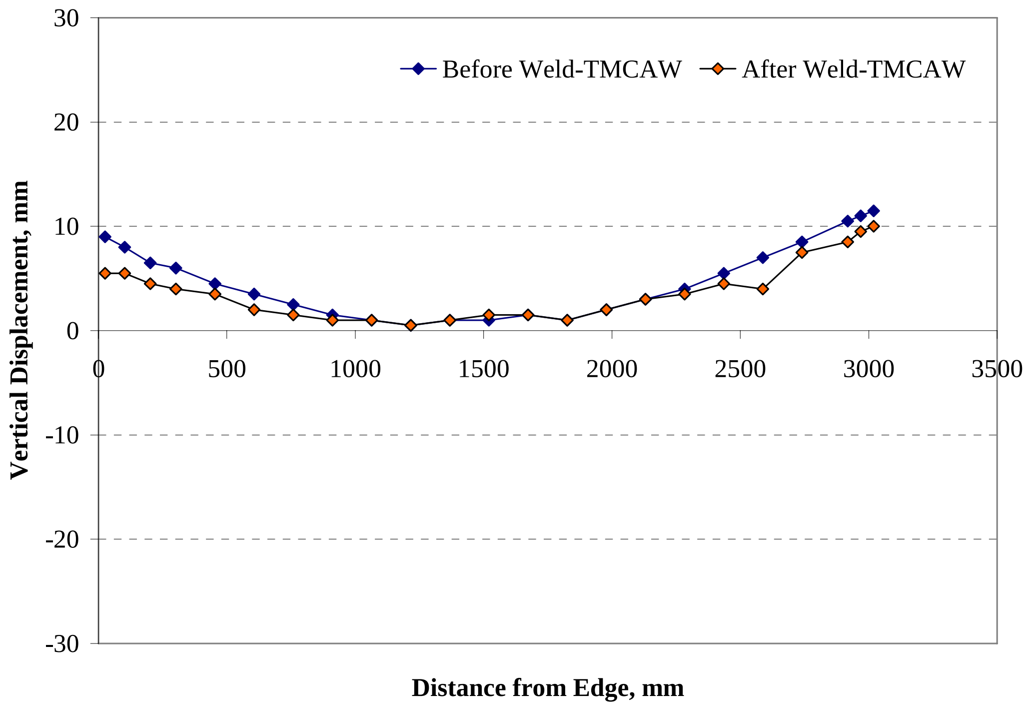


Figure F.1: Net Displacement along Longitudinal Section A for T-MCAW Stiffener Benchmark Assembly

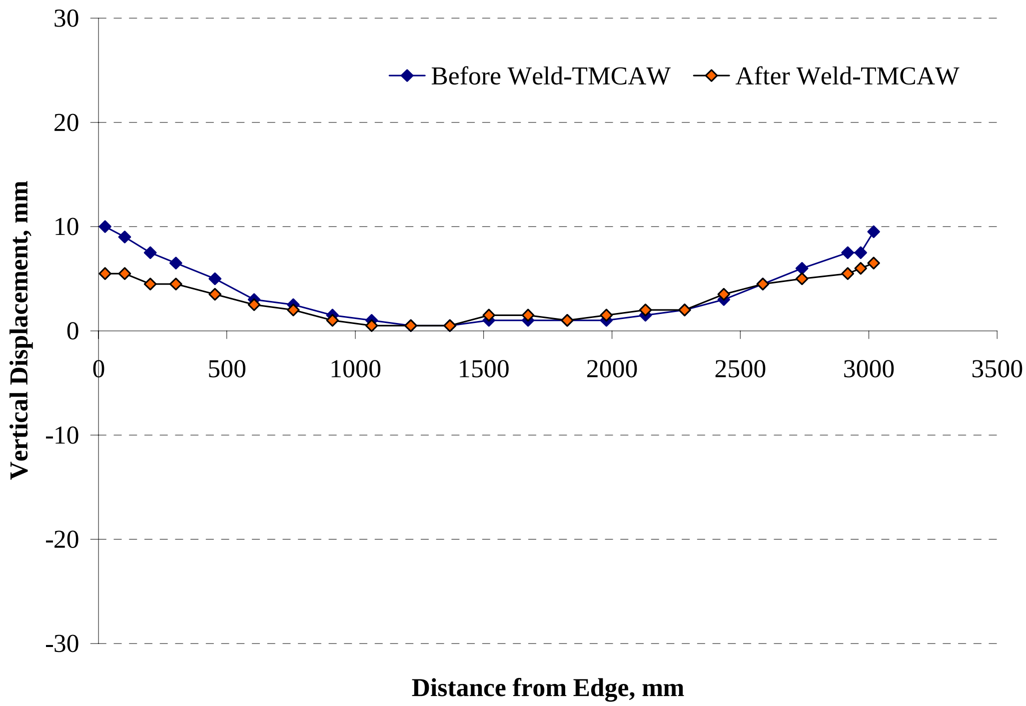


Figure F.2: Net Displacement along Longitudinal Section B for T-MCAW Stiffener Benchmark Assembly

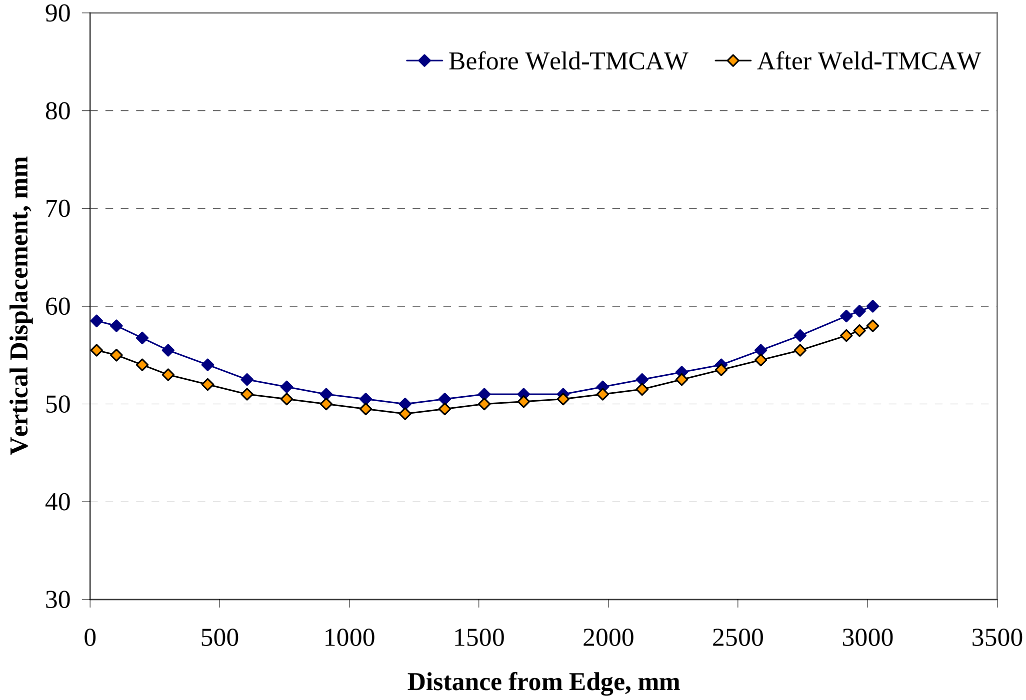
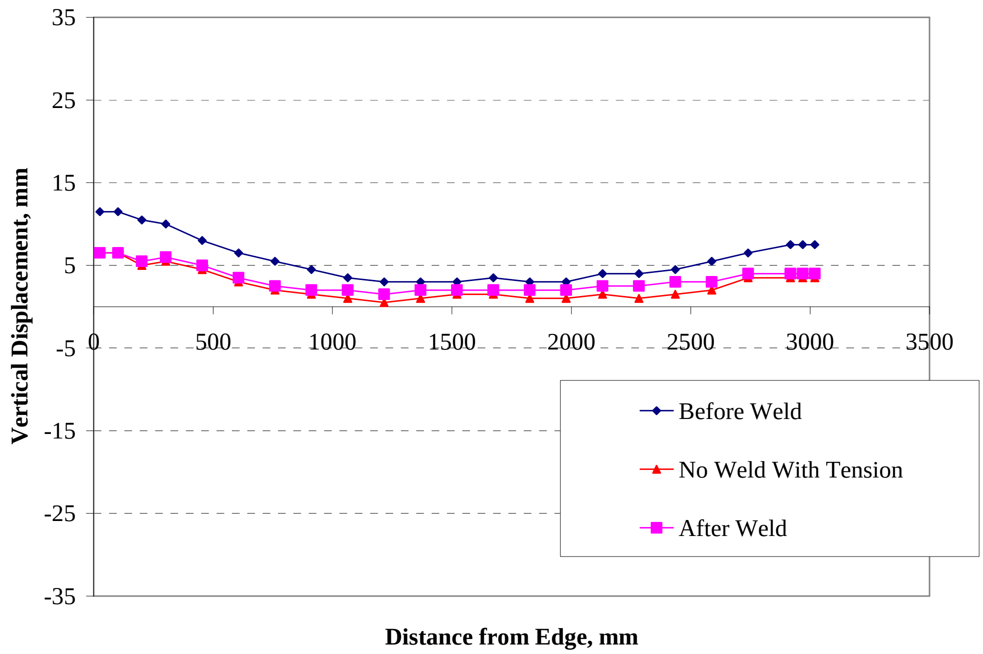


Figure F.3: Net Displacement along Longitudinal Section T for T-MCAW Stiffener Benchmark Assembly



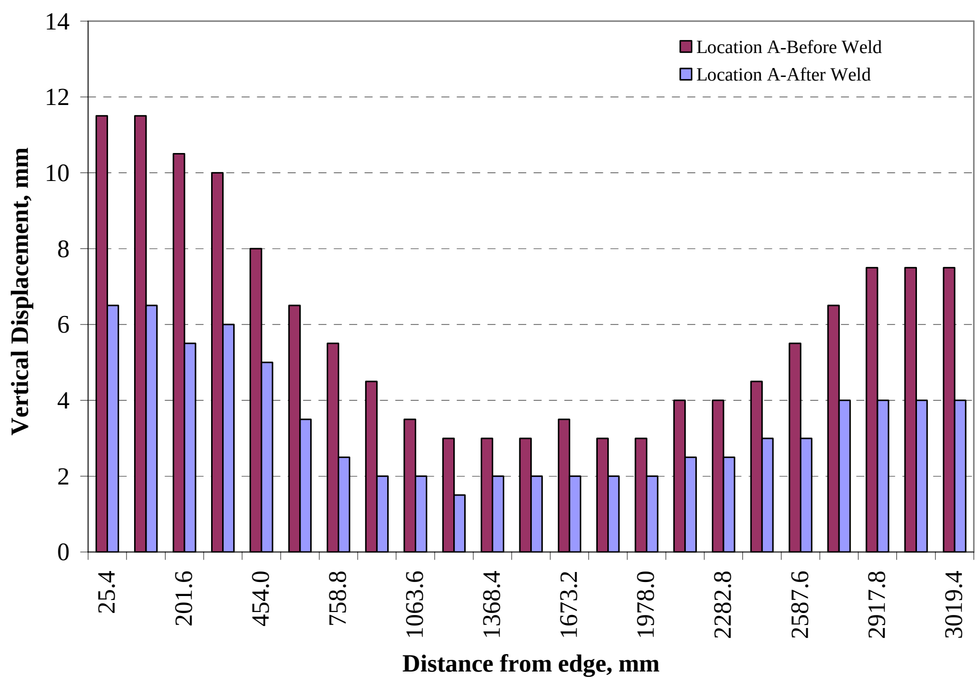
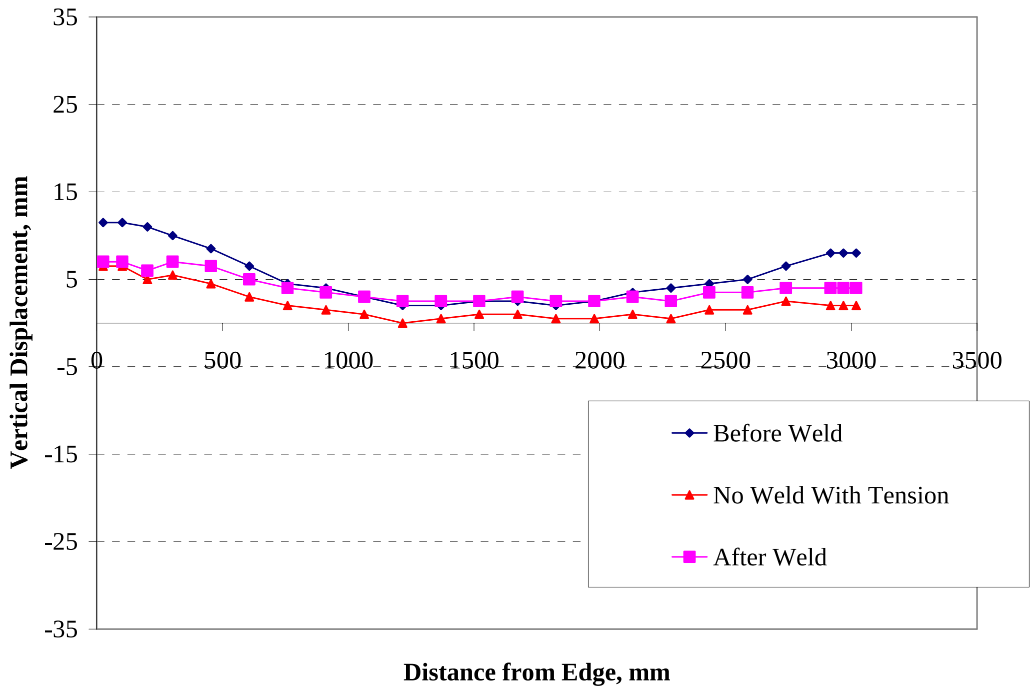


Figure F.4: Net Displacement along Longitudinal Section A for T-MCAW Stiffener Assembly 2



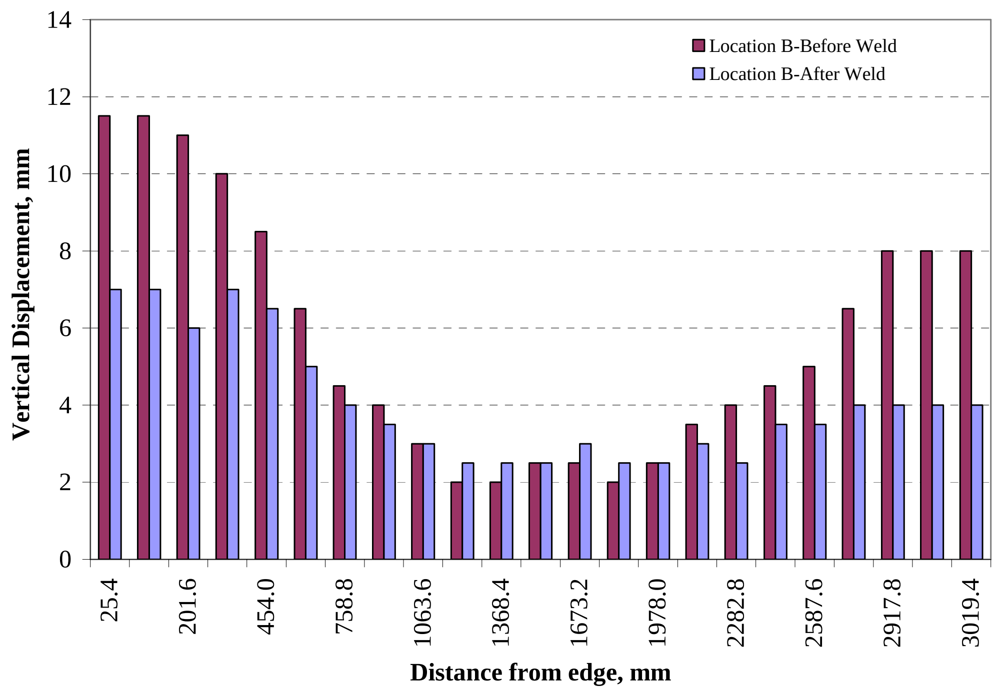


Figure F.5: Net Displacement along Longitudinal Section B for T-MCAW Stiffener Assembly 2

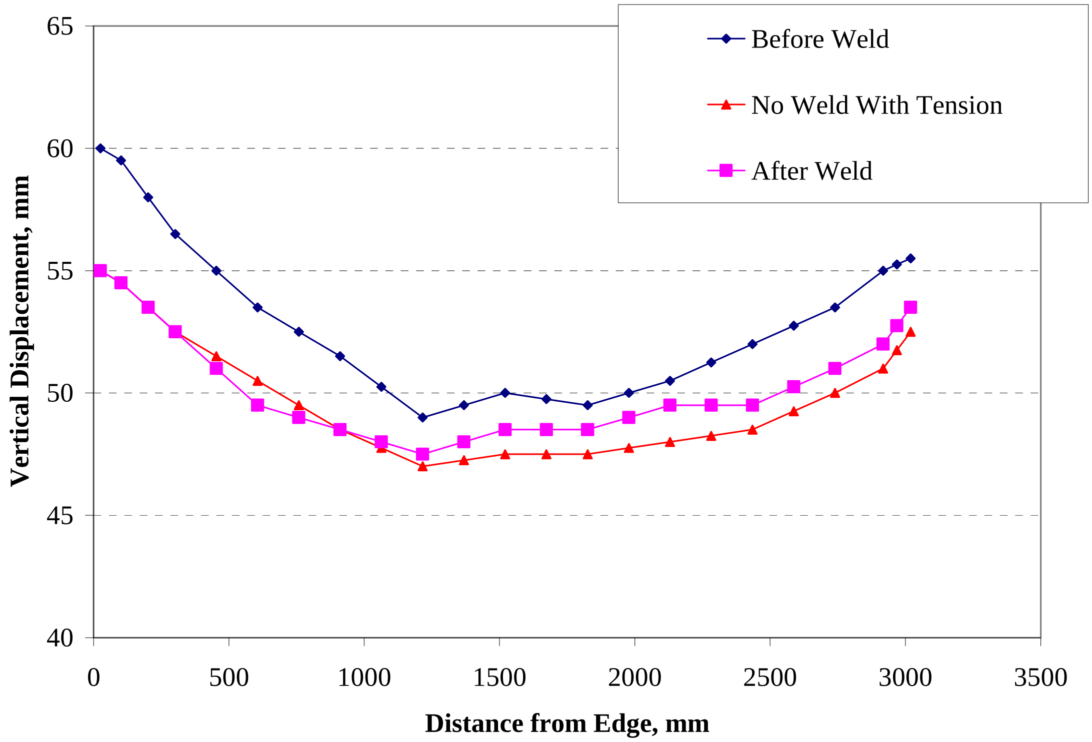


Figure F.6: Net Displacement along Longitudinal Section T for T-MCAW Stiffener Assembly 2

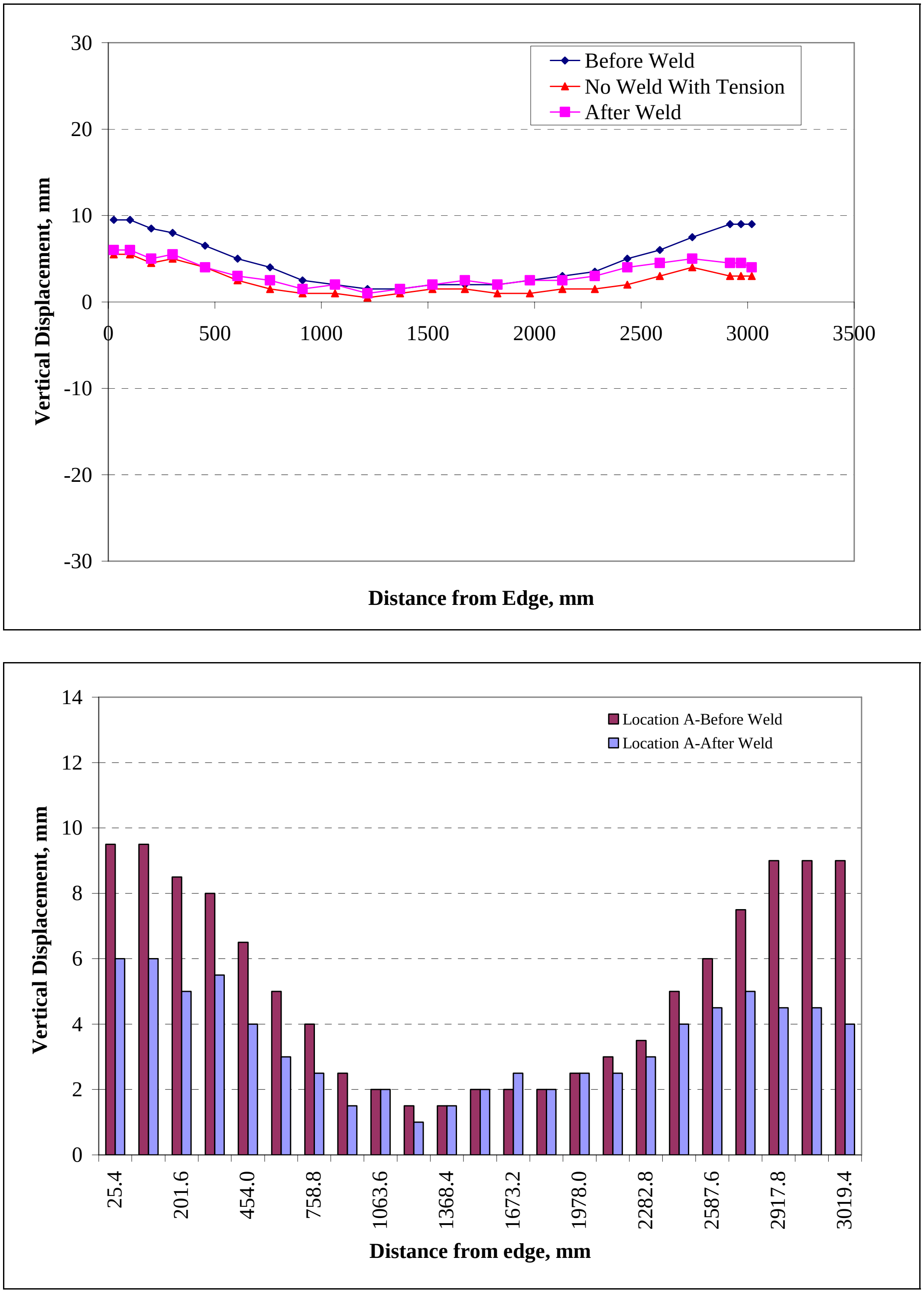


Figure F.7: Net Displacement along Longitudinal Section A for TMCAW Stiffener Assembly 3

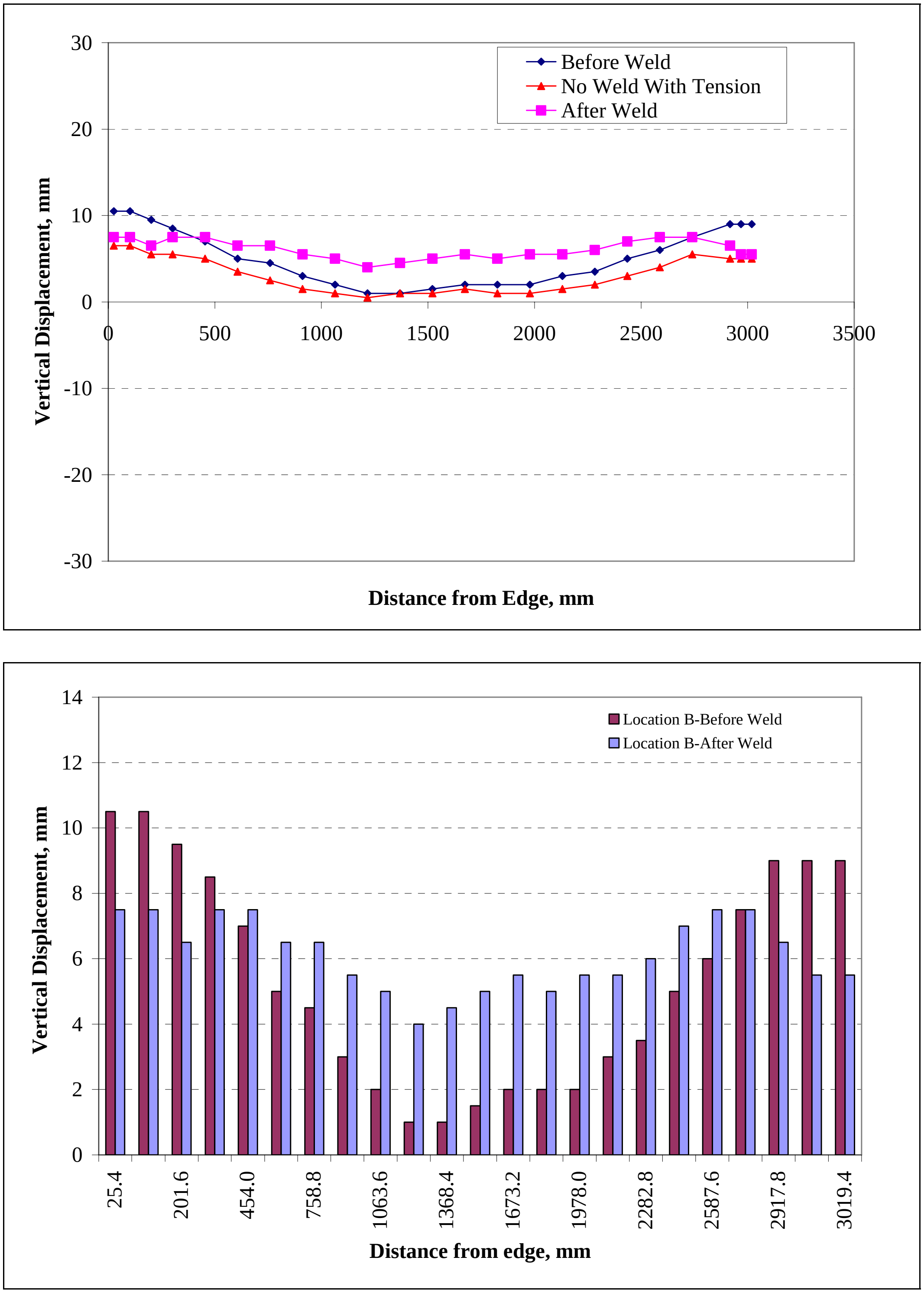


Figure F.8: Net Displacement along Longitudinal Section B for TMCAW Stiffener Benchmark Assembly 3

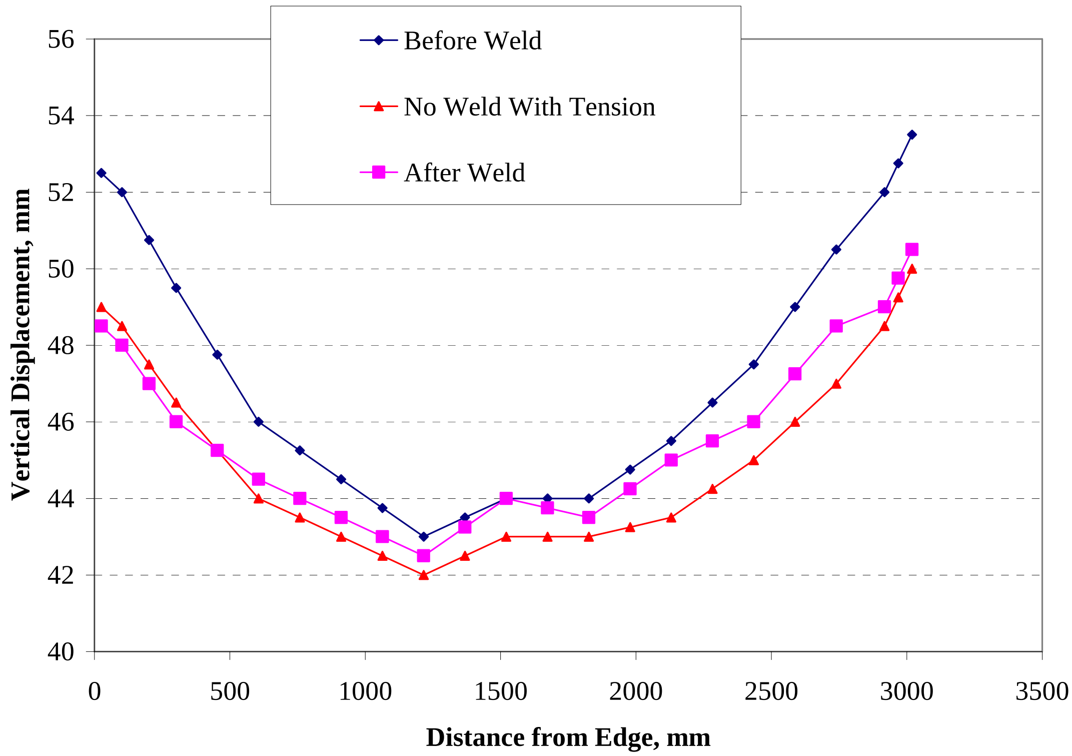
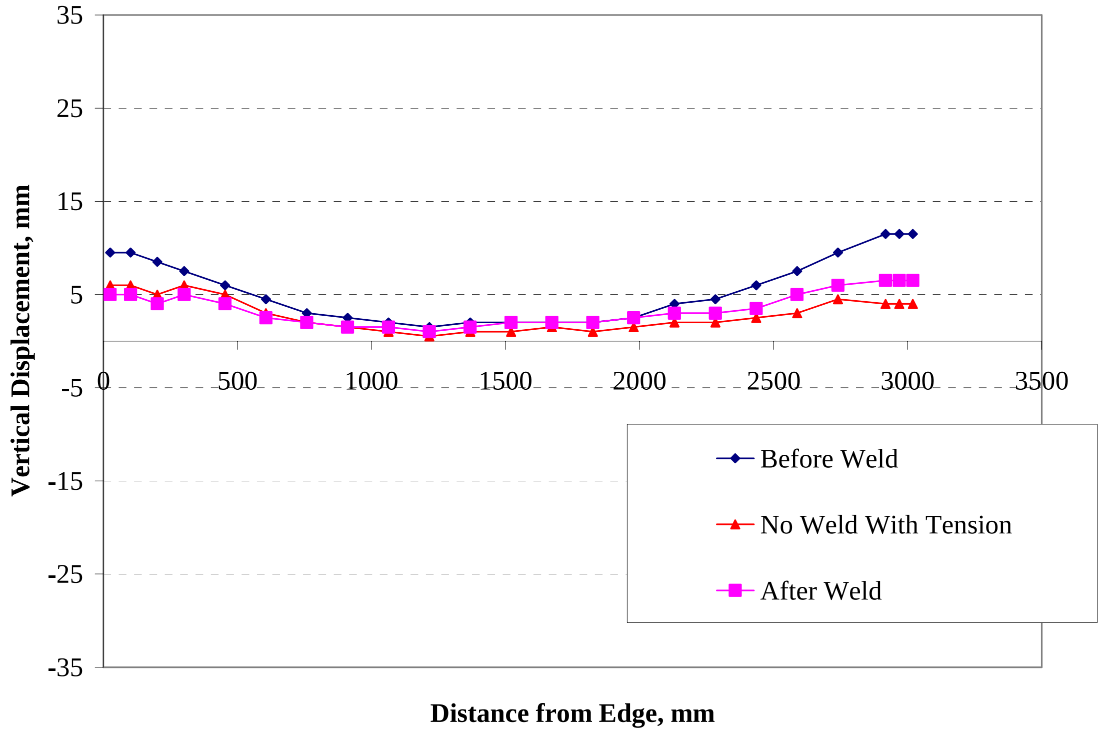


Figure F.9: Net Displacement along Longitudinal Section T for TMCAW Stiffener Benchmark Assembly 3



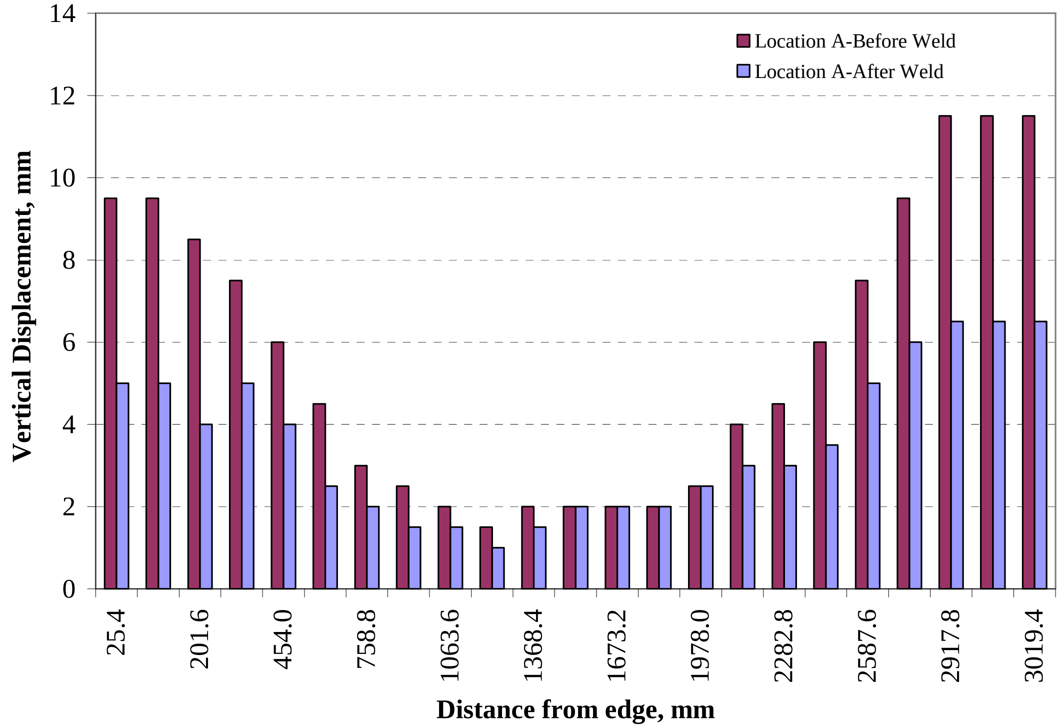
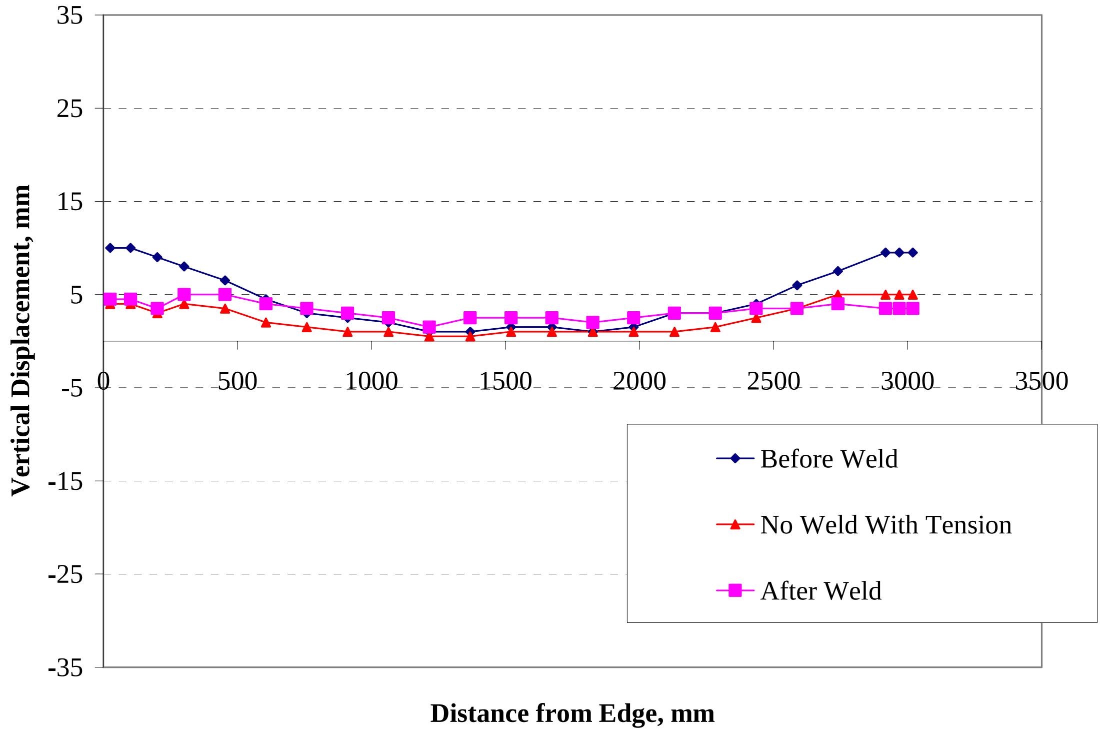


Figure F.10: Net Displacement along Longitudinal Section A for TMCAW Stiffener Assembly 4



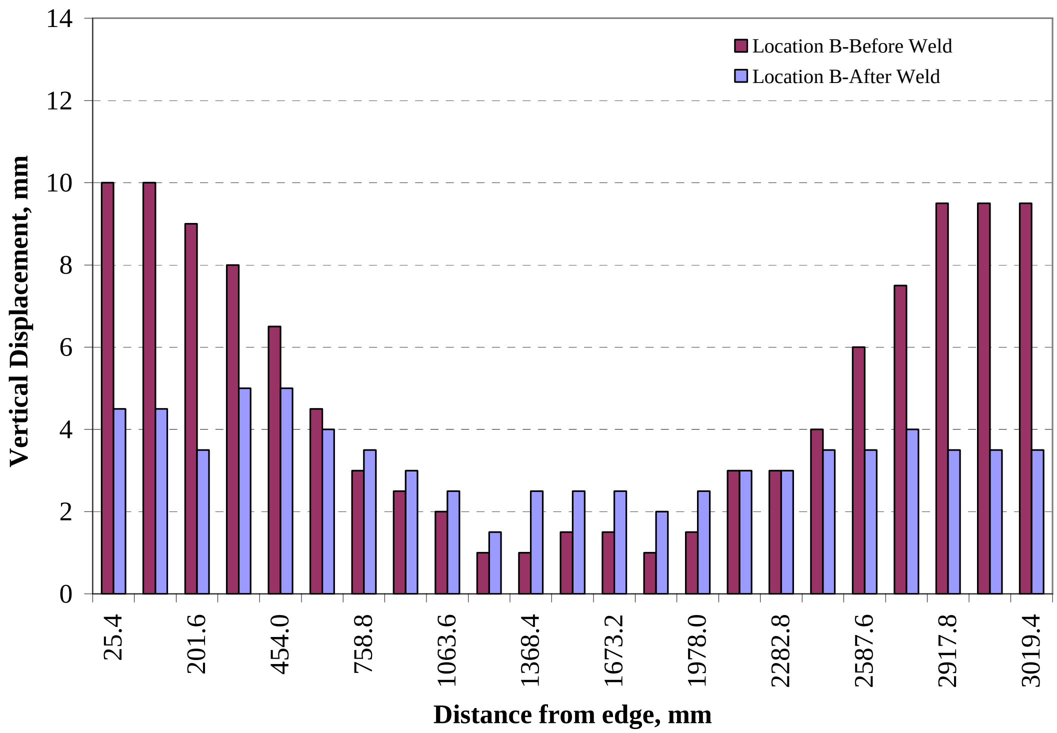


Figure F.11: Net Displacement along Longitudinal Section B for TMCAW Stiffener Benchmark Assembly 4

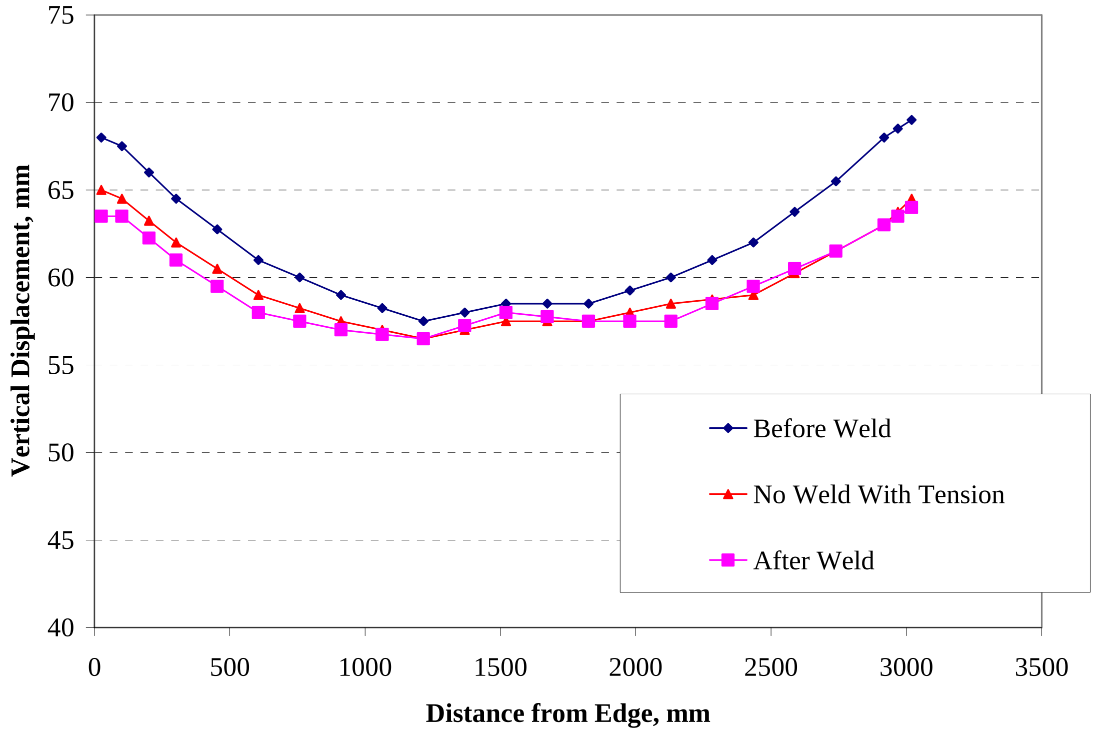


Figure F.12: Net Displacement along Longitudinal Section T for TMCAW Stiffener Benchmark Assembly 4

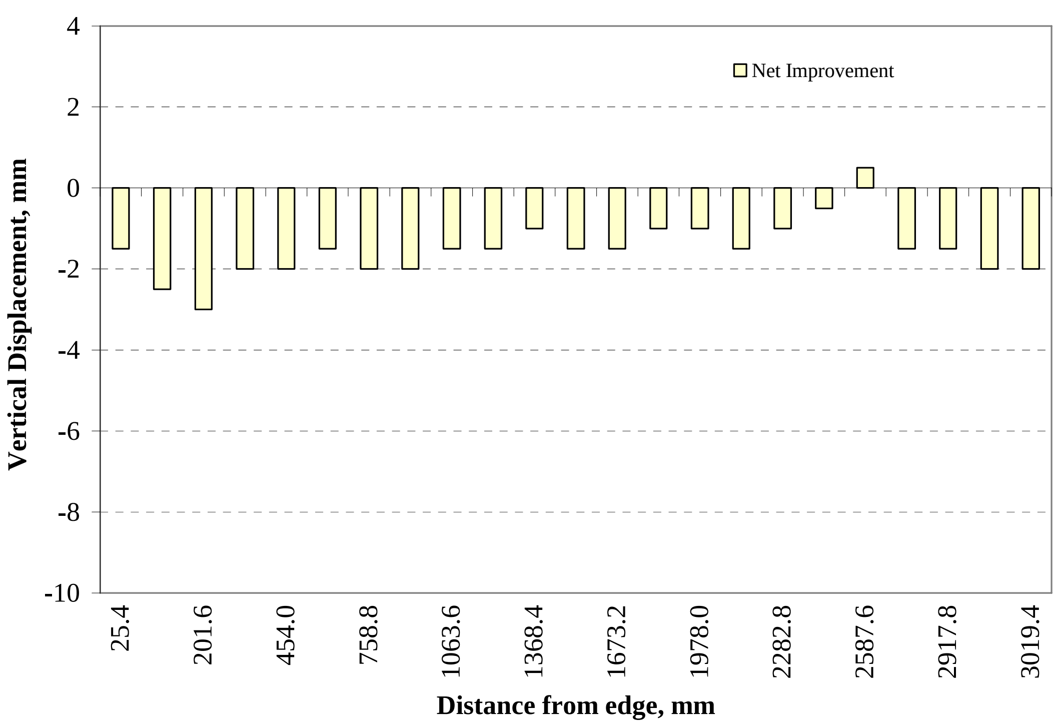


Figure F.13: Plate 2 Location A – Net Improvement

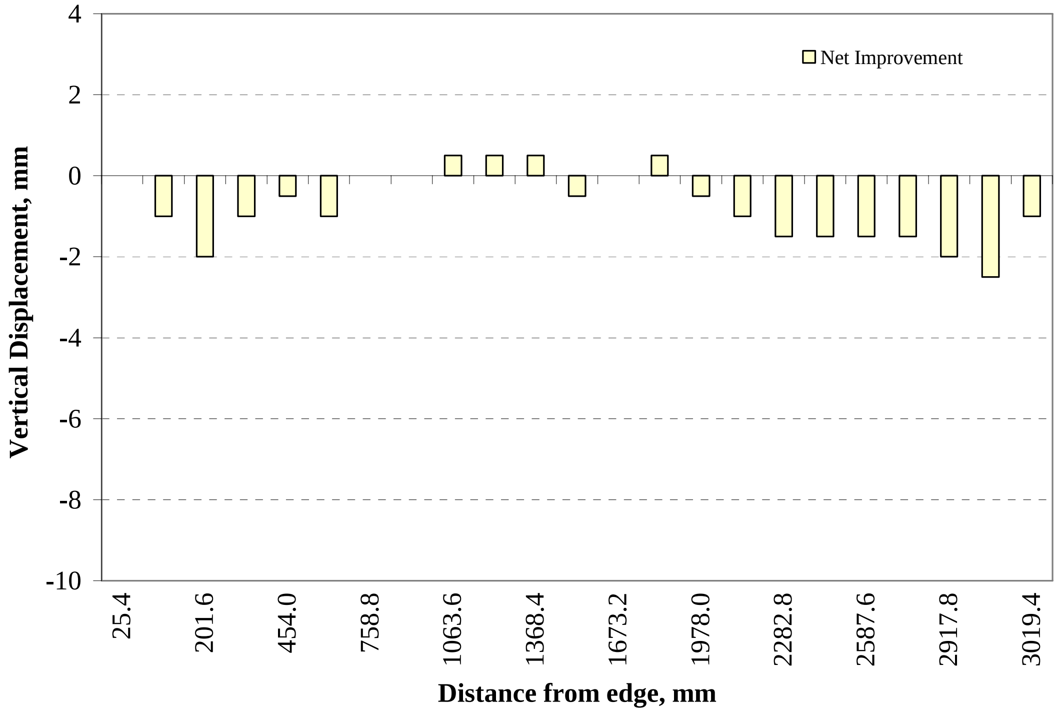


Figure F.14: Plate 2 Location B – Net Improvement

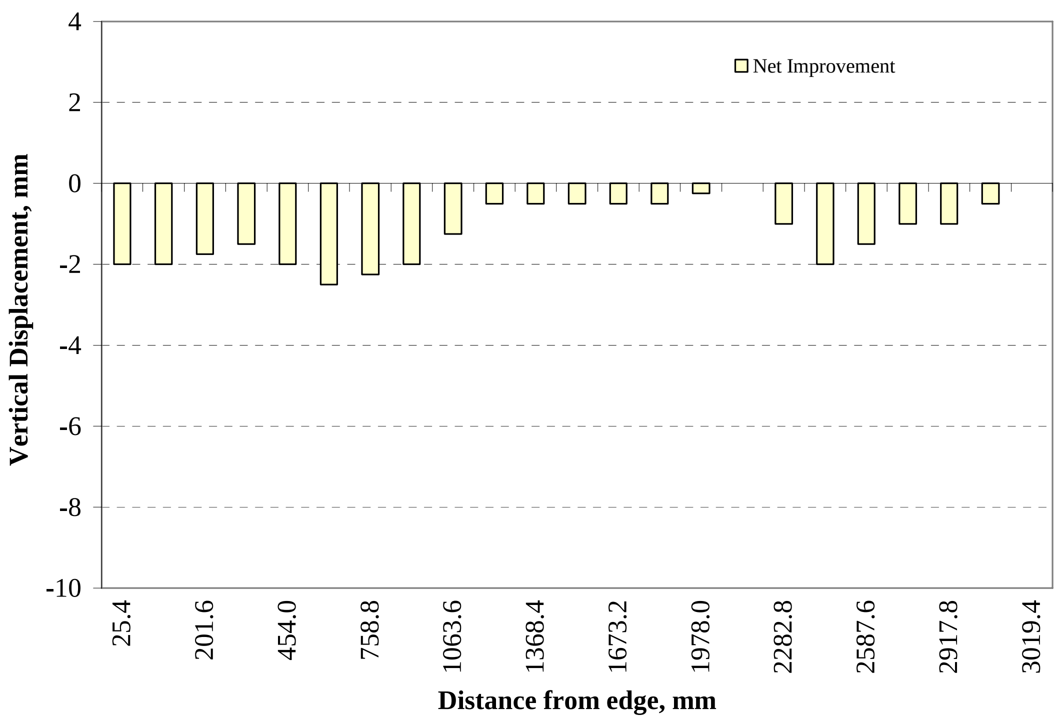


Figure F.15: Plate 2 At Stiffener – Net Improvement

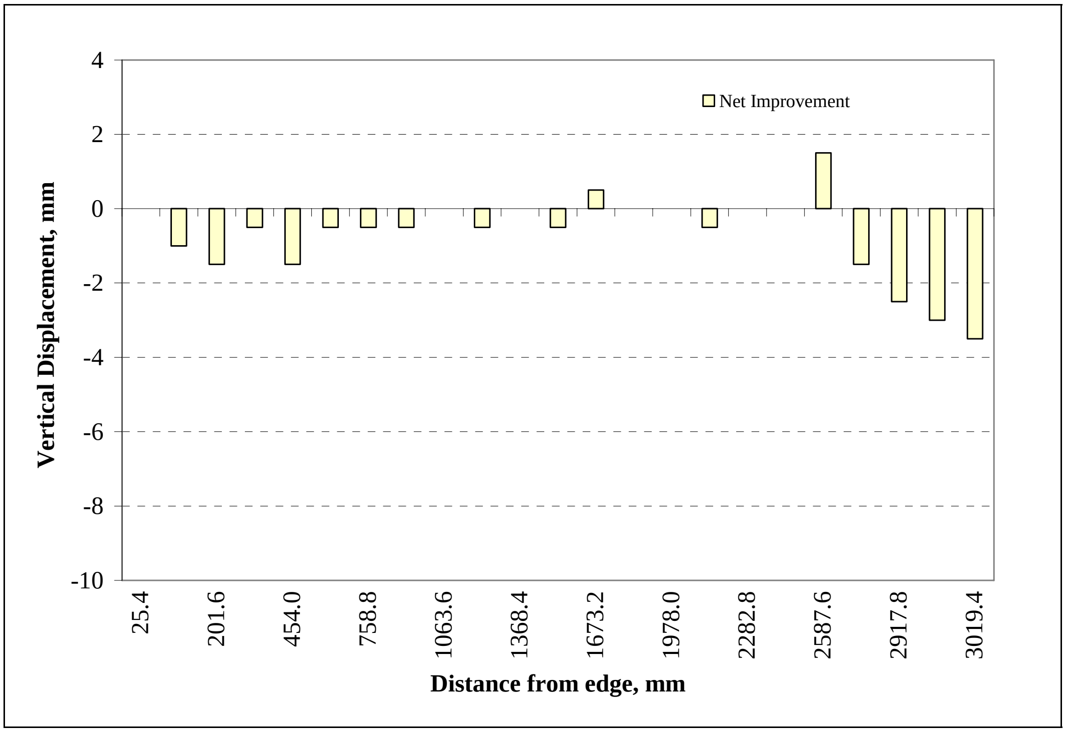


Figure F.16: TMCAW_Stiff_3 -Net Improvement at Location A.

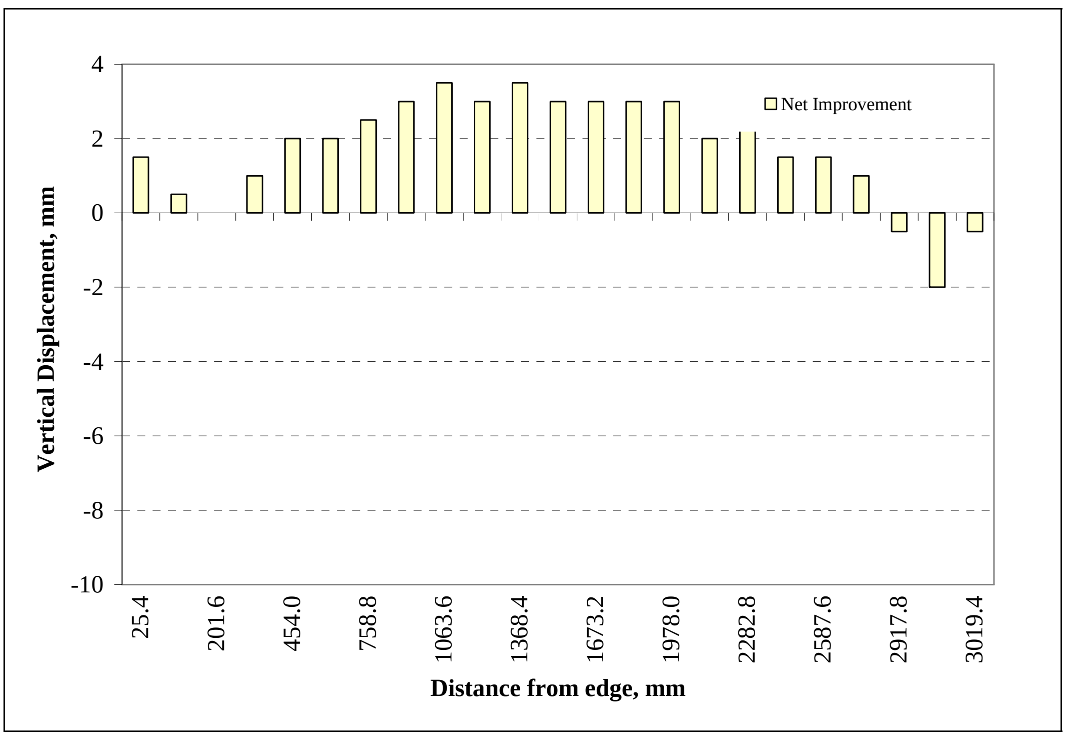


Figure F.17: TMCAW_Stiff_3 -Net Improvement at Location B.

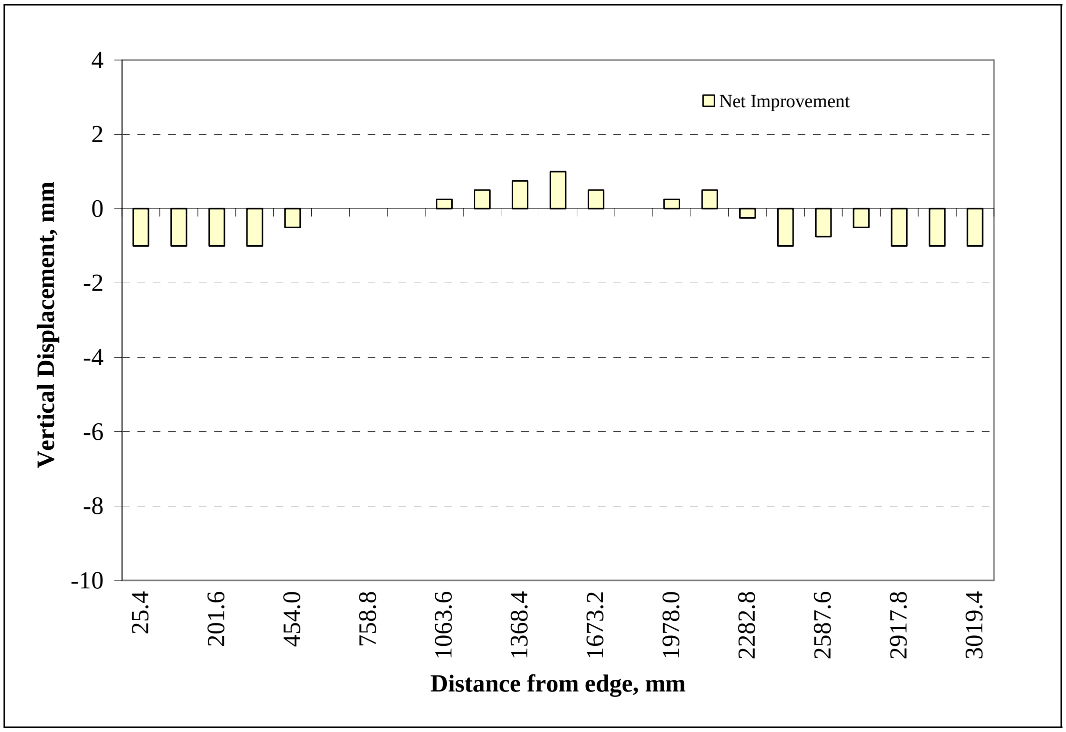


Figure F.18: TMCAW_Stiff_3 -Net Improvement at Location T.

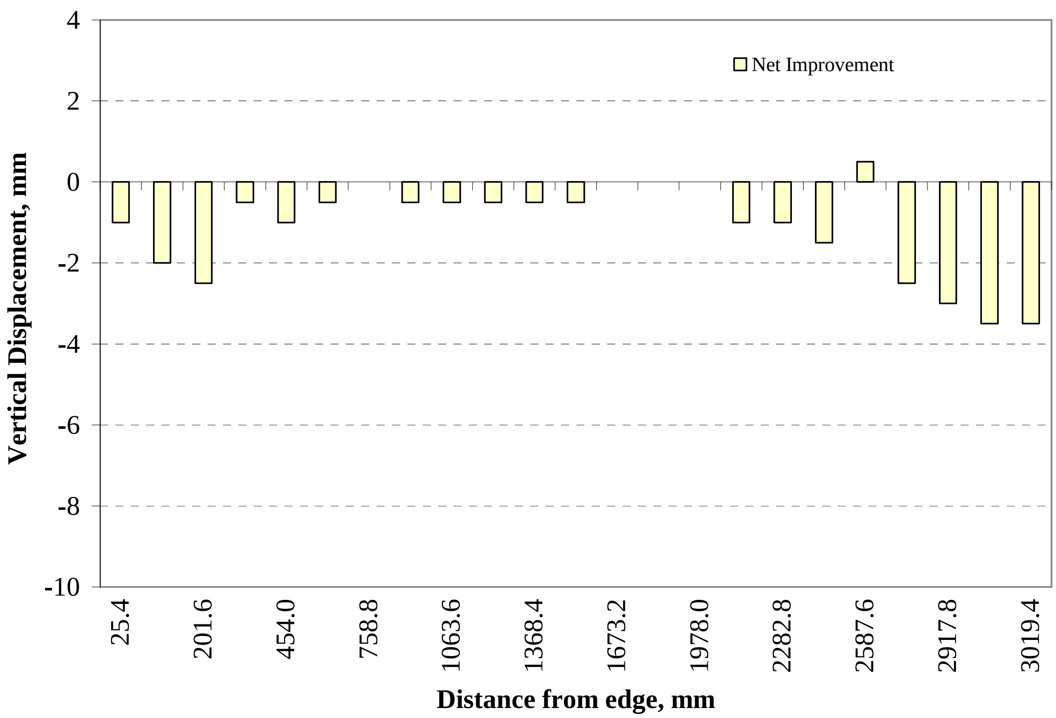


Figure F.19: TMCAW_Stiff_4 -Net Improvement at Location A.

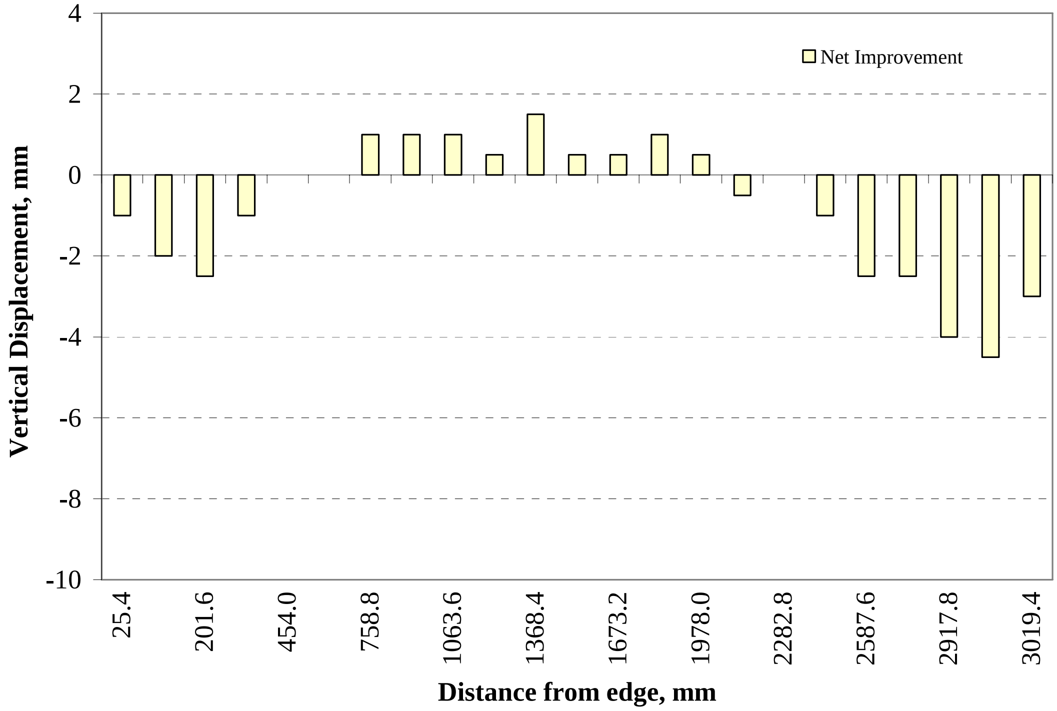


Figure F.20: TMCAW_Stiff_4 -Net Improvement at Location B.

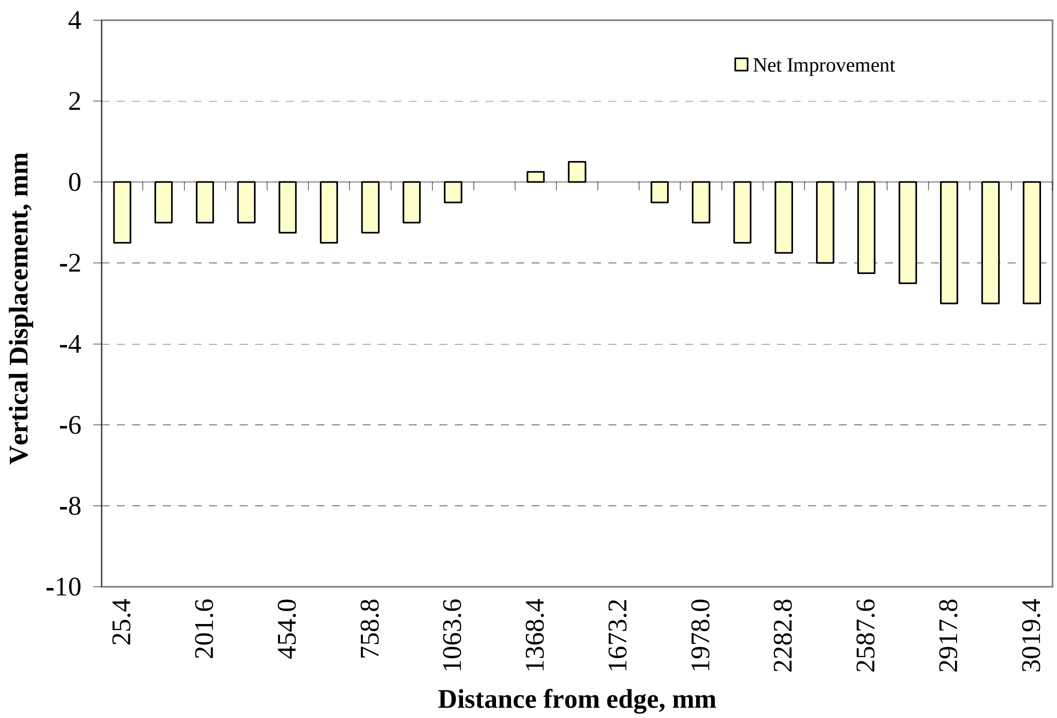


Figure F.21: TMCAW_Stiff_4 -Net Improvement at Location T.

APPENDIX G

NET DISPLACEMENTS FOR FCAW and T-MCAW (4' x 10' HSLA 80 BASE PLATES)

Table G.1: FCAW Benchmark Plate 7 Distortion Data Before Welding

Before Weld - Plate 7											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	22	26	27.5	27.5	28.5	160	28	26.5	25	24	21
2	23.5	28	29	28.5	29.5	160	28	27	26.5	24	20
3	24	28	29	28.5	28.5	159.5	28	26	25	23.5	19
4	23.5	27	28.5	29.5	29.5	159	27.5	26	25	23.5	19.5
5	21	24.5	26	26	27	159	27	26	25	23.5	20.5
6	18.5	22.5	24	25.5	25.5	158.5	26.5	25.5	25	23	21
7	16.5	21	24	25	25.5	158	25.5	25	24	23	20.5
8	16	21	24	24	25.5	159	26	25.5	24	23.5	20.5
9	16.5	21	23	25	25	159	25.5	25	24	23	21
10	17.5	22.5	23.5	25	26.5	159	25	24.5	23.5	23	21
11	20	24	24.5	26	25.5	159.5	24.5	24	23	23	20.5
12	21.5	25	26	27	26.5	160	25	24.5	23	23	20.5
13	21.5	26	26.5	28	28	161	26	25	23.5	22	20.5
14	17.5	22	23.5	25	24.5	160	24	23.5	22.5	20.5	20
15	16	21	23	24.5	25	161	25	24.5	24	22	20
16	15	25	23	24.5	25	162.5	26.5	26	24.5	23	20
17	14.5	19.5	22	24.5	25	161.5	25.5	25.5	24.5	22.5	20.5
18	15	19.5	23	24.5	26	162	24.5	24.5	23.5	22	21
19	19	23	25.5	26.5	27.5	163	25	24.5	23.5	22	21
20	21.5	25	26.5	28.5	29	164.5	24.5	24.5	23.5	22	19.5
21	23	27.5	29	29.5	30.5	165.5	25.5	25	23.5	21.5	19
22	23.5	27.5	29	29.5	31.5	166.5	26	25	22.5	20.5	17
23	22.5	26.5	28.5	29.5	31	167	26	25	22.5	20	17

Table G-2: FCAW Benchmark Plate 7 Distortion Data After Welding

After Weld - Plate 7											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	24.5	27	26.5	27	25	155	20	19	19	19	16.5
2	26	28	27.5	28	26	155	20.5	20	20	20	17.5
3	25.5	28	27.5	28	25	154.5	21	20	20.5	20.5	18.5
4	24	26.5	26.5	28.5	26.5	154	21.5	21	22	22	19.5
5	20	23	23	24.5	23	154	22	22.5	23.5	23.5	22.5
6	16.5	19	20.5	23	21.5	153.5	22.5	23.5	25.5	26	25
7	13.5	17	19	22	21.5	153	22.5	24.5	26	26.5	26
8	12.5	16.5	18.5	20.5	21.5	153.5	23	24.5	26.5	27	26
9	13.5	17.5	18	21.5	21	154	22.5	24.5	25	26.5	25
10	16.5	20	20	22.5	23	154.5	22	23	23.5	23.5	23
11	21	24.5	23	24.5	22.5	154	20.5	21.5	21.5	22	20.5
12	25.5	27.5	26	26.5	24.5	155	21	21.5	21.5	21.5	19.5
13	27.5	29	27.5	27.5	25.5	156	22	22	22.5	21.5	20
14	23	25	24	24	21.5	154.5	20.5	21.5	22	22.5	22
15	19.5	22.5	22.5	23	21.5	156	22	23.5	25	25	24.5
16	17	20	21	22	21.5	157	23.5	25	26.5	27	27.5
17	15.5	18.5	19.5	22	21	156.5	21.5	25	26	26.5	28
18	15.5	18.5	20	21.5	22	157	20.5	23	24	25.5	26
19	18.5	21.5	22.5	23	22.5	158	21	22	22.5	23.5	24.5
20	21	24	24.5	24.5	24	159	19.5	20.5	21	21.5	20.5
21	22	25	25.5	25.5	25	159.5	20.5	20	20	19.5	18.5
22	22	24.5	25	25.5	25.5	160.5	20	19	18.5	17	15
23	21	24	24.5	24.5	25.5	161	20	19	17.5	16.5	14

Table G-3: T-MCAW Benchmark Plate 8 Distortion Data Before Welding

Before Weld - Plate 8

Displacement w.r.t to Frame, mm

	A	B	C	D	E	F	G	H	I	J	K
1	13.5	17	19	20.5	23	151	22.5	21	19.5	17.5	13
2	15	18.5	20.5	22	24	151	23	21.5	20	18.5	14
3	16	19.5	21.5	22.5	23	150	23	21.5	19.5	19	15
4	17	20	22.5	24	24.5	149.5	22.5	21	20.5	19.5	15
5	17	20.5	22.5	22.5	23	149.5	21.5	20.5	19.5	19	16
6	18.5	22	23.5	23.5	22.5	149	20.5	19.5	18	17.5	14.5
7	21	24	25	24.5	23	148.5	19	18	16.5	15	12
8	22.5	25.5	26	25	24	149	20	18	16.5	14.5	11.5
9	22	25	24.5	25	23.5	149	20	18.5	16.5	15.5	12.5
10	19.5	22.5	22.5	23.5	23.5	149	20.5	19	18	16.5	14
11	17	20.5	20.5	21.5	22.5	149	20.5	20	19	18.5	16.5
12	17	19.5	19	21	22.5	150	21	20.5	19.5	19	16.5
13	18	20.5	20	21.5	23	150.5	22	21	20	19	17
14	17	19.5	19.5	20	21	150	20	19	18	16.5	14.5
15	19	22.5	22	22.5	22.5	150	21	19.5	18.5	16.5	15.5
16	21.5	24.5	24.5	24	23.5	151	21	20.5	18.5	17	14.5
17	20.5	23.5	24	24.5	23.5	150.5	20.5	20	18.5	17	15
18	18.5	21.5	23	24	24.5	150.5	21	21	19	17.5	17
19	17	20.5	22	23.5	25	152	21.5	22	20.5	20	19.5
20	16.5	20	22	24.5	26.5	153	23	22.5	21.5	21	18
21	17	21	23	25	26.5	154	24	23.5	22.5	21.5	18.5
22	19.5	22.5	24.5	27	28.5	155	25	24	22.5	20.5	17
23	20	23	25.5	27.5	29	155.5	25.5	24.5	24	20.5	17

Table G-4: T-MCAW Benchmark Plate 8 Distortion Data After Welding

After Weld No Tension - Plate 8

Displacement w.r.t to Frame, mm

	A	B	C	D	E	F	G	H	I	J	K
1	11	13	14.5	16	15.5	145	16.5	17	17	17	13
2	13.5	15.5	17	17.5	16.5	145	17	17.5	17.5	17.5	14
3	16.5	18	19	19	16.5	144.5	16.5	17.5	17	17.5	14.5
4	18.5	20.5	21.5	21.5	18.5	144	16.5	17.5	18	18	14.5
5	21.5	23.5	23.5	21.5	18	143.5	16	16.5	16.5	16.5	14
6	26	27	26.5	24	18	143	15	15	14.5	14	11
7	31	31	29.5	26.5	20	143	13.5	12.5	11.5	11	7
8	33	33	31.5	27	20.5	143	13.5	12.5	11	10	6.5
9	31.5	32	29.5	27.5	20	143	14	13.5	11.5	11.5	7.5
10	26	27	25.5	24	20.5	143	15	14.5	13.5	13.5	9.5
11	20.5	22	20.5	20	18.5	143	15	16.5	16.5	16.5	15
12	17.5	19	17.5	18	17	144	16	17.5	18.5	18	17
13	18.5	19.5	18	18.5	18	144.5	16.5	18.5	18.5	19.5	18
14	19	19.5	18.5	18	16.5	142.5	15	16	17	17	15.5
15	24	24.5	23	21.5	18.5	143.5	15.5	16.5	17	16	15
16	28.5	28.5	26.5	24	19.5	144.5	16	16.5	17	16.5	15
17	27.5	28	25.5	24	20	144	15	16	16.5	16	15
18	23.5	24	23.5	22	20	144	15	16	16.5	16.5	17
19	20	20.5	20.5	20	19.5	145	15.5	17	17	17.5	18.5
20	16.5	18.5	18.5	19.5	19.5	145.5	16	17	17	17.5	17
21	16.5	18.5	18.5	19.5	20.5	146.5	17	17.5	17.5	17.5	16.5
22	16.5	18.5	19.5	21	21.5	147	17	17	17	16.5	15
23	17	19	20.5	21.5	21.5	147.5	17.5	17.5	17	16	14.5

Table G-5: FCAW Plate 3 Distortion Data, No-Tension Before Welding

Before Weld - Plate 3											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	24	27	27	28.5	30	164	30.5	29.5	25	22	17
2	24.5	27.5	28	28.5	30.5	163.5	31	30	26.5	24	19
3	24.5	27	27	27.5	28.5	162	31	30	27	23.5	19.5
4	23.5	26	27	28.5	30	161	30	30	27.5	24.5	20
5	20.5	23.5	24.5	25	27.5	159.5	29.5	29.5	27.5	25	21
6	17	21	23	24	25	158.5	28	29	26.5	25	21
7	15	19.5	22	24	25	157	27	28	26	23.5	20.5
8	15	19.5	22	23	25	156.5	26.5	27.5	25.5	23.5	20
9	16	19	20.5	23	23.5	156	26	26.5	25	24	19.5
10	16.5	19	19.5	21.5	24	155.5	25	26	25	23.5	20.5
11	18	19.5	19	20.5	21.5	154	23.5	25.5	25.5	24	20.5
12	19.5	20.5	19.5	20.5	21.5	154	23.5	26	25.5	24	21
13	20	21	19.5	21	22	154	24.5	26	25.5	23.5	21
14	17	17.5	17	18	19	151.5	22	23.5	23.5	22	20
15	15.5	17	16.5	17.5	19	151.5	22	23.5	23.5	22	19
16	15.5	17.5	17	18	19	151.5	22	23	22.5	21.5	19
17	15	16.5	16.5	18.5	19	150	21	21.5	21.5	20	19.5
18	15.5	17	17.5	18.5	19.5	149.5	19.5	21	20	20.5	20
19	17	18	18.5	19	20	149.5	20	21	21.5	21.5	21
20	18.5	18.5	19	19.5	20.5	149.5	19.5	21.5	21.5	22	20.5
21	17	17.5	18.5	19.5	21	150	19.5	20.5	21	20	20
22	13.5	14.5	16	18.5	20	150.5	18	18	17.5	17	17
23	10.5	12	14	17	19.5	150.5	17	16.5	15.5	15	15

Table G-6: FCAW Plate 3 Distortion Data, Tension Before Welding

Tension No Weld - Plate 3											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	18	19.5	19	18.5	20	154.5	19	19	17.5	15.5	13.5
2	20	21	20	20	21	154	21	21.5	19.5	18	15
3	20	22.5	20	20	20.5	153	21.5	21.5	21	19	17.5
4	20.5	22	22	21.5	22.5	152.5	21.5	22.5	21.5	21.5	18
5	20	21.5	20.5	19	21	151.5	22	22.5	22.5	22	19
6	18	19.5	20	19.5	19.5	151	21.5	22	21.5	21.5	19
7	16	18.5	19.5	19.5	19.5	150	20	20.5	20.5	20	17.5
8	16	18.5	19.5	19	20	150	20	21	21	20	17.5
9	16.5	19	18.5	19.5	19.5	150	19	20.5	20.5	19.5	17
10	17	19	18.5	19.5	20	149.5	19	20.5	20.5	20	18
11	18	19	17.5	18.5	18.5	149	18.5	20.5	20.5	20.5	19.5
12	19.5	20.5	18.5	19	19.5	149.5	19	21	21.5	20.5	19
13	20	21	19	19.5	20	149.5	20	22	22	21	19
14	17	18	16.5	16.5	17	147.5	17.5	19.5	21	19.5	18
15	17	18	17	17.5	17.5	148	18.5	20	20	19.5	17.5
16	17.5	18.5	17.5	17.5	17.5	148.5	18.5	20	20	19	17
17	16.5	17.5	17	18.5	17.5	147.5	17.5	19.5	19.5	18	17.5
18	16.5	18	17.5	17.5	18	147.5	17	19	19	18	18.5
19	17.5	18	18	18.5	19	147.5	18	19.5	19	19	20
20	18	18	18	18.5	19	148	18	19	19.5	19	18.5
21	17.5	17	17.5	18.5	19	149.5	18.5	19	18.5	18	18
22	13.5	14	15.5	17.5	18.5	149.5	16	16.5	15.5	14.5	14
23	10	12	13.5	16.5	18	149.5	14.5	14	13	13	12

Table G-7: FCAW Plate 3 Distortion Data, Tension After Welding

After Weld - Plate 3											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	25	25.5	23.5	21.5	21	154	18.5	18.5	17	16.5	13.5
2	26	26.5	24	22.5	22	153.5	20.5	21	20	19	16
3	26	26.5	24	22.5	21	152.5	21.5	22	21.5	21	18.5
4	25.5	26	24.5	24.5	23	152	22	24	22.5	23.5	20
5	21.5	23	22.5	21.5	21	151	23	25	24	25	22
6	16.5	19.5	20	20	19.5	150.5	23	25	24	25.5	22
7	13	17	19.5	20.5	20	149.5	22	24	23.5	24	21
8	13	17	19.5	20	20.5	150	22.5	24.5	23.5	23	20.5
9	14.5	17.5	18.5	20.5	20	150	22	24	23.5	23	19
10	16	18	18.5	19.5	21	150	22	24	24	23	20
11	18.5	19.5	18.5	19	19	149.5	21.5	25	25.5	24.5	22
12	20	20.5	19	21	20	150	23	25.5	27.5	27	25
13	20.5	21	19.5	20	21	150.5	24	27.5	29.5	29.5	28
14	17	18	17	17	17.5	148.5	22.5	25.5	28.5	29	30
15	16.5	18	17	17.5	18	149	22.5	26	28.5	29.5	30
16	17.5	19.5	18.5	19	19	150	22.5	25	27	27.5	27.5
17	19	20	19.5	20.5	20	149.5	21	23.5	25	24.5	24
18	21	21.5	21.5	21.5	21	149.5	20	22	22.5	22.5	22
19	23.5	23.5	23	22.5	21.5	150.5	20.5	21.5	22	22	22
20	24	23.5	23	23	22.5	151	20.5	20.5	21.5	21.5	20
21	22.5	22	22	23	23	151.5	20.5	20.5	20.5	20.5	19.5
22	18.5	19	19.5	21	22	152.5	18	18	18	17	16
23	16.5	16.5	17.5	19.5	21	153	16	16	15	14.5	14

Table G-8: T-MCAW Plate 9 Distortion Data, No-Tension Before Welding

Before Weld - Plate 9											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	6	12.5	17	19.5	23	157.5	25	24	19.5	18	13
2	10.5	17.5	20.5	22.5	25.5	157.5	25.5	25	20.5	19	14
3	15.5	26.5	23.5	25.5	26.5	157	26	24.5	20.5	19	14
4	19	25	26.5	28.5	29	156.5	26	23	21.5	19.5	15
5	20.5	26	26.5	26.5	27	156	25	22.5	21	19.5	15.5
6	19.5	25	26	26.5	26	155.5	25.5	22	20.5	19	15.5
7	17.5	22.5	25	26	25.5	154.5	24.5	21	18.5	17	13.5
8	16	21	24	24.5	25.5	154.5	24.5	21	19	17	14
9	14.5	19.5	22	24	24	153.5	24.5	21	19.5	17	14
10	14.5	19.5	21	23.5	25	153	24.5	21.5	19.5	17.5	15.5
11	16.5	20.5	21.5	22.5	24.5	152	24	26	19.5	18.5	17
12	18.5	23	24	25	25.5	152.5	23.5	21	20	19	17
13	21	25	25.5	26.5	26	153.5	23	21	19.5	18.5	17
14	20	23	24.5	24.5	23.5	151.5	21	18.5	17.5	16.5	15
15	20	23.5	24.5	25	24	152.5	21.5	19	18	16.5	14.5
16	19.5	23	24.5	24.5	24.5	153	22.5	19.5	18.5	17	15.5
17	16.5	20.5	22	23.5	23.5	152.5	21.5	19.5	18.5	17.5	16
18	15.5	19	21.5	22.5	24	152.5	21.5	20	19	17.5	18
19	16.5	19.5	22	23.5	24.5	154	22.5	21	19.5	19	19
20	17.5	21.5	24	25	25.5	154.5	22.5	21	20.5	19	18
21	18.5	22.5	25	26.5	26.5	155	22.5	21.5	20.5	19.5	17
22	19	23	25.5	26.5	27	156	22.5	21.5	20	18.5	16.5
23	18	22.5	25.5	26.5	27	156.5	22.5	21.5	20	18.5	16.5

Table G-9: T-MCAW Plate 9 Distortion Data, Tension Before Welding

Tension No Weld - Plate 9											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	4.5	9	11	13	16	150	13.5	14	13.5	14.5	9
2	9.5	13	15	16	18	150	15	15.5	15	16	10
3	14	17.5	18.5	18.5	19	149.5	16.5	16	16.5	16.5	12.5
4	17	20.5	21	21.5	21.5	149	17	17	17	17	13
5	18	21	20.5	19.5	20	148.5	16	17	17.5	17	14
6	17	19.5	20	19.5	18	148	16	16.5	16.5	16.5	14
7	14.5	18.5	19	19	18	146.5	15.5	15.5	15.5	15	11.5
8	13.5	16.5	18.5	18	18	146.5	15.5	15.5	15.5	14.5	11.5
9	12.5	15.5	16.5	17.5	16.5	146	15.5	15.5	15.5	15	12.5
10	13	15.5	16	17	17.5	145.5	16	15.5	16	15.5	14
11	15	17	16	17	17	145	15	15.5	16	16	15
12	17	18.5	18	18	18	145	15.5	16	16.5	16.5	15.5
13	18	20	19.5	19.5	18.5	145.5	15.5	16	16	16.5	15.5
14	16	18	18	17.5	16	143.5	13.5	13.5	14	14.5	13.5
15	16	18.5	18.5	18	16.5	143.5	13.5	14	14	14.5	13
16	16	18.5	18.5	18	17	145.5	14.5	15	15	14.5	13.5
17	14.5	16.5	16.5	17	16.5	145	14	14.5	15	15	15
18	14	15	16.5	16.5	17	145	14	15	15.5	16	17
19	15	16	17	17	17.5	146	15	16	16.5	16.5	18
20	15.5	17.5	18.5	19	18.5	147	15.5	16	16.5	17	16.5
21	16.5	18.5	19.5	19.5	19.5	148.5	16	16.5	16.5	17	16
22	16	18	19.5	19.5	20	149	15.5	16	16	16	15
23	15	17.5	19	19	19.5	149.5	15.5	15.5	16	16	15

Table G-10: T-MCAW Plate 9 Distortion Data, Tension After Welding

After Weld No Tension - Plate 9											
Displacement w.r.t to Frame, mm											
	A	B	C	D	E	F	G	H	I	J	K
1	8	12	13.5	14.5	17	150	15	15	14	10.5	8
2	13.5	17	18	18	19.5	150	17	17	16	13.5	10.5
3	19	22.5	22.5	21	20.5	149.5	18	17.5	17	15.5	12.5
4	23	26	25.5	25	23.5	149	19	19.5	19.5	17	14
5	25.5	27.5	26	24	22	148.5	20	21	21.5	19.5	17
6	23.5	25.5	25	24	21	148	20.5	21.5	23	21.5	20.5
7	19.5	22	22.5	22	20	147	20.5	22.5	24	23.5	23
8	16	18.5	19.5	19	19.5	146.5	21.5	24	26	26	26.5
9	13	16	16.5	18	18	146	21.5	24.5	27	27	26.5
10	13	15.5	15.5	17.5	18	145.5	21.5	24	26	26	26.5
11	16	18	17	18	18	145	20	22.5	24	23.5	24
12	20.5	22.5	21.5	21.5	20	145.5	19	21	21.5	20.5	20
13	25.5	27	25.5	24	21.5	146	18.5	19	18.5	17	16
14	26.5	27.5	26	23	19	144.5	15.5	15.5	15	13	12.5
15	27	27.5	26	23.5	19.5	145	16	15.5	14.5	12.5	10.5
16	25	26	25	23	19.5	146	16.5	16.5	15.5	13.5	12
17	20	21.5	21	21	19	146	16.5	17	16	14.5	14.5
18	16.5	18	19	18.5	18.5	146	16	17	16.5	16	17
19	15.5	17.5	18.5	18.5	18.5	147	16.5	17.5	17.5	17.5	18.5
20	16	17.5	19	19.5	19	148	16.5	16.5	17	17.5	17.5
21	16.5	18.5	20	20	20	148.5	16.5	17	16.5	17	17
22	15.5	18	19.5	19.5	19.5	149.5	15.5	16	16	16	15
23	15	17.5	19	19	19	150	15	15.5	16	16	14.5

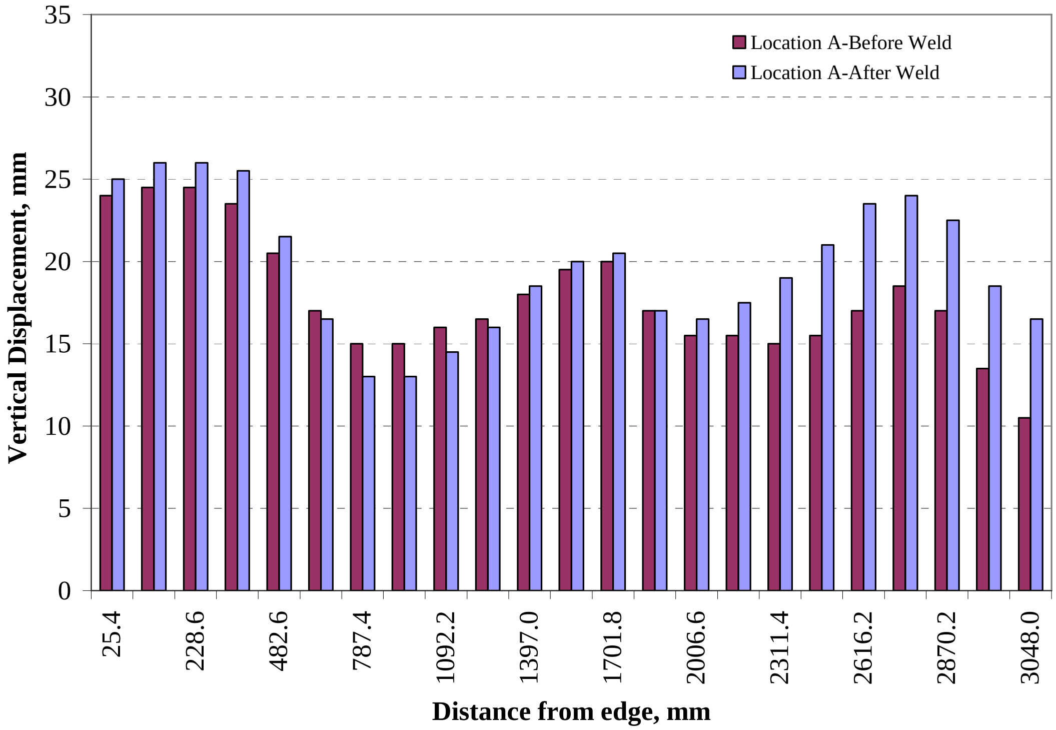


Figure G.1: Plate 3 Location A – Before and After Weld Distortion

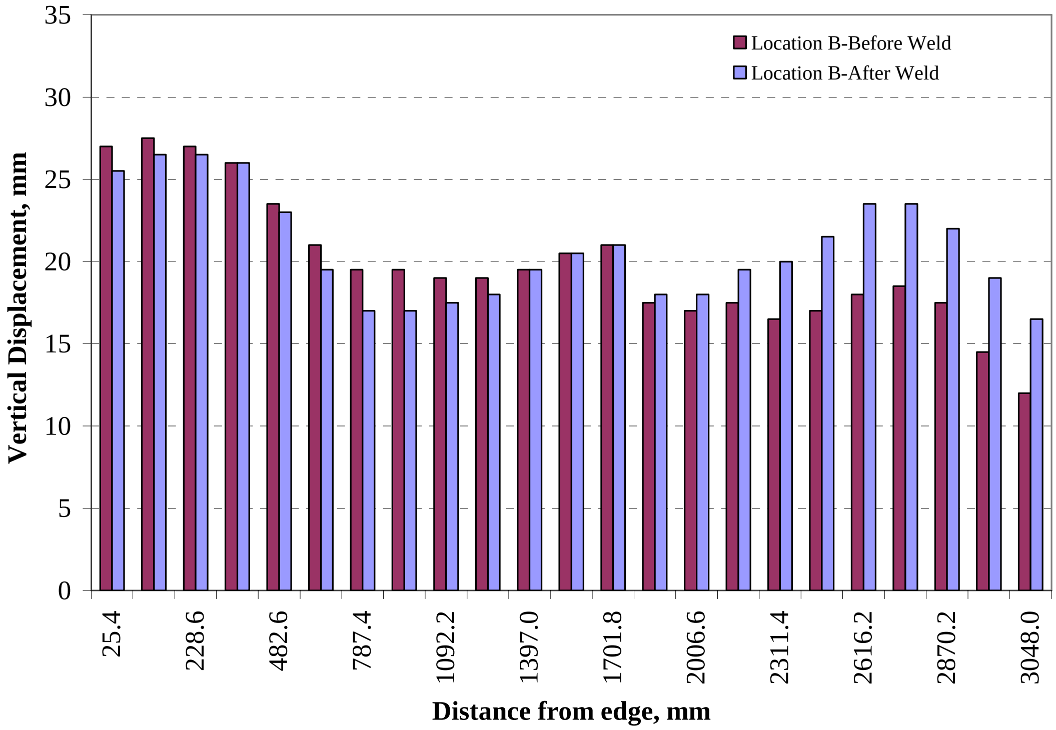


Figure G.2: Plate 3 Location B – Before and After Weld Distortion

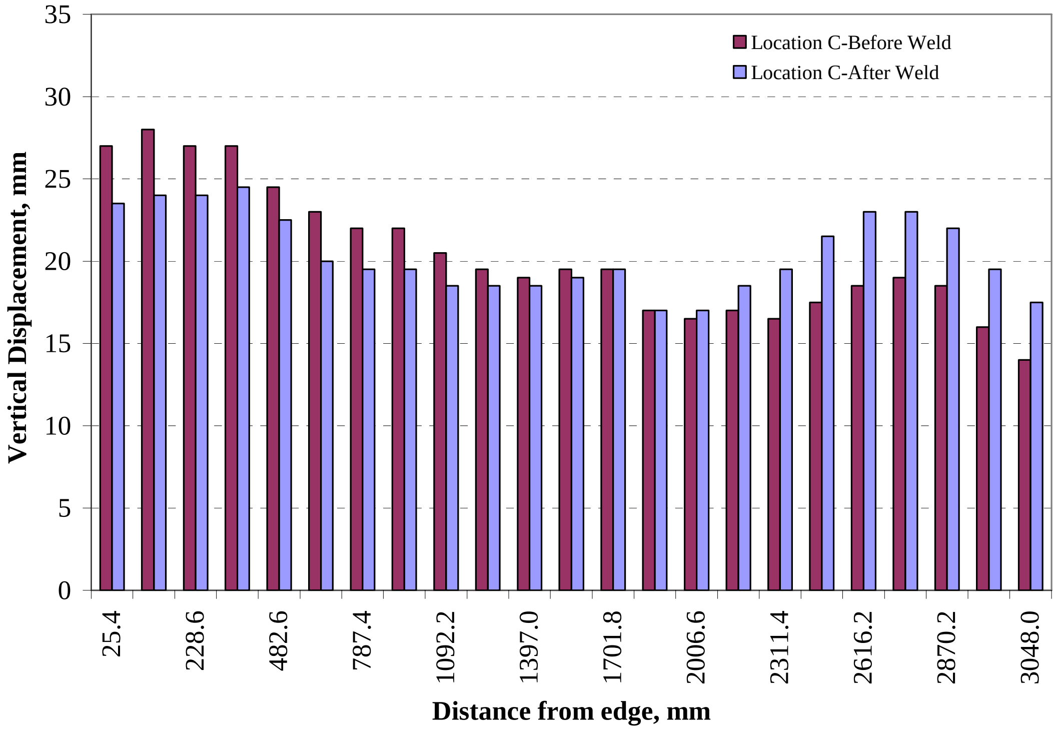


Figure G.3: Plate 3 Location C – Before and After Weld Distortion

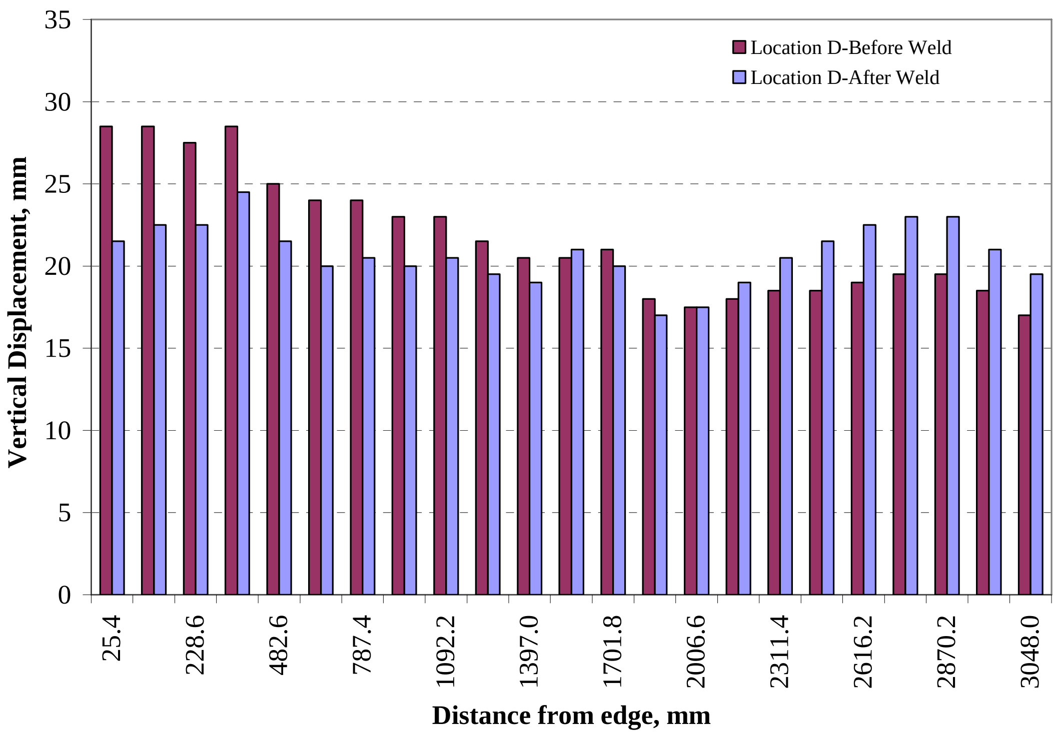


Figure G.4: Plate 3 Location D – Before and After Weld Distortion

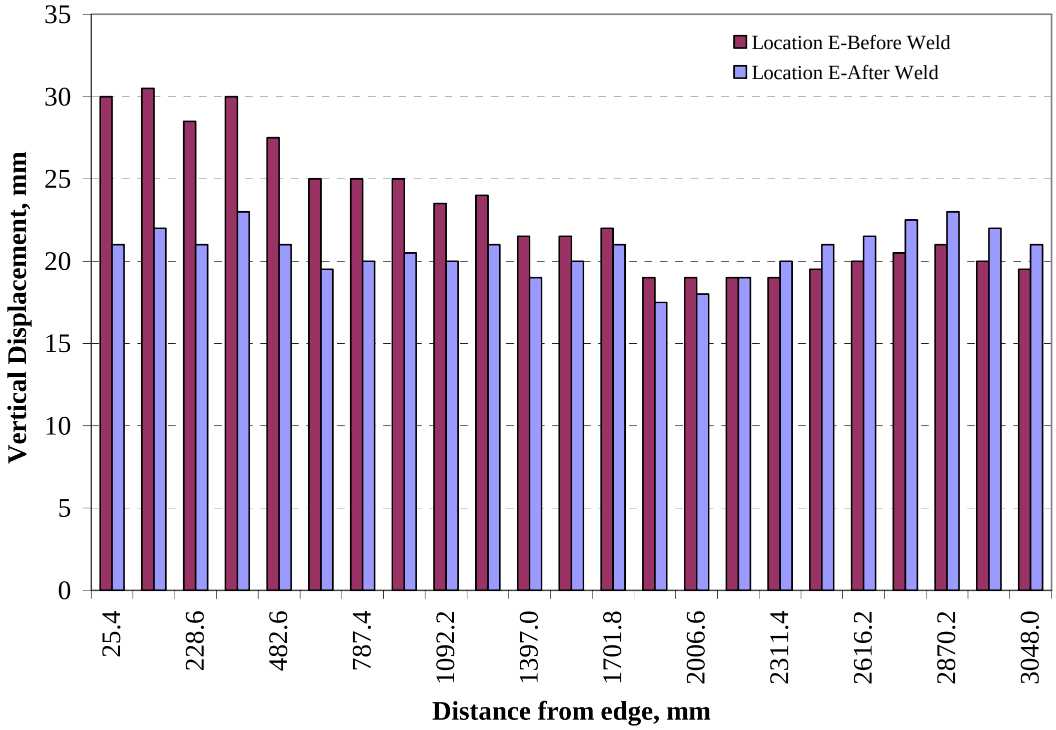


Figure G.5: Plate 3 Location E – Before and After Weld Distortion

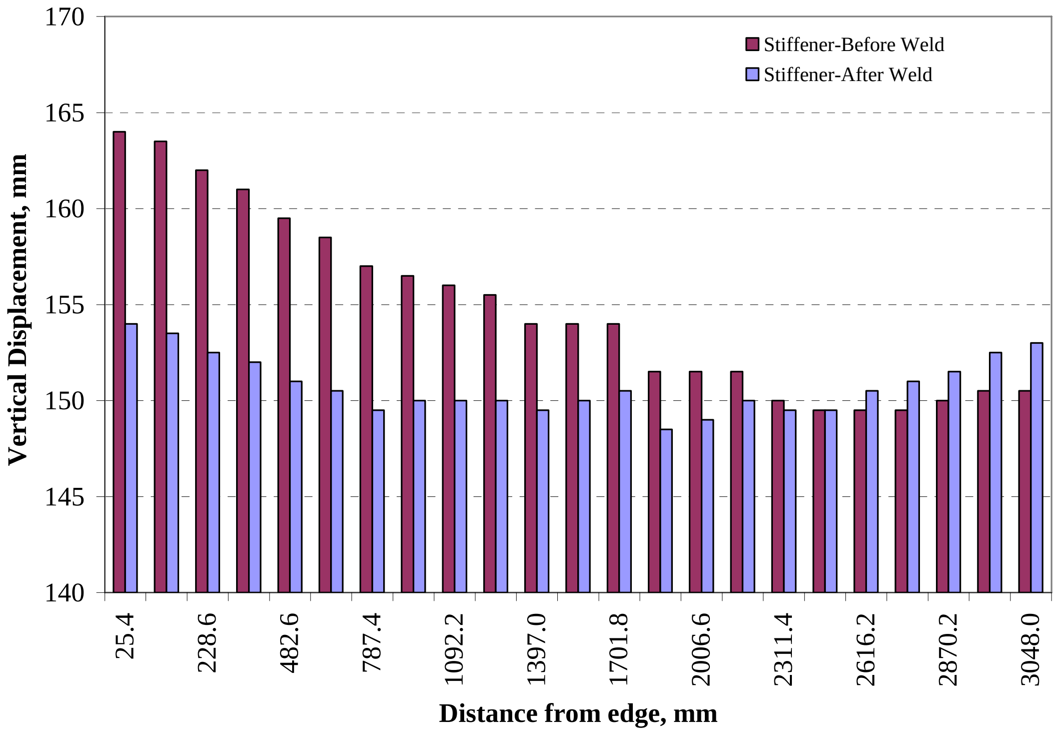


Figure G.6: Plate 3 At Stiffener – Before and After Weld Distortion

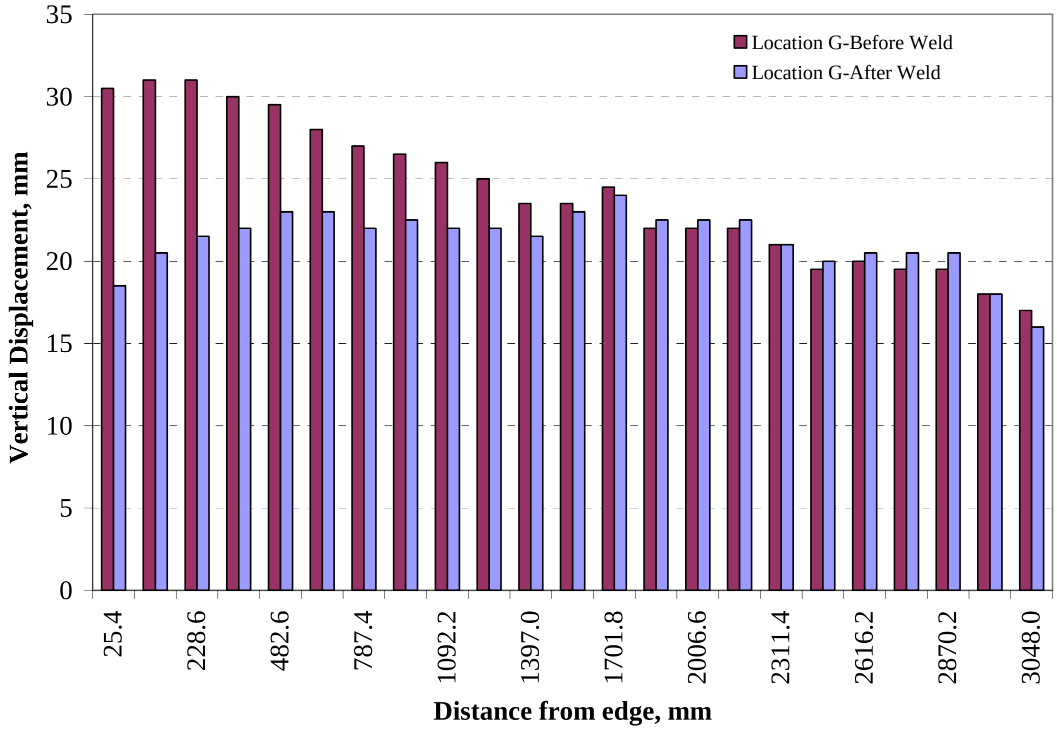


Figure G.7: Plate 3 Location G – Before and After Weld Distortion

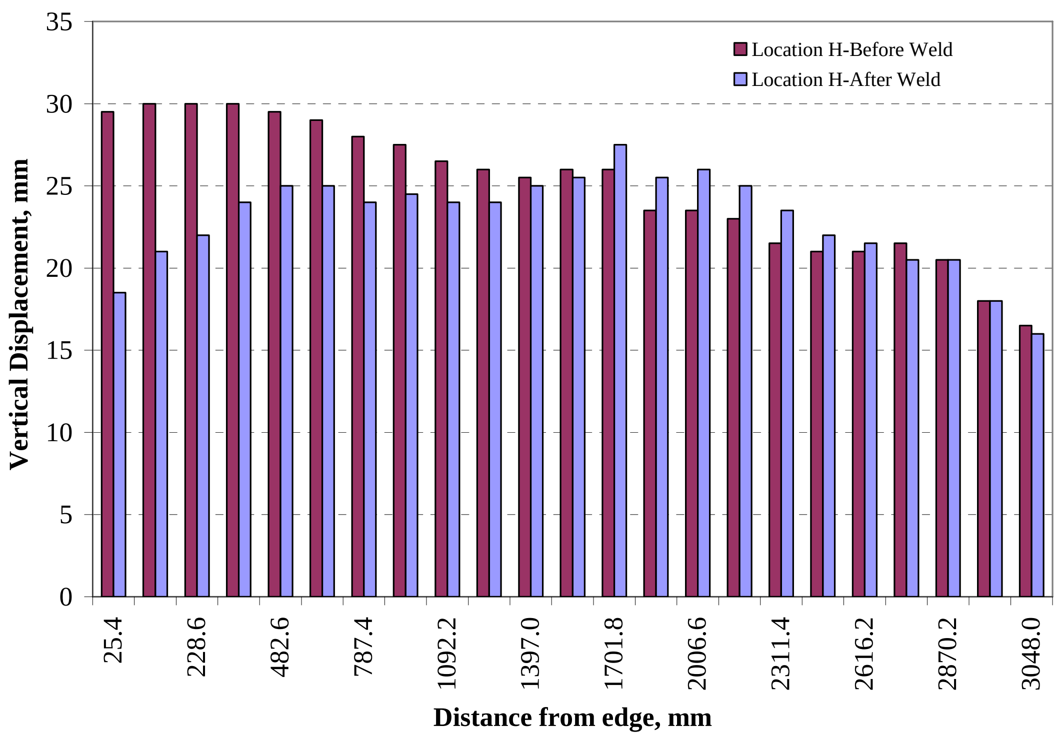


Figure G.8: Plate 3 Location H – Before and After Weld Distortion

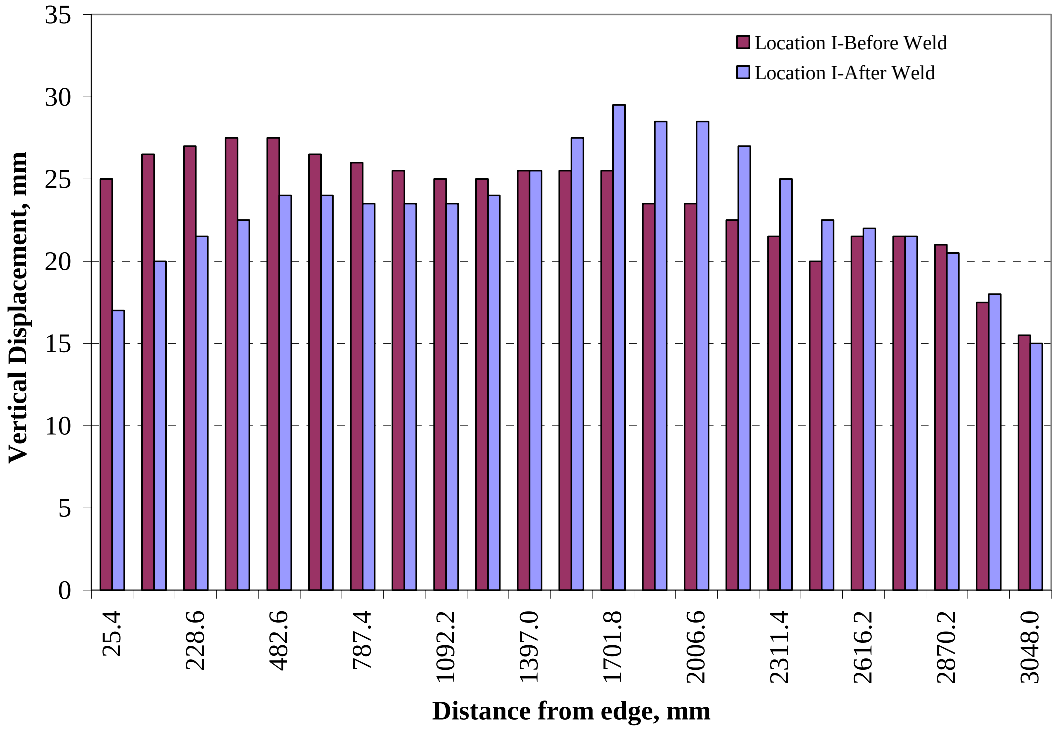


Figure G.9: Plate 3 Location I – Before and After Weld Distortion

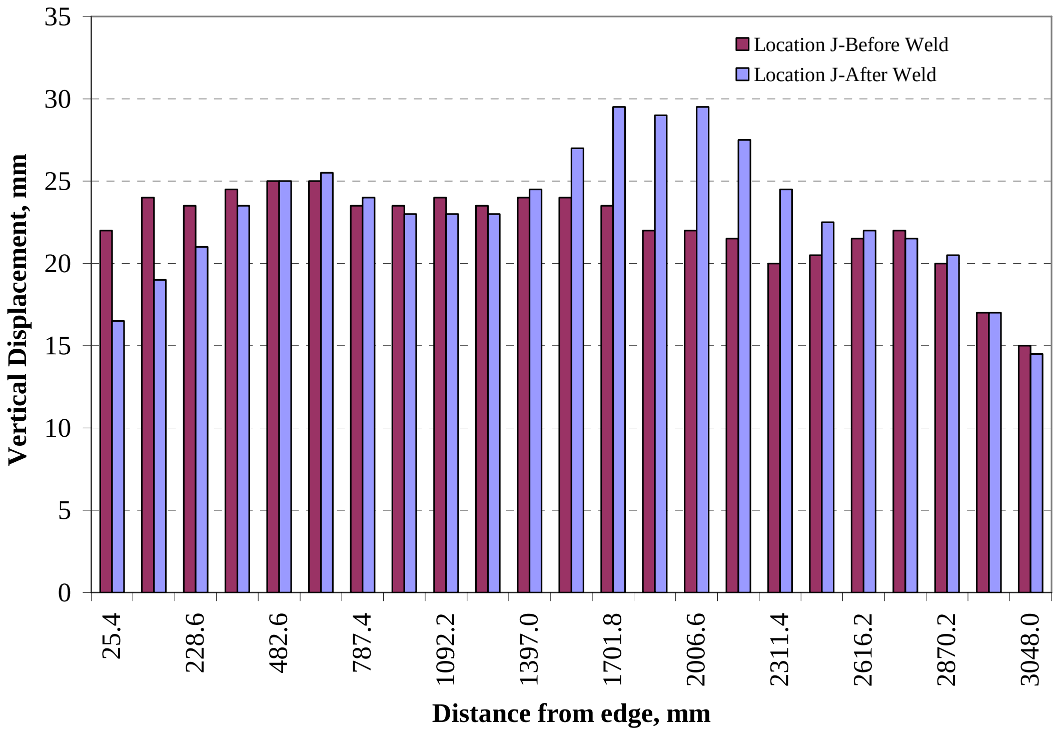


Figure G.10: Plate 3 Location J – Before and After Weld Distortion

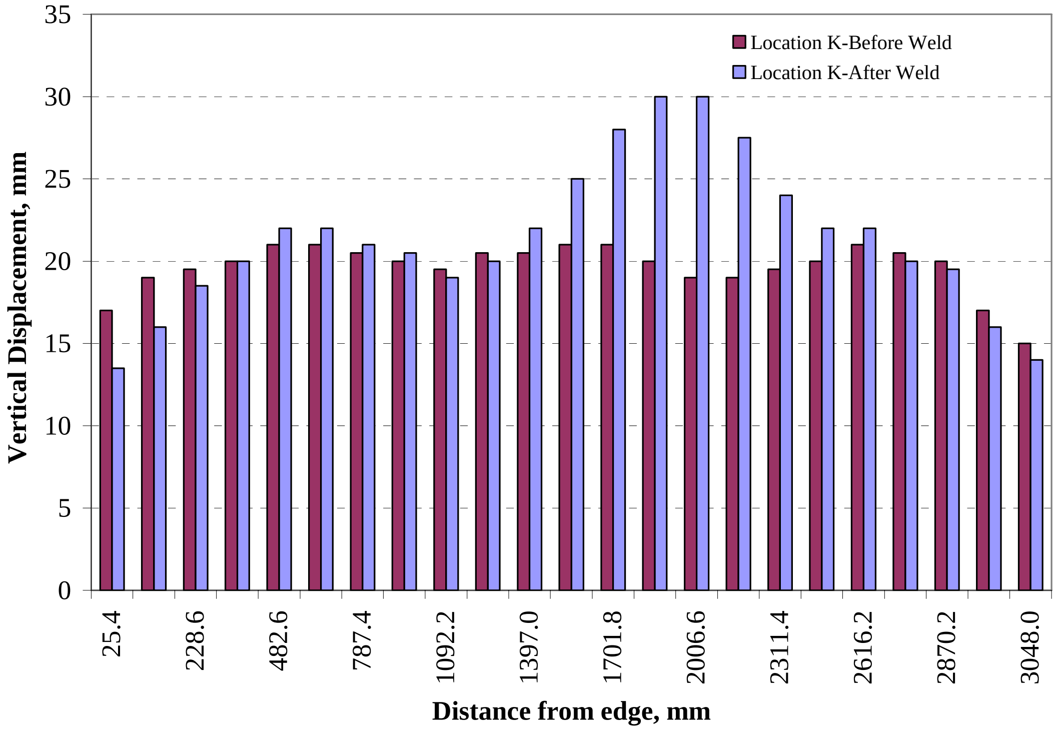


Figure G.11: Plate 3 Location K – Before and After Weld Distortion

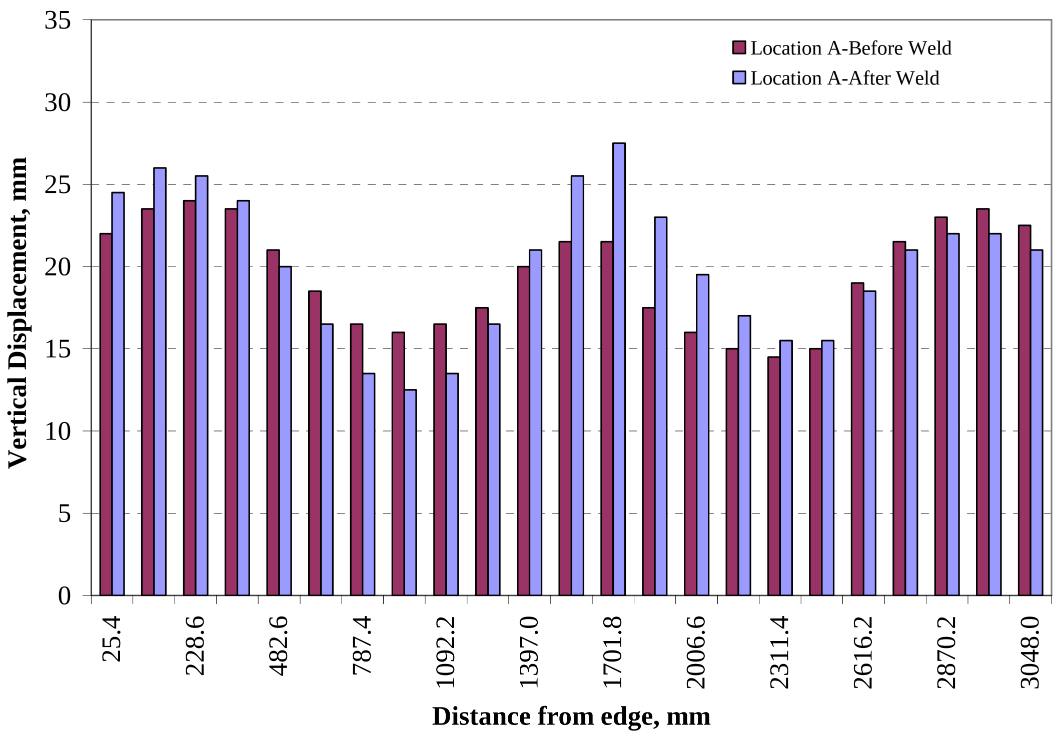


Figure G.12: Plate 7 Location A – Before and After Weld Distortion

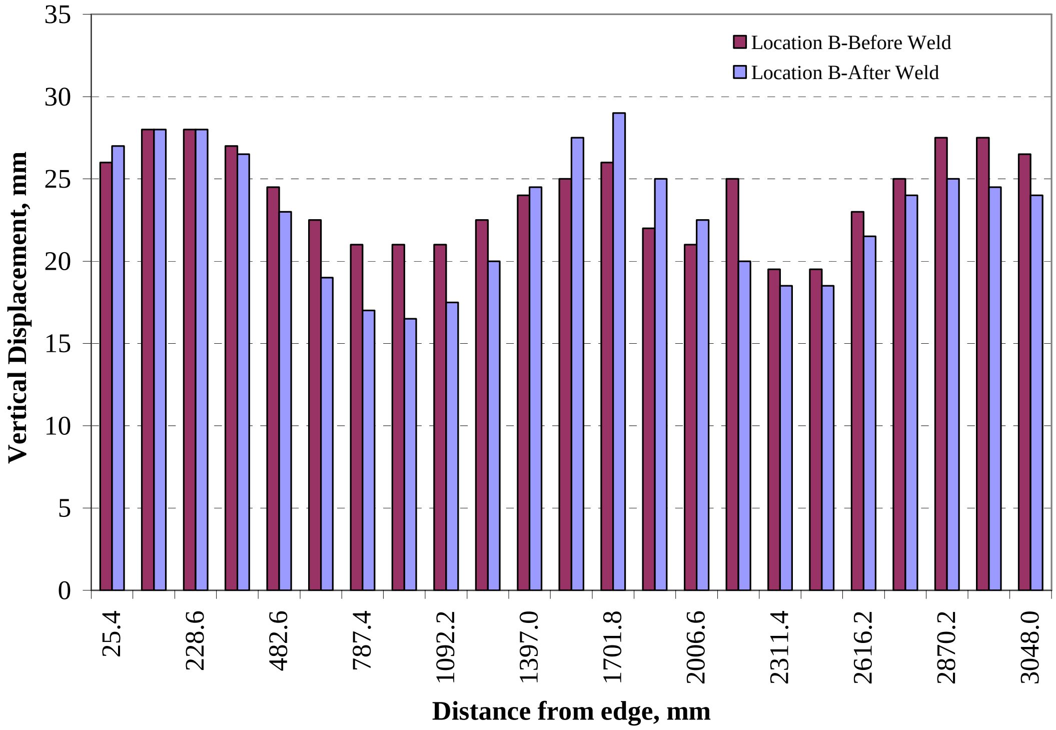


Figure G.13: Plate 7 Location B – Before and After Weld Distortion

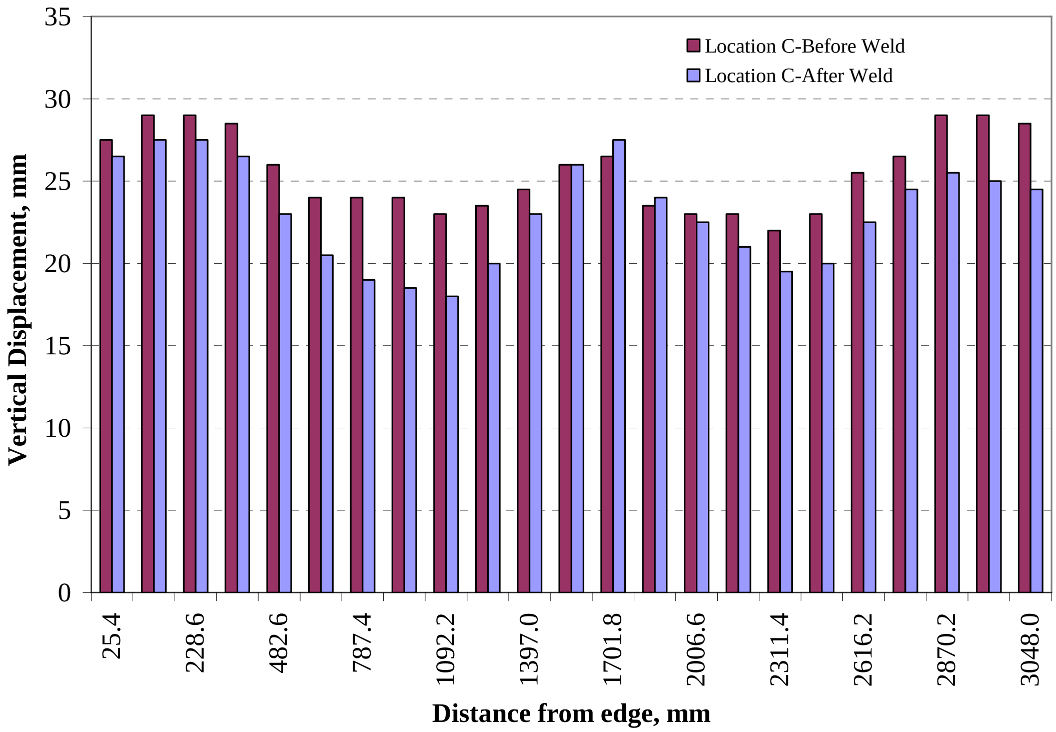


Figure G.14: Plate 7 Location C – Before and After Weld Distortion

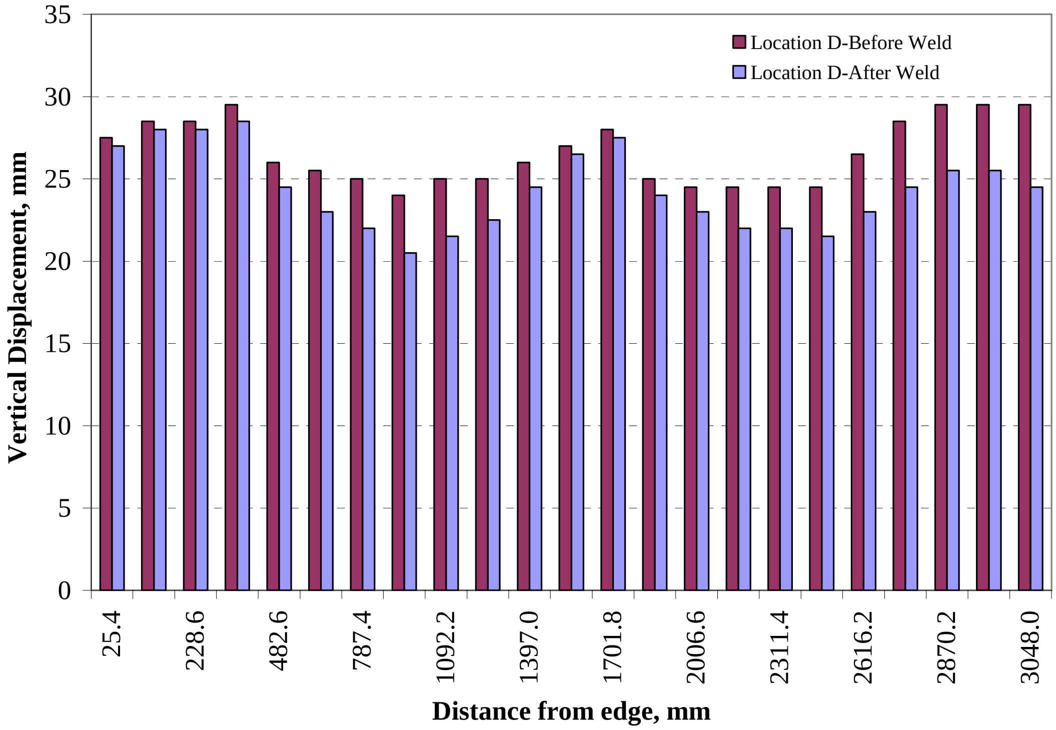


Figure G.15: Plate 7 Location D – Before and After Weld Distortion

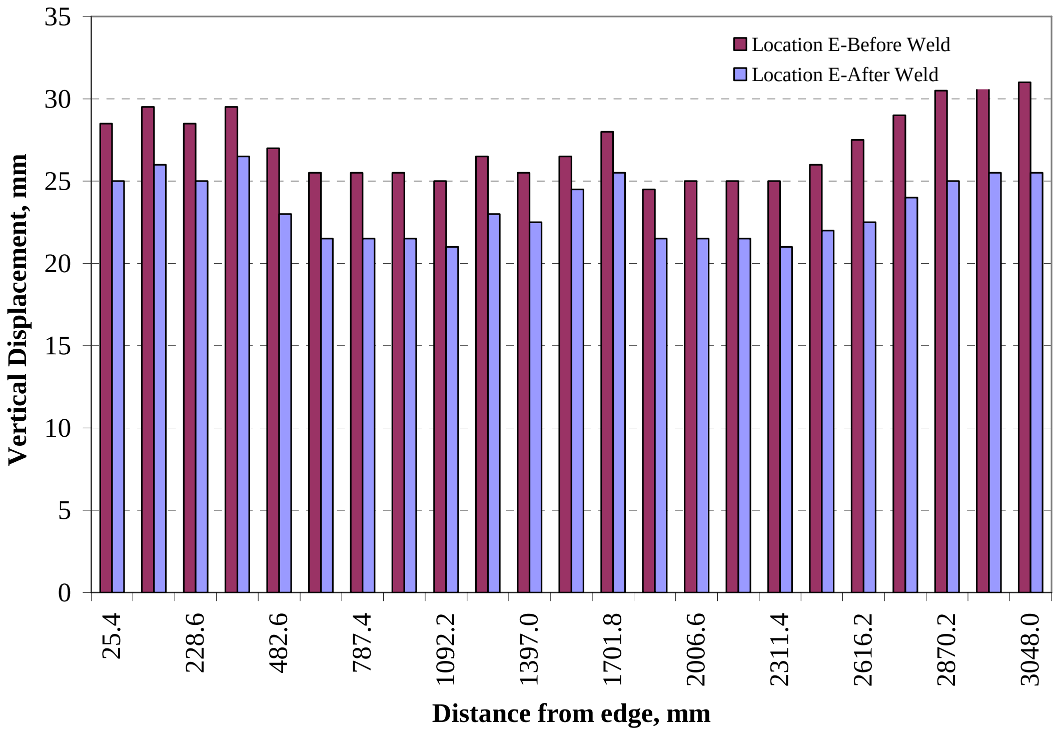


Figure G.16: Plate 7 Location E – Before and After Weld Distortion

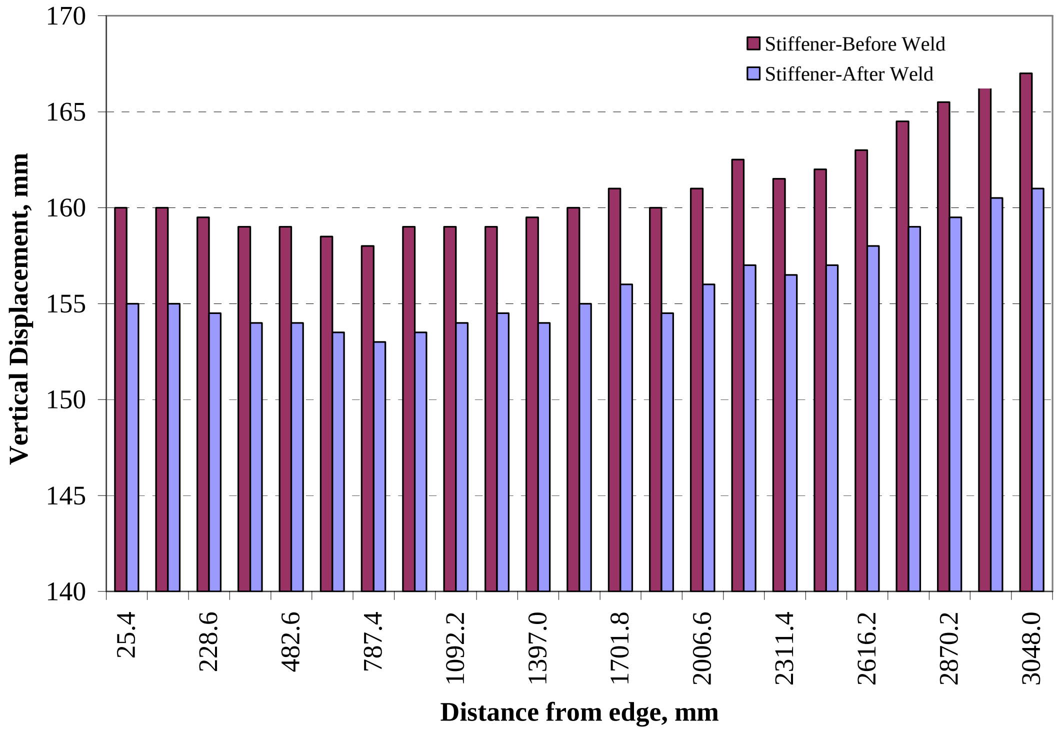


Figure G.17: Plate 7 At Stiffener – Before and After Weld Distortion

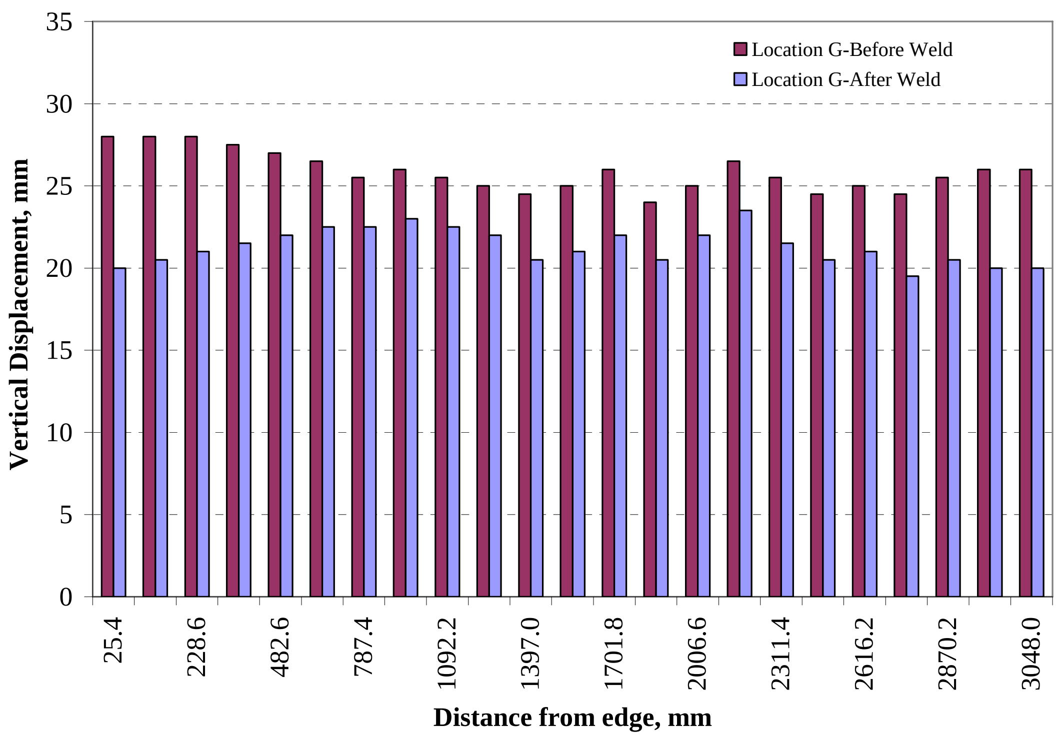


Figure G.18: Plate 7 Location G – Before and After Weld Distortion

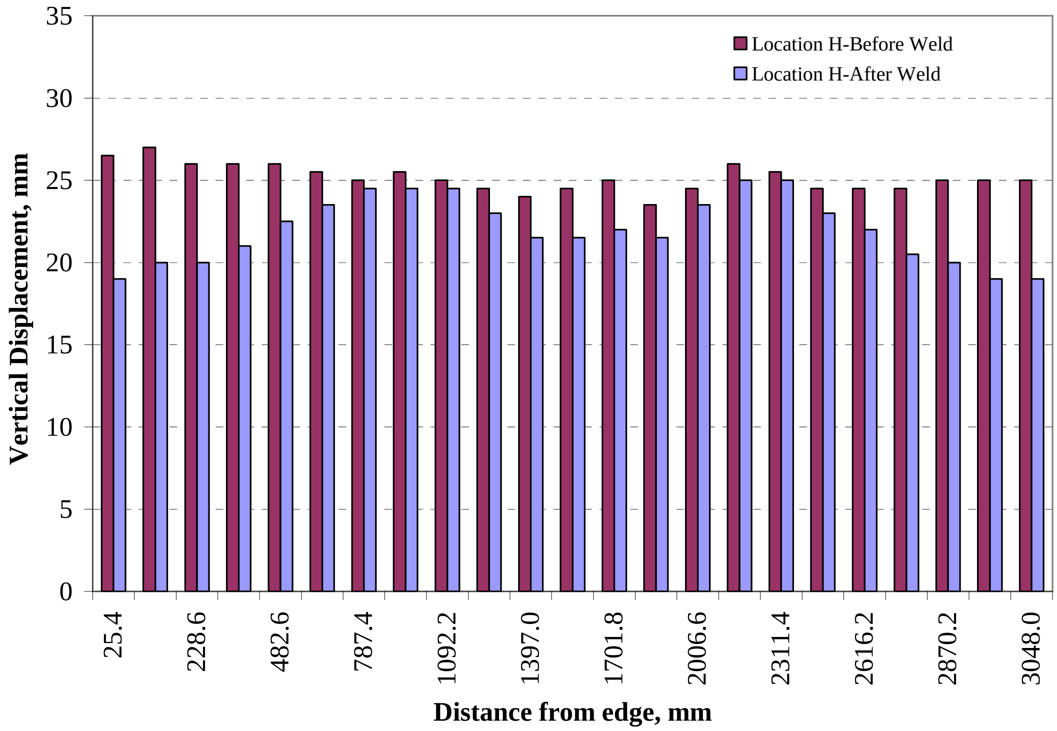


Figure G.19: Plate 7 Location H – Before and After Weld Distortion

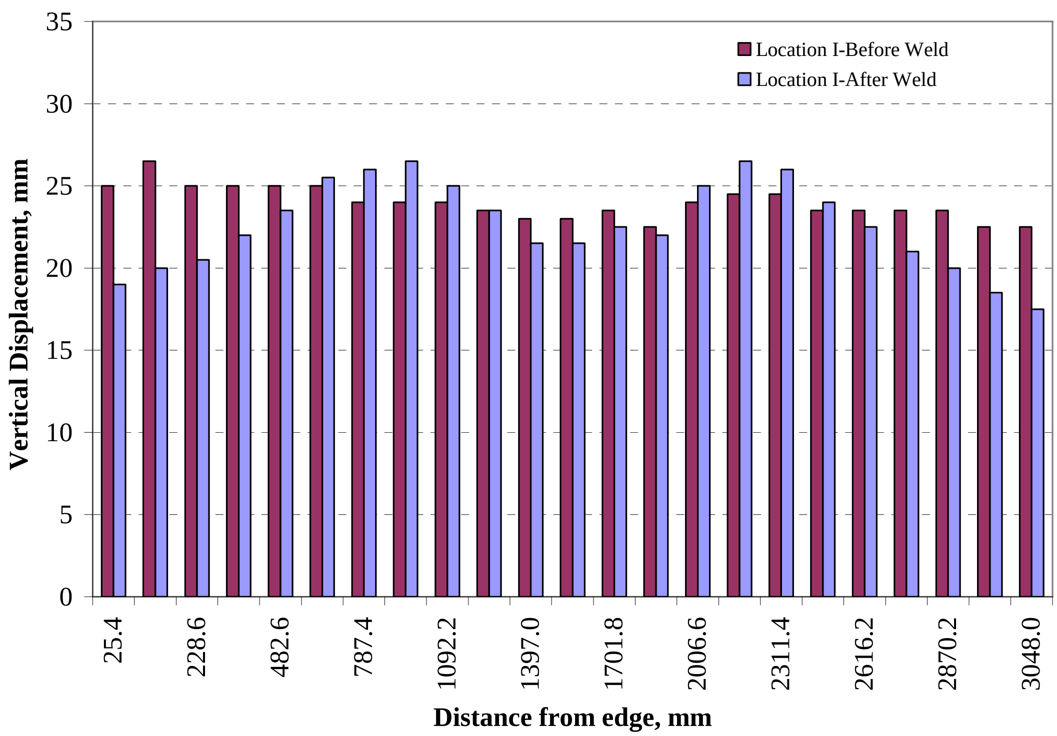


Figure G.20: Plate 7 Location I – Before and After Weld Distortion

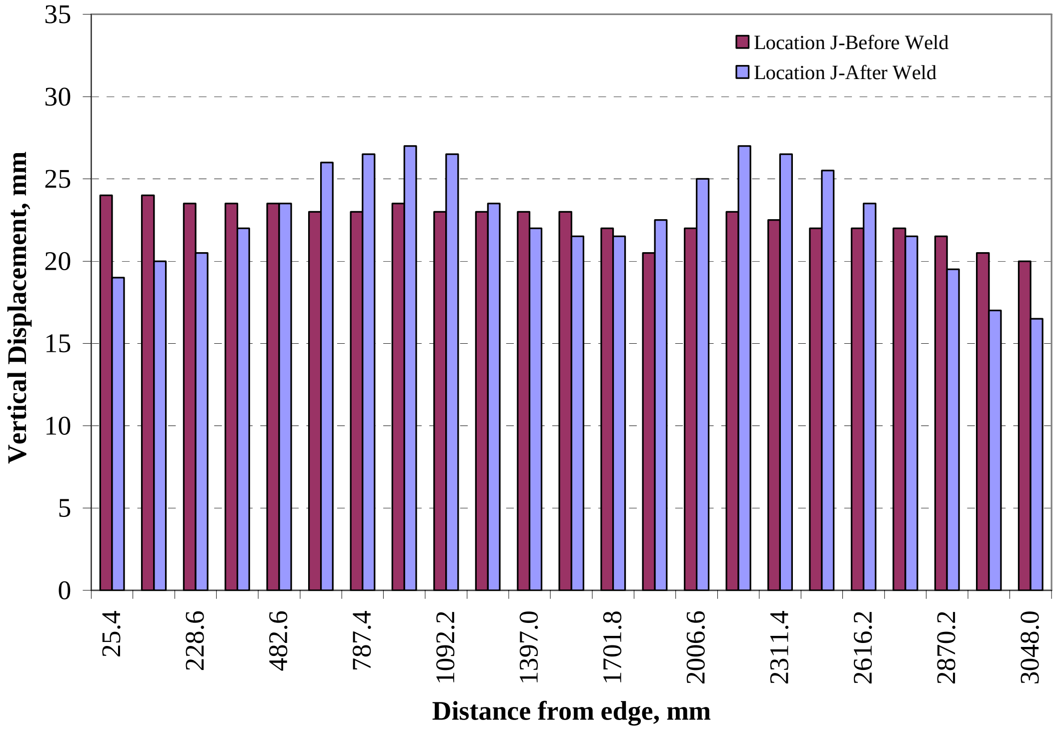


Figure G.21: Plate 7 Location J – Before and After Weld Distortion

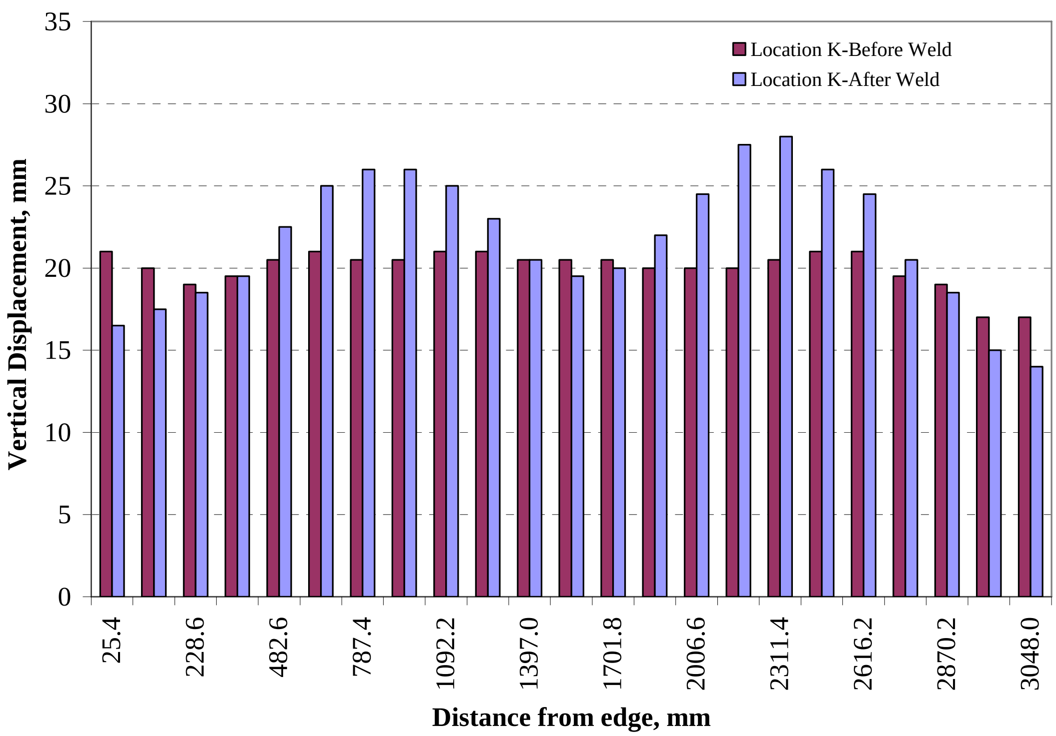


Figure G.22: Plate 7 Location K – Before and After Weld Distortion

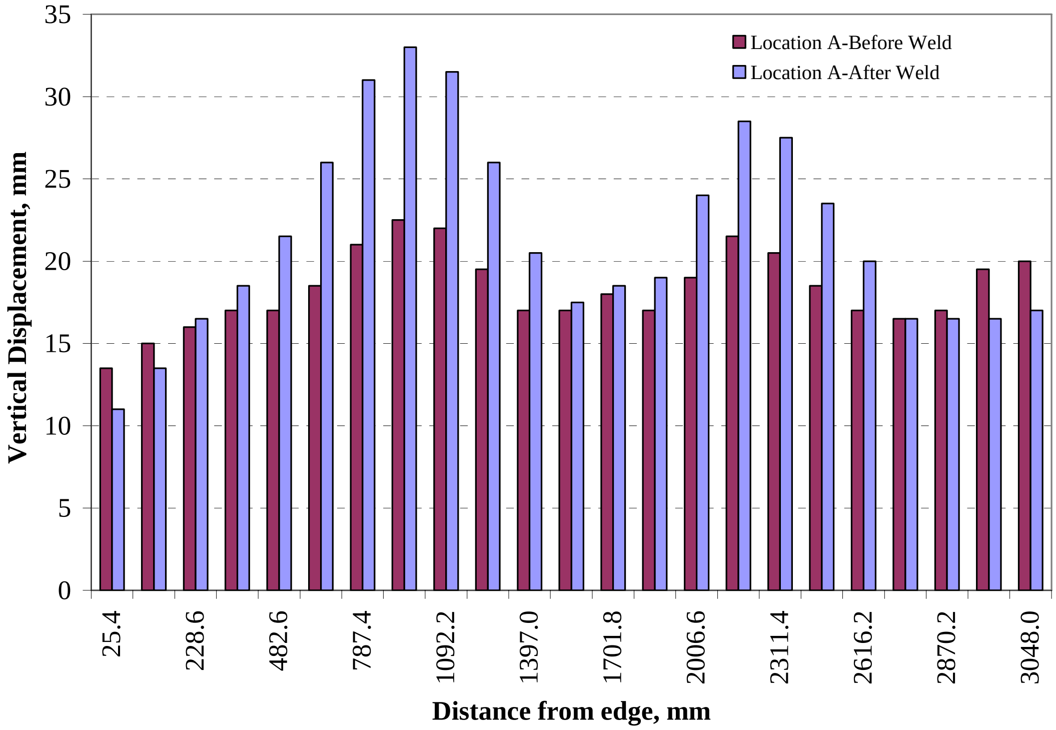


Figure G.23: Plate 8 Location A – Before and After Weld Distortion

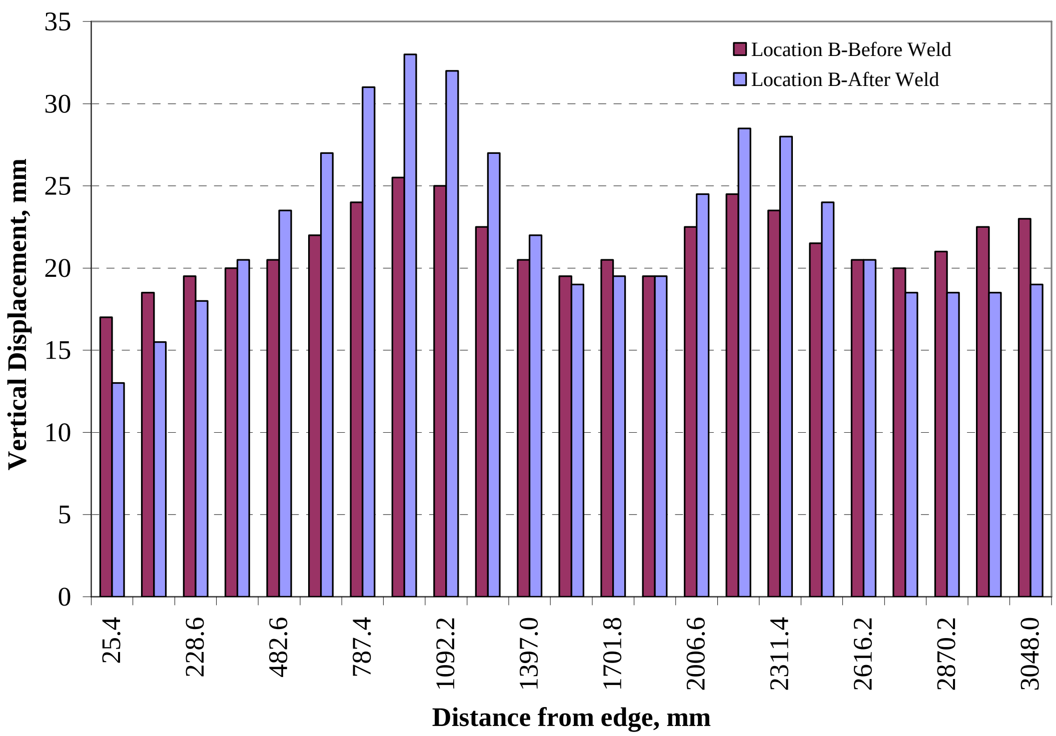


Figure G.24: Plate 8 Location B – Before and After Weld Distortion

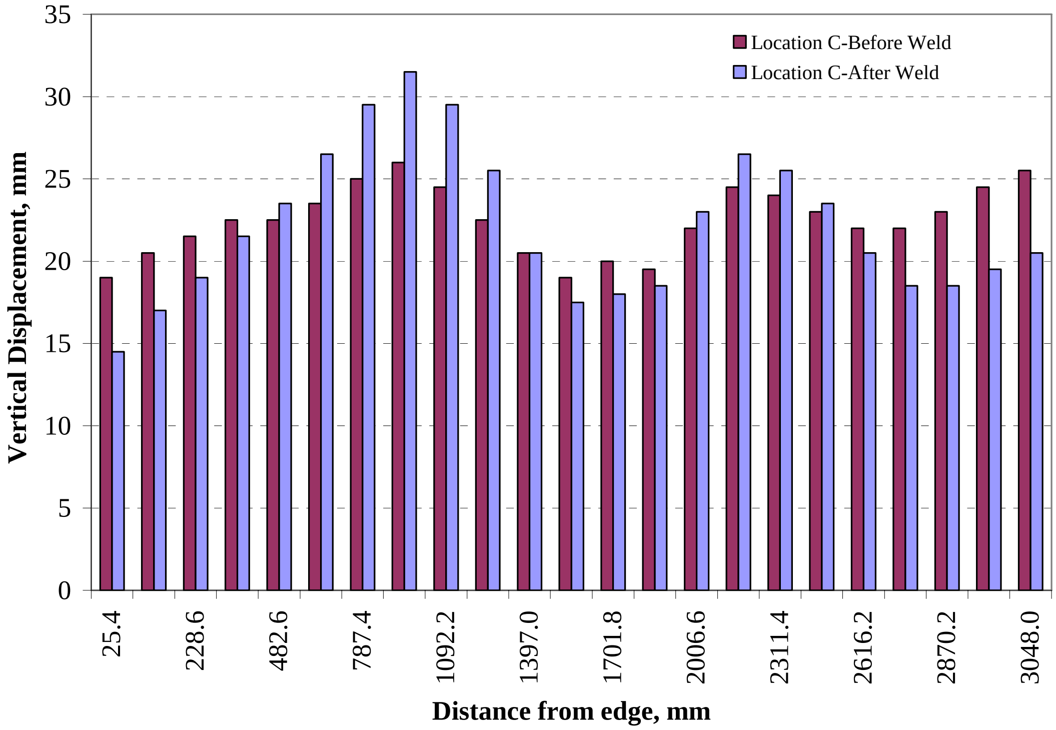


Figure G.25: Plate 8 Location C – Before and After Weld Distortion

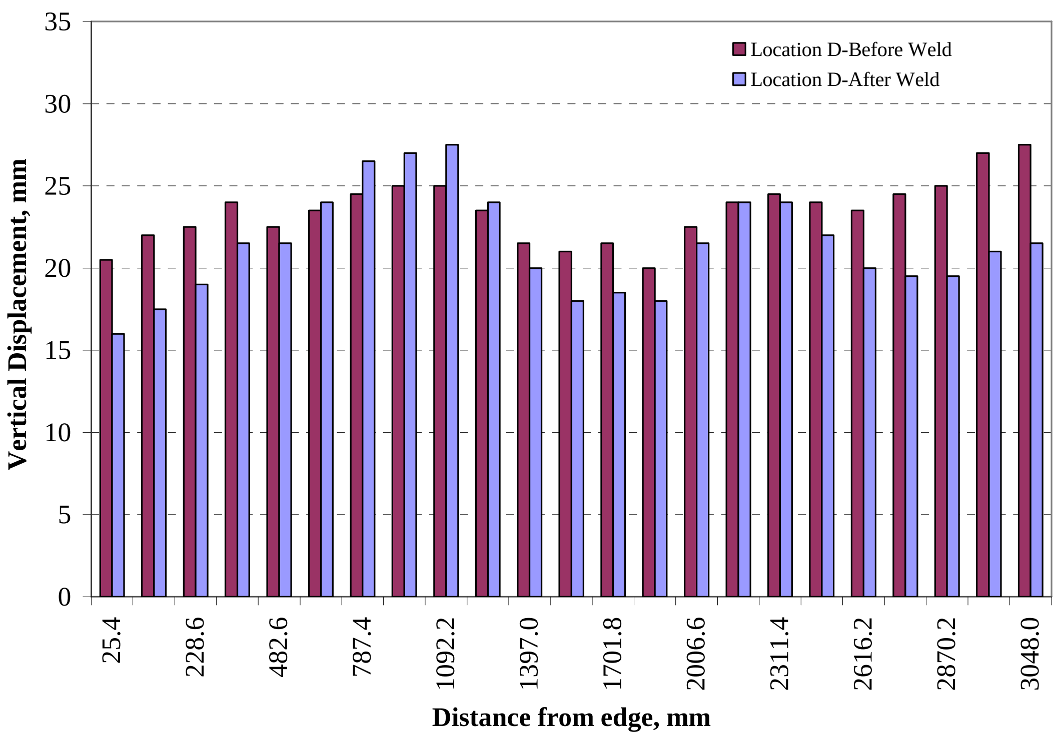


Figure G.26: Plate 8 Location D – Before and After Weld Distortion

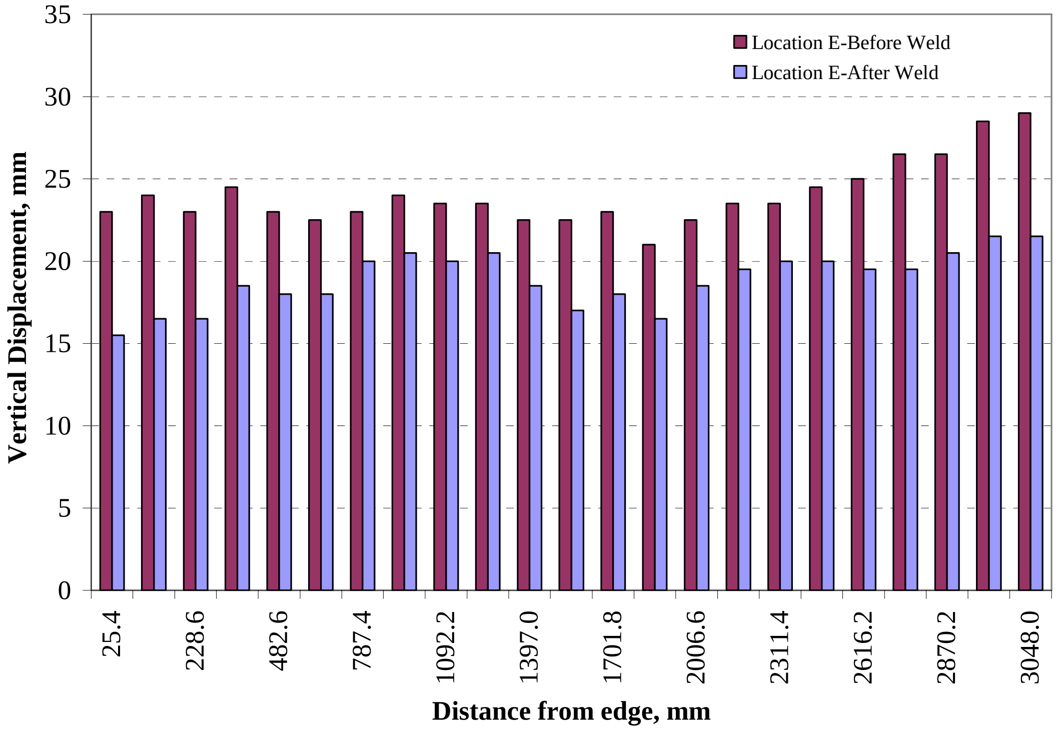


Figure G.27: Plate 8 Location E – Before and After Weld Distortion

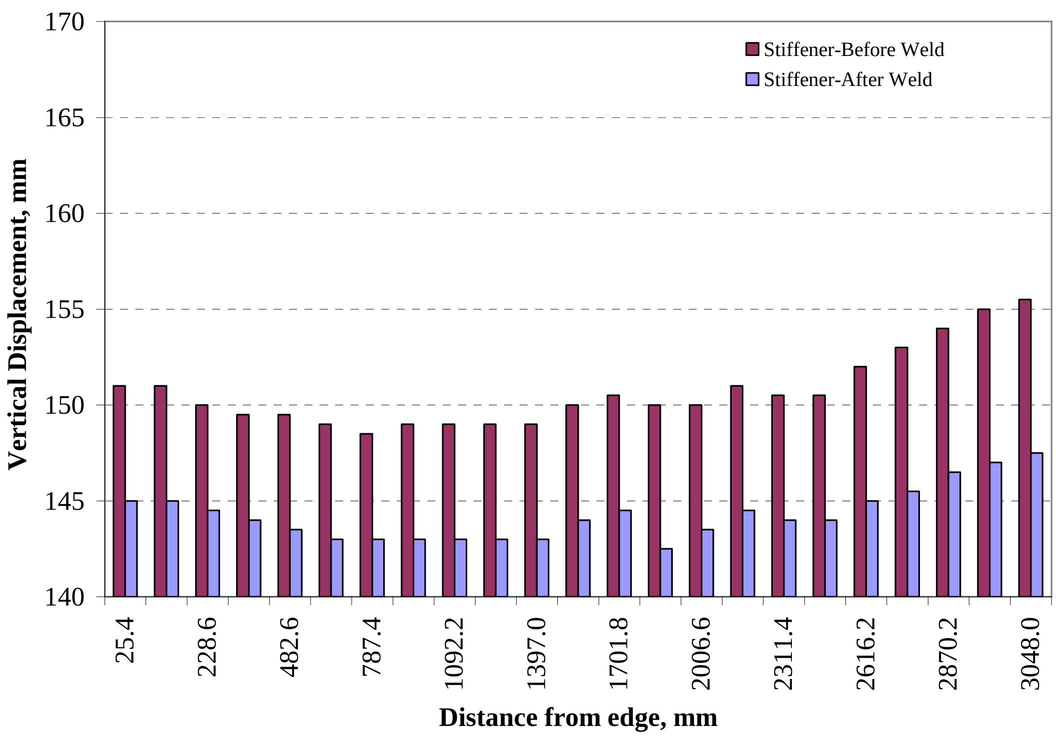


Figure G.28: Plate 8 At Stiffener – Before and After Weld Distortion

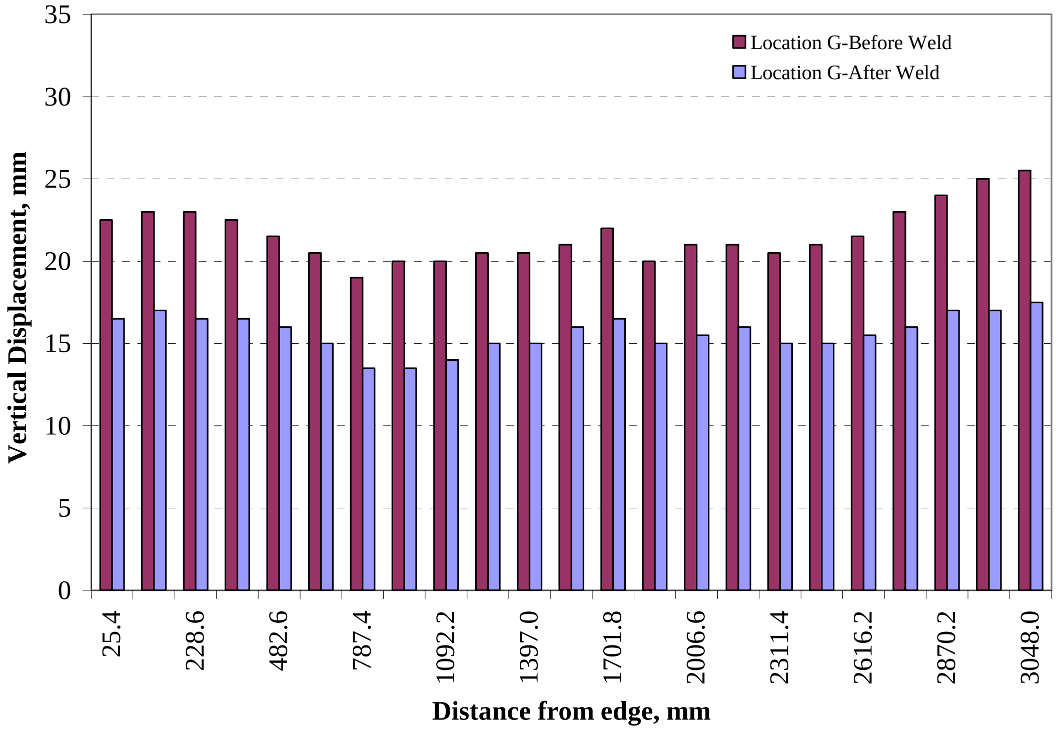


Figure G.29: Plate 8 Location G – Before and After Weld Distortion

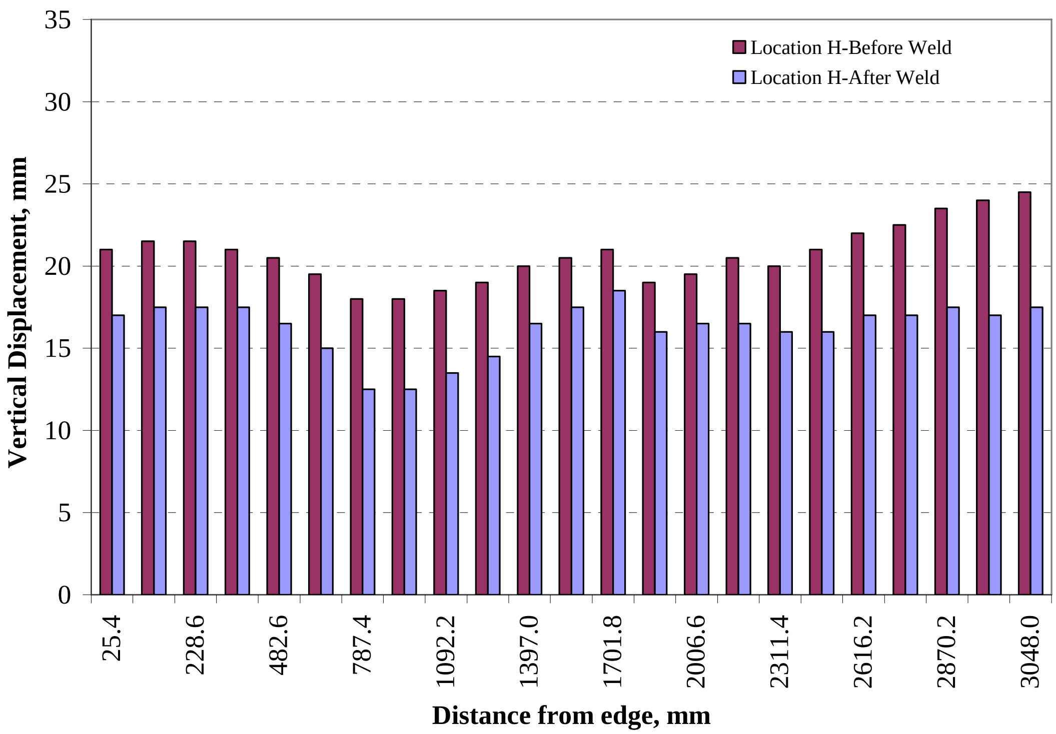


Figure G.30: Plate 8 Location H – Before and After Weld Distortion

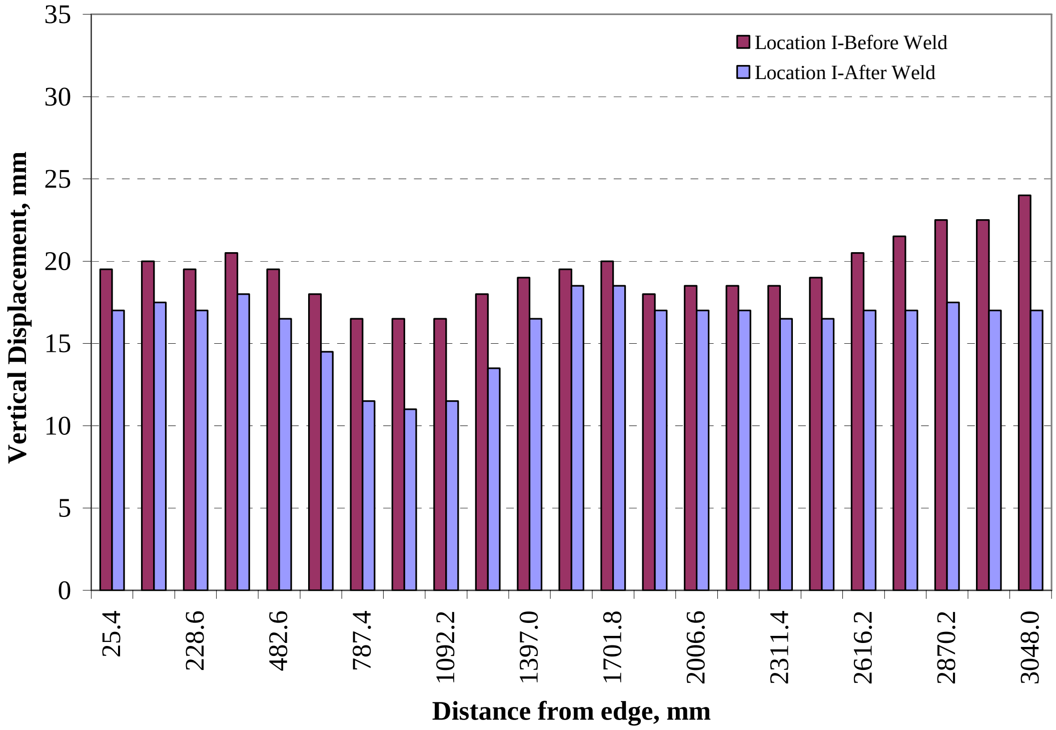


Figure G.31: Plate 8 Location I – Before and After Weld Distortion

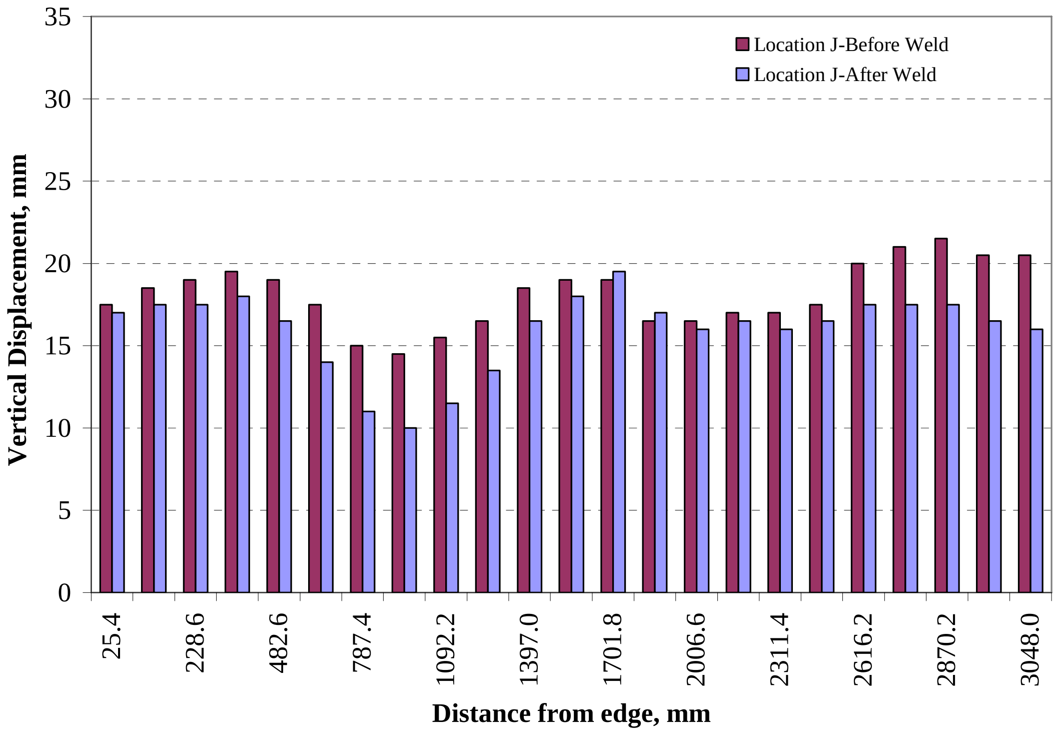


Figure G.32: Plate 8 Location J – Before and After Weld Distortion

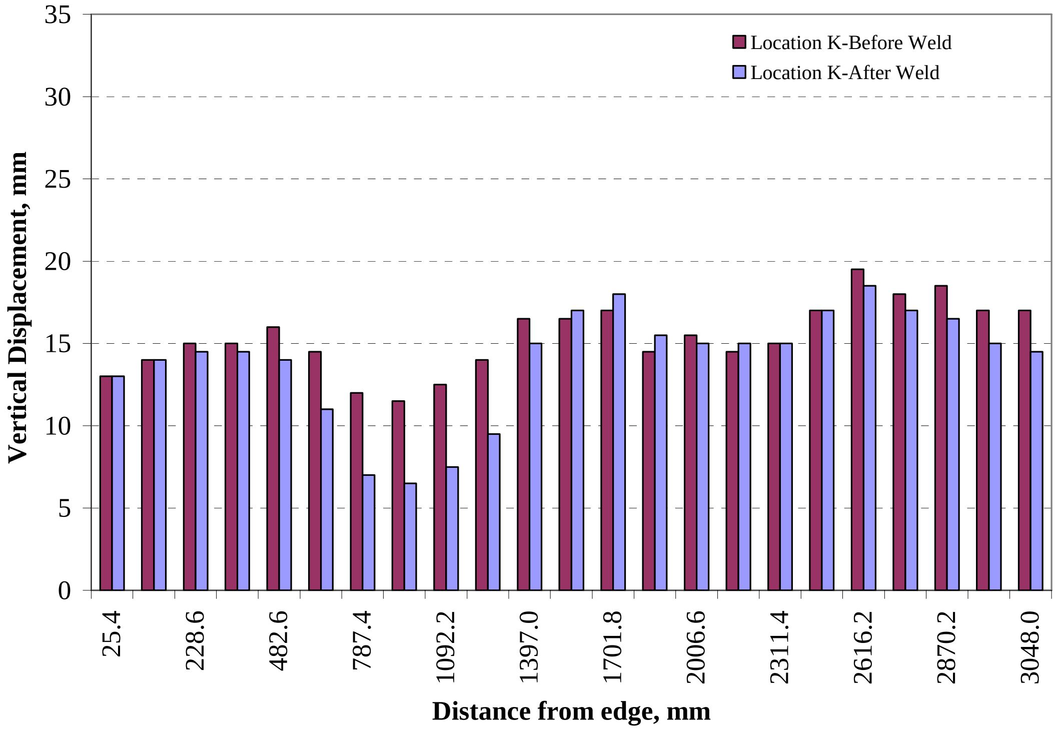


Figure G.33: Plate 8 Location K – Before and After Weld Distortion

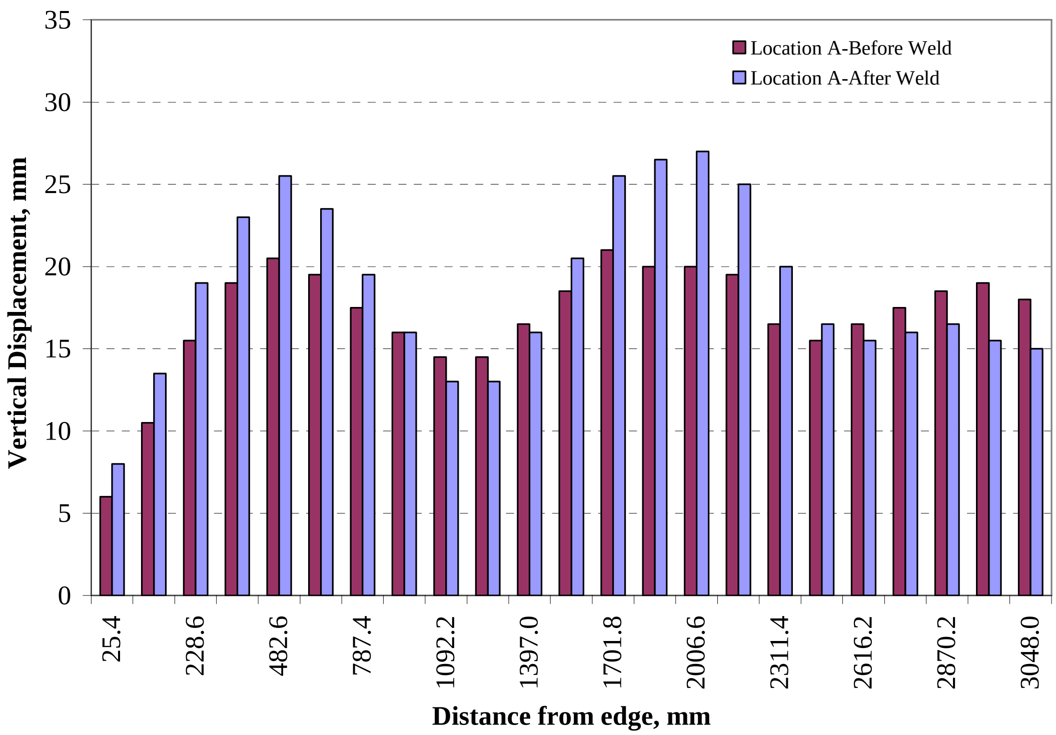


Figure G.34: Plate 9 Location A – Before and After Weld Distortion

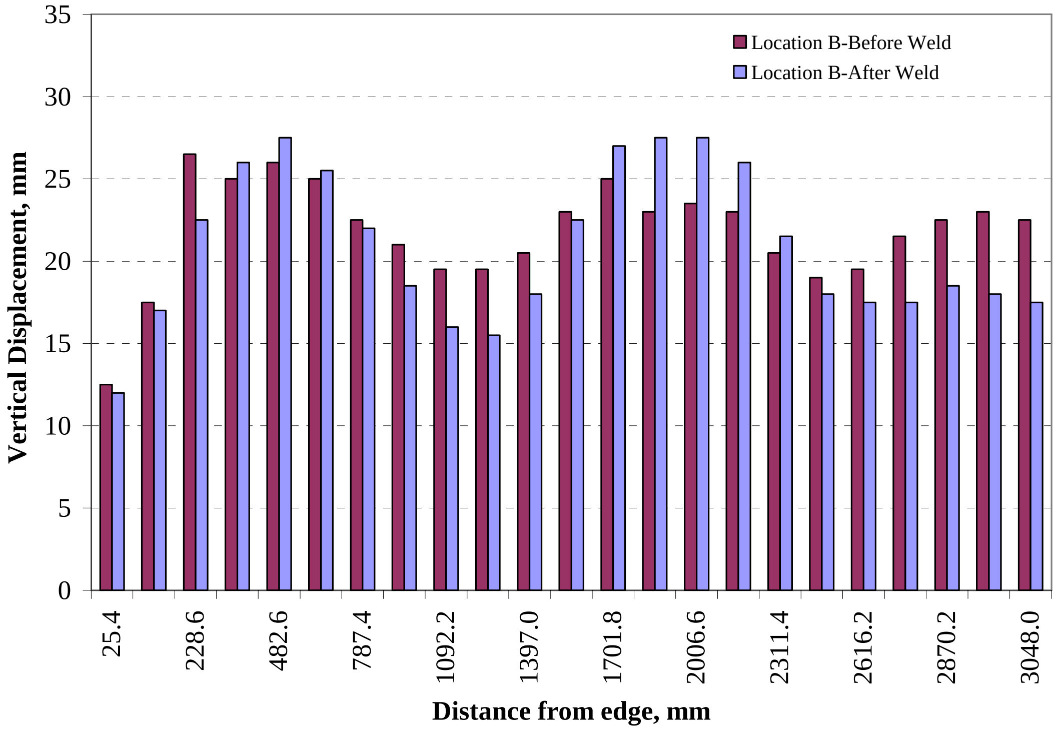


Figure G.35: Plate 9 Location B – Before and After Weld Distortion

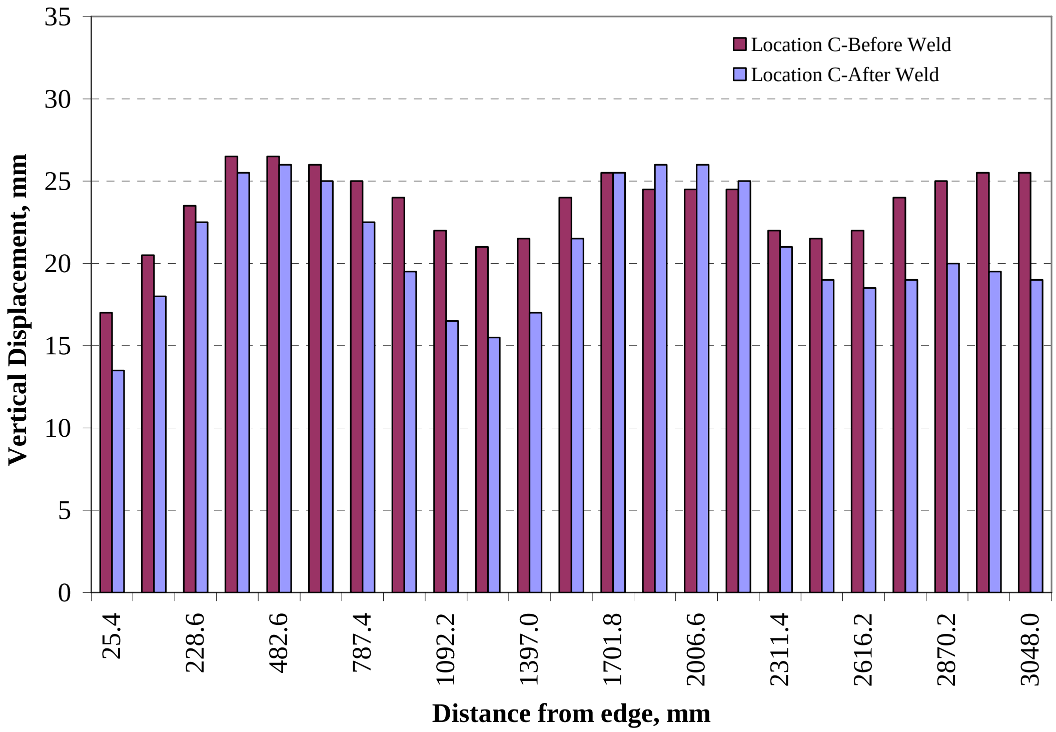


Figure G.36: Plate 9 Location C – Before and After Weld Distortion

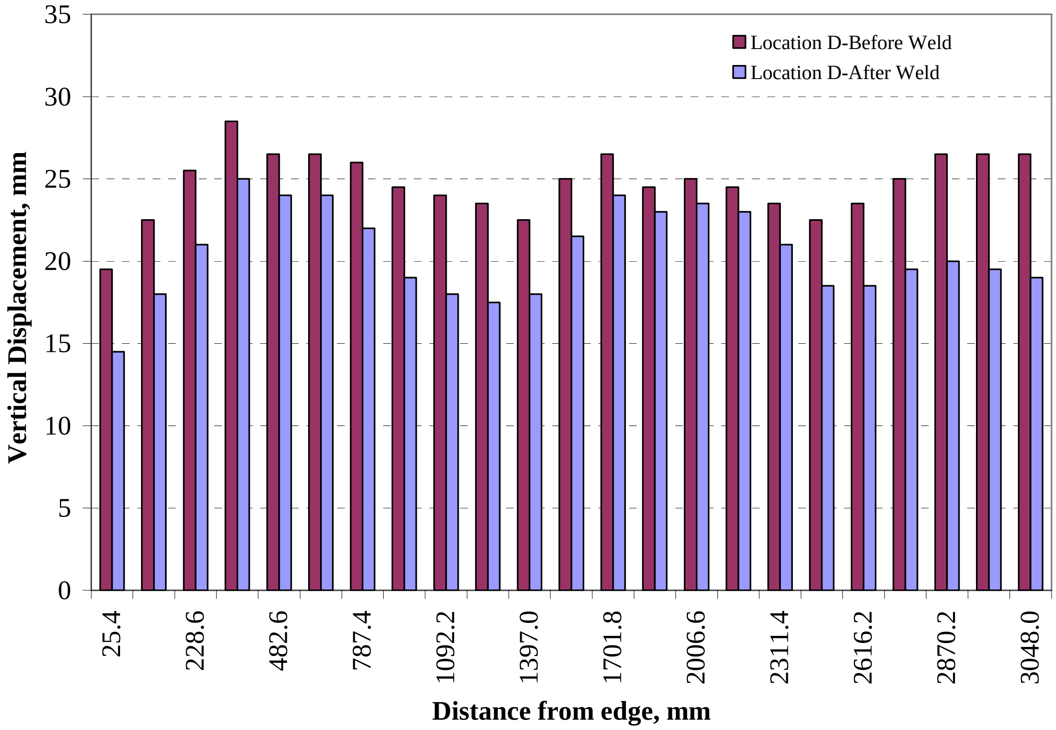


Figure G.37: Plate 9 Location D – Before and After Weld Distortion

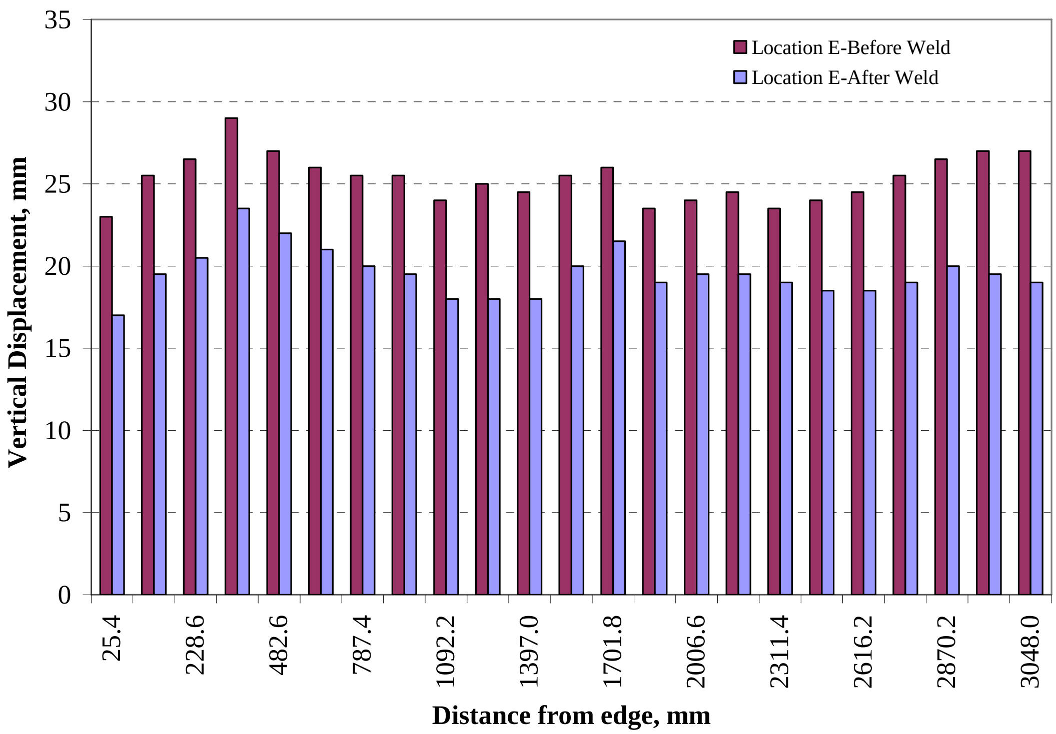


Figure G.38: Plate 9 Location E – Before and After Weld Distortion

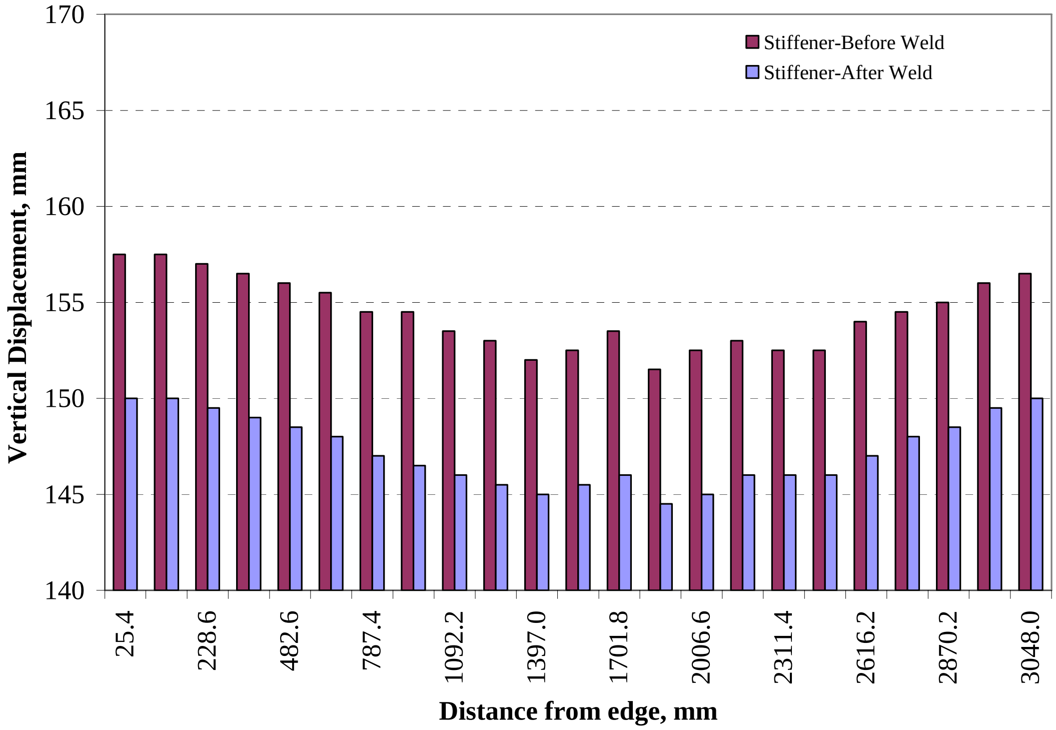


Figure G.39: Plate 9 At Stiffener – Before and After Weld Distortion

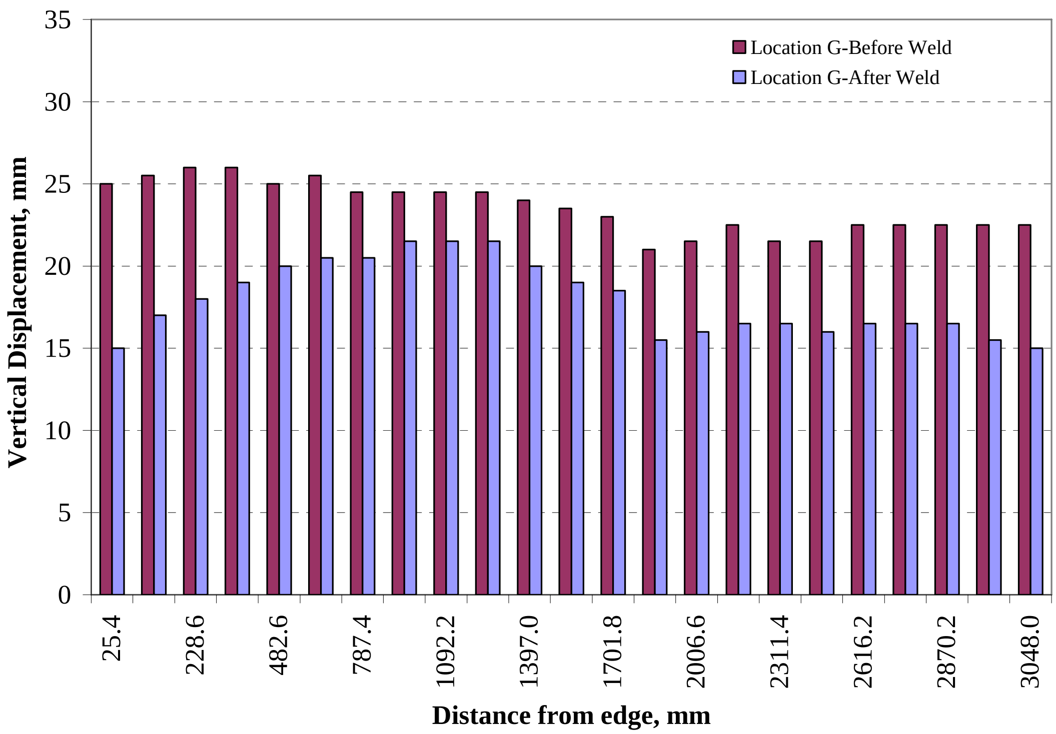


Figure G.40: Plate 9 Location G – Before and After Weld Distortion

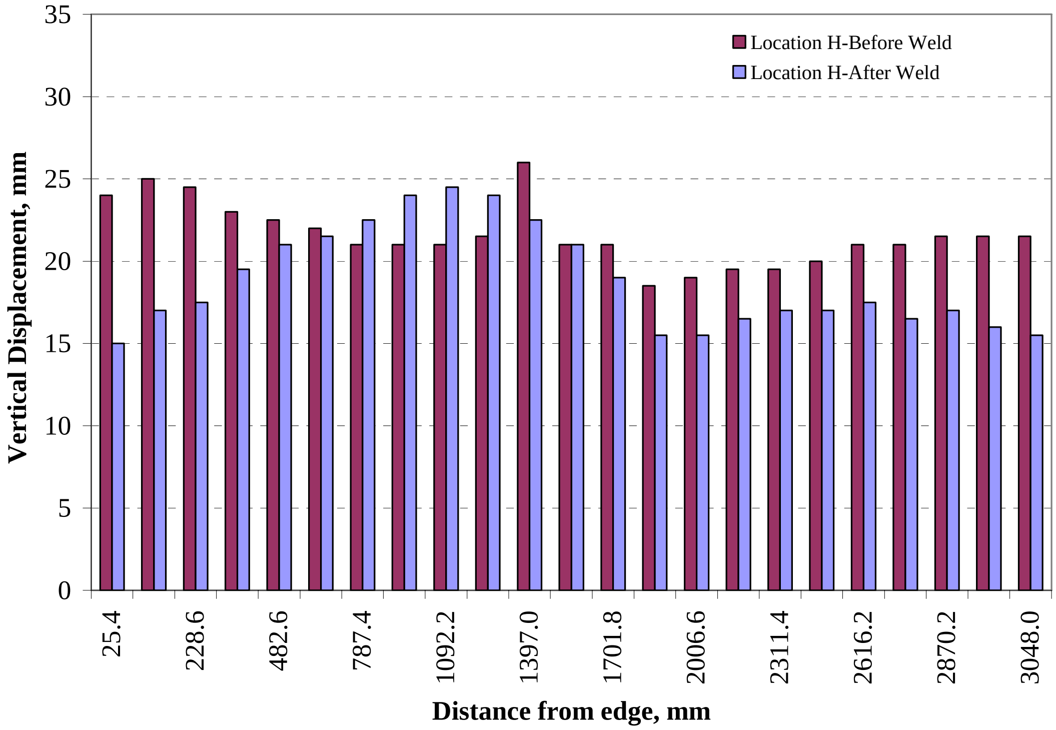


Figure G.41: Plate 9 Location H – Before and After Weld Distortion

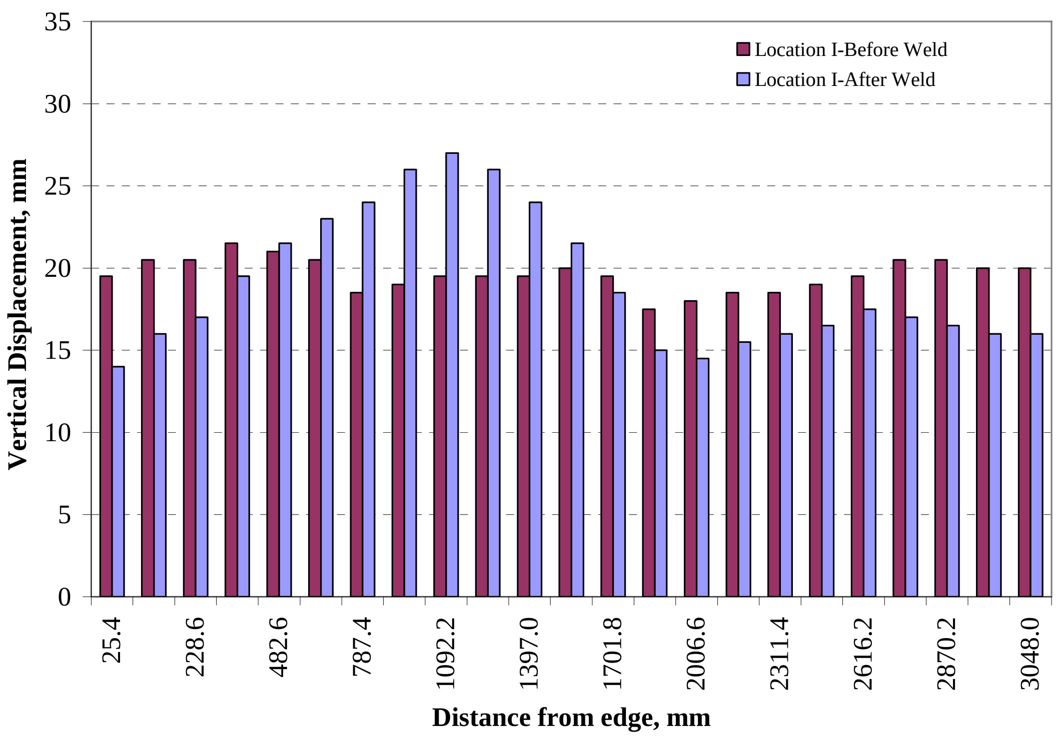


Figure G.42: Plate 9 Location I – Before and After Weld Distortion

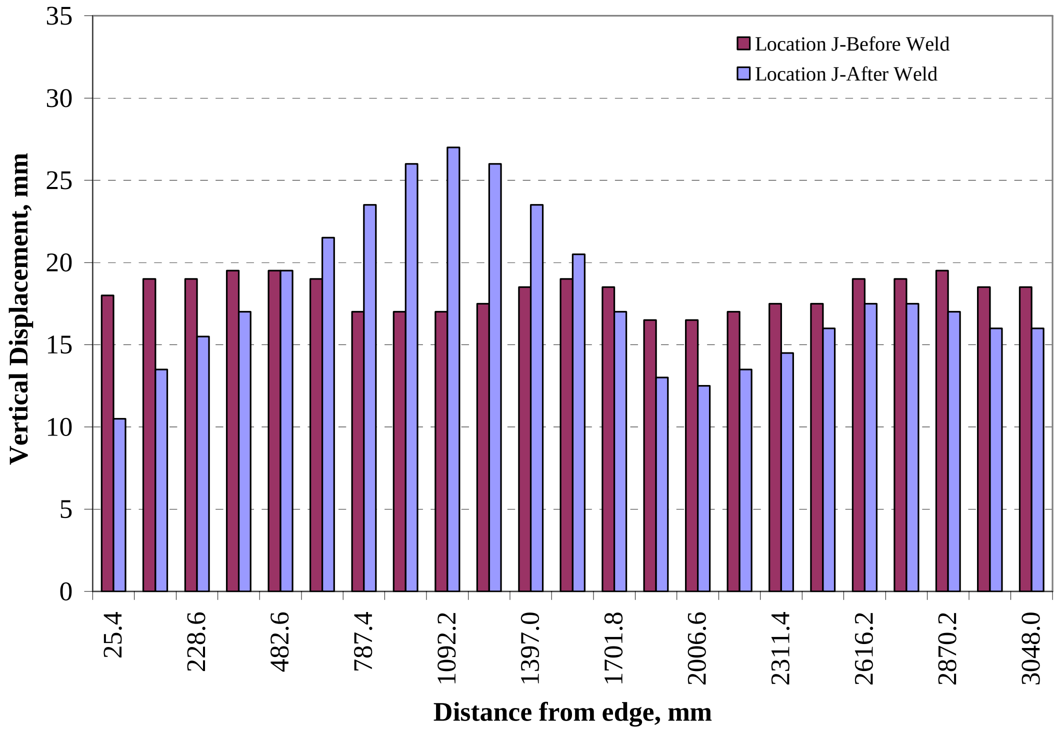


Figure G.43: Plate 9 Location J – Before and After Weld Distortion

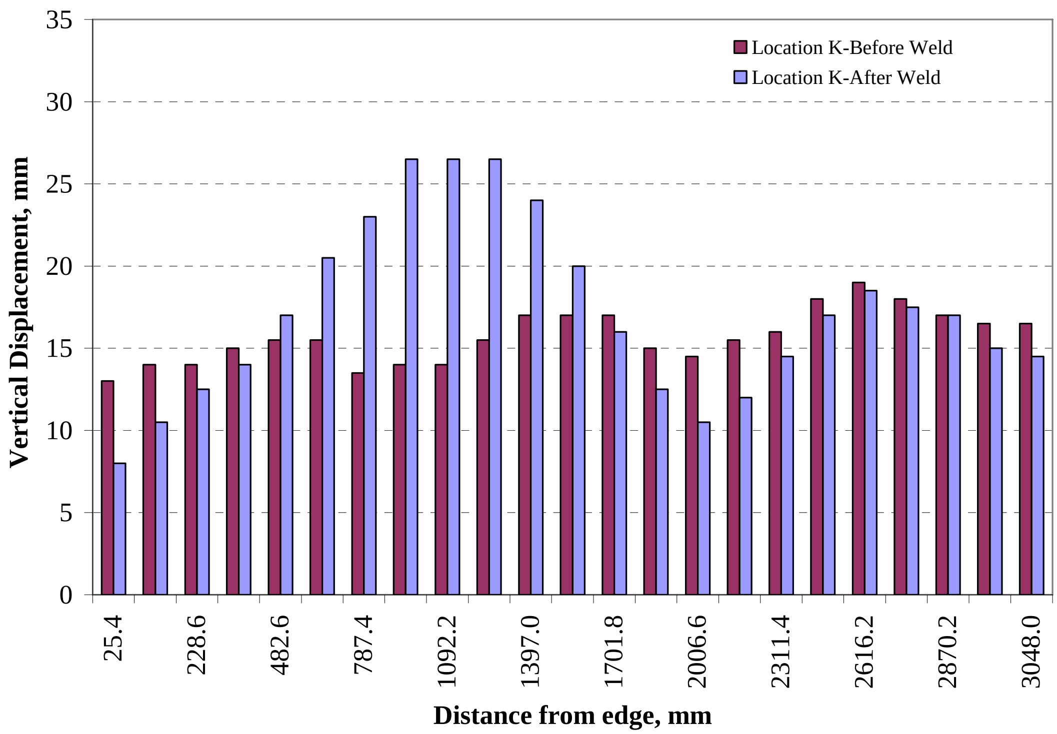


Figure G.44: Plate 9 Location K – Before and After Weld Distortion

APPENDIX H

NET IMPROVEMENT VERSUS BENCHMARK PLATE 7
(4’ x 10’ HSLA 80 BASE PLATES)

Table H.1: Net Improvement, T-MCAW Plate 8 vs. FCAW Plate 7 (No Tension)

Net Improvement, mm										
Benchmark										
A	B	C	D	E	F	G	H	I	J	K
-5	-5	-3.5	-4	-4	-1	2	3.5	3.5	4.5	4.5
-4	-3	-2	-4	-4	-1	1.5	3	4	3	2.5
-1	-1.5	-1	-3	-3	-0.5	0.5	2	2	1.5	0
1	1	1	-1.5	-3	-0.5	0	1.5	0.5	0	-0.5
5.5	4.5	4	0.5	-1	-1	-0.5	-0.5	-1.5	-2.5	-4
9.5	8.5	6.5	3	-0.5	-1	-1.5	-2.5	-4	-6.5	-7.5
13	11	9.5	5	1	-0.5	-2.5	-5	-7	-7.5	-10.5
14	12	11	5.5	0.5	-0.5	-3.5	-4.5	-8	-8	-10.5
12.5	10.5	10	6	0.5	-1	-3	-4.5	-6	-7.5	-9
7.5	7	6.5	3	0.5	-1.5	-2.5	-3	-4.5	-3.5	-6.5
2.5	1	1.5	0	-1	-0.5	-1.5	-1	-1	-1	-1.5
-3.5	-3	-1.5	-2.5	-3.5	-1	-1	0	0.5	0.5	1.5
-5.5	-4	-3	-2.5	-2.5	-1	-1.5	0.5	-0.5	1	1.5
-3.5	-3	-1.5	-1	-1.5	-2	-1.5	-1	-0.5	-1.5	-1
1.5	0.5	1.5	0.5	-0.5	-1.5	-2.5	-2	-2.5	-3.5	-5
5	9	4	2.5	-0.5	-1	-2	-3	-3.5	-4.5	-7
6	5.5	4	2	0.5	-1.5	-1.5	-3.5	-3.5	-5	-7.5
4.5	3.5	3.5	1	-0.5	-1.5	-2	-3.5	-3	-4.5	-5
3.5	1.5	1.5	0	-0.5	-2	-2	-2.5	-2.5	-4	-4.5
0.5	-0.5	-1.5	-1	-2	-2	-2	-1.5	-2	-3	-2
0.5	0	-1	-1.5	-0.5	-1.5	-2	-1	-1.5	-2	-1.5
-1.5	-1	-1	-2	-1	-2	-2	-1	-1.5	-0.5	0
-1.5	-1.5	-1	-1	-2	-2	-2	-1	-2	-1	0.5

Table H.2: Net Improvement, T-MCAW Plate 9 vs. FCAW Plate 7 (No Tension)

Net Improvement, mm										
Benchmark										
A	B	C	D	E	F	G	H	I	J	K
-0.5	-1.5	-2.5	-4.5	-2.5	-2.5	-2	-1.5	0.5	-2.5	-0.5
0.5	-0.5	-1	-4	-2.5	-2.5	-1	-1	2	-1.5	-1
2	-4	0.5	-4	-2.5	-2.5	-1	-1	1	-0.5	-1
3.5	1.5	1	-2.5	-2.5	-2.5	-1	1.5	1	-1	-1
6	3	2.5	-1	-1	-2.5	0	2	2	0	-0.5
6	4	2.5	0	-1	-2.5	-1	1.5	2	-0.5	1
5	3.5	2.5	-1	-1.5	-2.5	-1	2	3.5	3	4
3.5	2	1	-2	-2	-2.5	0	4	4.5	5.5	7
1.5	0	-0.5	-2.5	-2	-2.5	0	4	6.5	6.5	8.5
-0.5	-1.5	-2	-3.5	-3.5	-3	0	4	6.5	8	9
-1.5	-3	-3	-3	-3.5	-1.5	0	-1	6	6	7
-2	-3	-2.5	-3	-3.5	-2	-0.5	3	3	3	4
-1.5	-1	-1	-2	-2	-2.5	-0.5	1	0	-1	-0.5
1	1.5	1	-0.5	-1.5	-1.5	-2	-1	-2	-5.5	-4.5
3.5	2.5	2	0	-1	-2.5	-2.5	-2.5	-4.5	-7	-8.5
3.5	8	2.5	1	-1.5	-1.5	-3	-2	-5	-7.5	-11
2.5	2	1.5	0	-0.5	-1.5	-1	-2	-4	-7	-9
0.5	0	0.5	-1	-1.5	-1.5	-1.5	-1.5	-3	-5	-6
-0.5	-0.5	-0.5	-1.5	-1	-2	-2	-1	-1	-3	-4
-1	-3	-3	-1.5	-1.5	-1	-1	-0.5	-1	-1	-1.5
-1	-1.5	-1.5	-2.5	-1	-0.5	-1	0.5	-0.5	-0.5	0.5
-2	-2	-2	-3	-1.5	-0.5	-1	0.5	0	1	0.5
-1.5	-2.5	-2.5	-2.5	-2.5	-0.5	-1.5	0	1	1	1

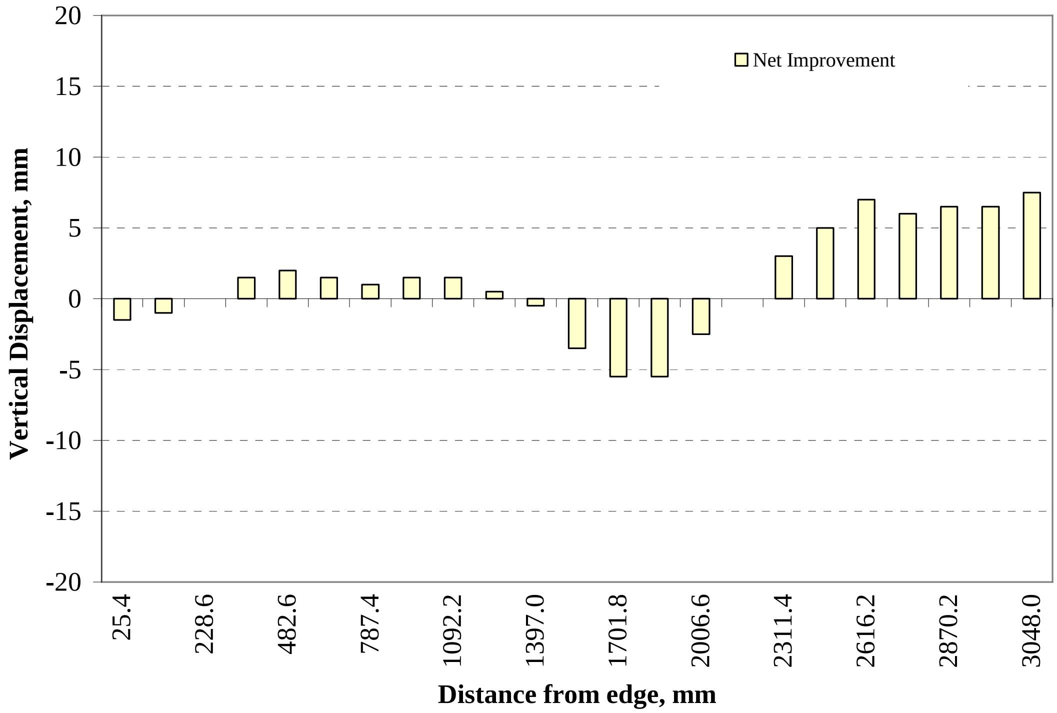


Figure H.1: Plate 3 vs. Plate 7 Location A – Net Improvement

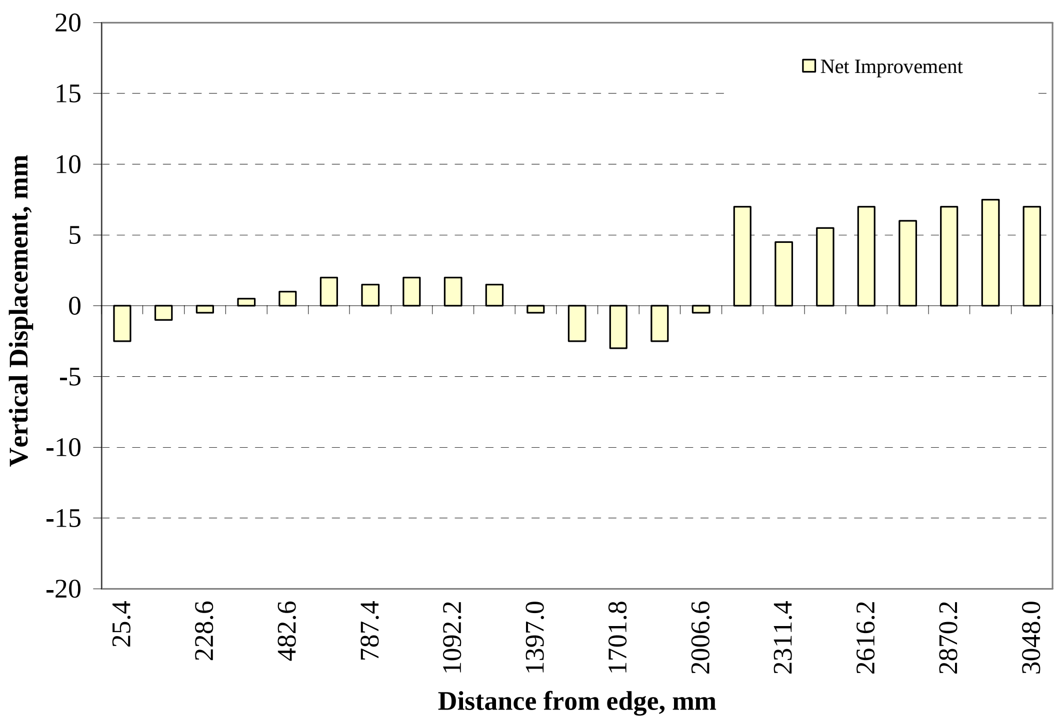


Figure H.2: Plate 3 vs. Plate 7 Location B – Net Improvement

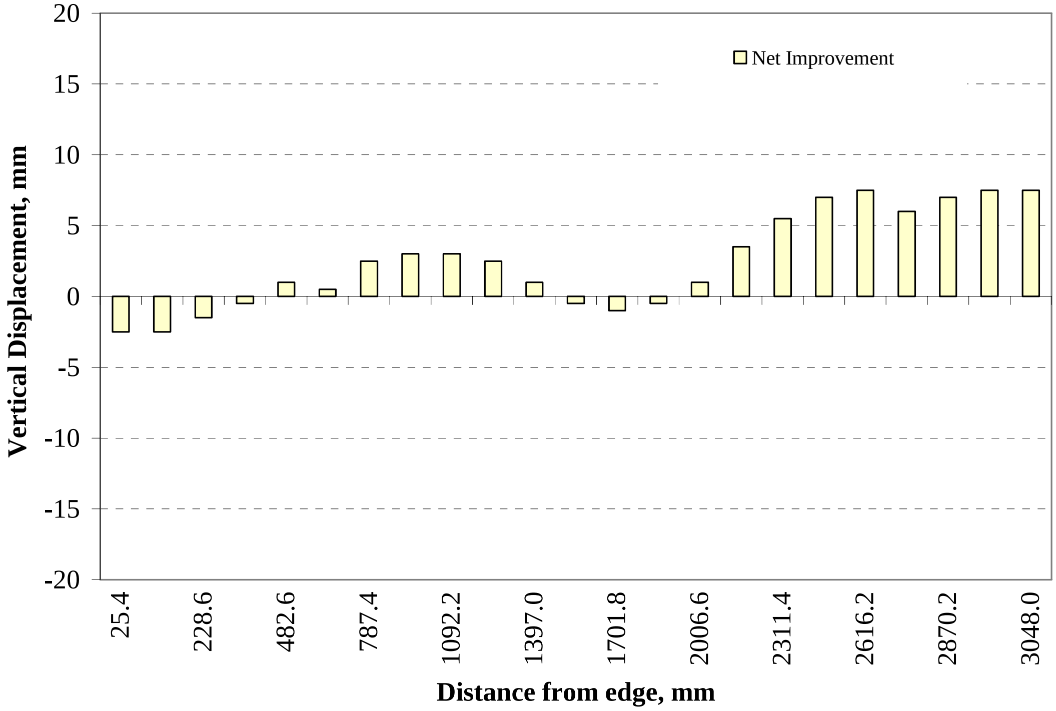


Figure H.3: Plate 3 vs. Plate 7 Location C – Net Improvement

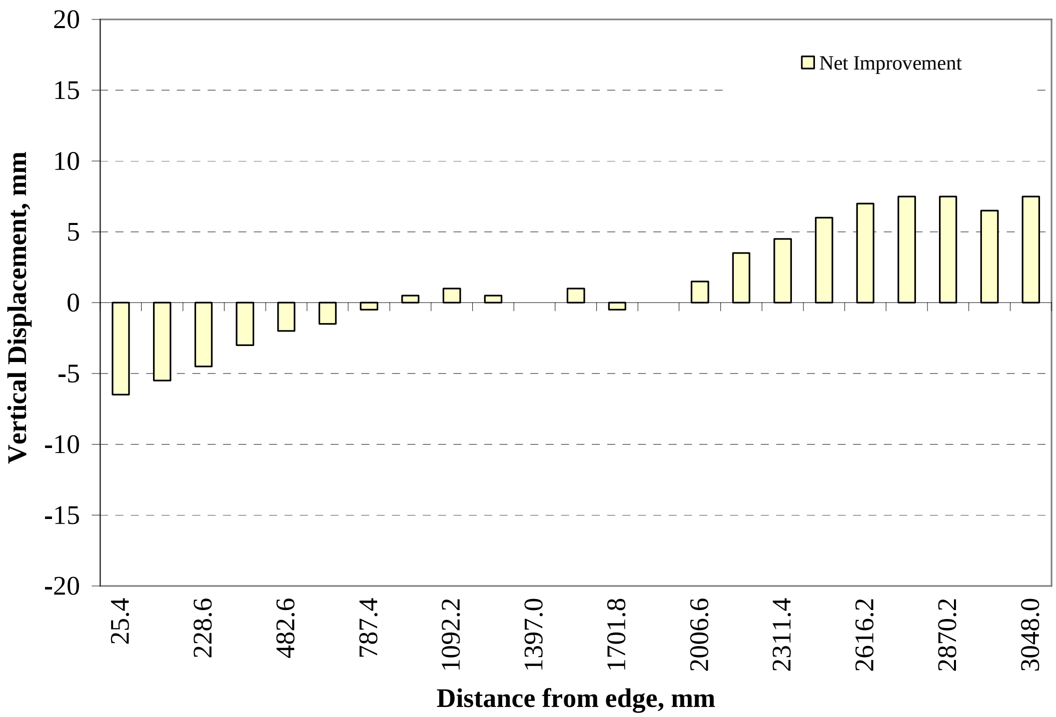


Figure H.4: Plate 3 vs. Plate 7 Location D – Net Improvement

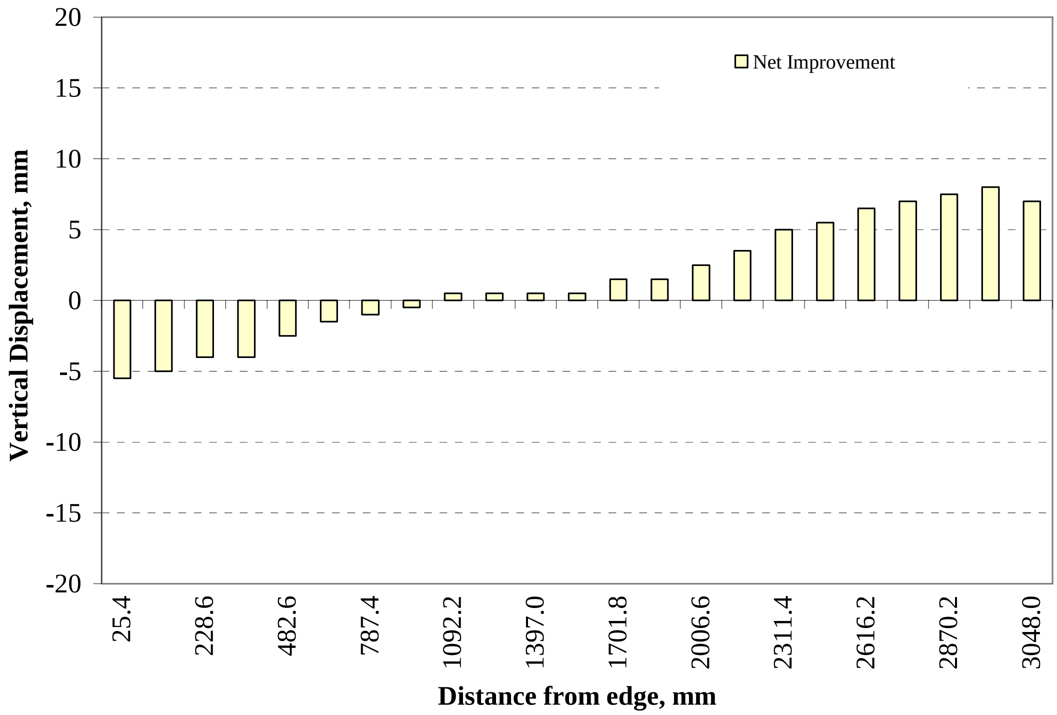


Figure H.5: Plate 3 vs. Plate 7 Location E – Net Improvement

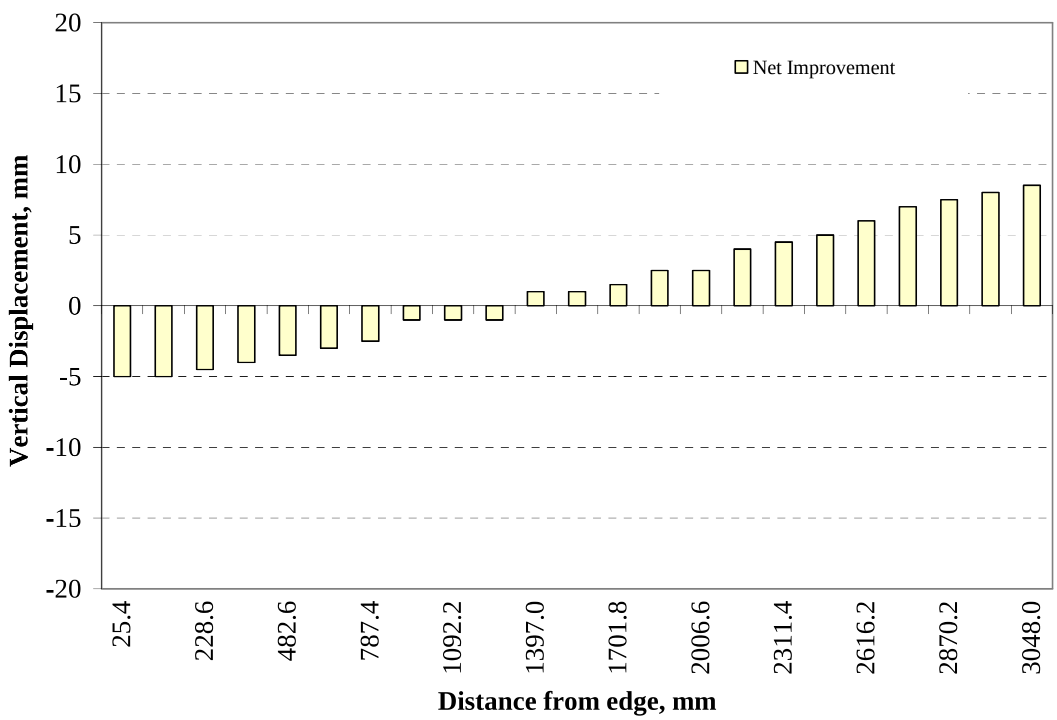


Figure H.6: Plate 3 vs. Plate 7 At Stiffener – Net Improvement

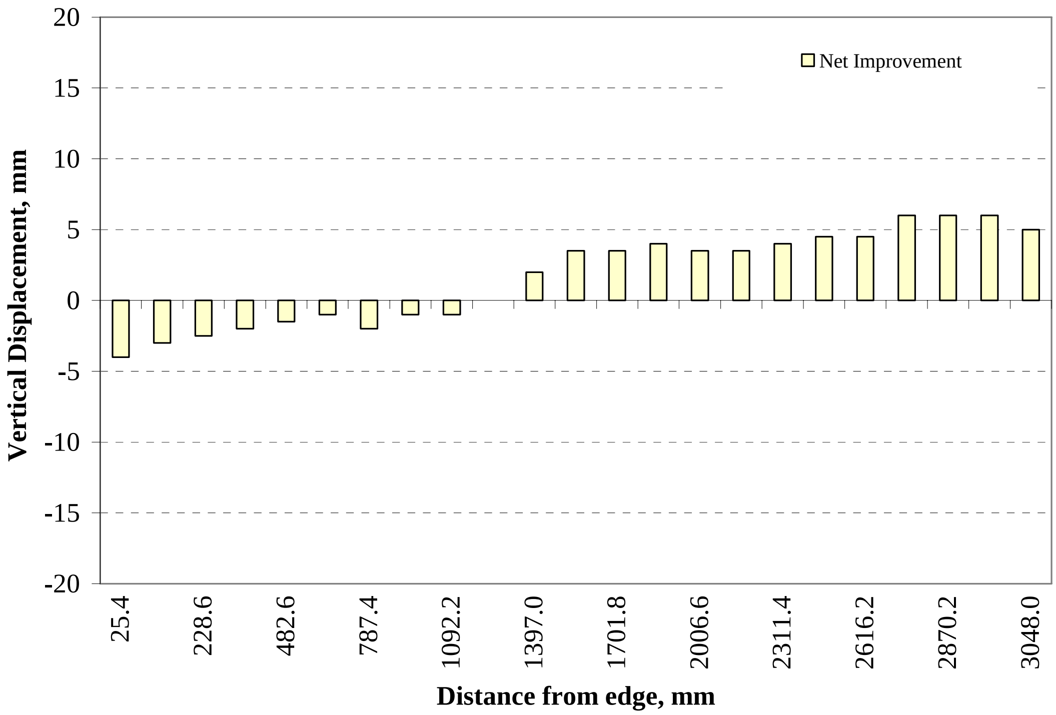


Figure H.7: Plate 3 vs. Plate 7 Location G – Net Improvement

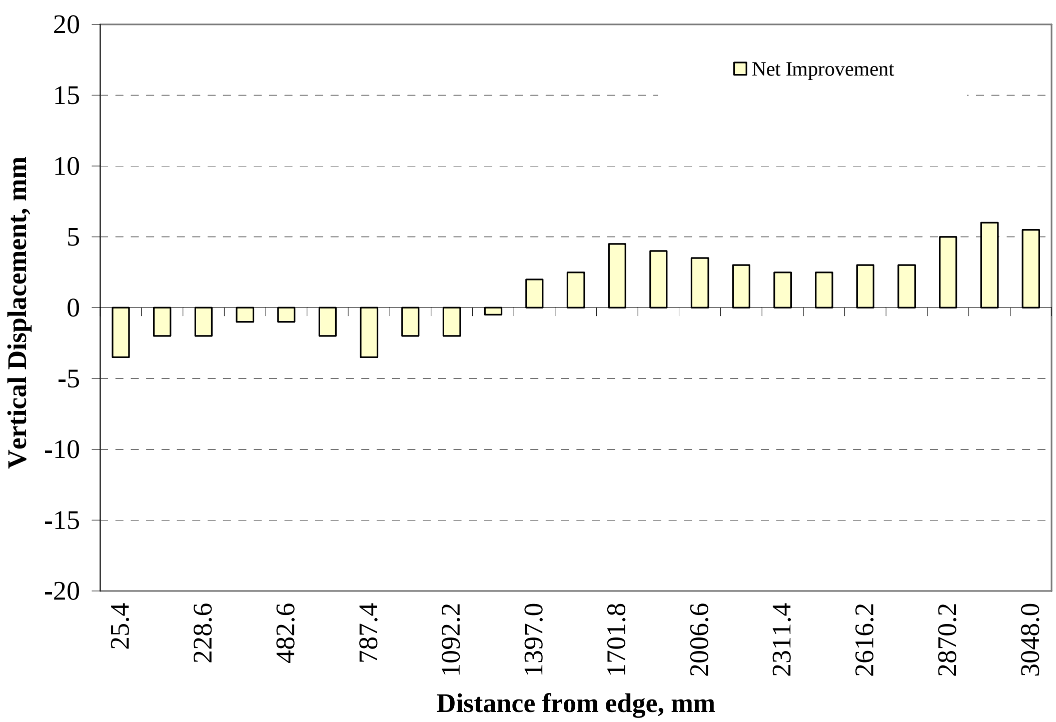


Figure H.8: Plate 3 vs. Plate 7 Location H – Net Improvement

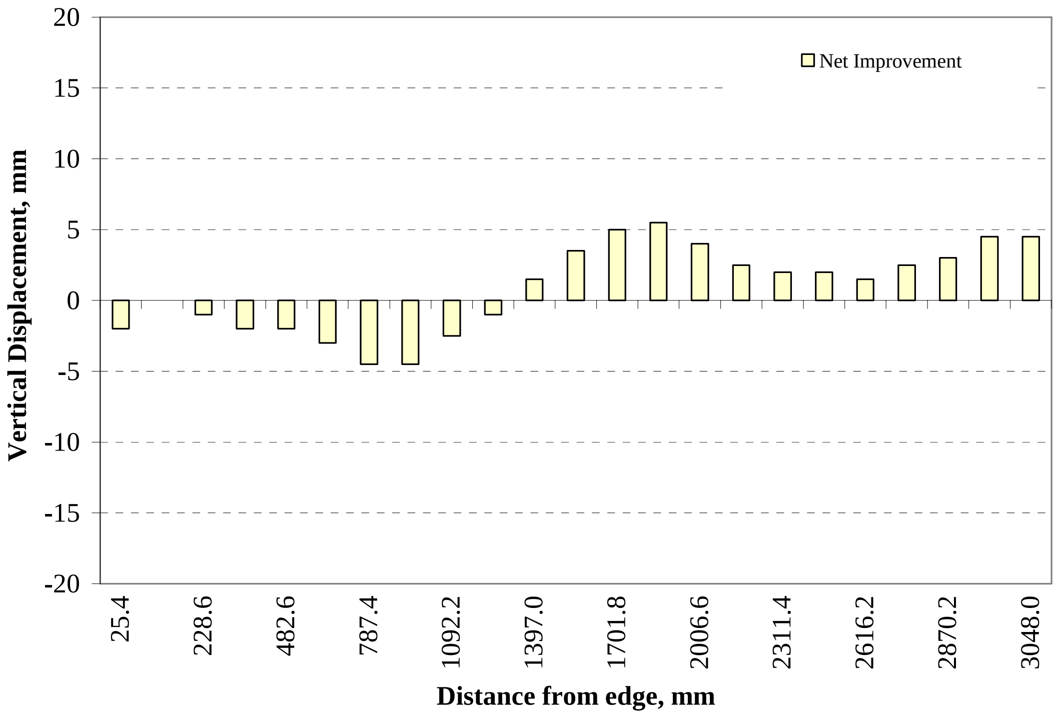


Figure H.9: Plate 3 vs. Plate 7 Location I – Net Improvement

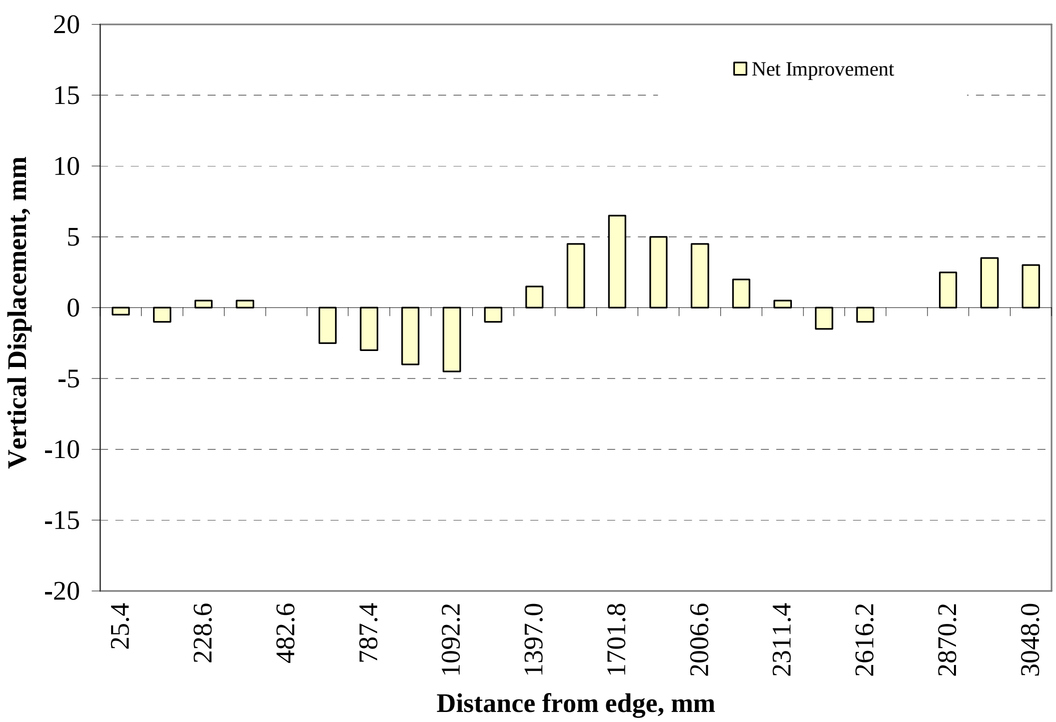


Figure H.10: Plate 3 vs. Plate 7 Location J – Net Improvement

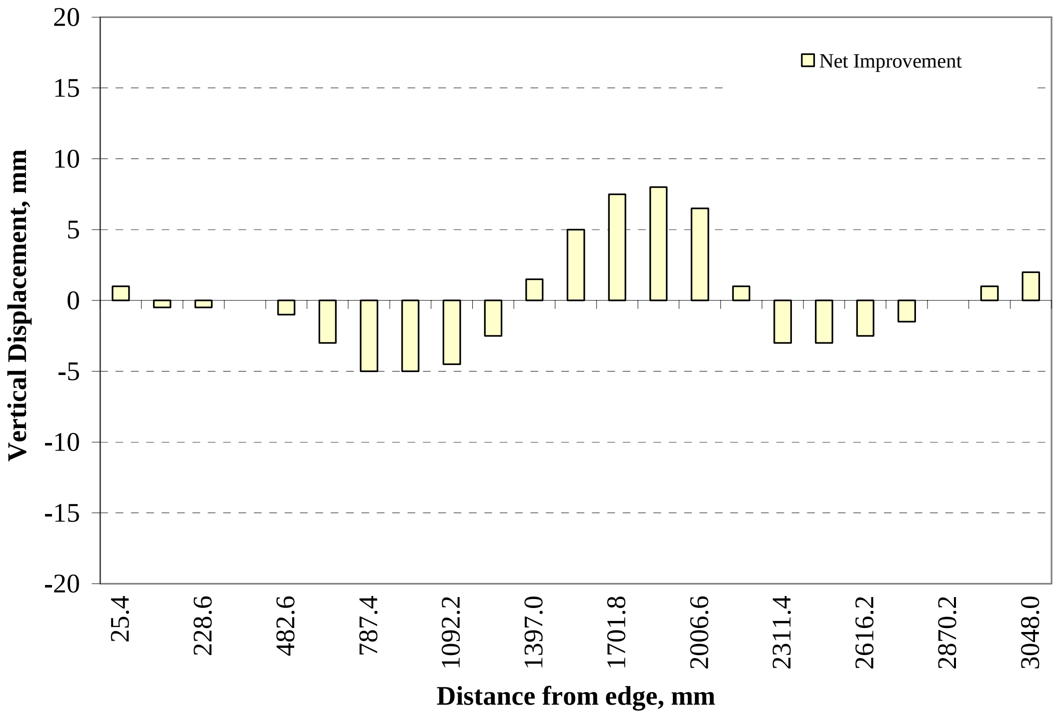


Figure H.11: Plate 3 vs. Plate 7 Location K – Net Improvement

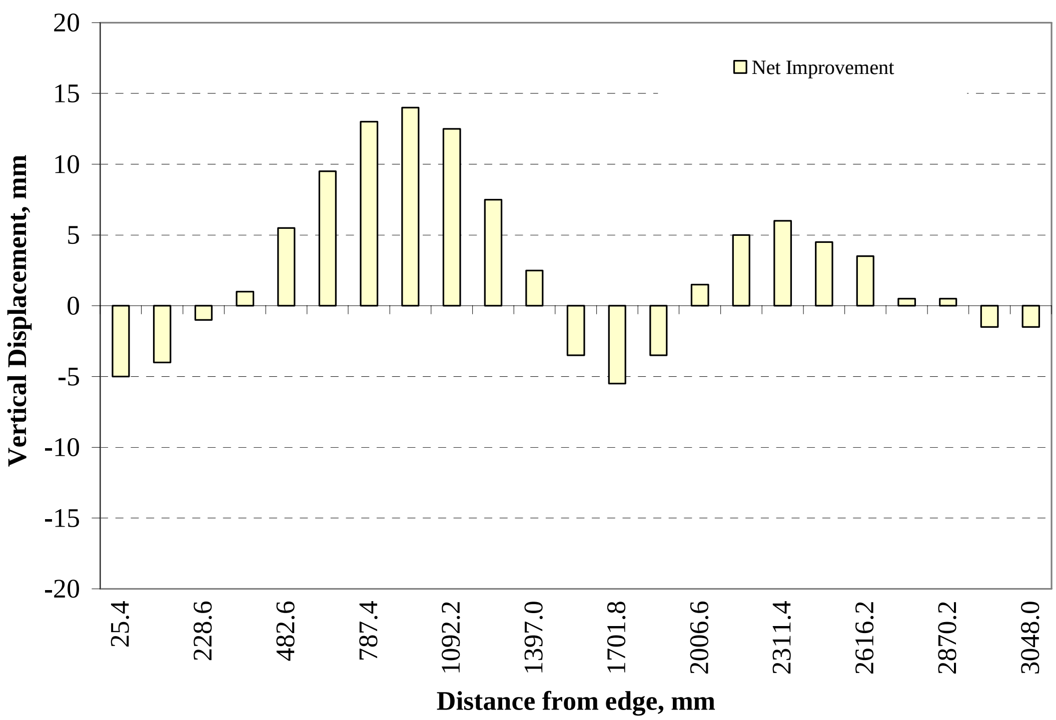


Figure H.12: Plate 8 vs. Plate 7 Location A – Net Improvement

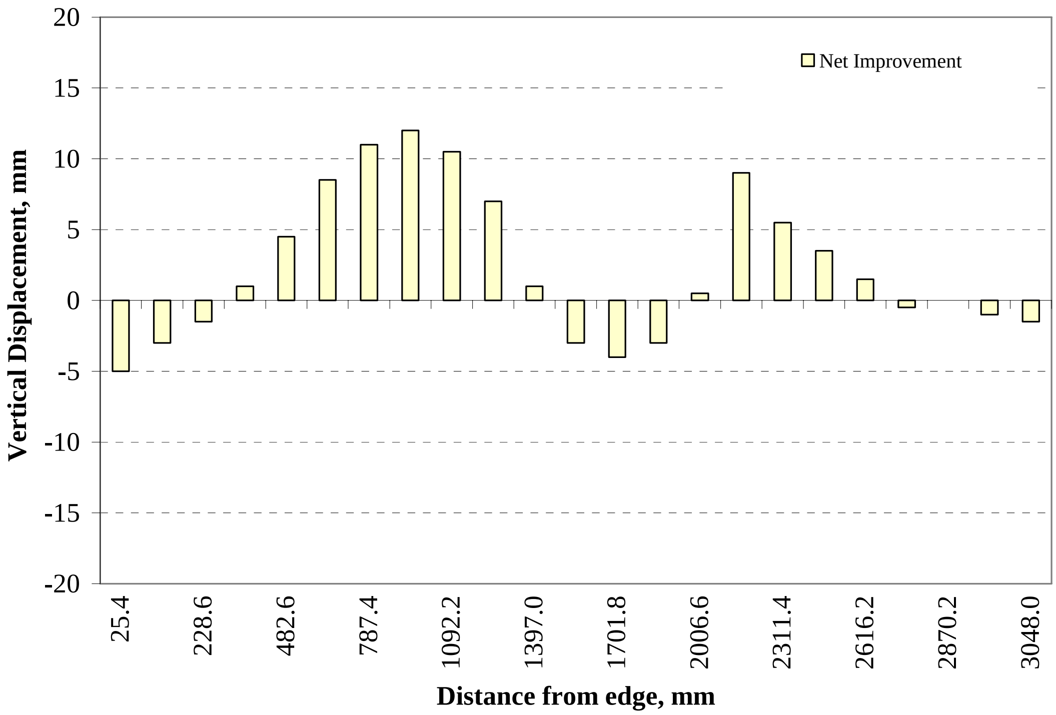


Figure H.13: Plate 8 vs. Plate 7 Location B – Net Improvement

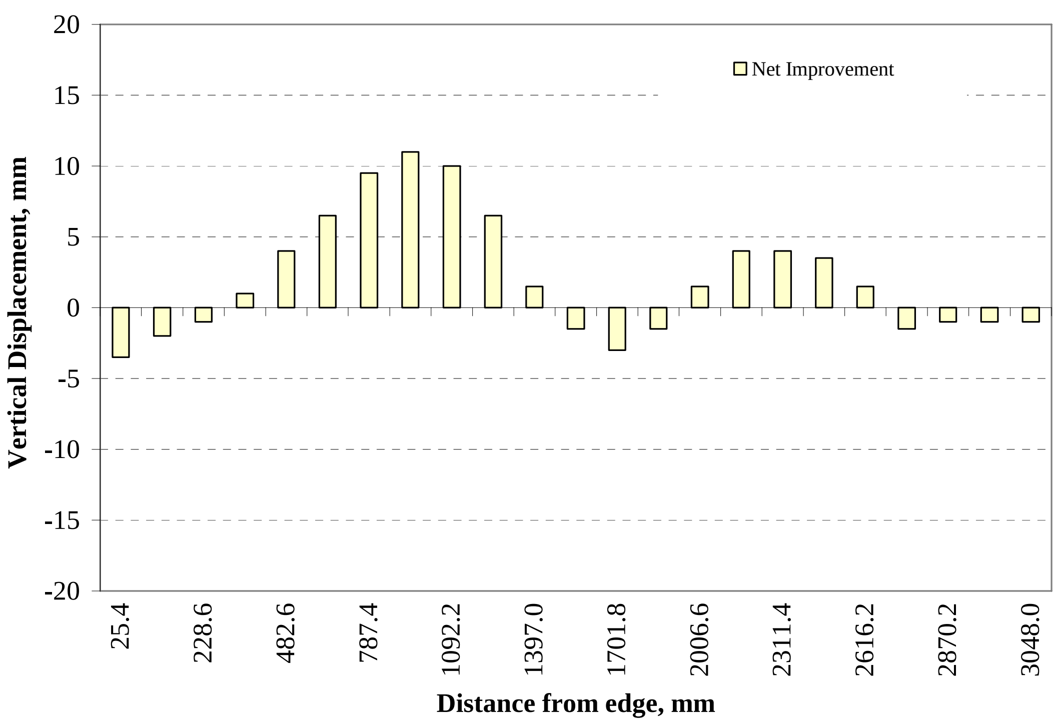


Figure H.14: Plate 8 vs. Plate 7 Location C – Net Improvement

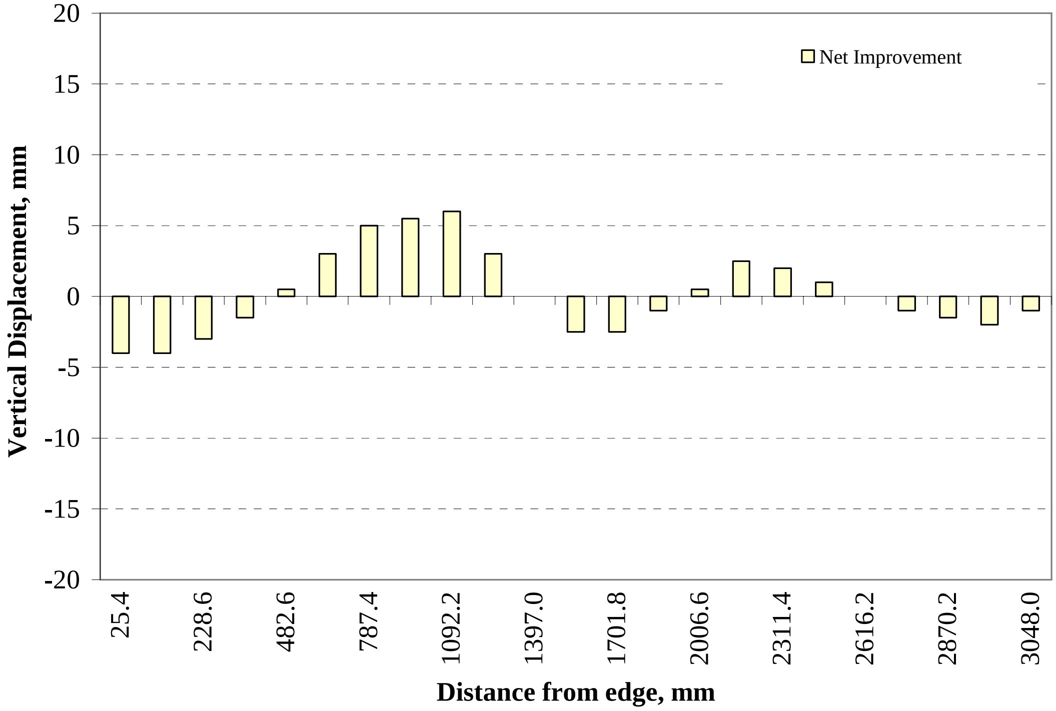


Figure H.15: Plate 8 vs. Plate 7 Location D – Net Improvement

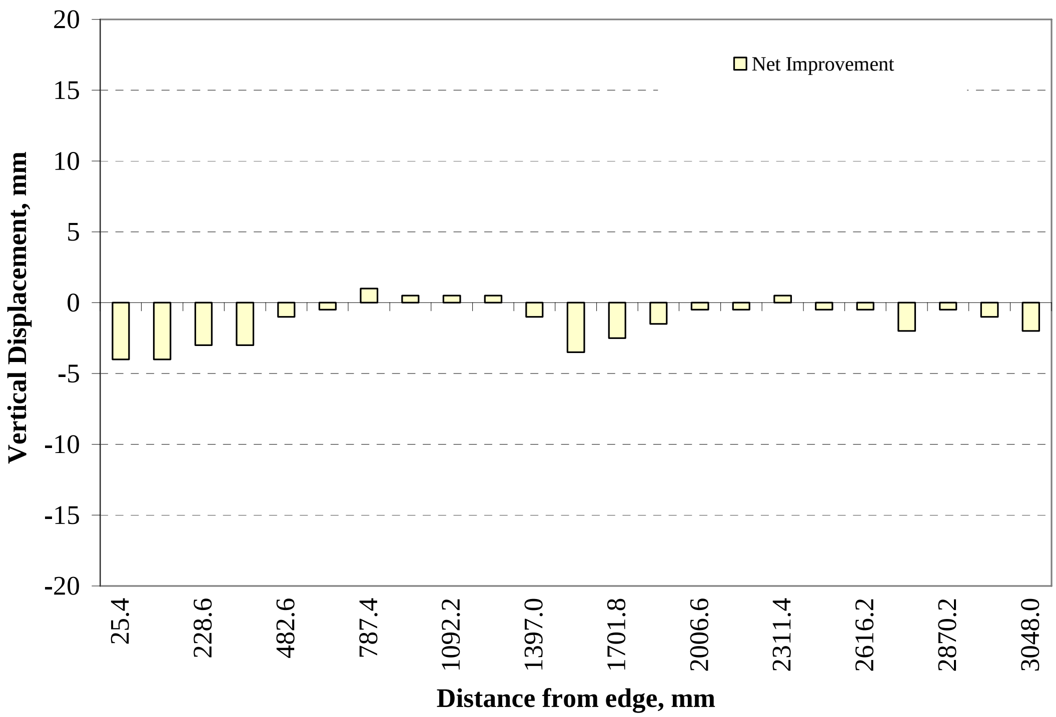


Figure H.16: Plate 8 vs. Plate 7 Location E – Net Improvement

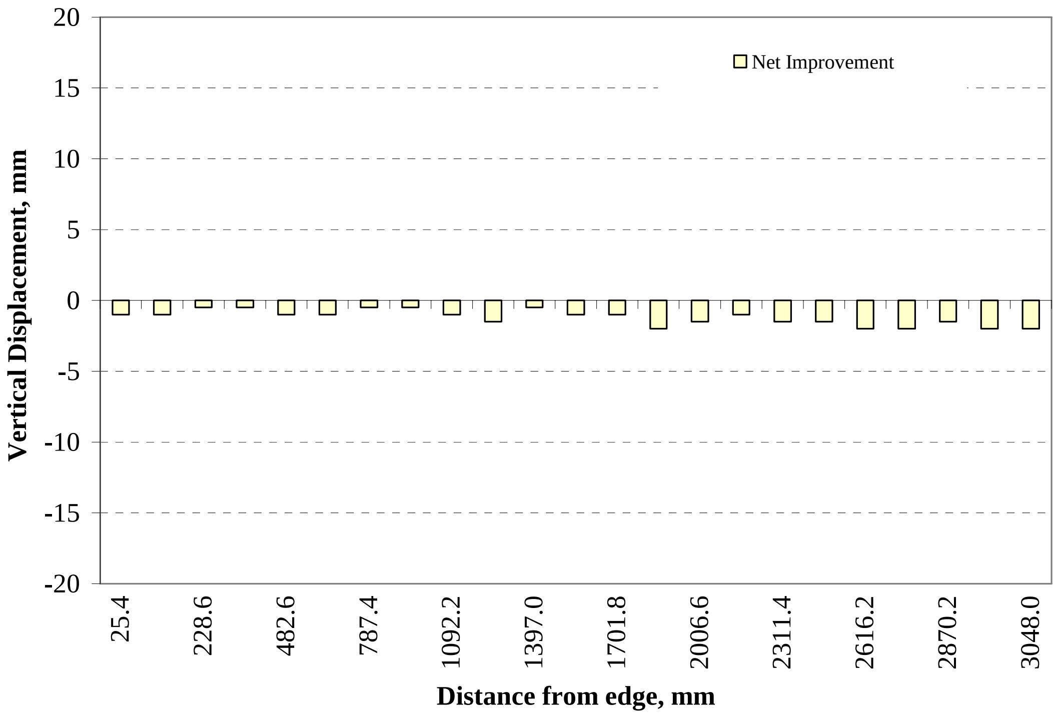


Figure H.17: Plate 8 vs. Plate 7 At Stiffener – Net Improvement

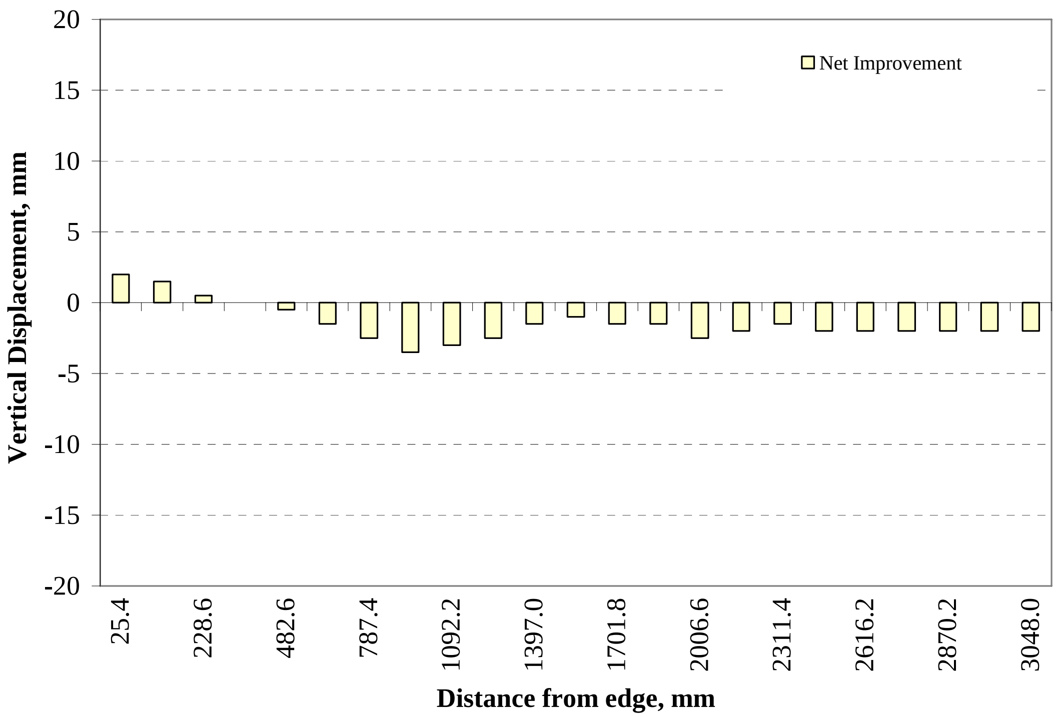


Figure H.18: Plate 8 vs. Plate 7 Location G – Net Improvement

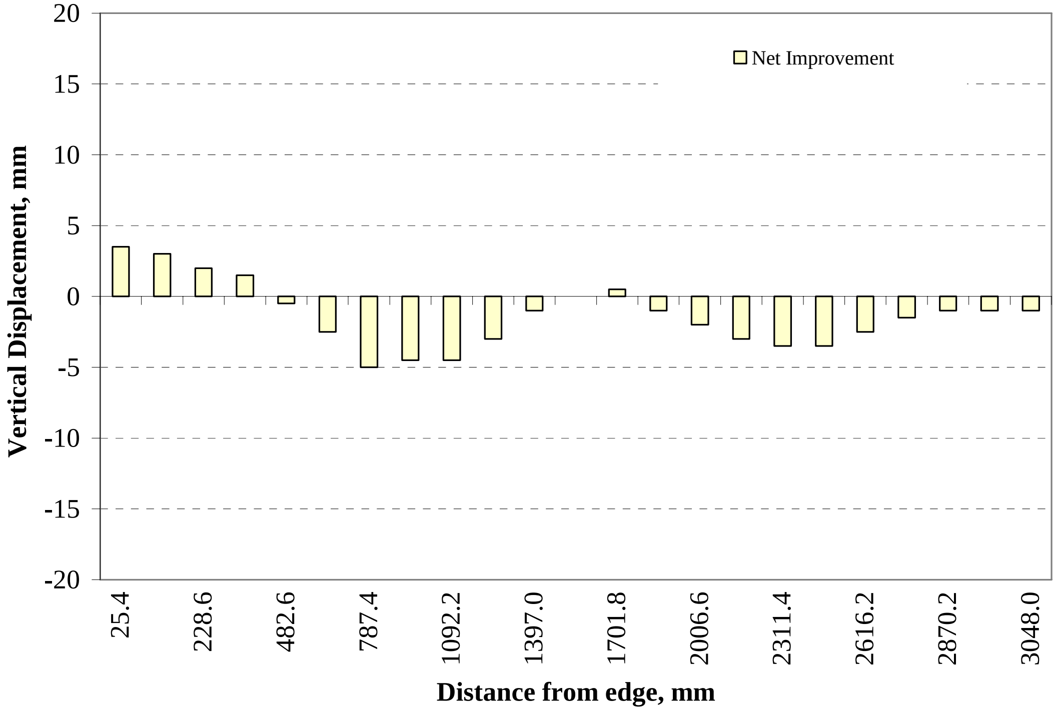


Figure H.19: Plate 8 vs. Plate 7 Location H – Net Improvement

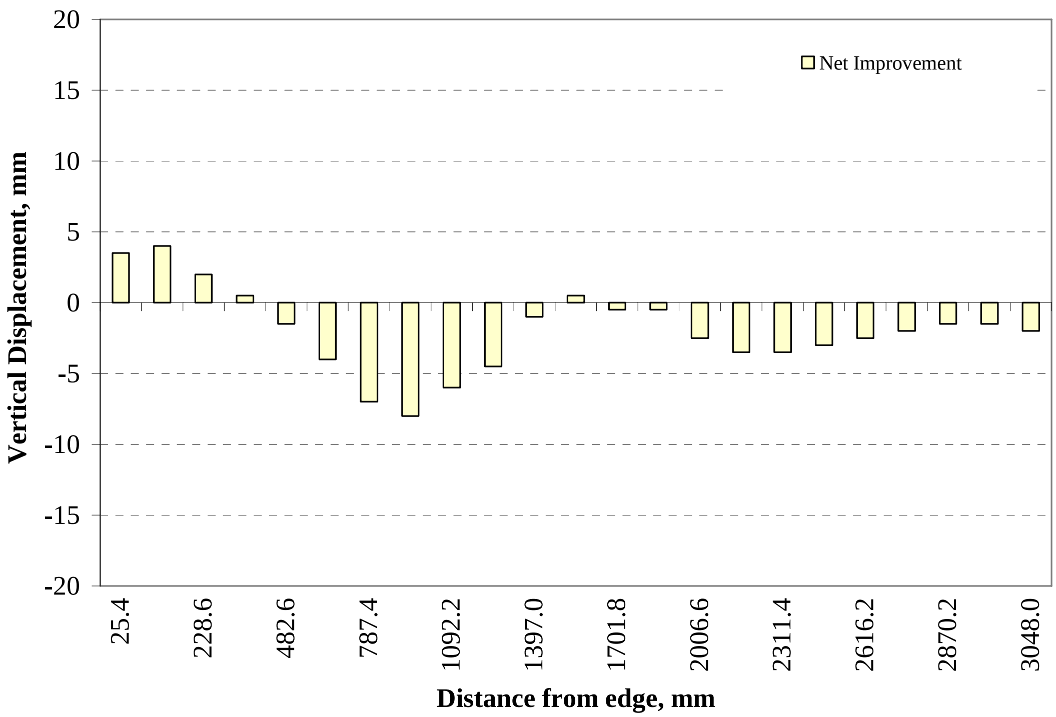


Figure H.20: Plate 8 vs. Plate 7 Location I – Net Improvement

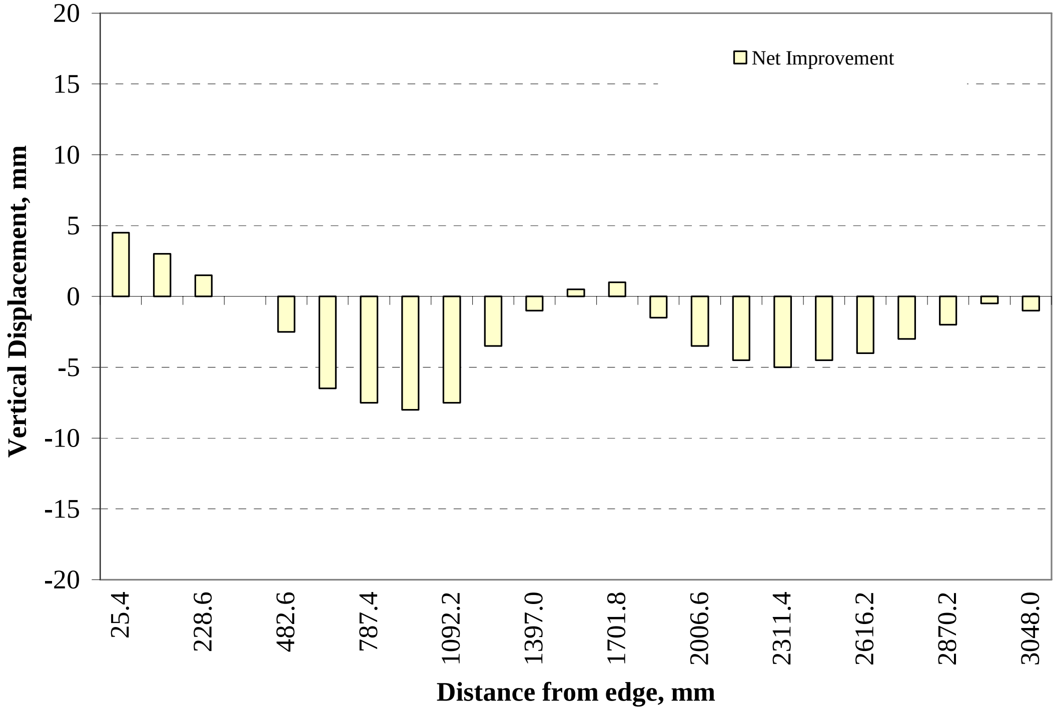


Figure H.21: Plate 8 vs. Plate 7 Location J – Net Improvement

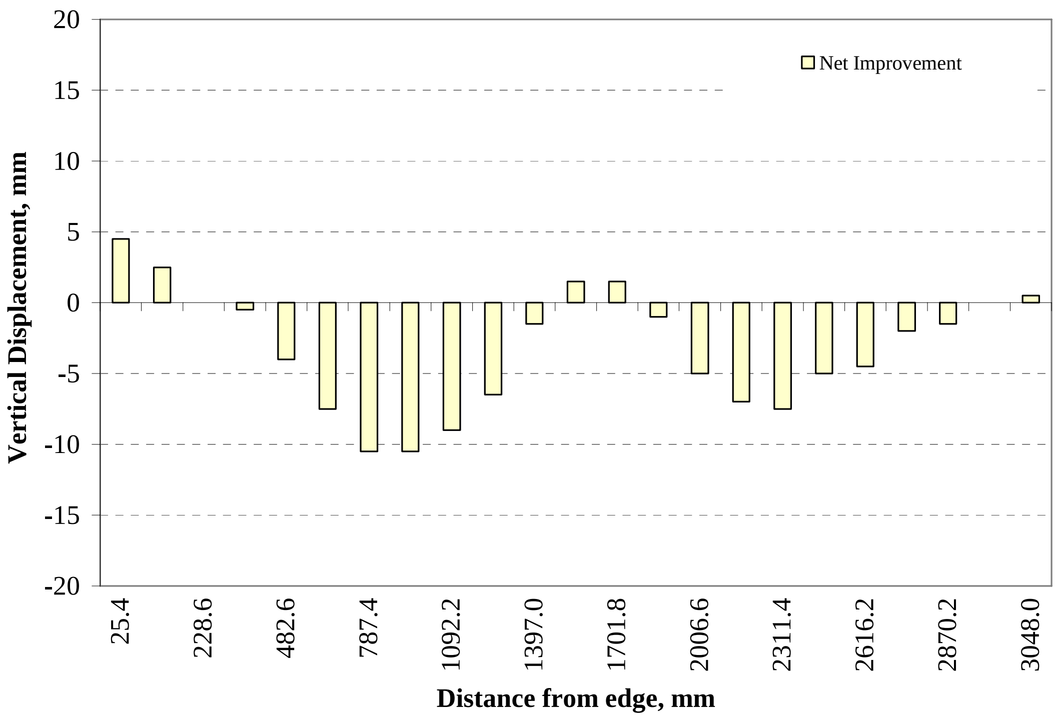


Figure H.22: Plate 8 vs. Plate 7 Location K – Net Improvement

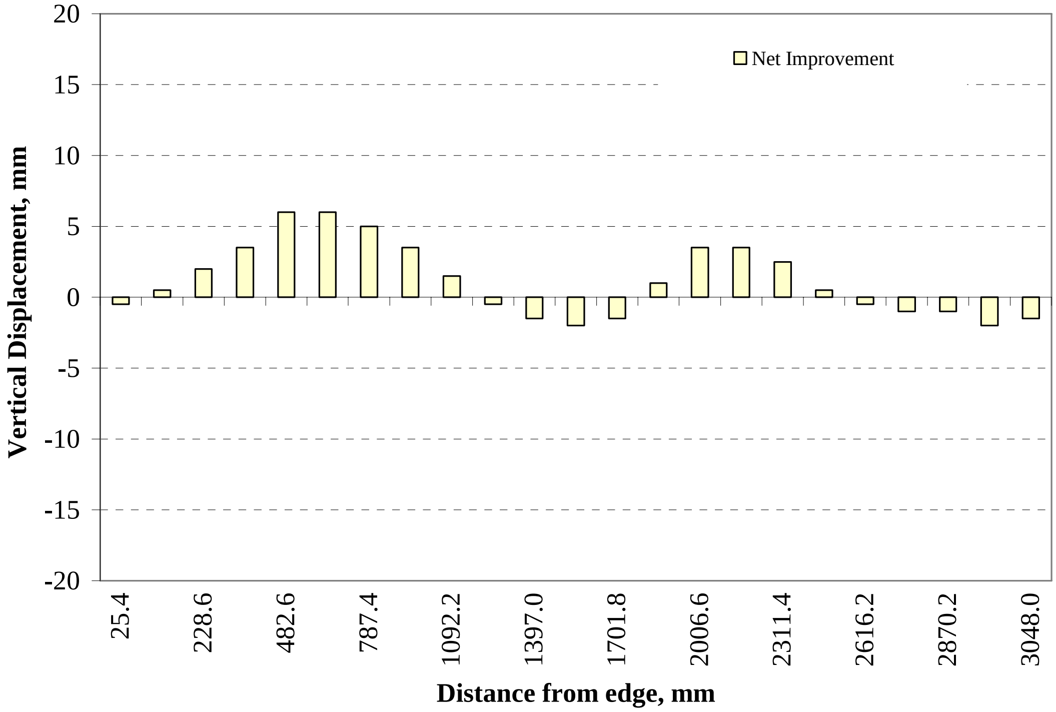


Figure H.23: Plate 9 vs. Plate 7 Location A – Net Improvement

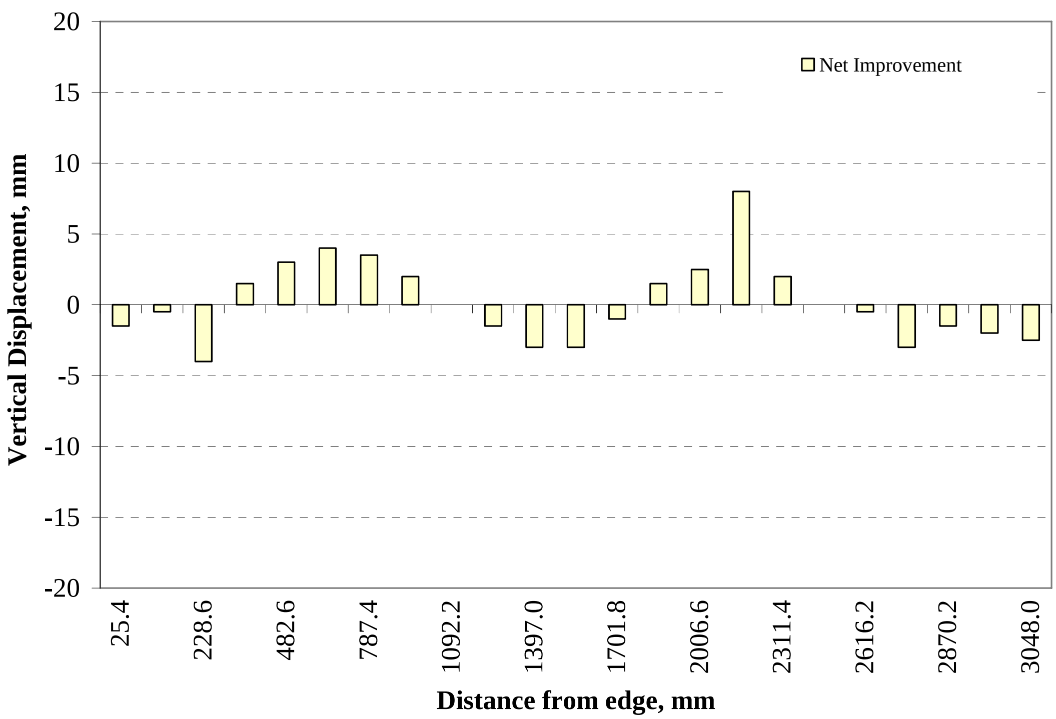


Figure H.24: Plate 9 vs. Plate 7 Location B – Net Improvement

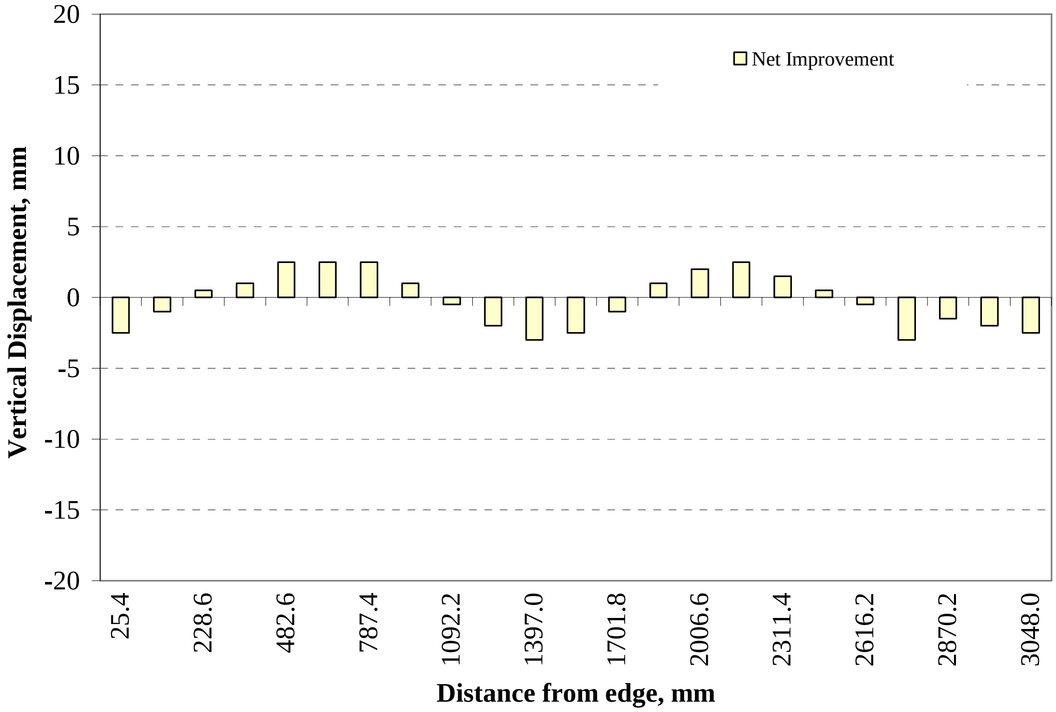


Figure H.25: Plate 9 vs. Plate 7 Location C – Net Improvement

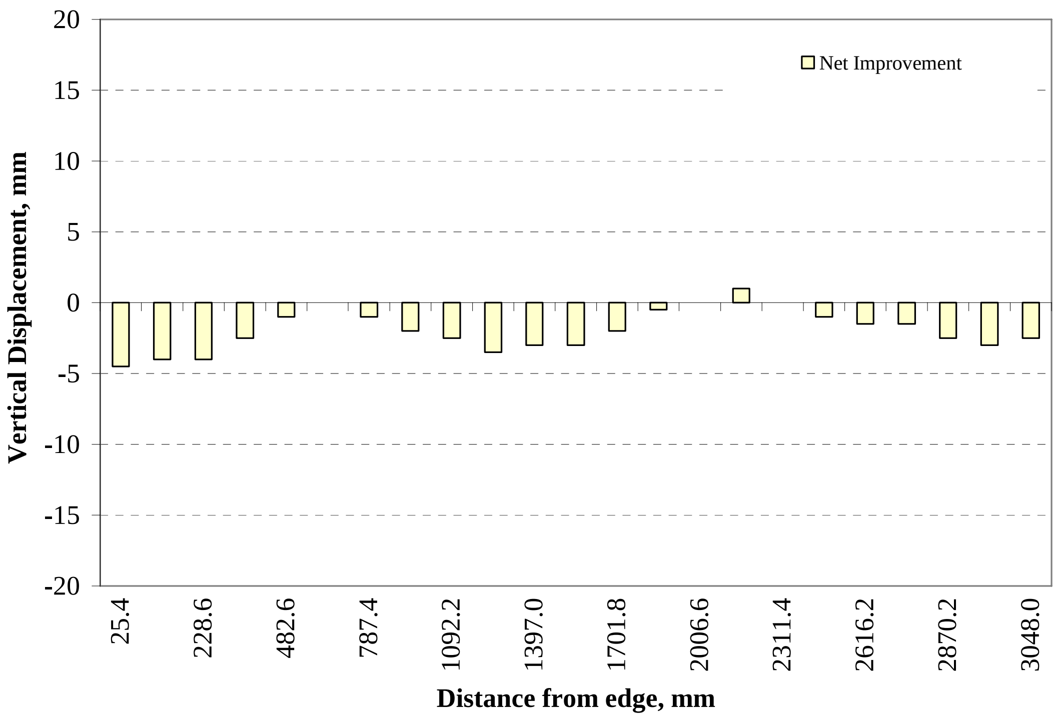


Figure H.26: Plate 9 vs. Plate 7 Location D – Net Improvement

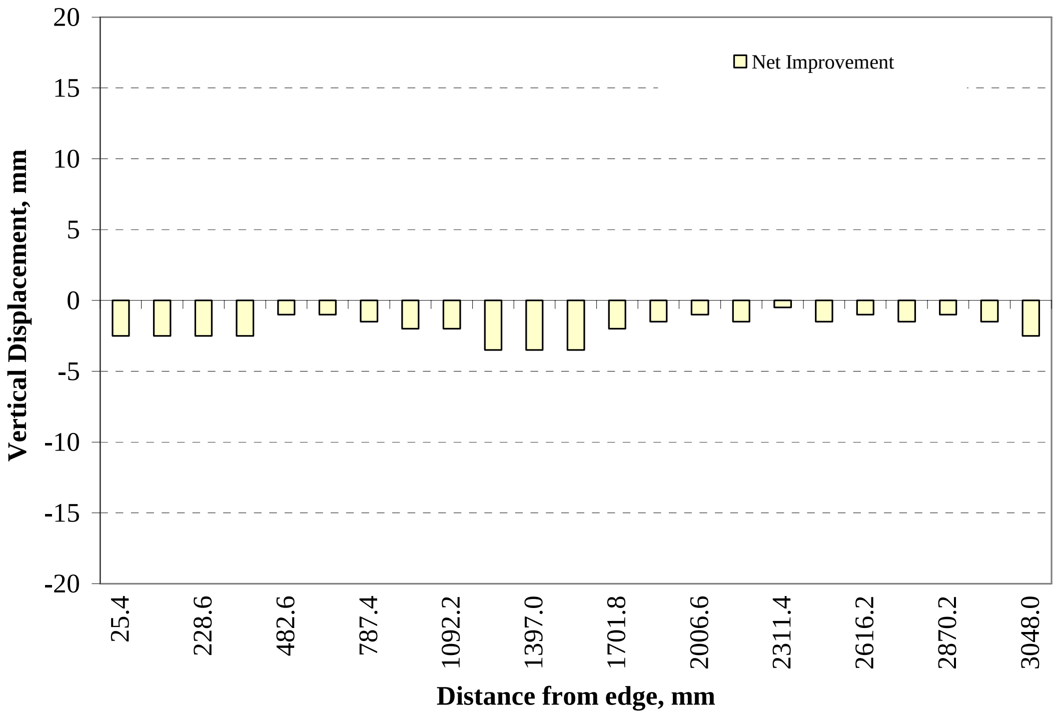


Figure H.27: Plate 9 vs. Plate 7 Location E – Net Improvement

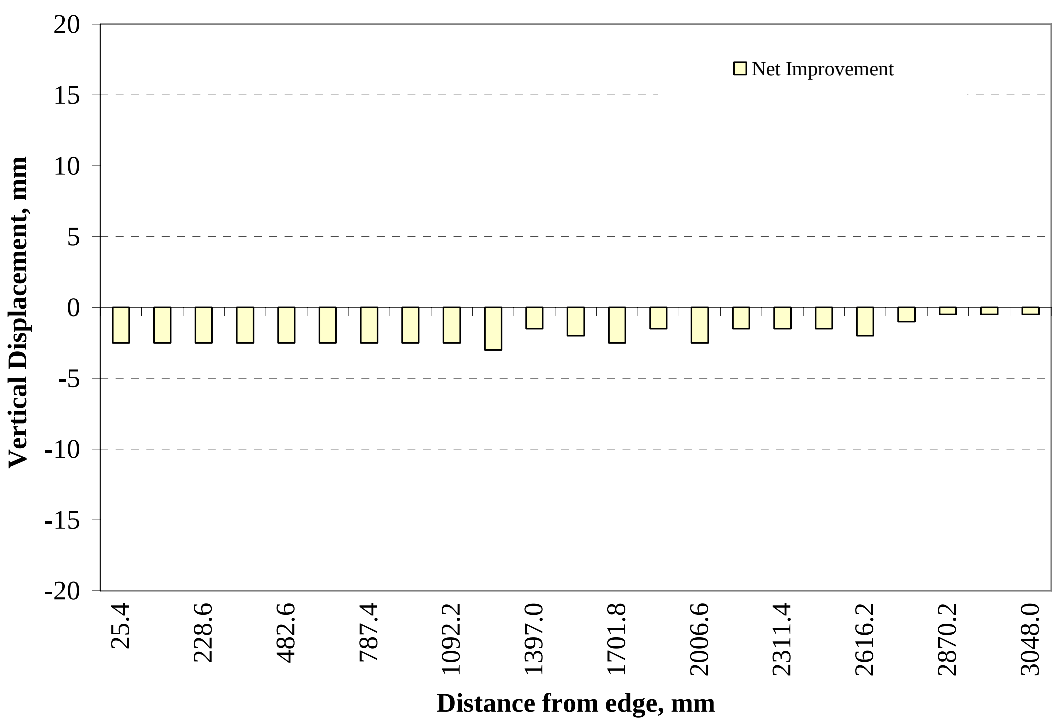


Figure H.28: Plate 9 vs. Plate 7 At Stiffener – Net Improvement

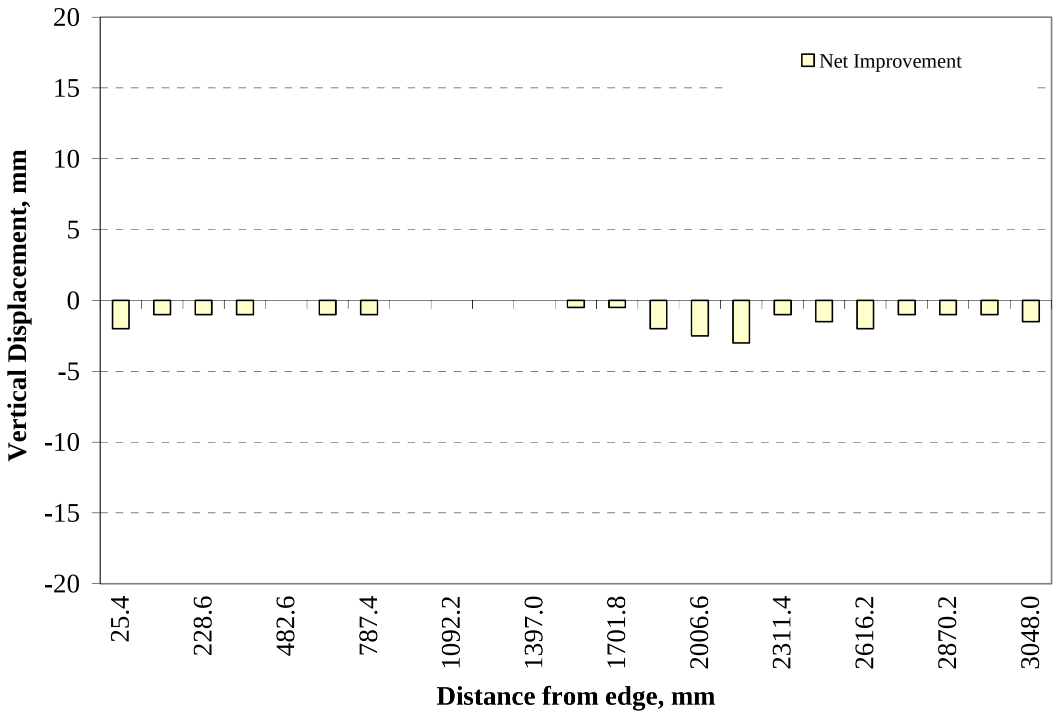


Figure H.29: Plate 9 vs. Plate 7 Location G – Net Improvement

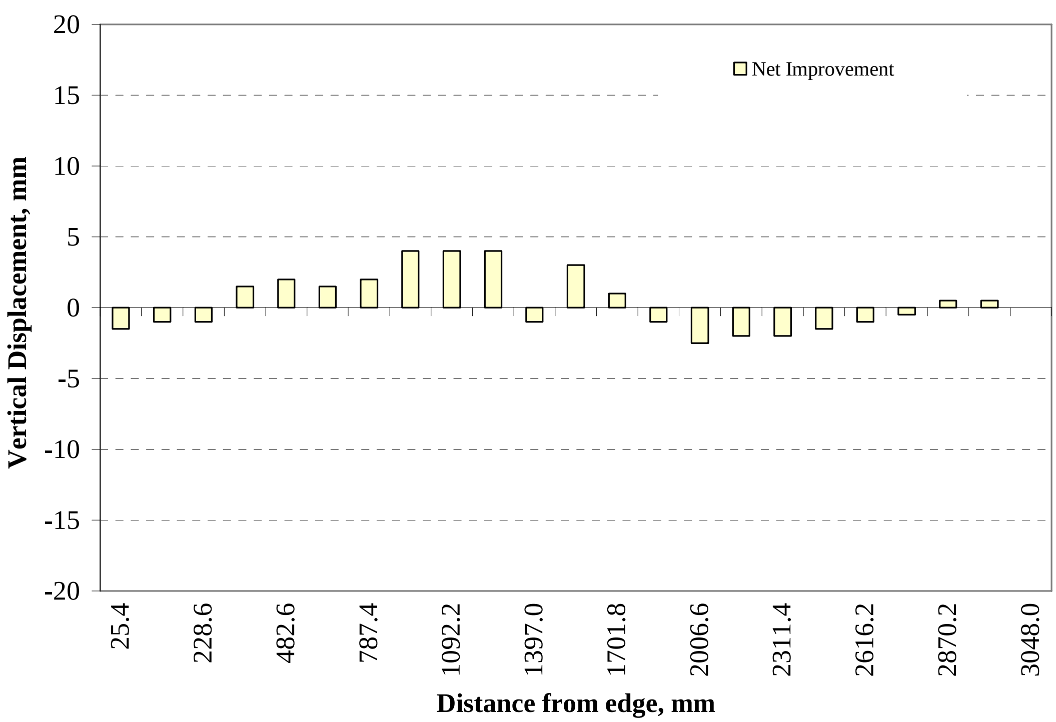


Figure H.30: Plate 9 vs. Plate 7 Location H – Net Improvement

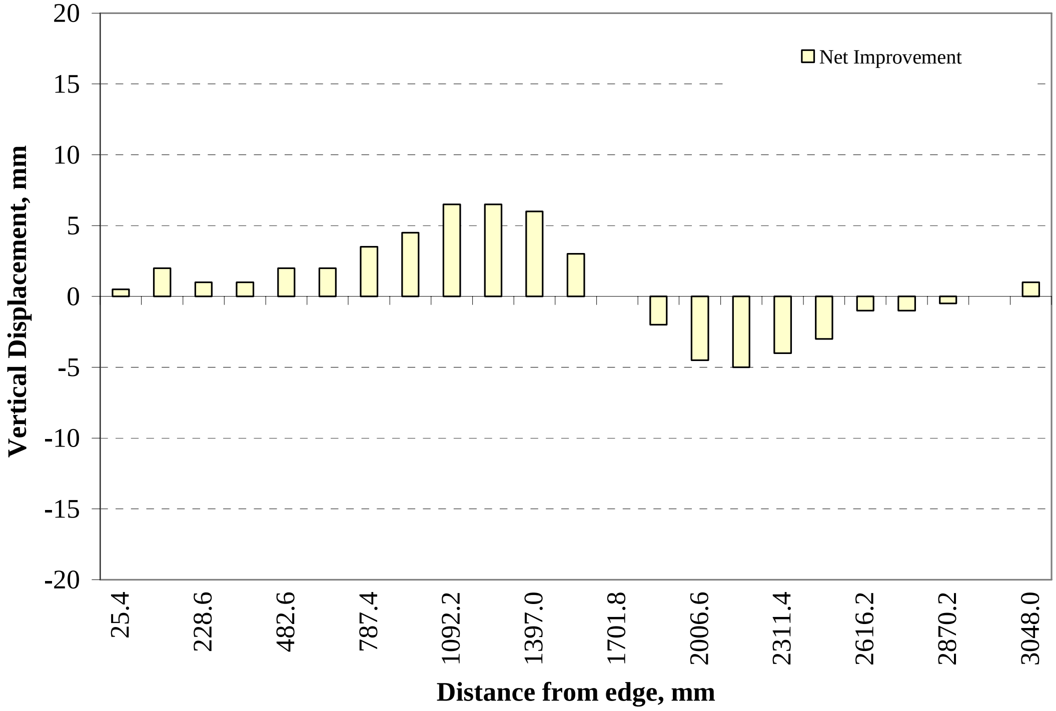


Figure H.31: Plate 9 vs. Plate 7 Location I – Net Improvement

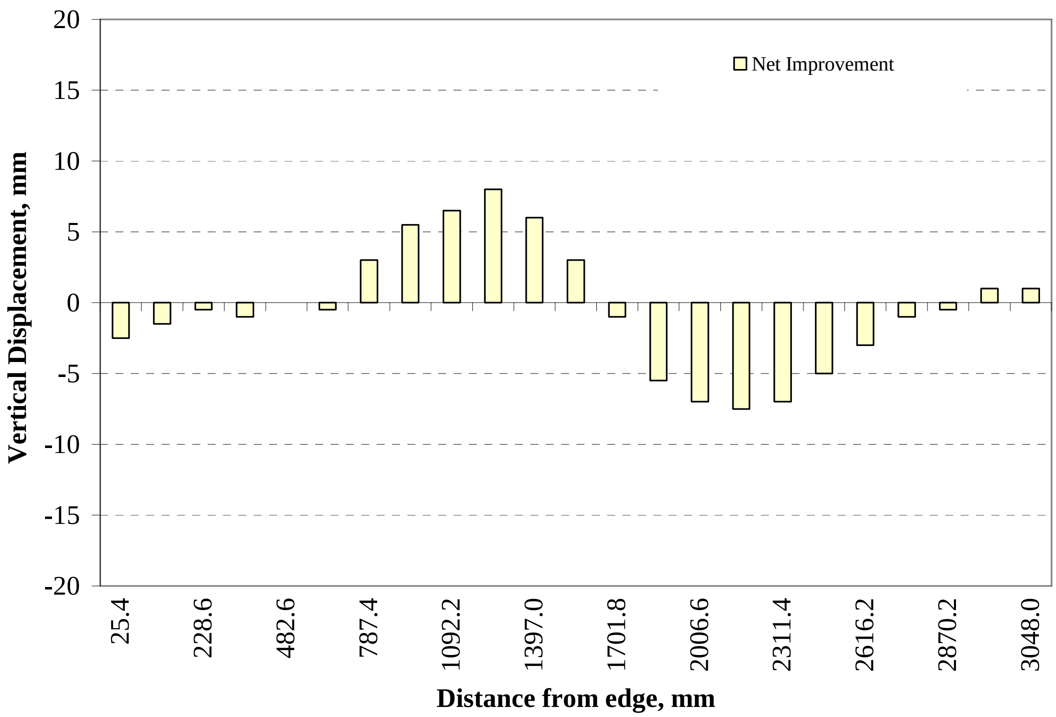


Figure H.32: Plate 9 vs. Plate 7 Location J – Net Improvement

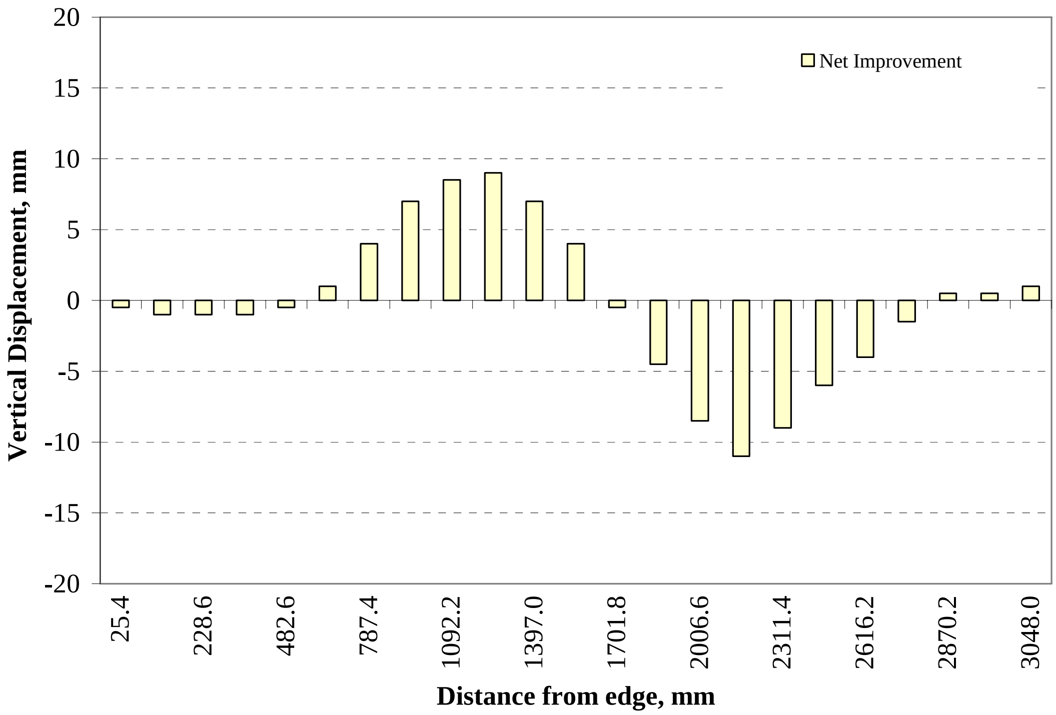


Figure H.33: Plate 9 vs. Plate 7 Location K – Net Improvement

APPENDIX I

CHANGE IN DISPLACEMENTS AFTER WELDING
(4’ x 10’ HSLA 80 BASE PLATES)

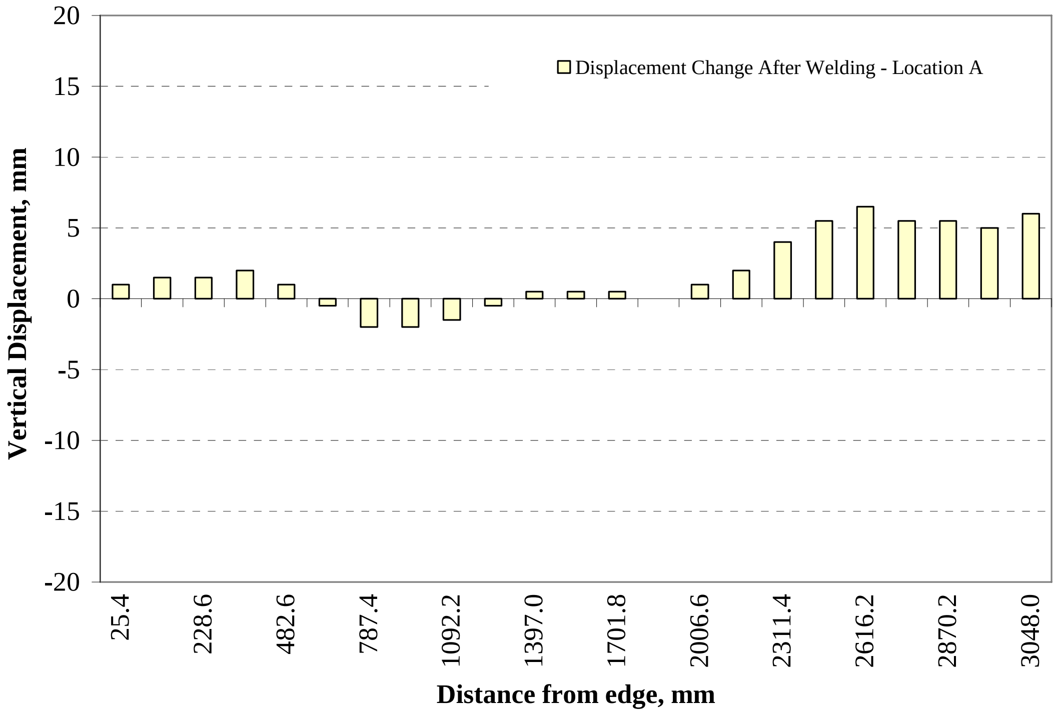


Figure I.1: Plate 3 Location A – Change in Displacement After Welding

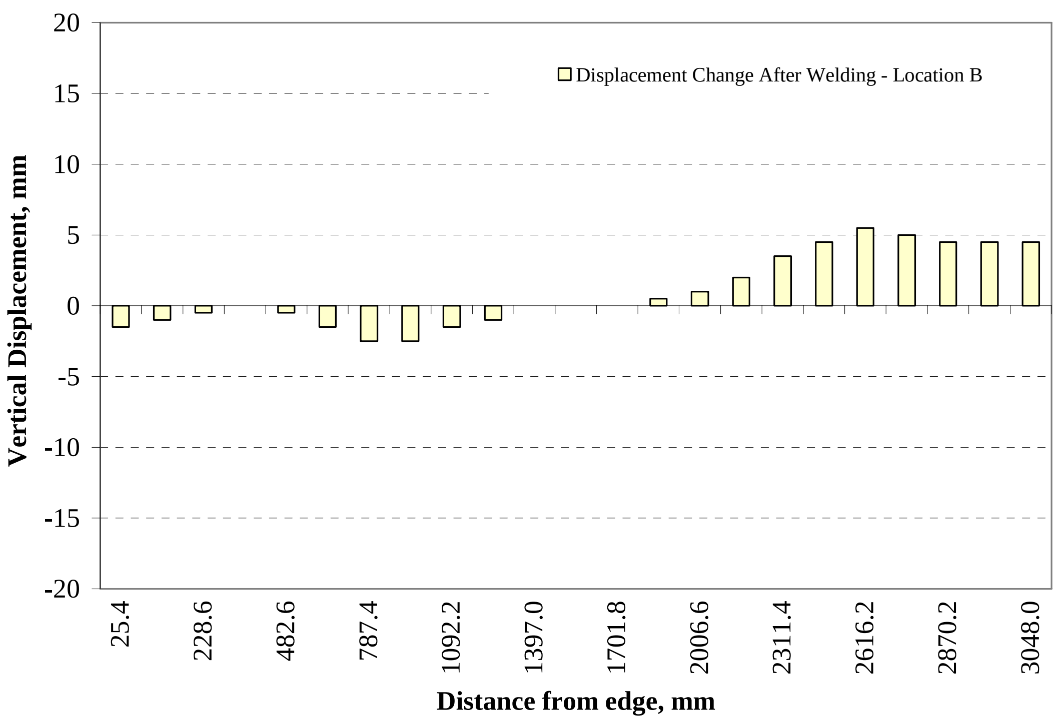


Figure I.2: Plate 3 Location B – Change in Displacement After Welding

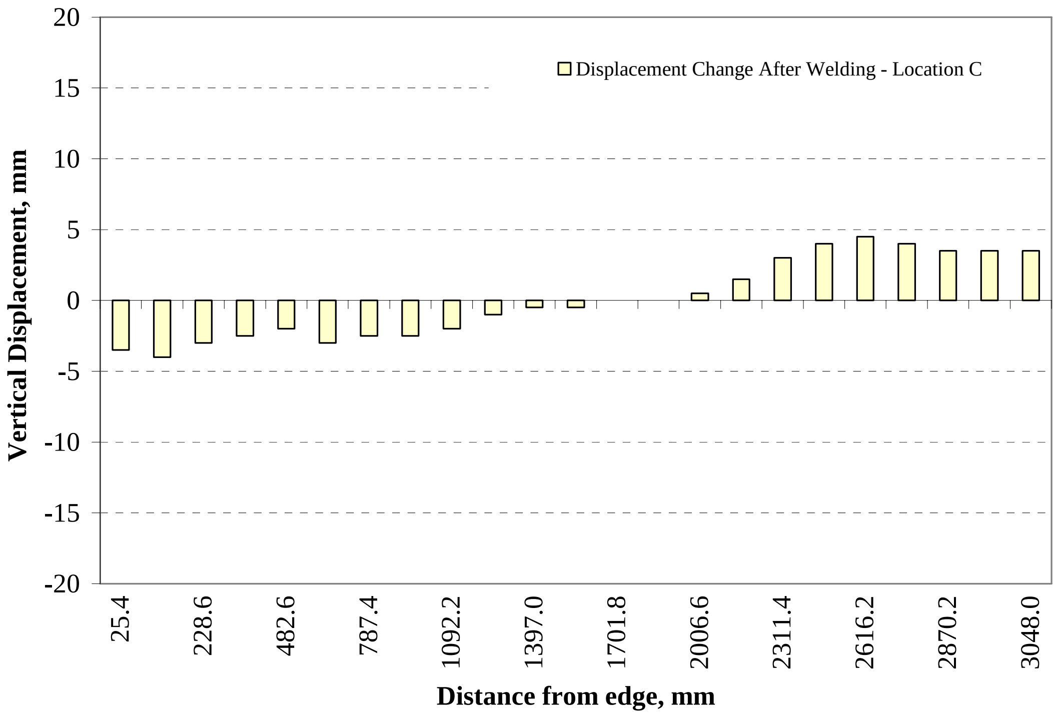


Figure I.3: Plate 3 Location C – Change in Displacement After Welding

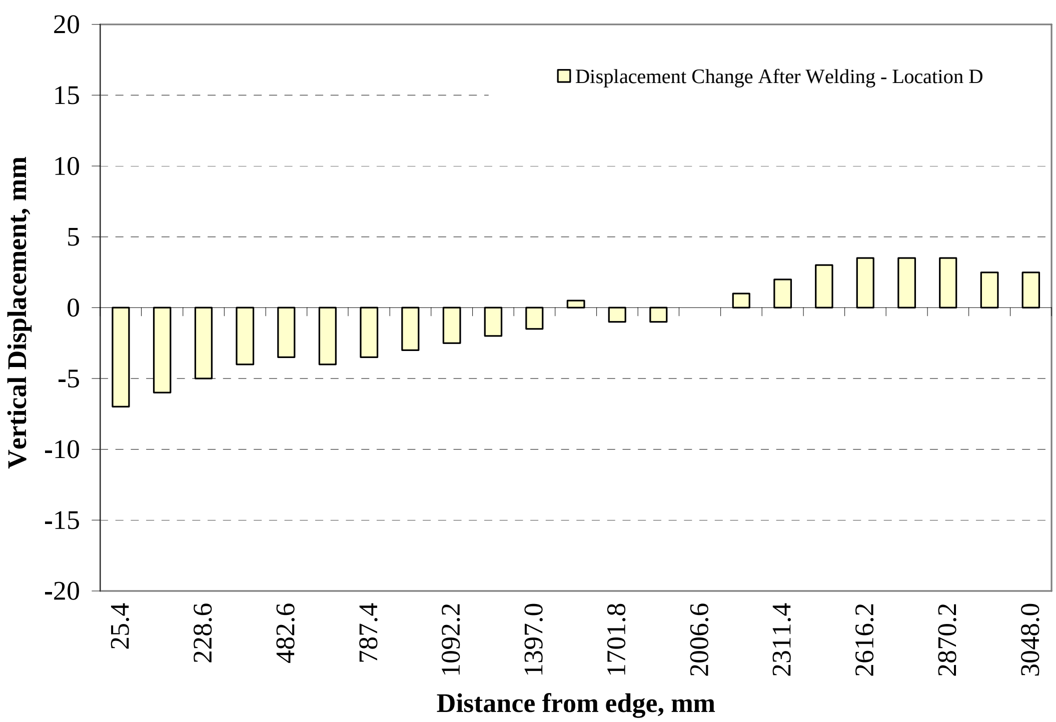


Figure I.4: Plate 3 Location D – Change in Displacement After Welding

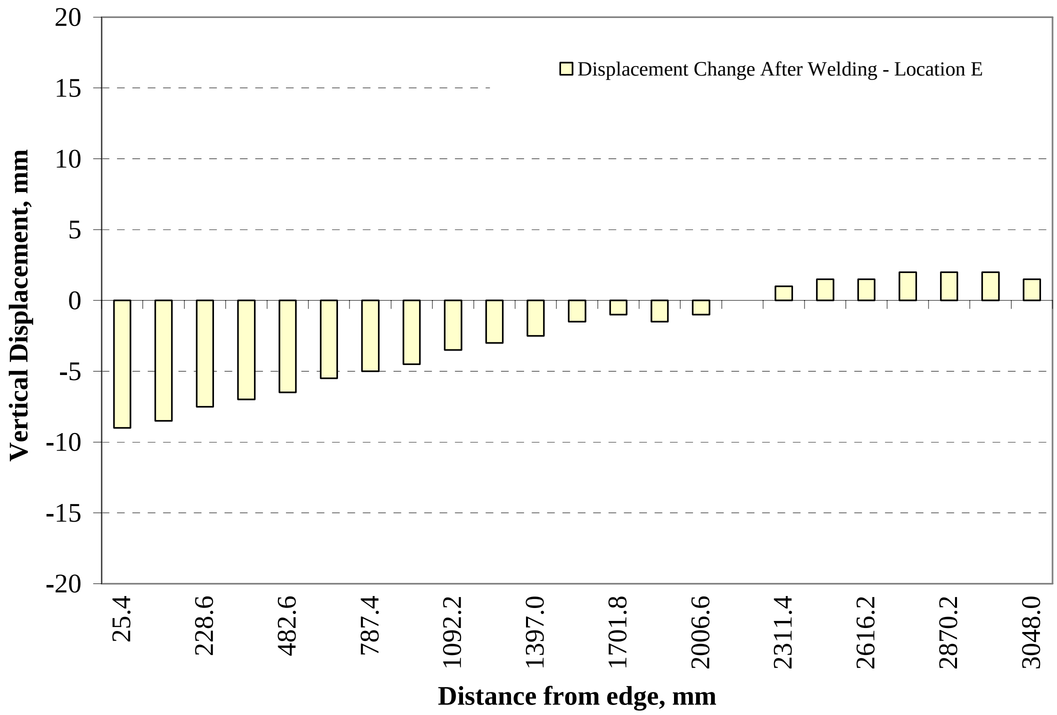


Figure I.5: Plate 3 Location E – Change in Displacement After Welding

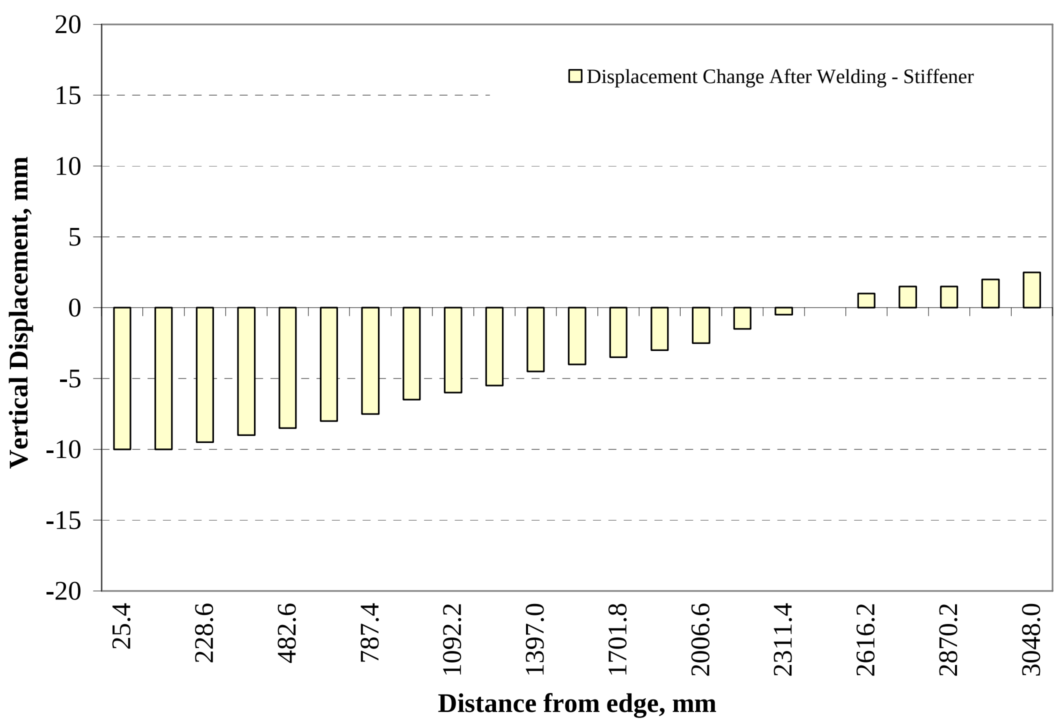


Figure I.6: Plate 3 At Stiffener – Change in Displacement After Welding

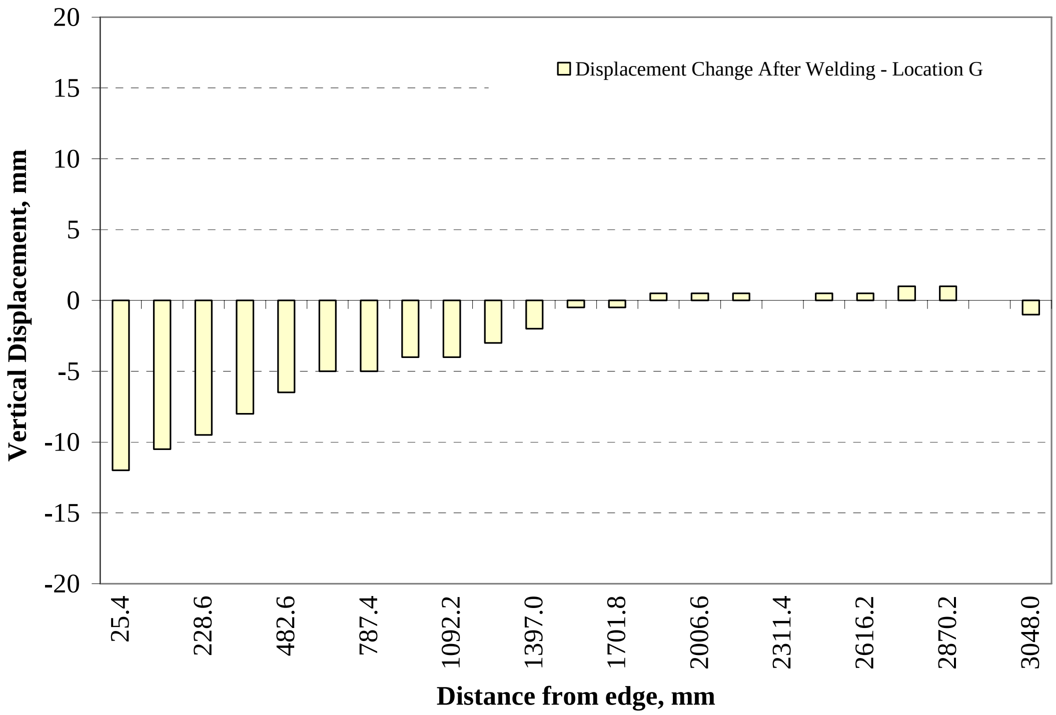


Figure I.7: Plate 3 Location G – Change in Displacement After Welding

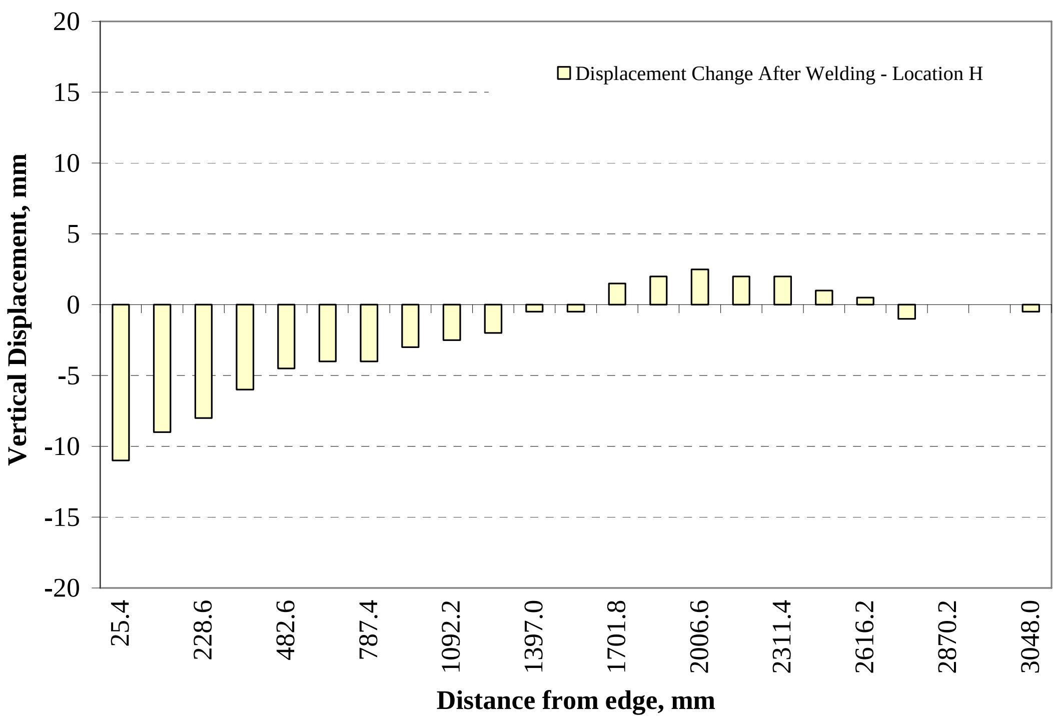


Figure I.8: Plate 3 Location H – Change in Displacement After Welding

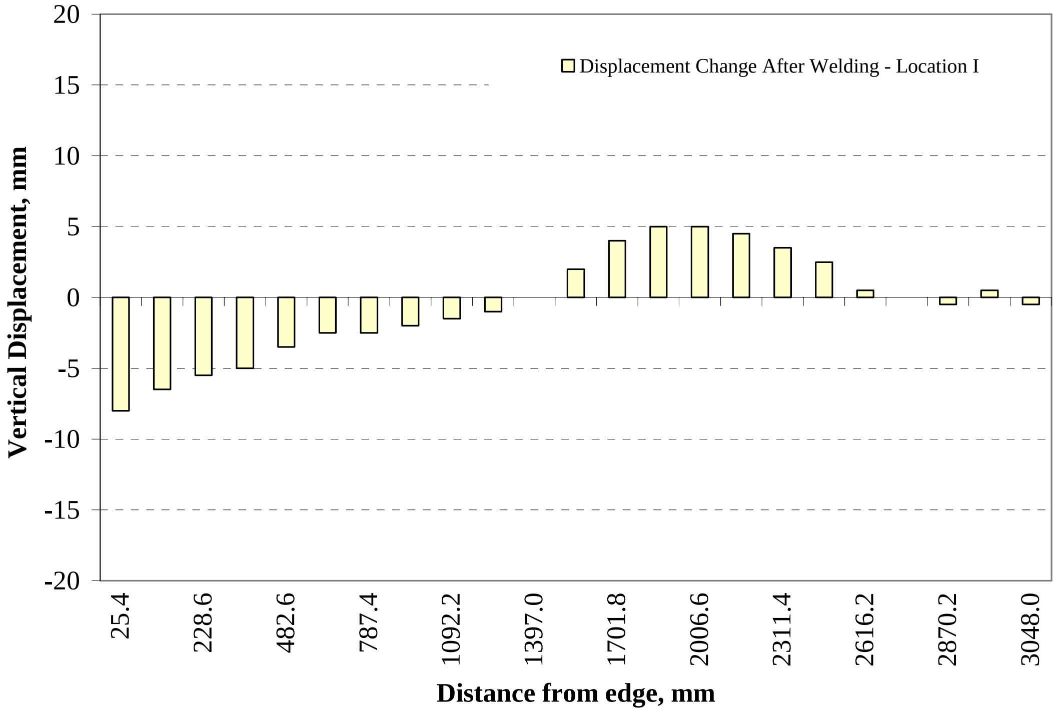


Figure I.9: Plate 3 Location I – Change in Displacement After Welding

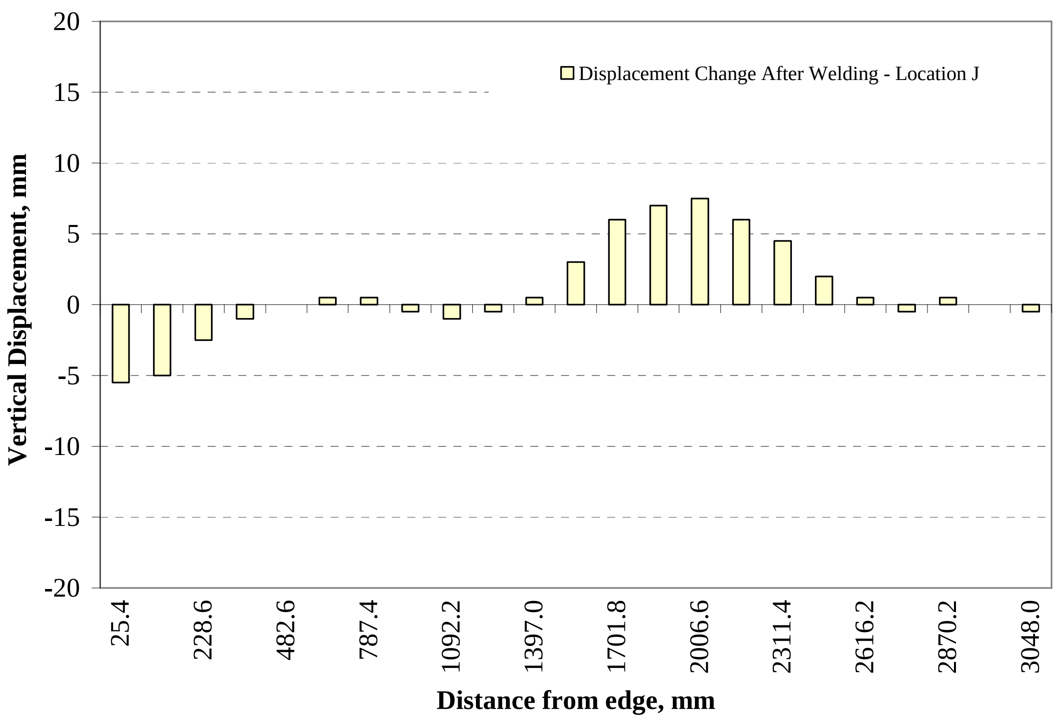


Figure I.10: Plate 3 Location J – Change in Displacement After Welding

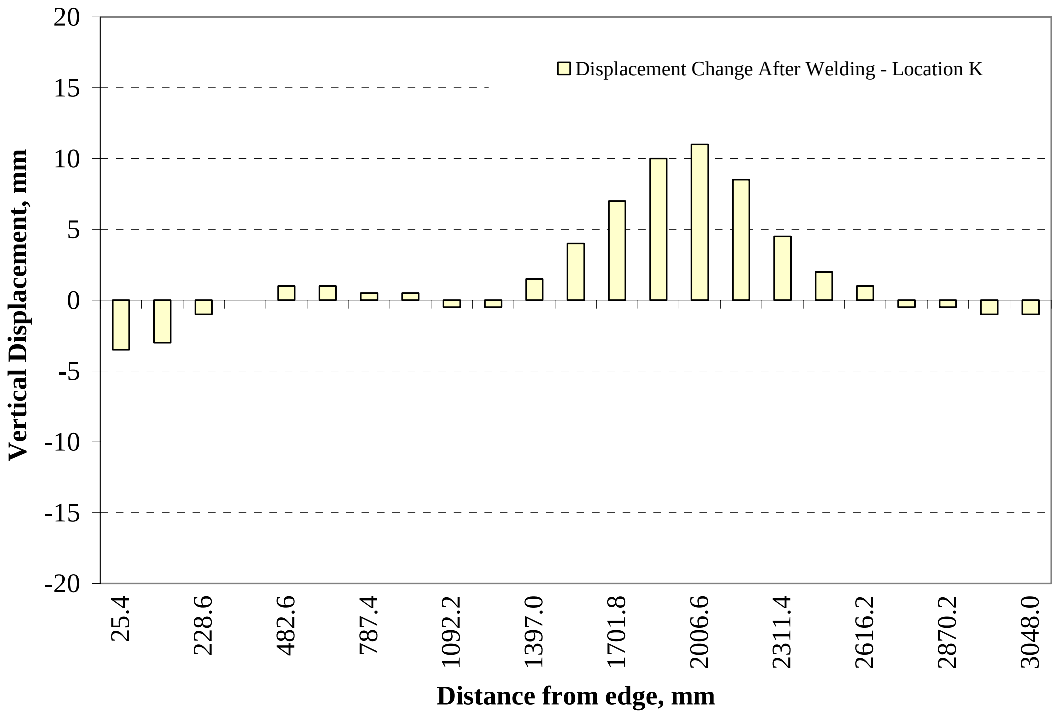


Figure I.11: Plate 3 Location K – Change in Displacement After Welding

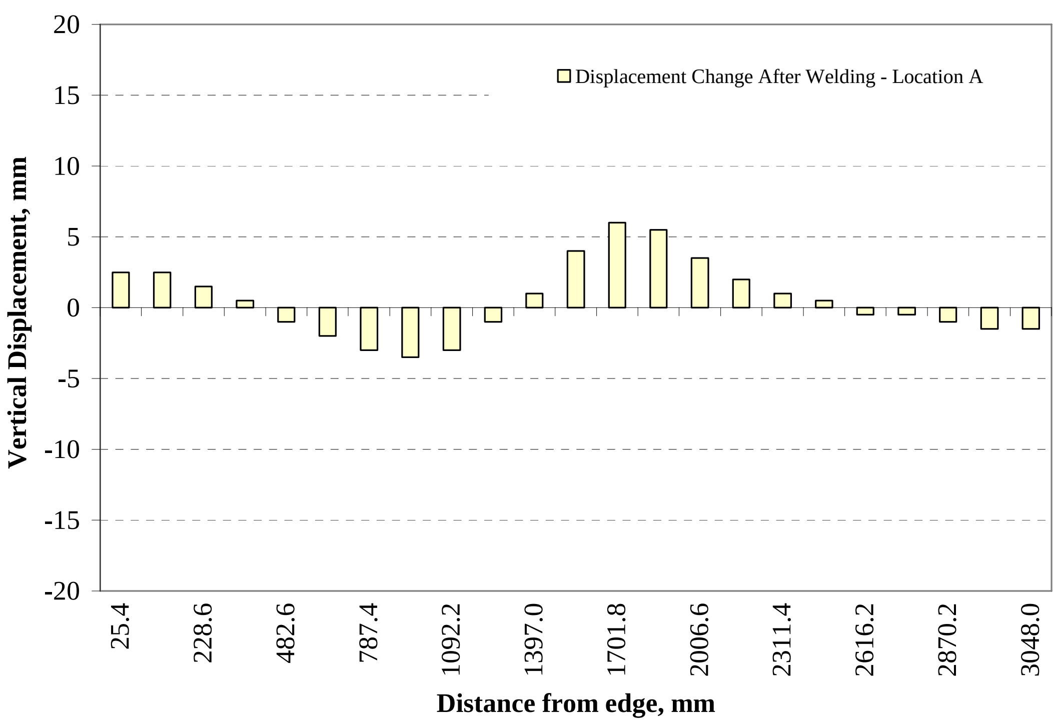


Figure I.12: Plate 7 Location A – Change in Displacement After Welding

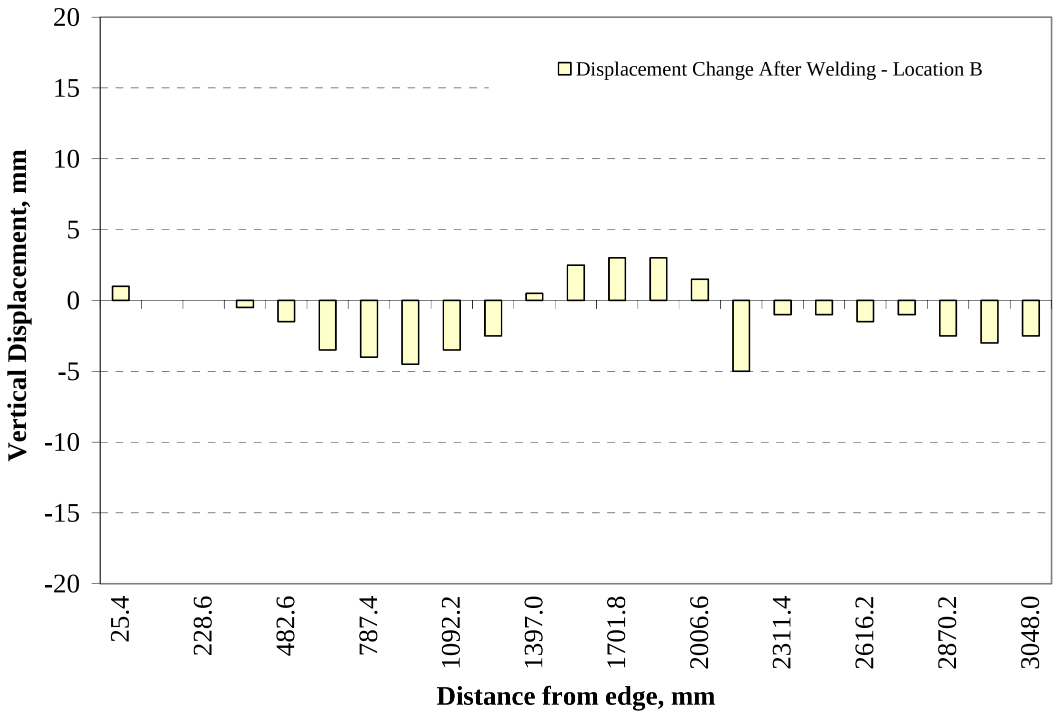


Figure I.13: Plate 7 Location B – Change in Displacement After Welding

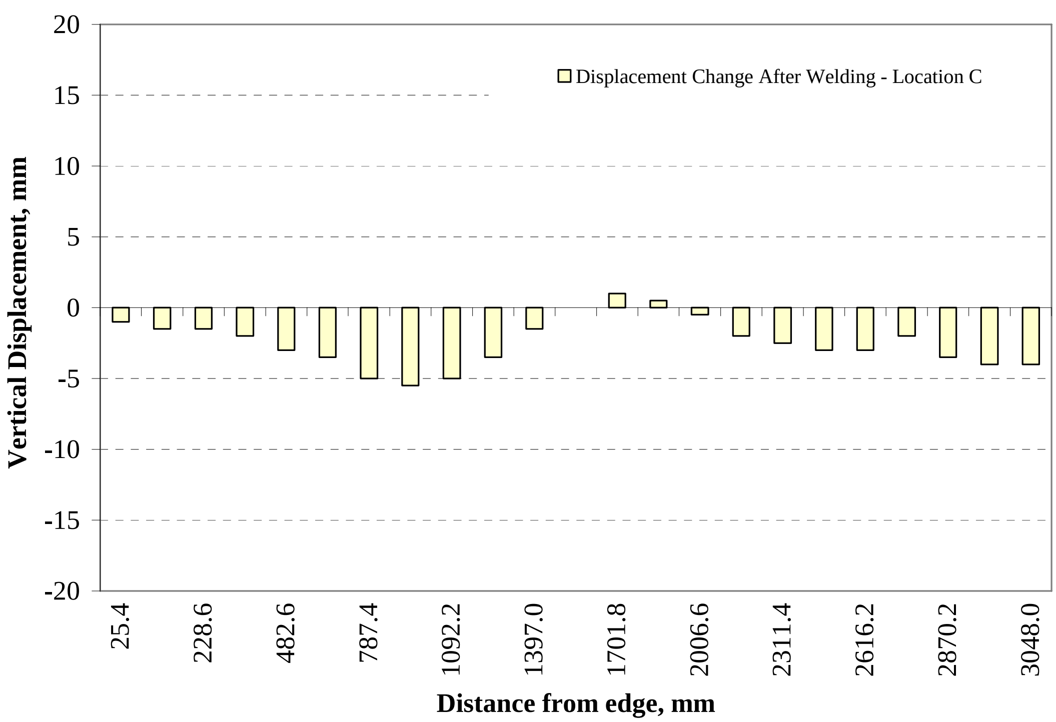


Figure I.14: Plate 7 Location C – Change in Displacement After Welding

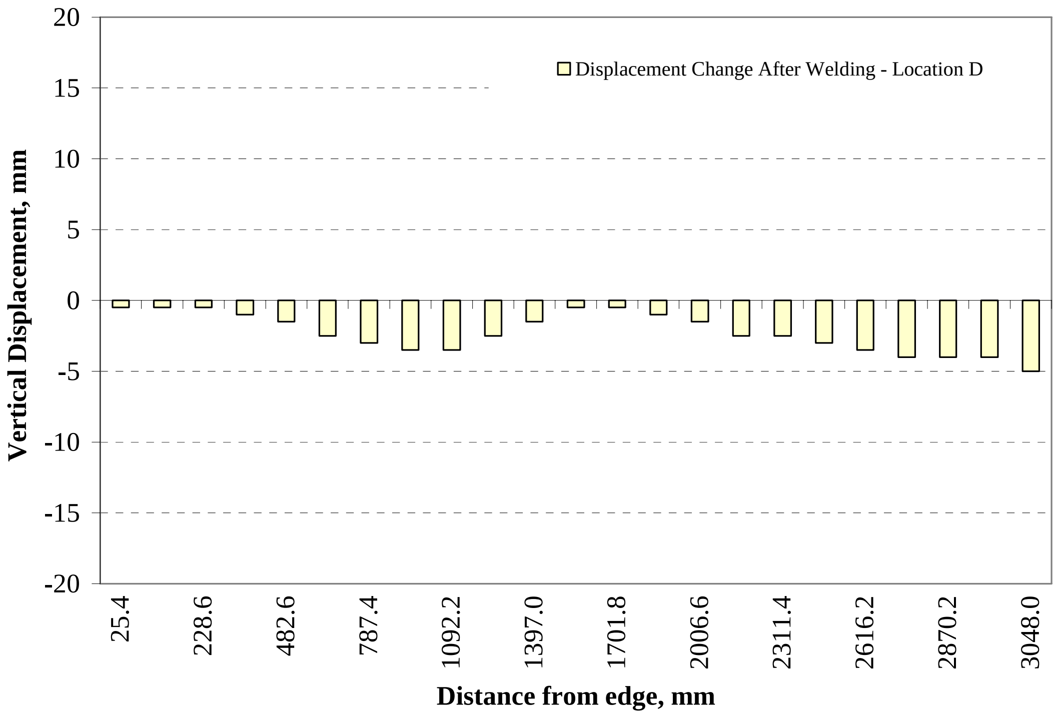


Figure I.15: Plate 7 Location D – Change in Displacement After Welding

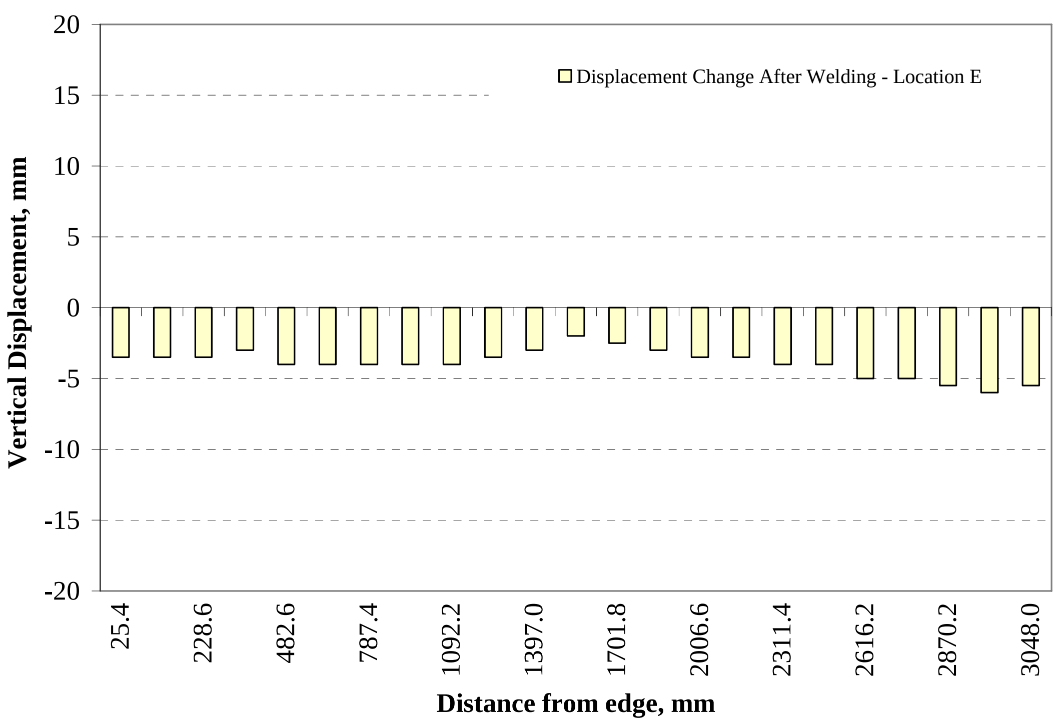


Figure I.16: Plate 7 Location E – Change in Displacement After Welding

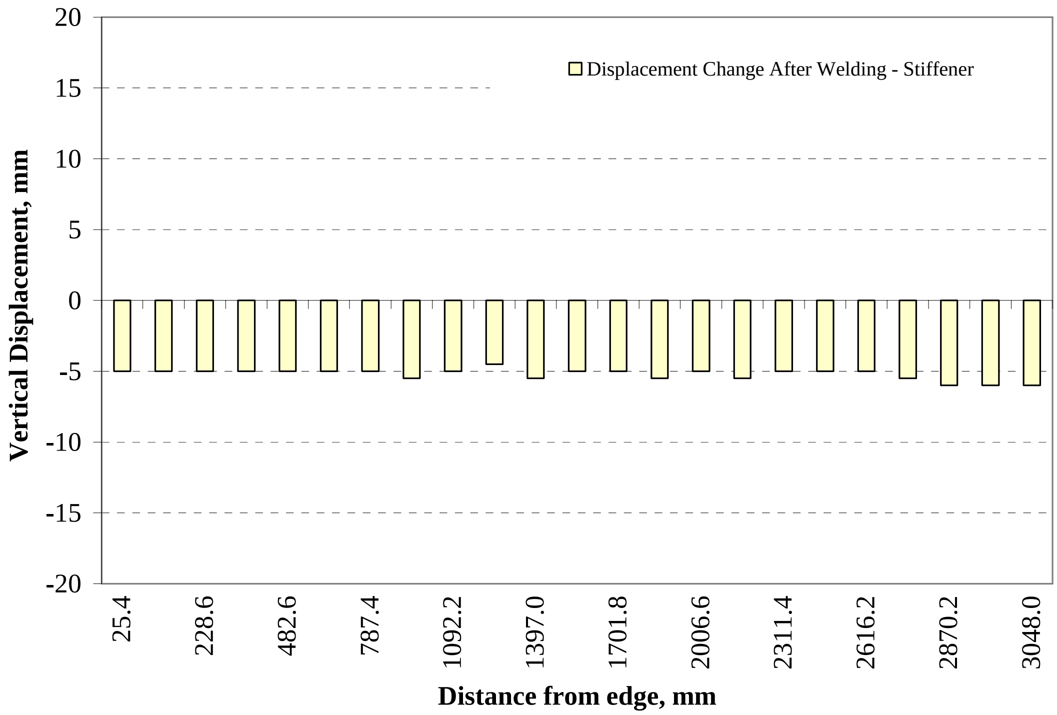


Figure I.17: Plate 7 At Stiffener – Change in Displacement After Welding

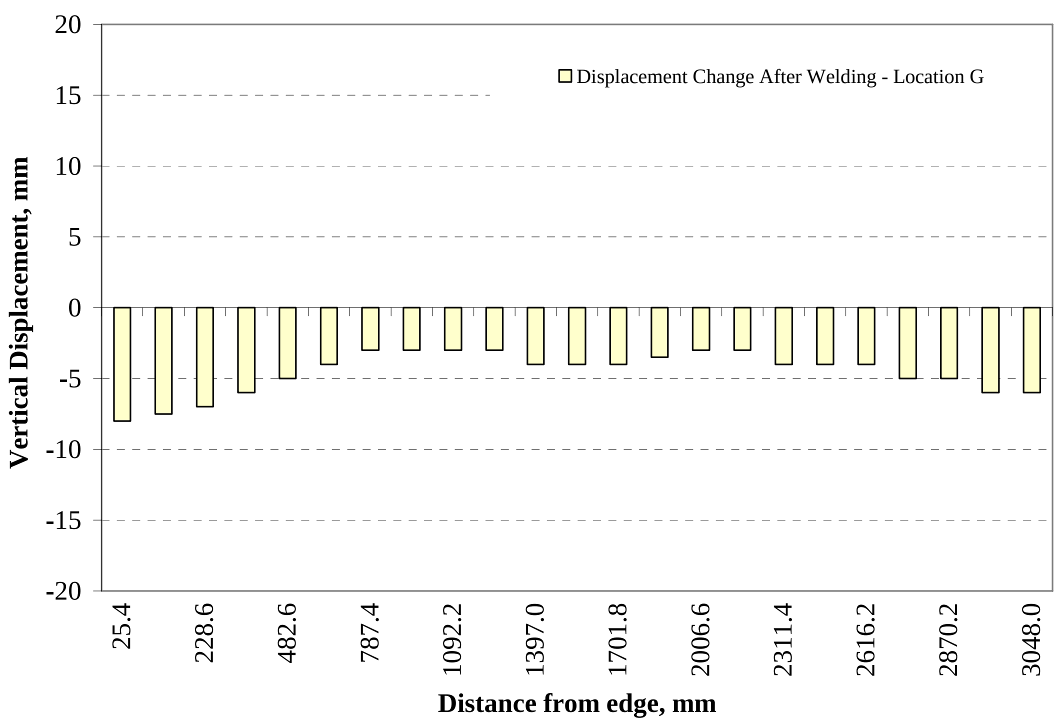


Figure I.18: Plate 7 Location G – Change in Displacement After Welding

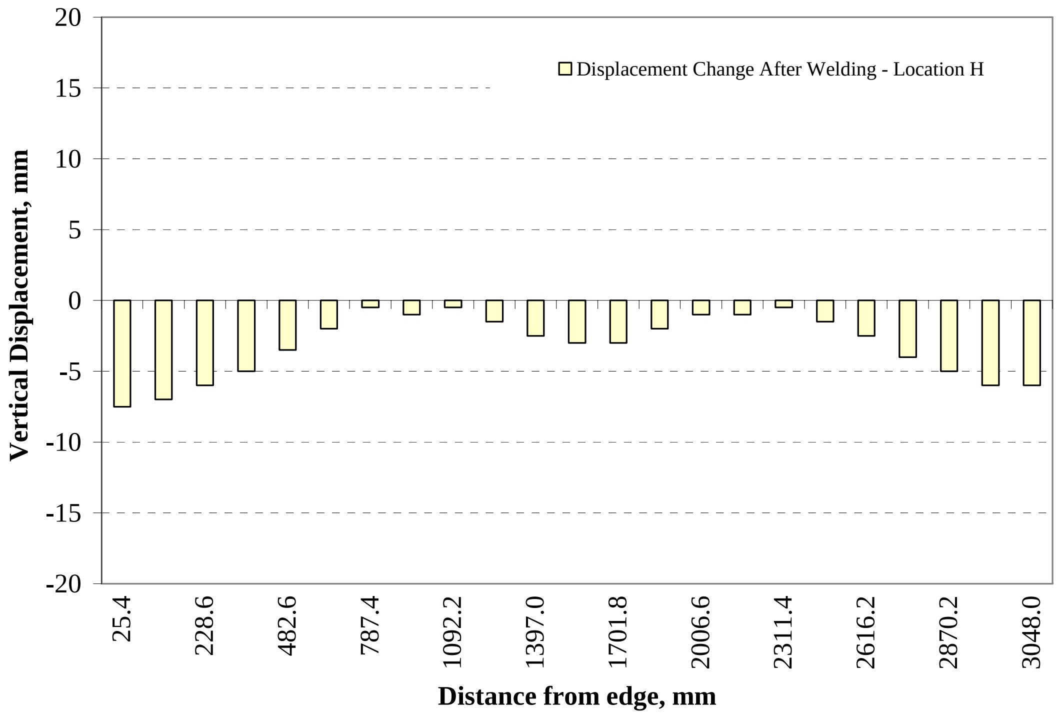


Figure I.19: Plate 7 Location H – Change in Displacement After Welding

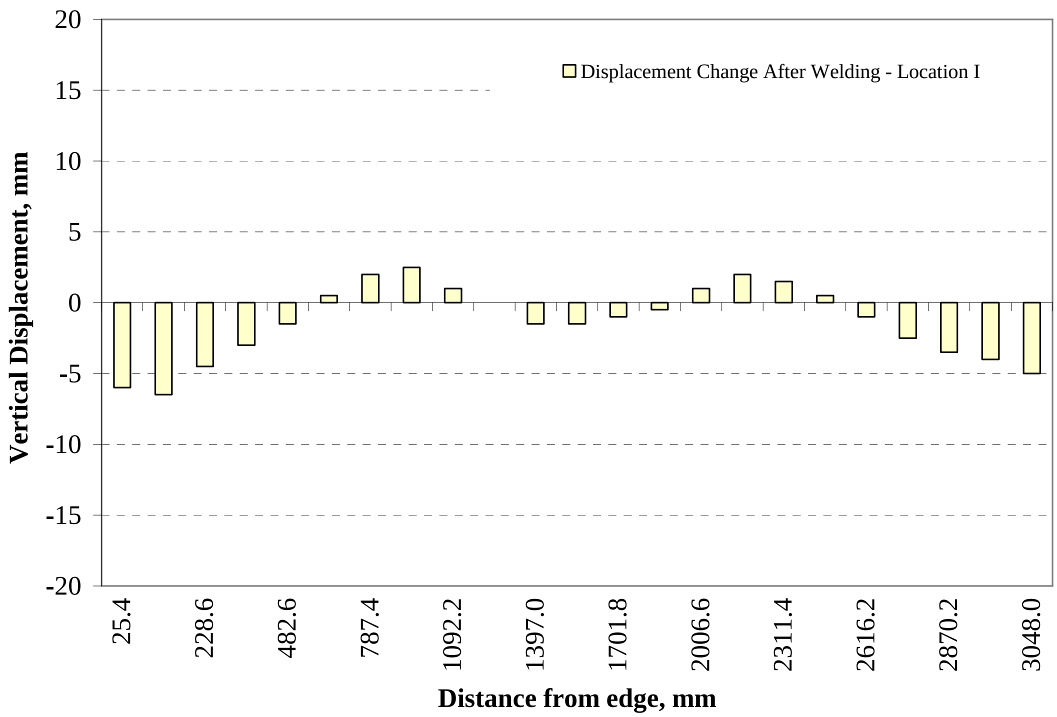


Figure I.20: Plate 7 Location I – Change in Displacement After Welding

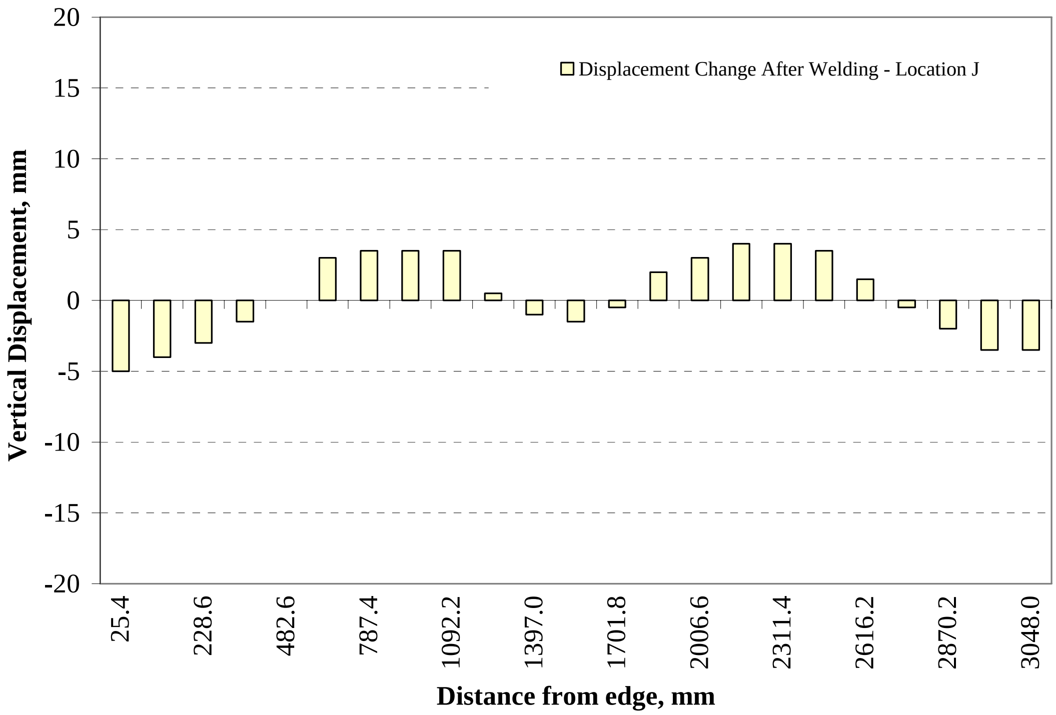


Figure I.21: Plate 7 Location J – Change in Displacement After Welding

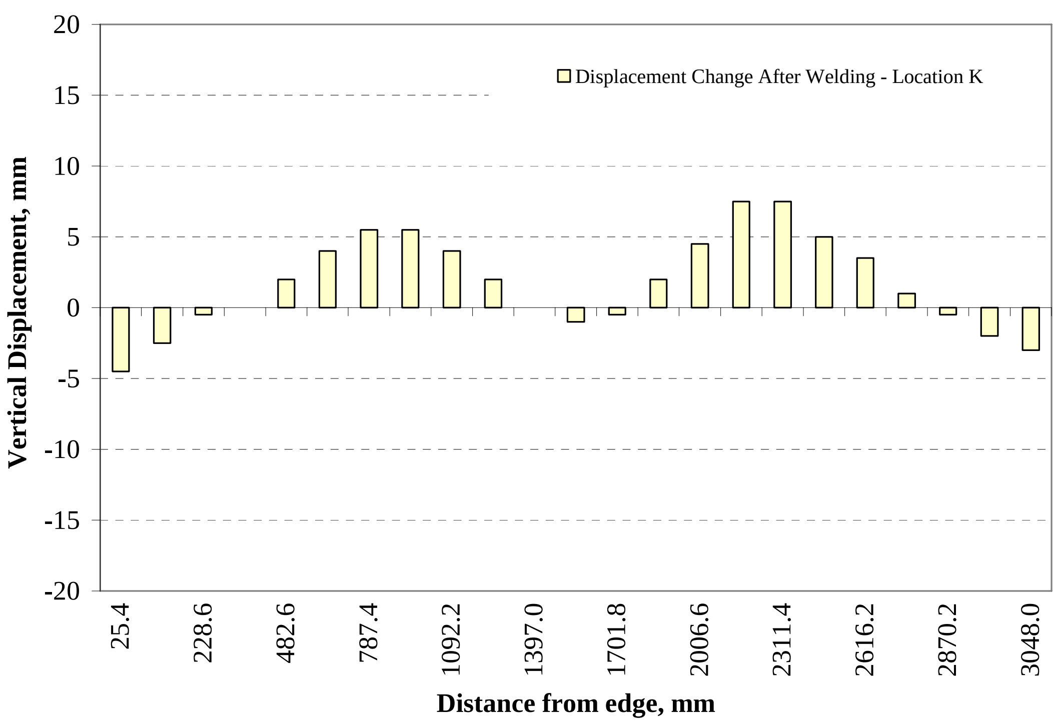


Figure I.22: Plate 7 Location K – Change in Displacement After Welding

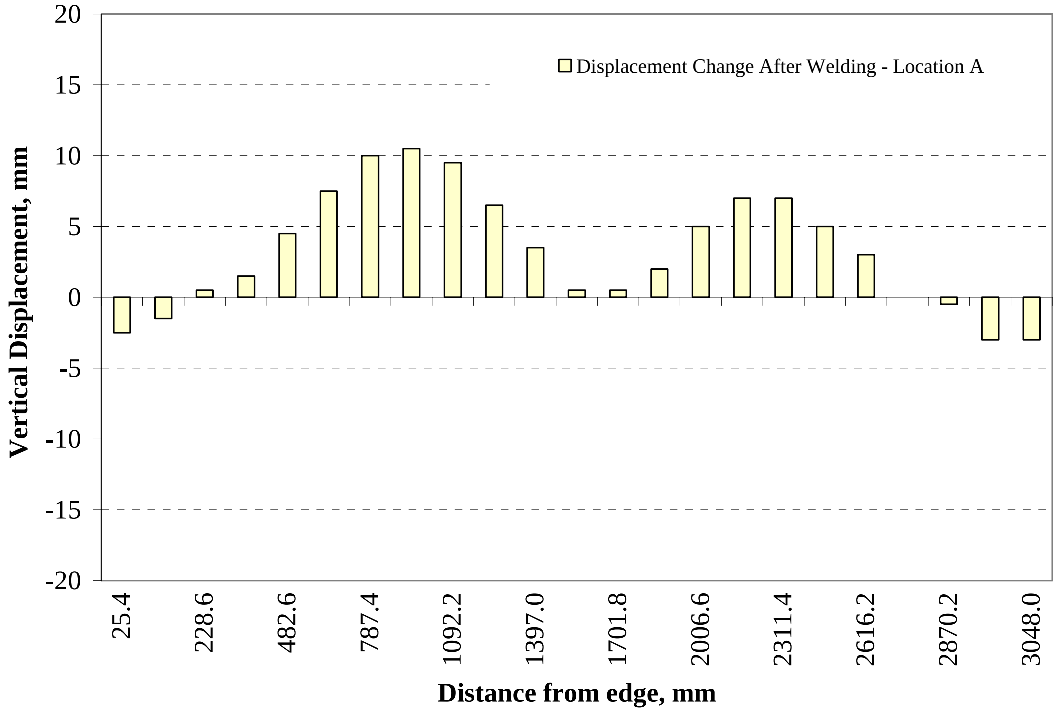


Figure I.23: Plate 8 Location A – Change in Displacement After Welding

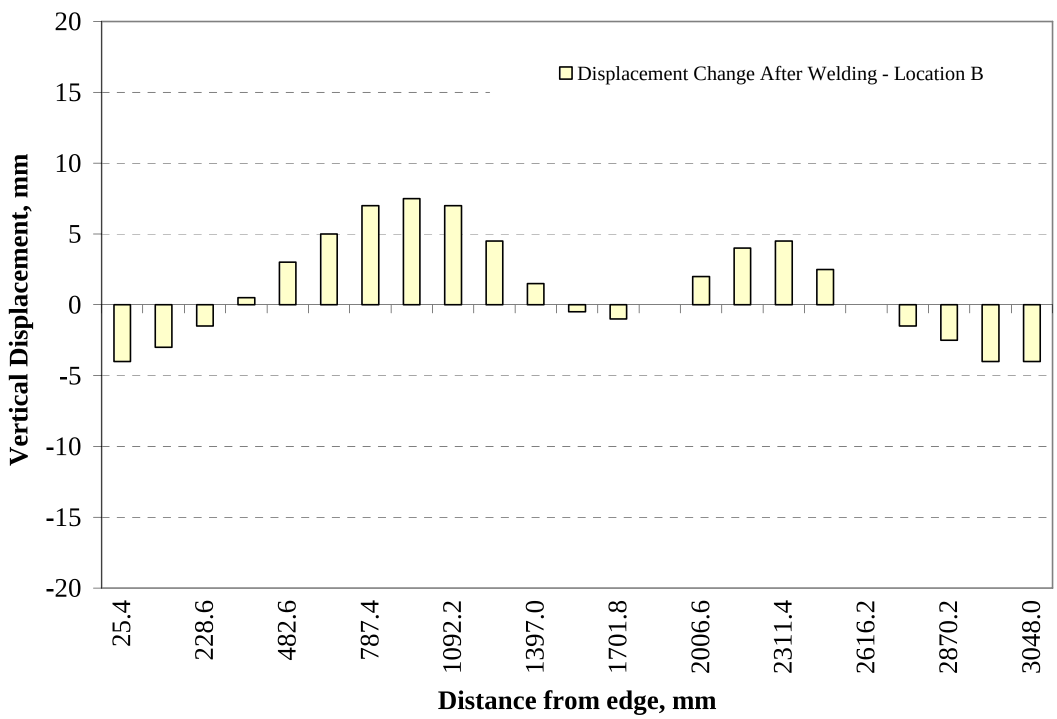


Figure I.24: Plate 8 Location B – Change in Displacement After Welding

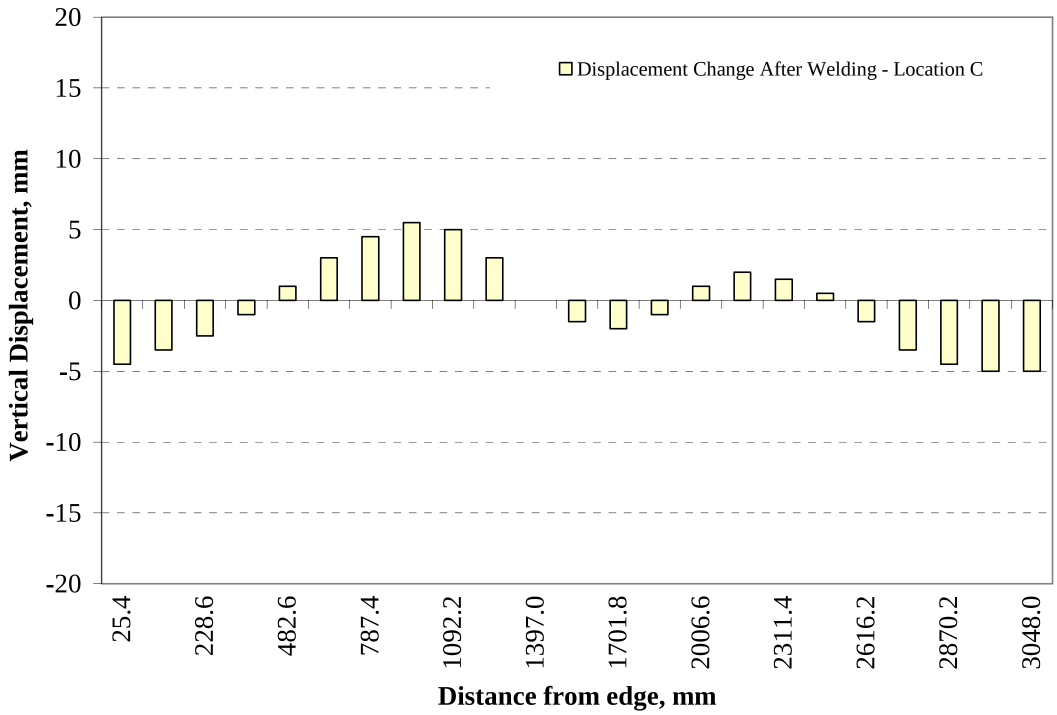


Figure I.25: Plate 8 Location C – Change in Displacement After Welding

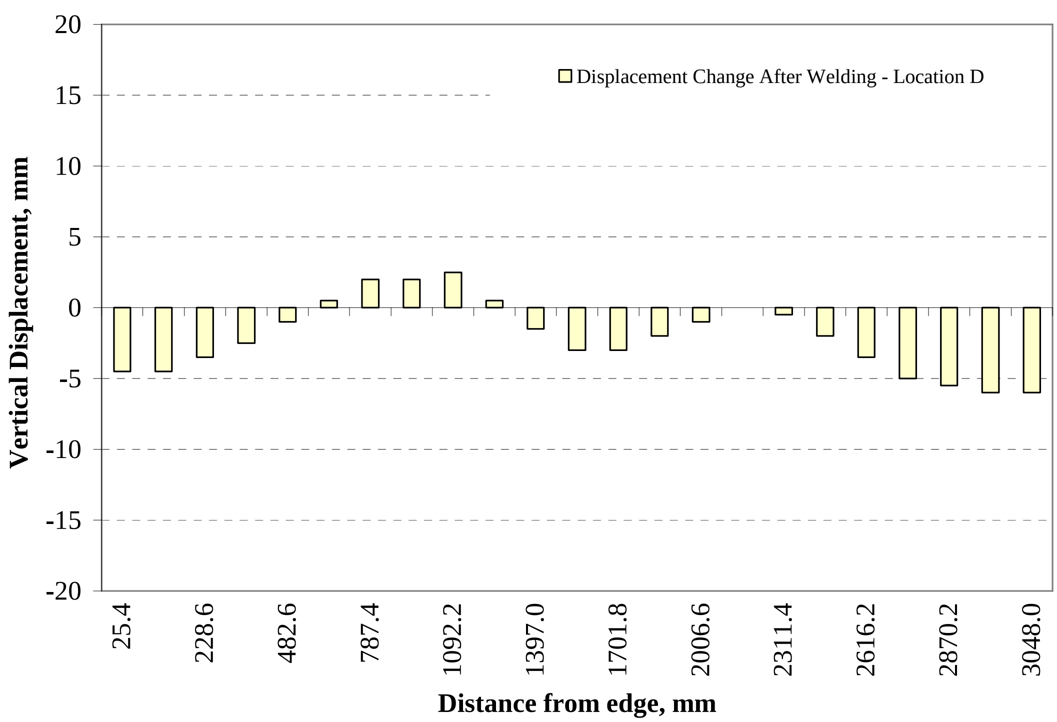


Figure I.26: Plate 8 Location D – Change in Displacement After Welding

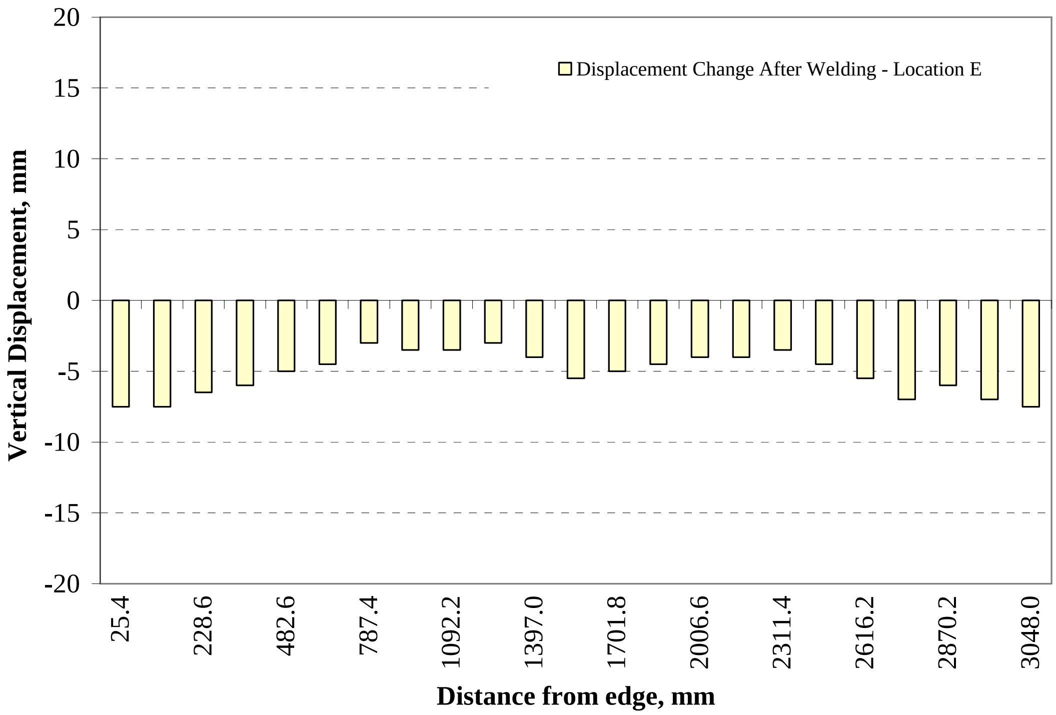


Figure I.27: Plate 8 Location E – Change in Displacement After Welding

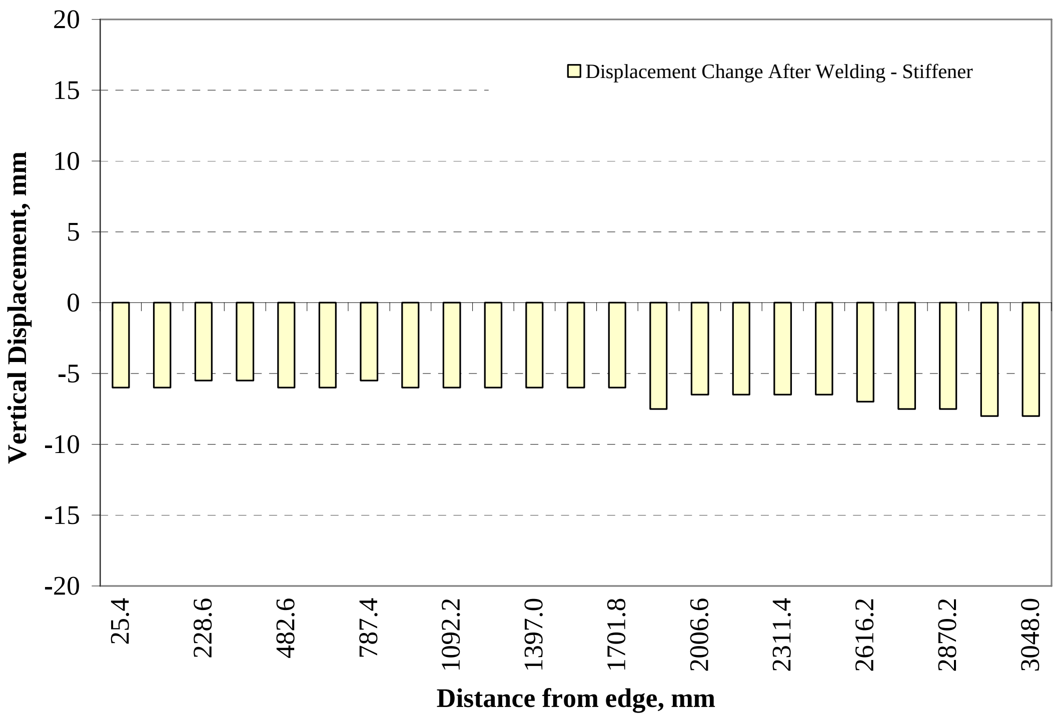


Figure I.28: Plate 8 At Stiffener – Change in Displacement After Welding

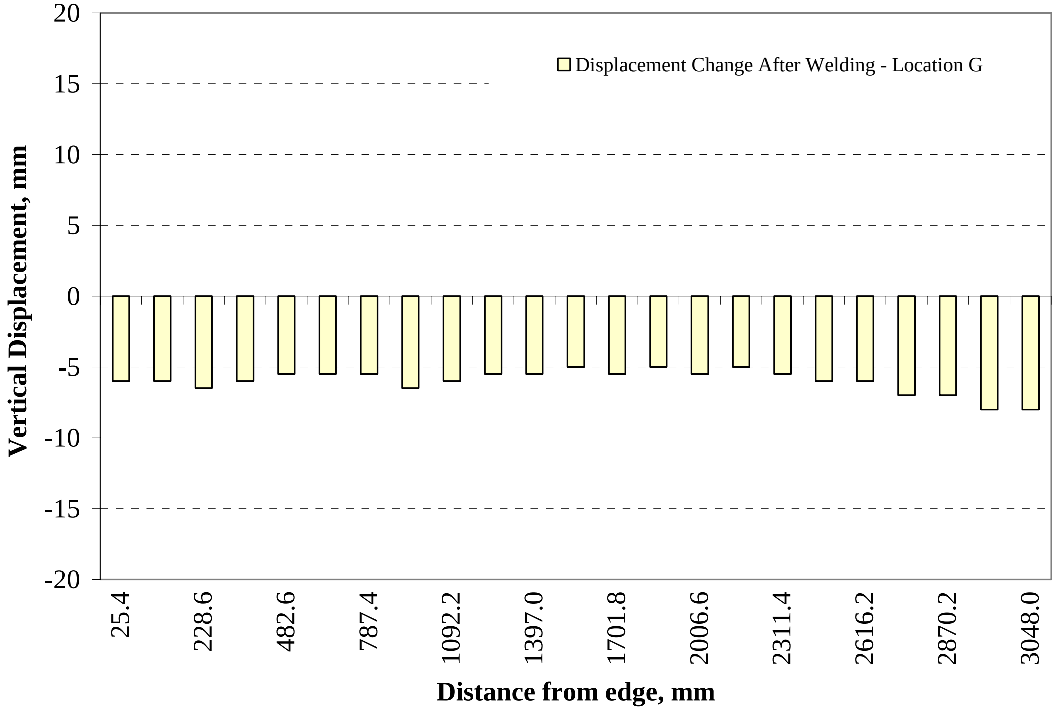


Figure I.29: Plate 8 Location G – Change in Displacement After Welding

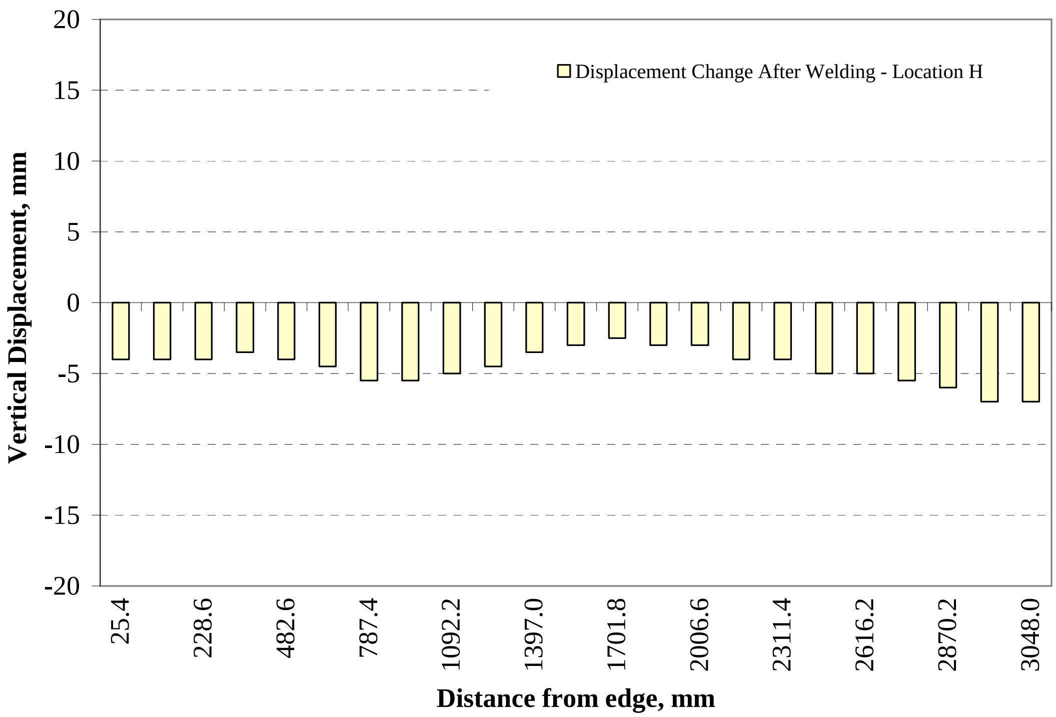


Figure I.30: Plate 8 Location H – Change in Displacement After Welding

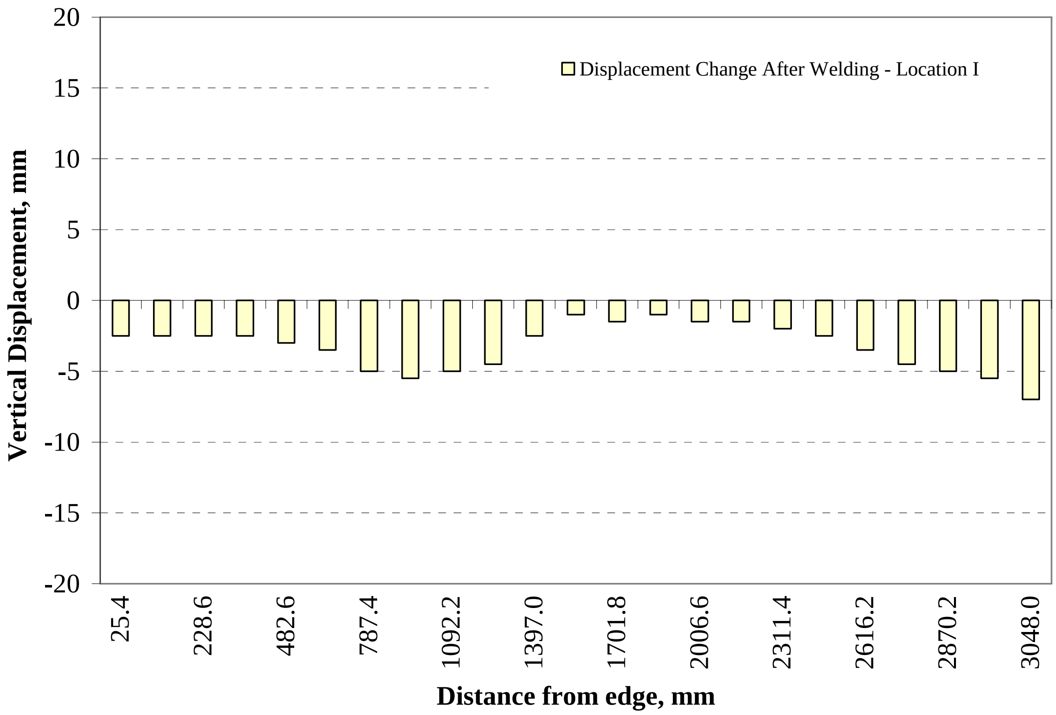


Figure I.31: Plate 8 Location I – Change in Displacement After Welding

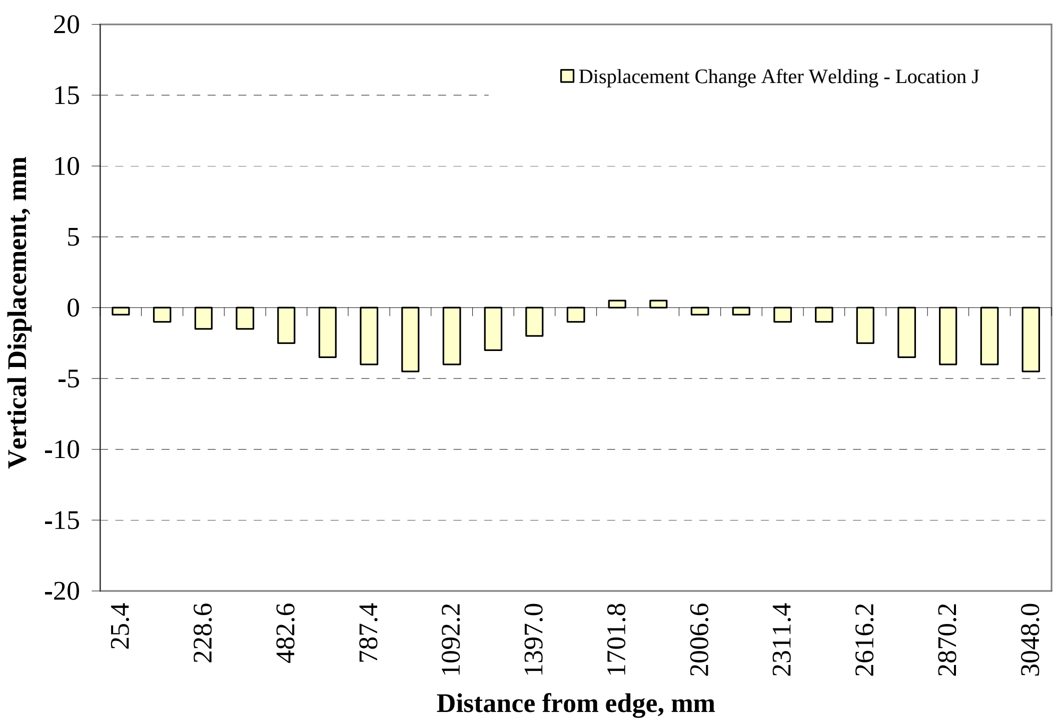


Figure I.32: Plate 8 Location J – Change in Displacement After Welding

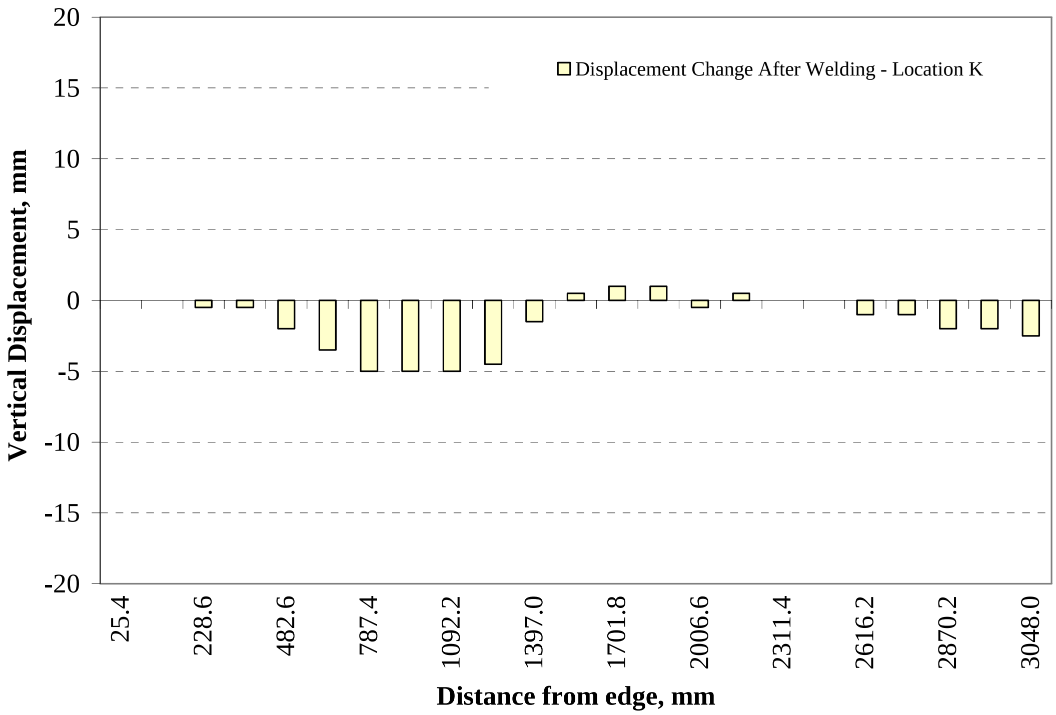


Figure I.33: Plate 8 Location K – Change in Displacement After Welding

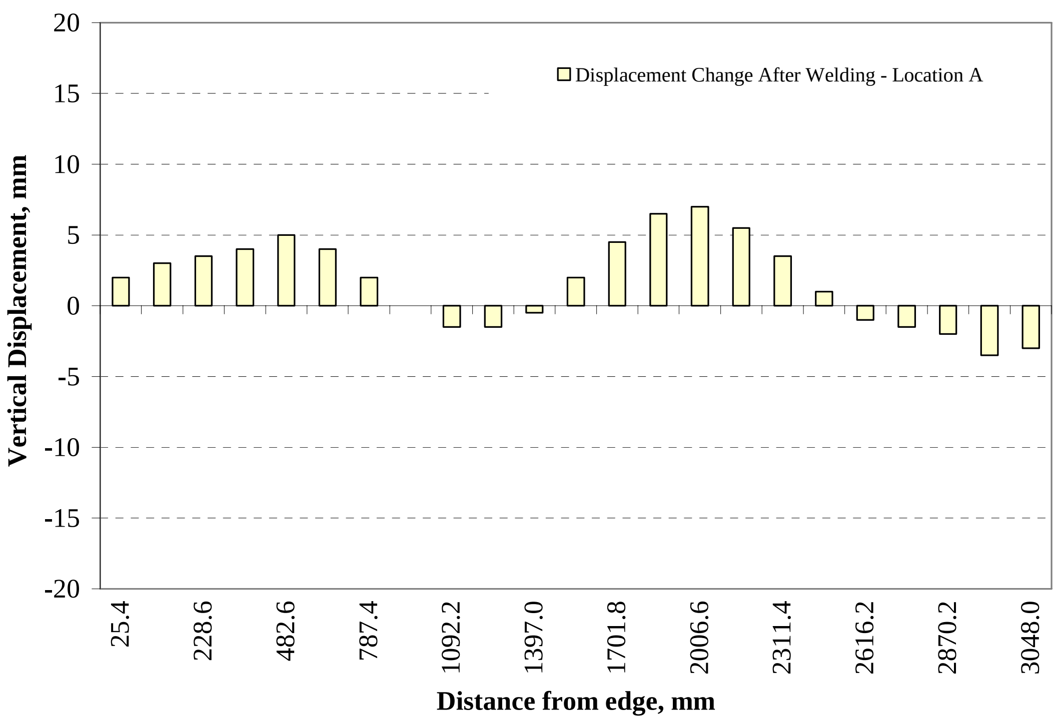


Figure I.34: Plate 9 Location A – Change in Displacement After Welding

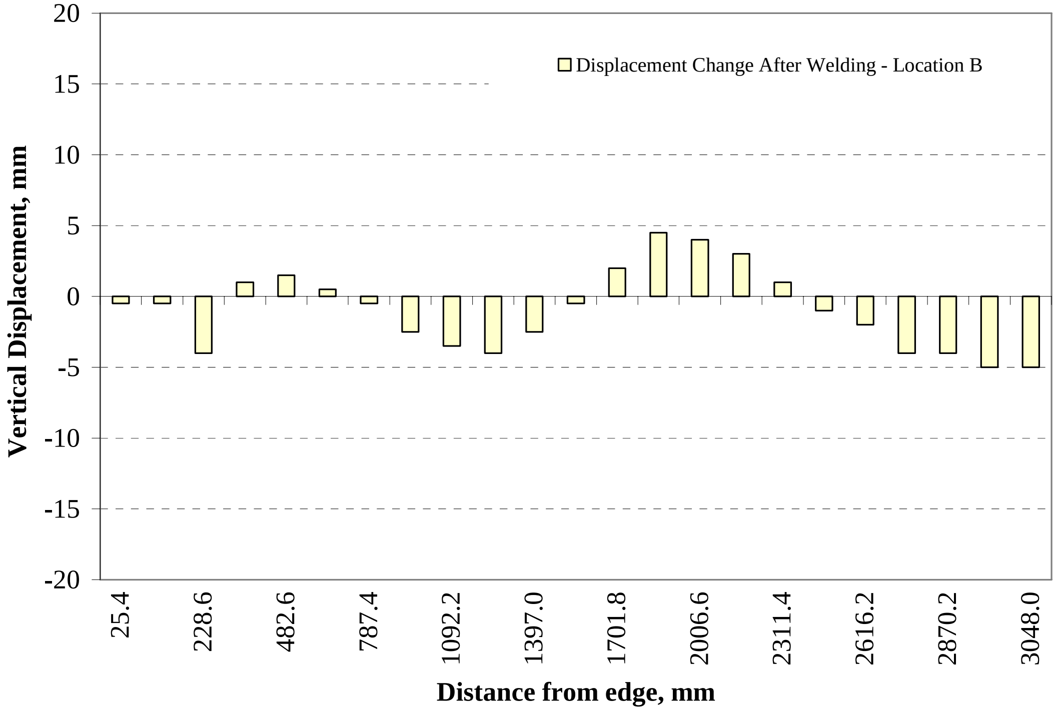


Figure I.35: Plate 9 Location B – Change in Displacement After Welding

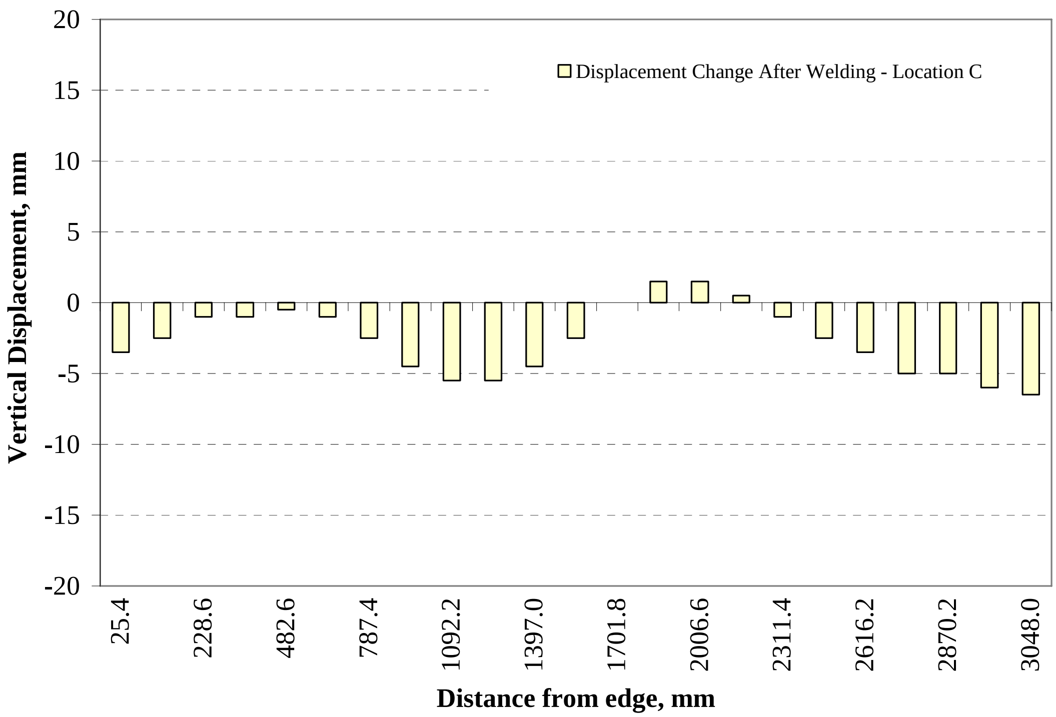


Figure I.36: Plate 9 Location C – Change in Displacement After Welding

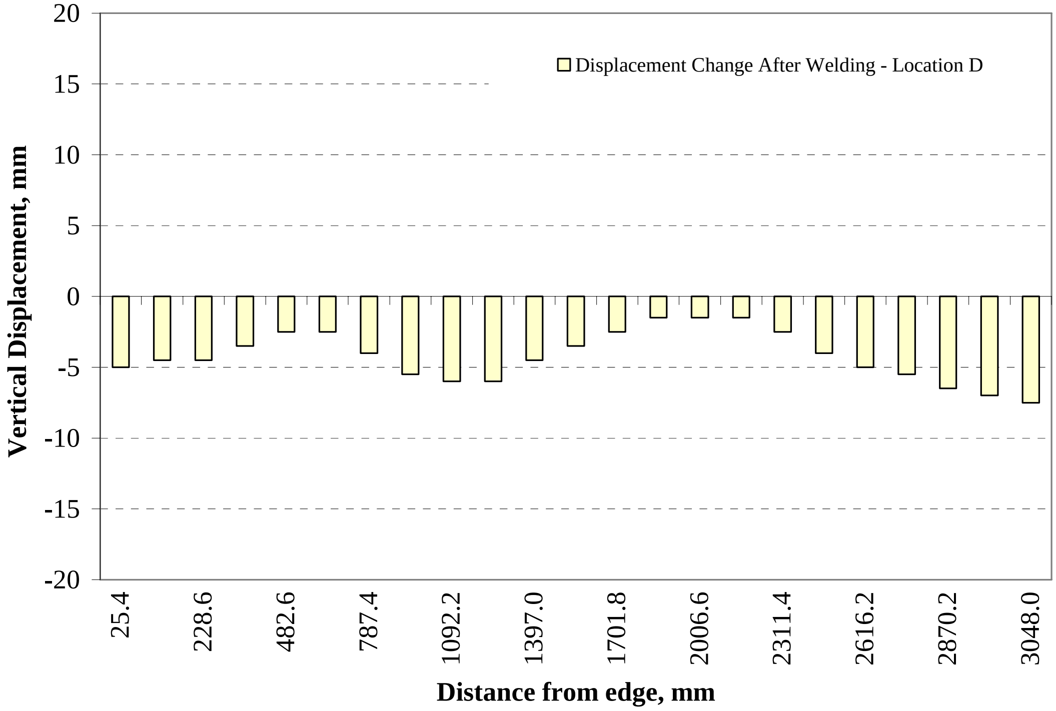


Figure I.37: Plate 9 Location D – Change in Displacement After Welding

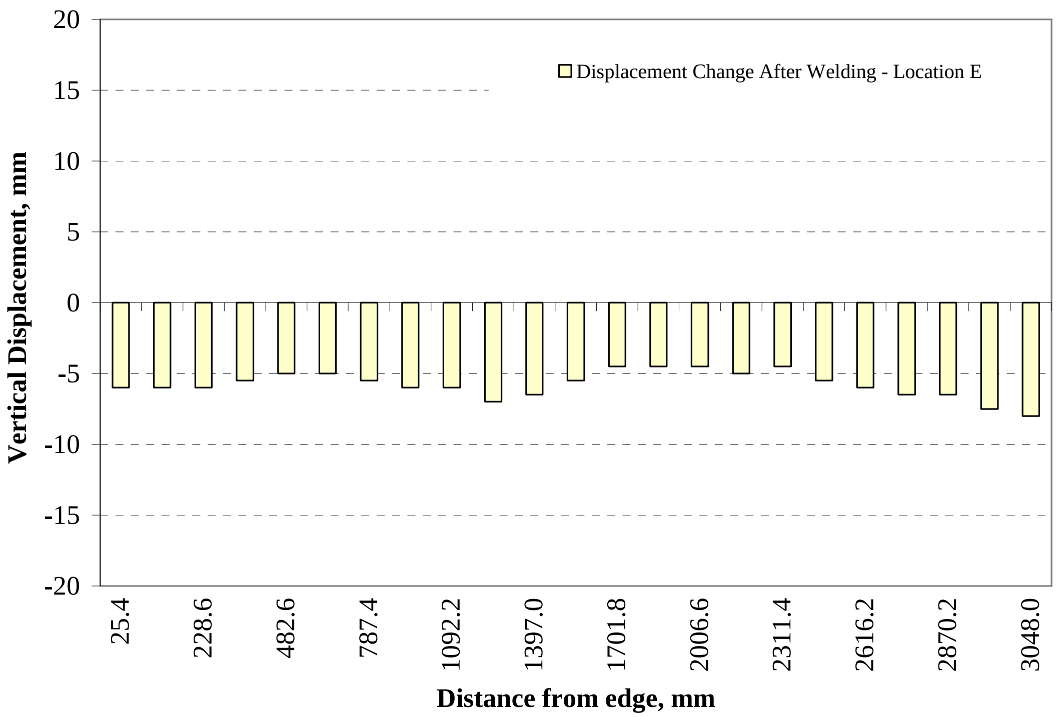


Figure I.38: Plate 9 Location E – Change in Displacement After Welding

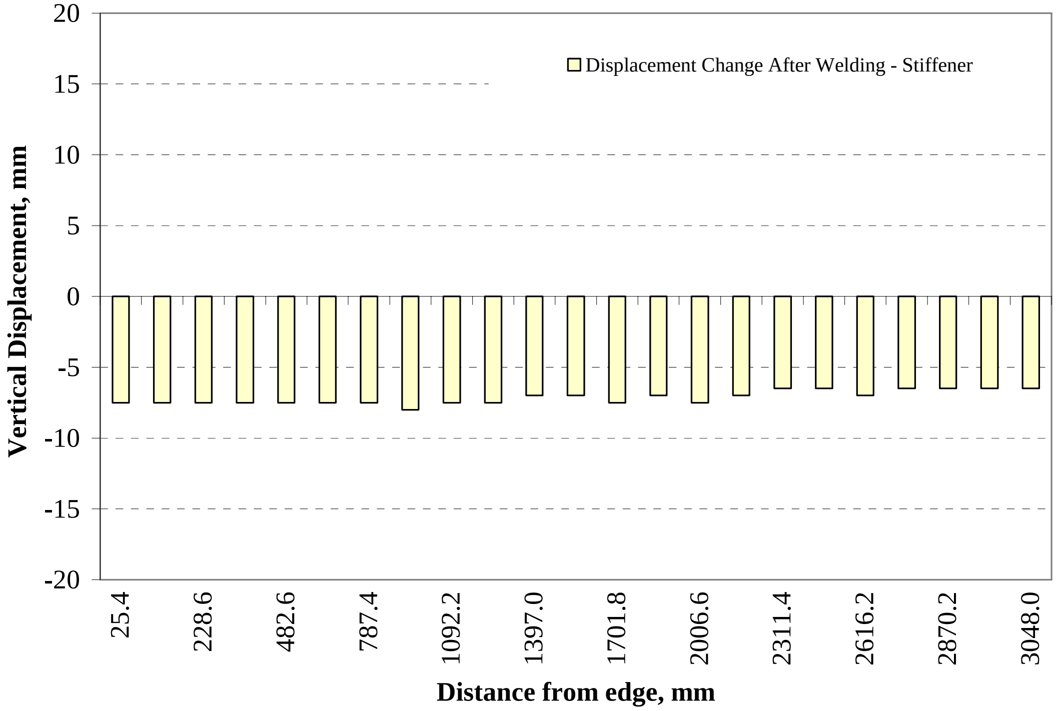


Figure I.39: Plate 9 At Stiffener – Change in Displacement After Welding

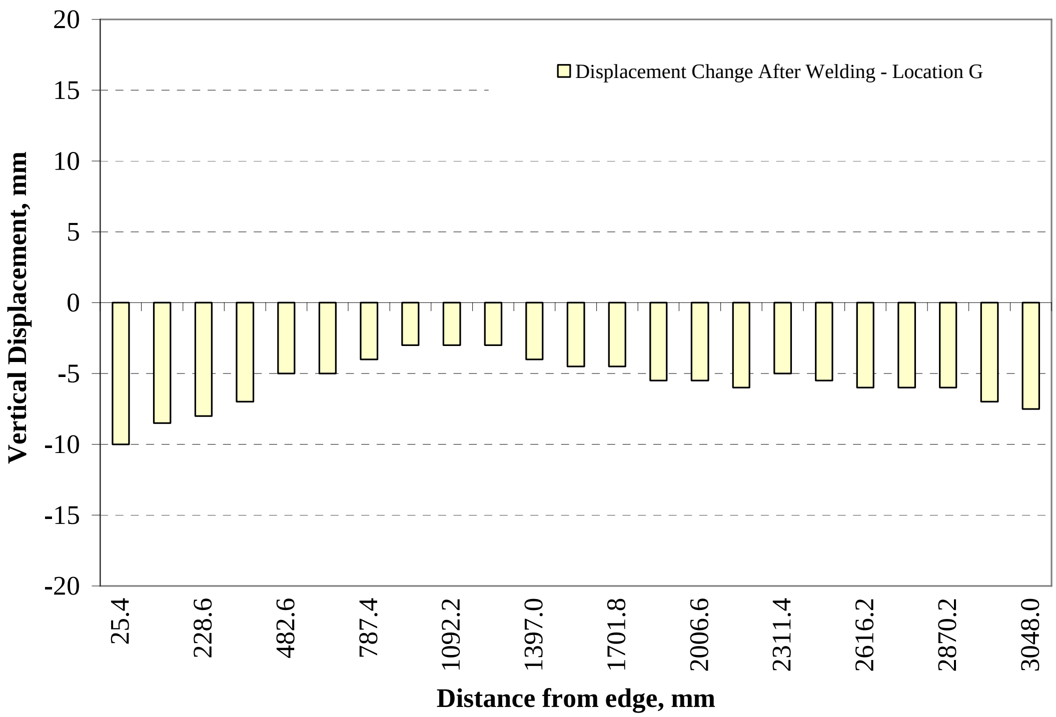


Figure I.40: Plate 9 Location G – Change in Displacement After Welding

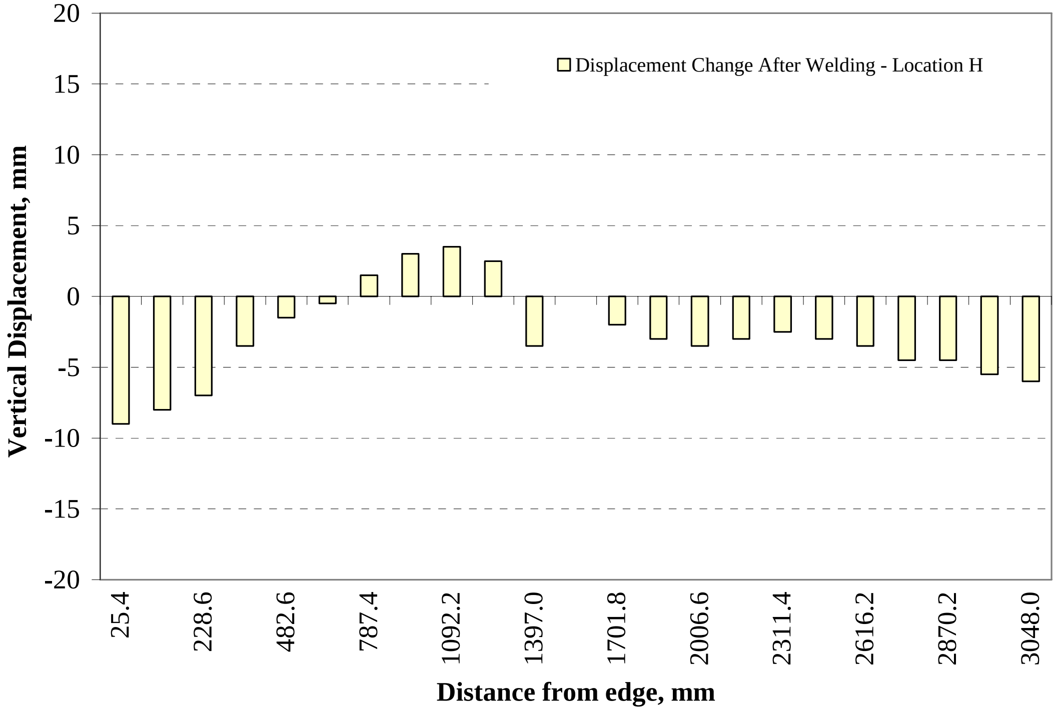


Figure I.41: Plate 9 Location H – Change in Displacement After Welding

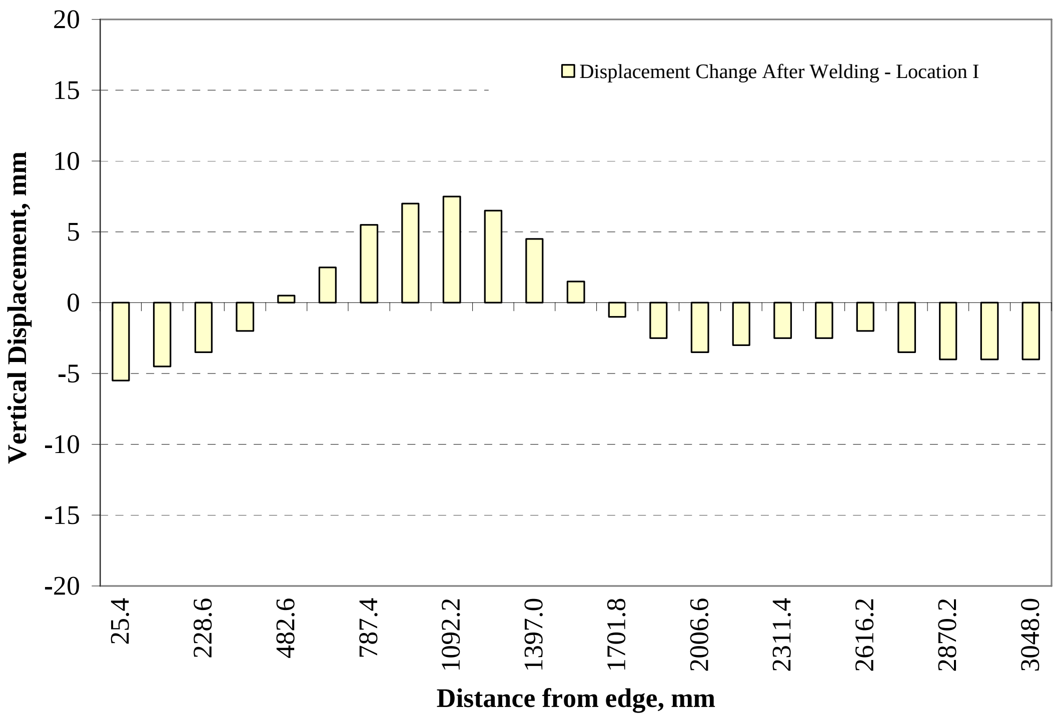


Figure I.42: Plate 9 Location I – Change in Displacement After Welding

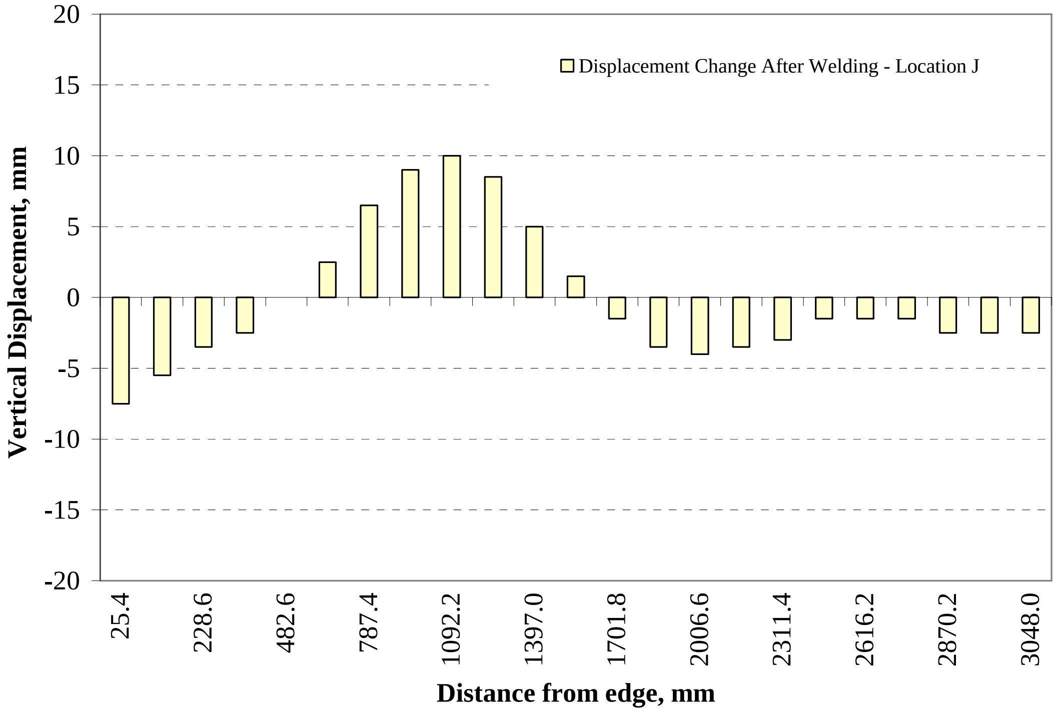


Figure I.43: Plate 9 Location J – Change in Displacement After Welding

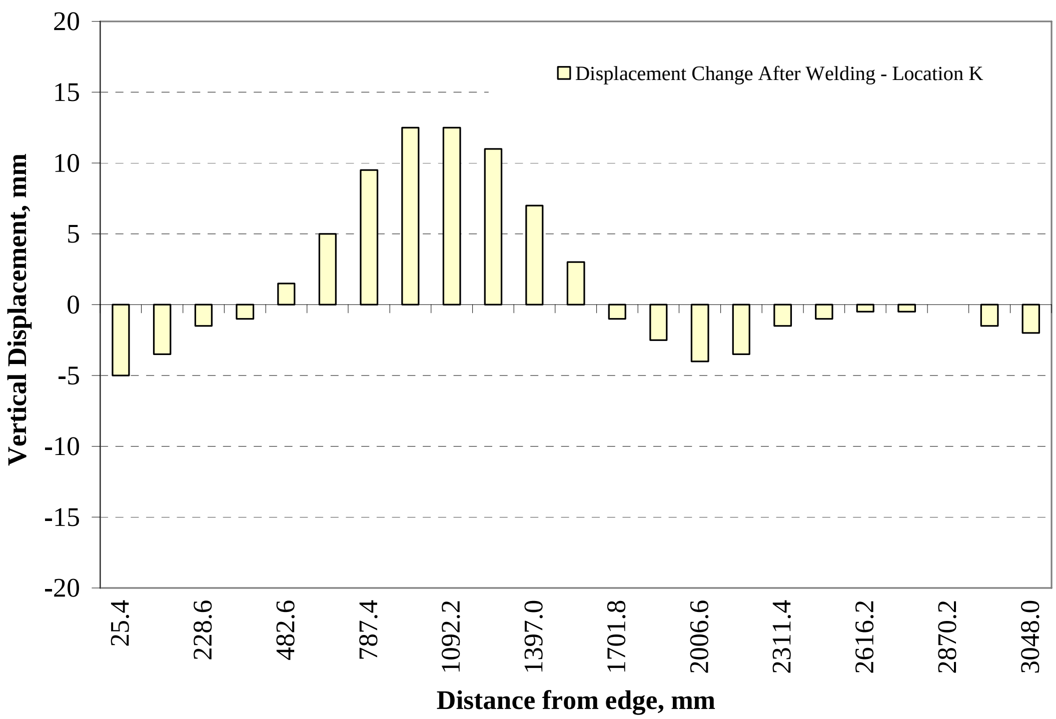


Figure I.44: Plate 9 Location K – Change in Displacement After Welding

APPENDIX J

NET DISPLACEMENTS FOR FCAW and T-MCAW
(4’ x 10’ HSLA 80 BASE PLATES)
WITH CALCULATED AVERAGE DISPLACEMENT

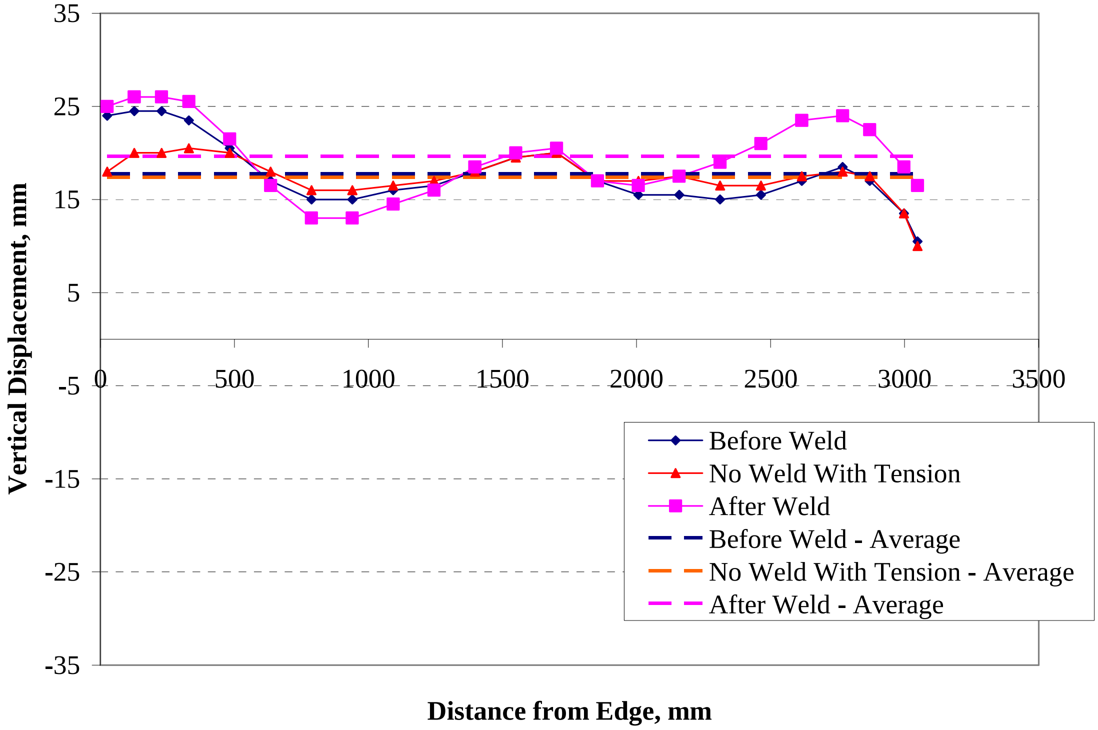


Figure J.1: Plate 3 Location A – Relative Displacement

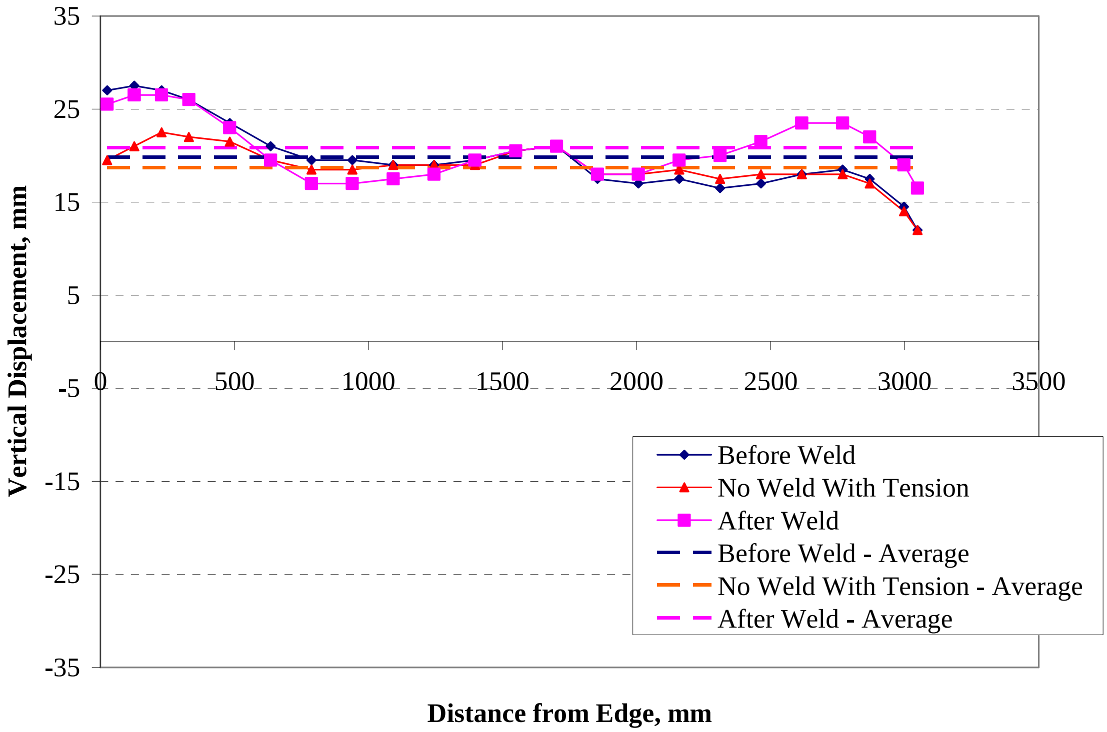


Figure J.2: Plate 3 Location B – Relative Displacement

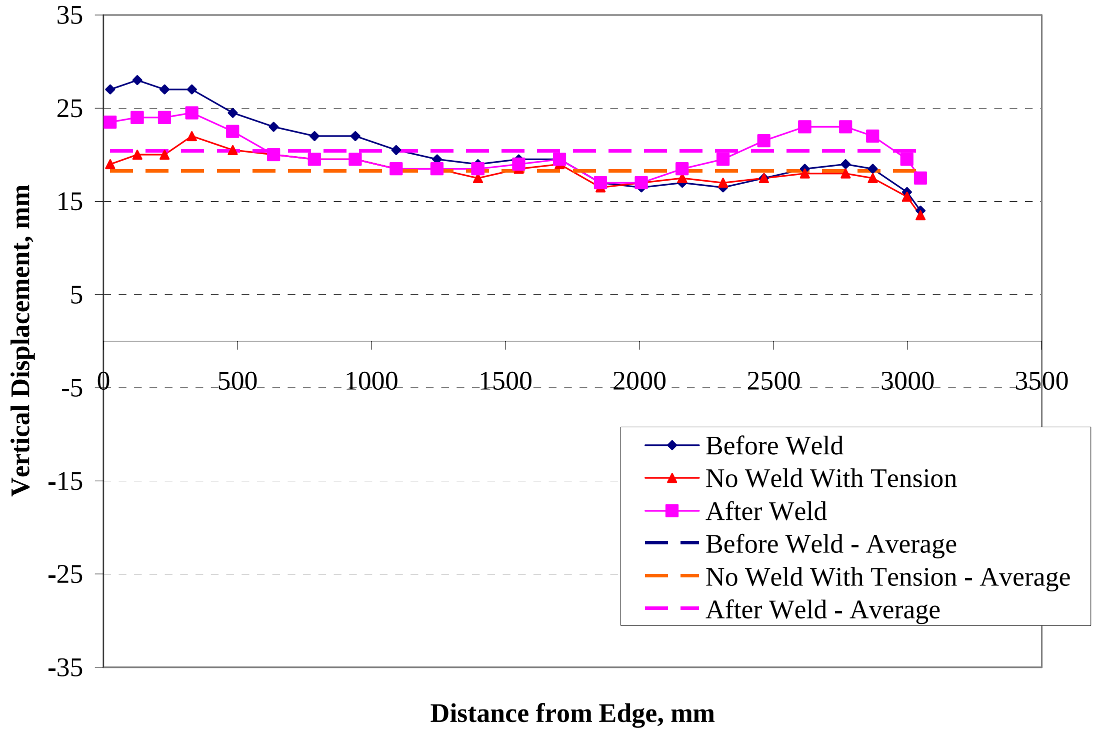


Figure J.3: Plate 3 Location C – Relative Displacement

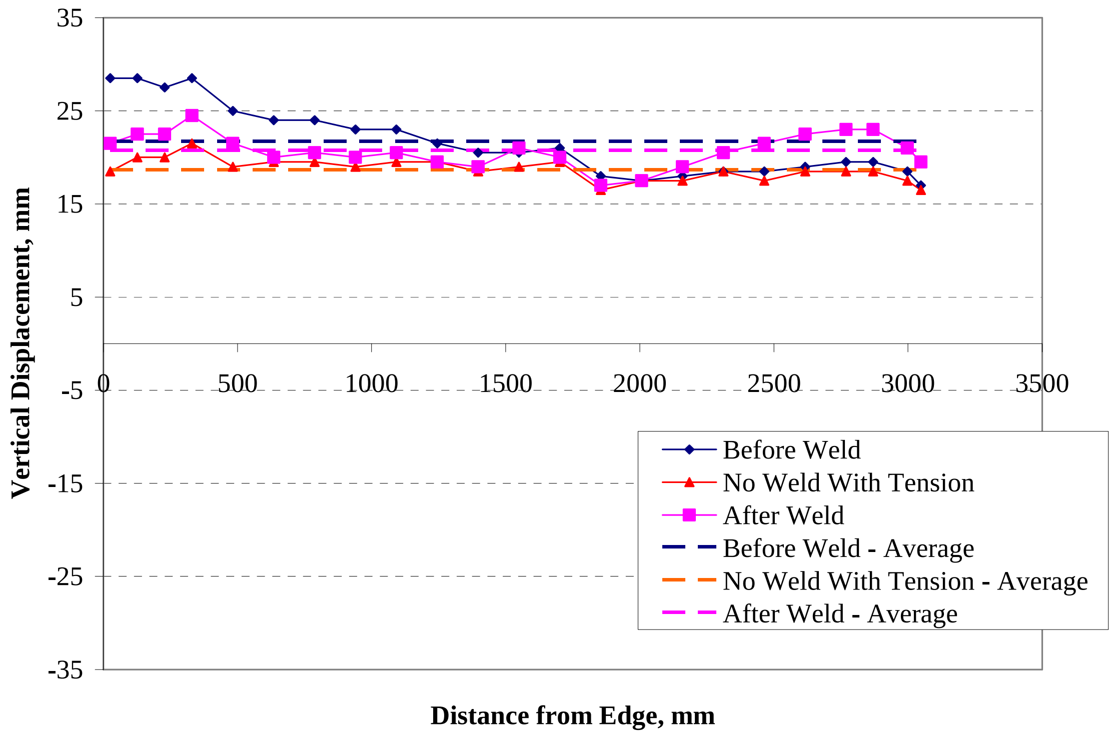


Figure J.4: Plate 3 Location D – Relative Displacement

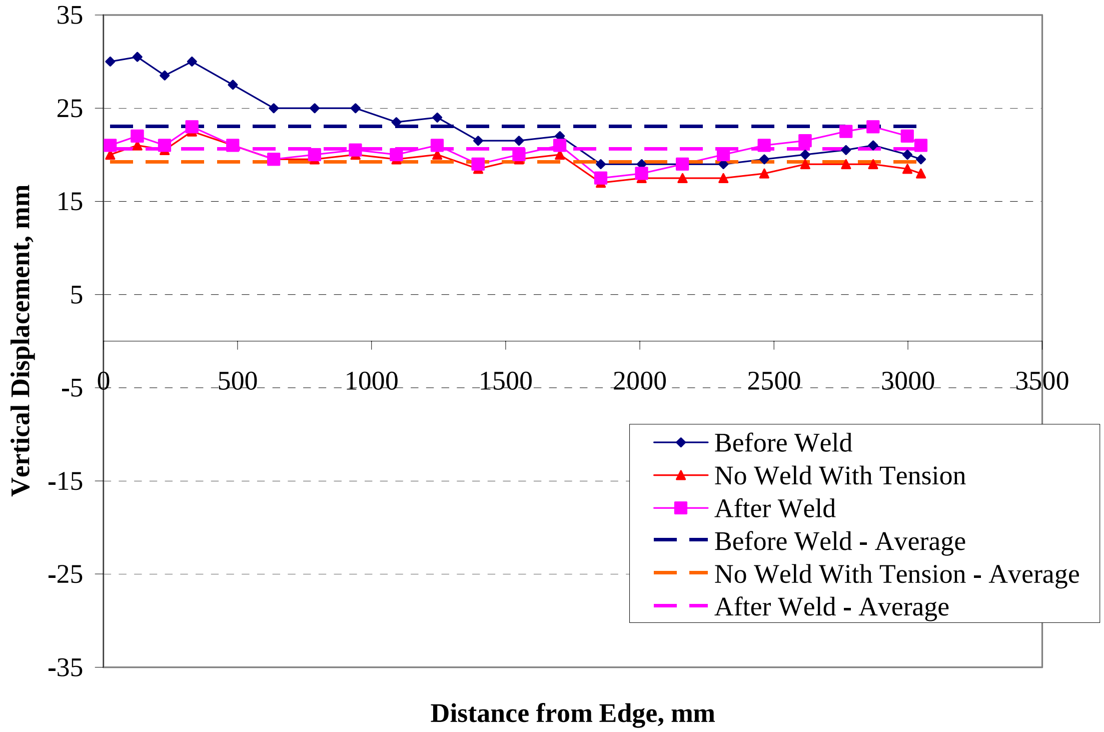


Figure J.5: Plate 3 Location E – Relative Displacement

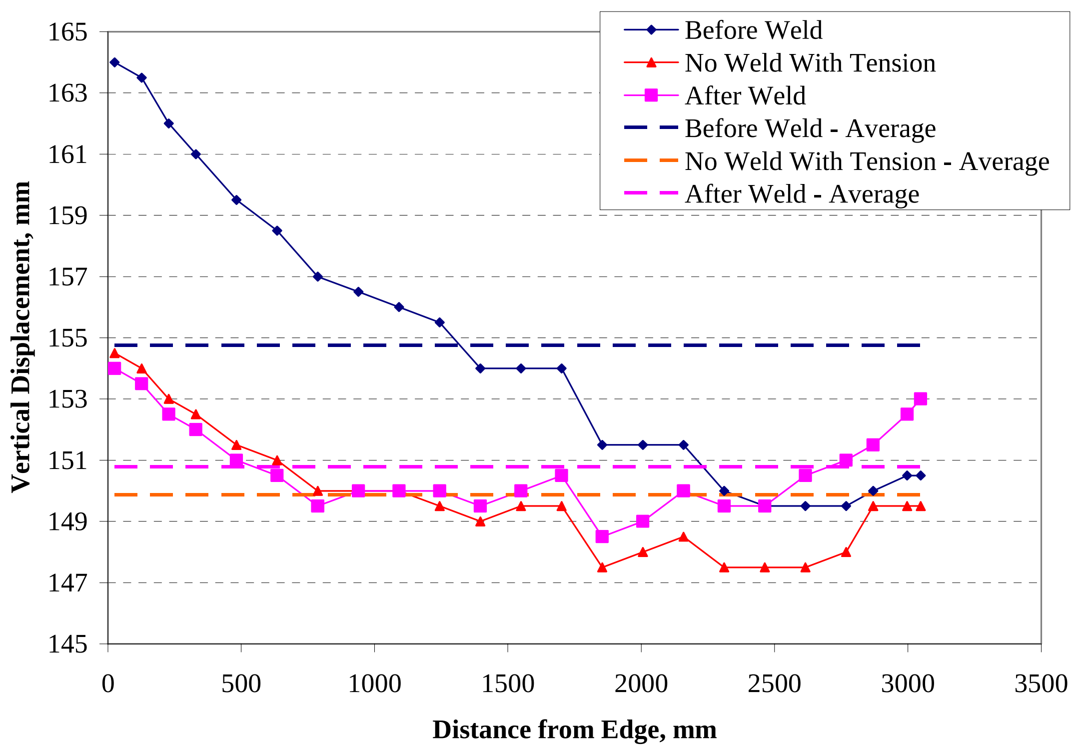


Figure J.6: Plate 3 At Stiffener – Relative Displacement

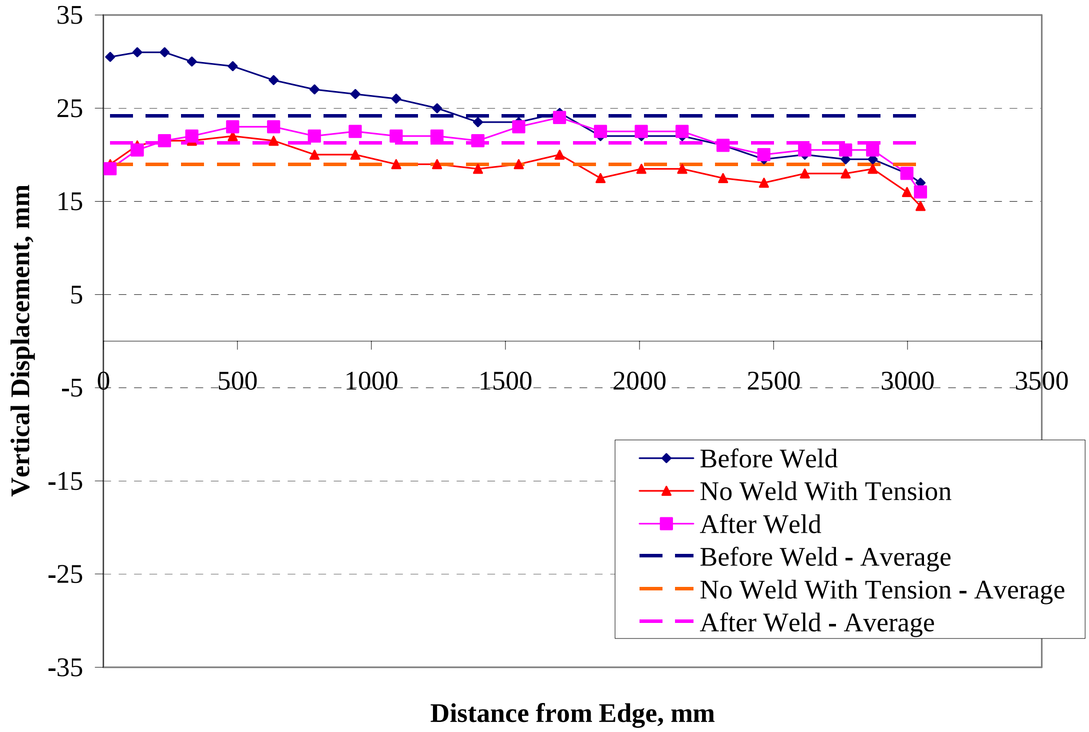


Figure J.7: Plate 3 Location G – Relative Displacement

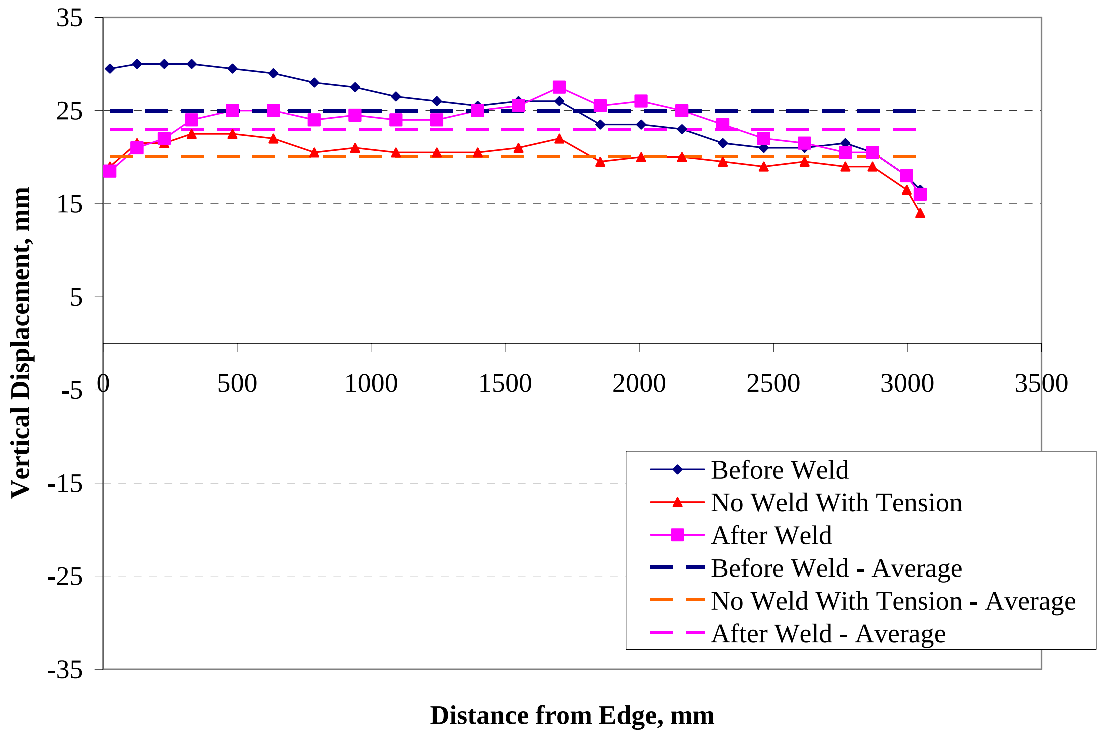


Figure J.8: Plate 3 Location H – Relative Displacement

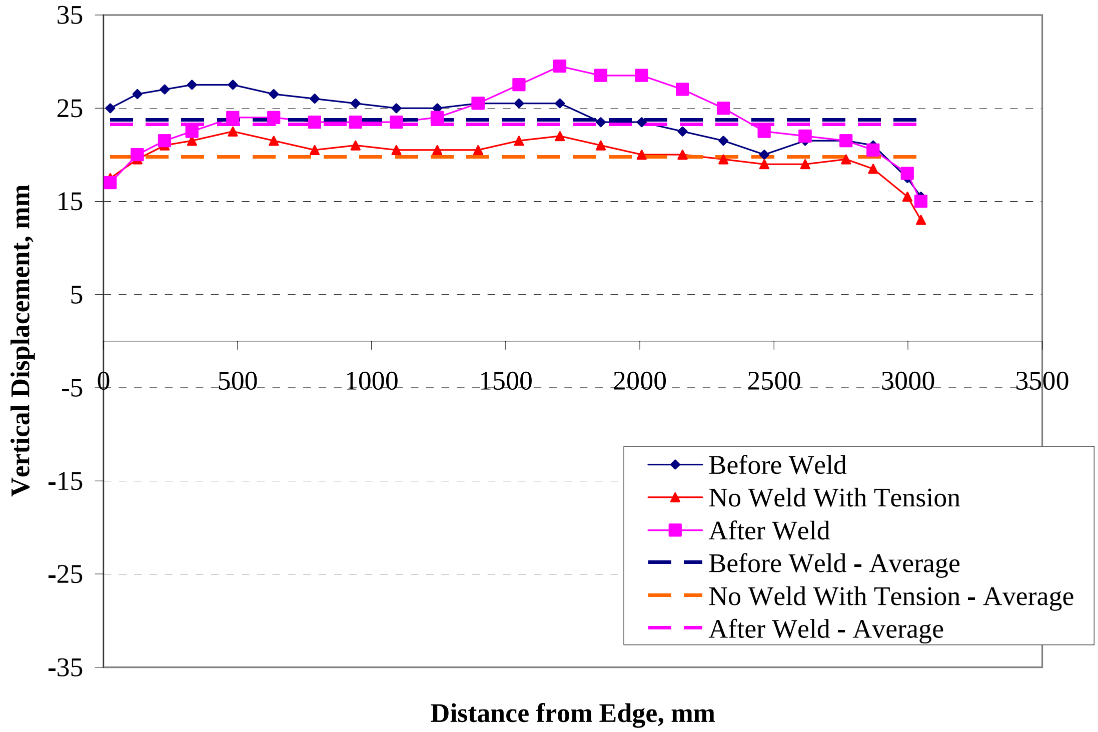


Figure J.9: Plate 3 Location I – Relative Displacement

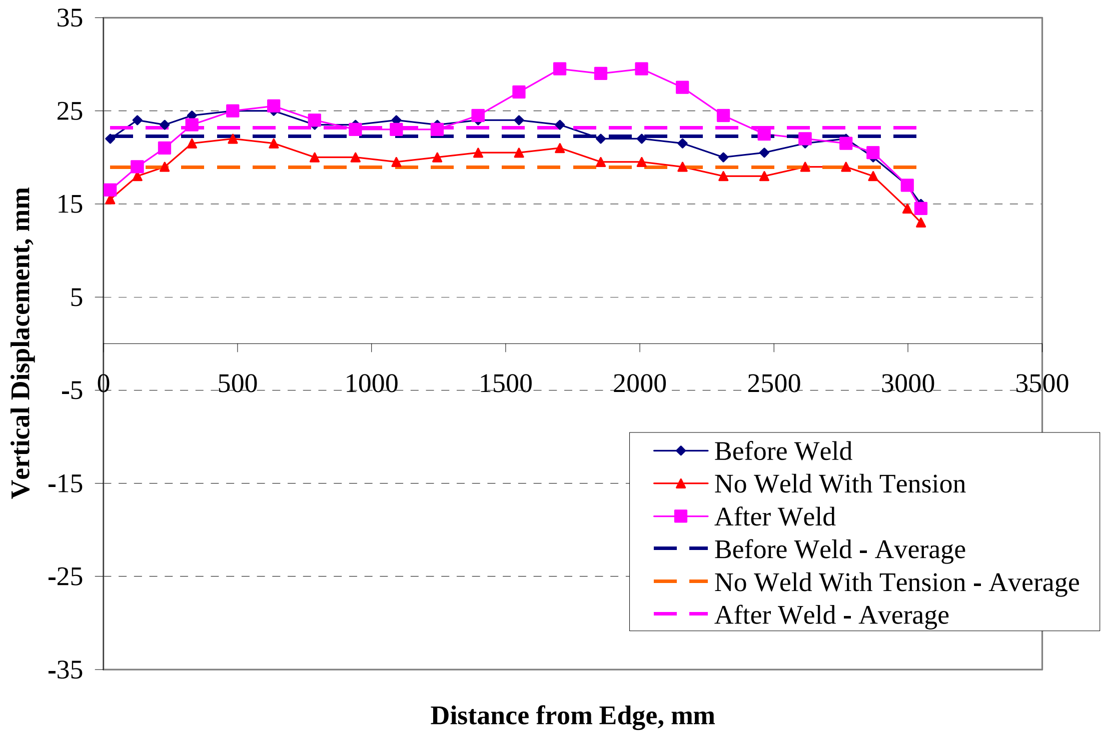


Figure J.10: Plate 3 Location J – Relative Displacement

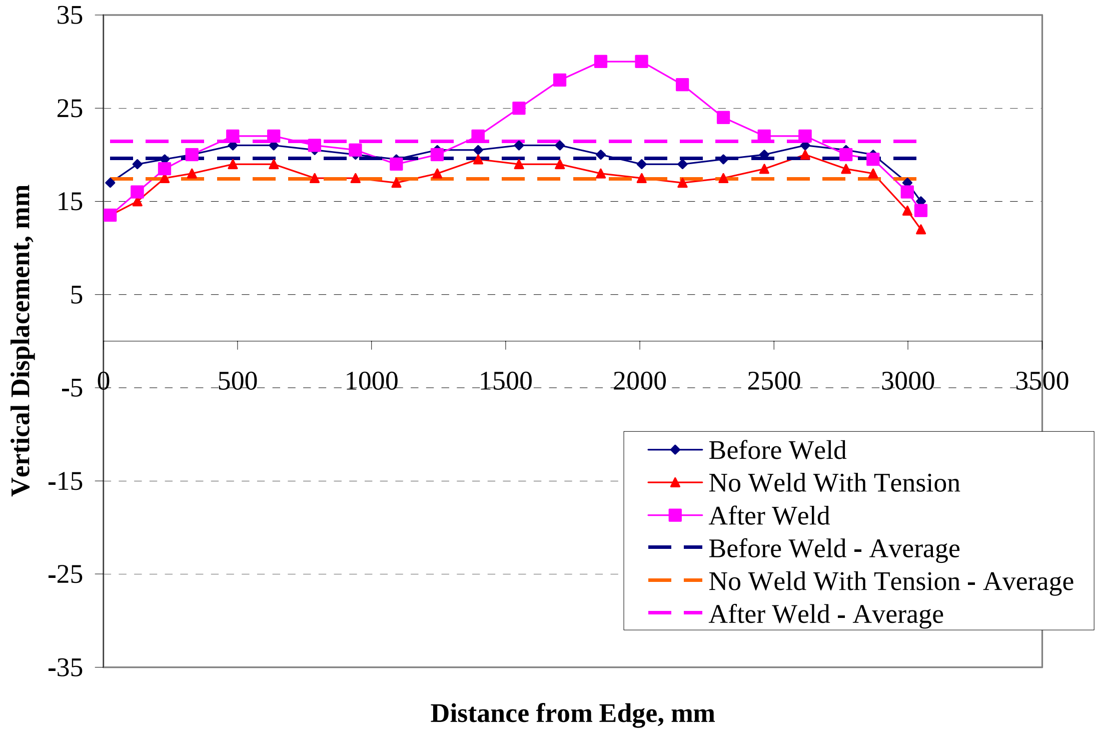


Figure J.11: Plate 3 Location K – Relative Displacement

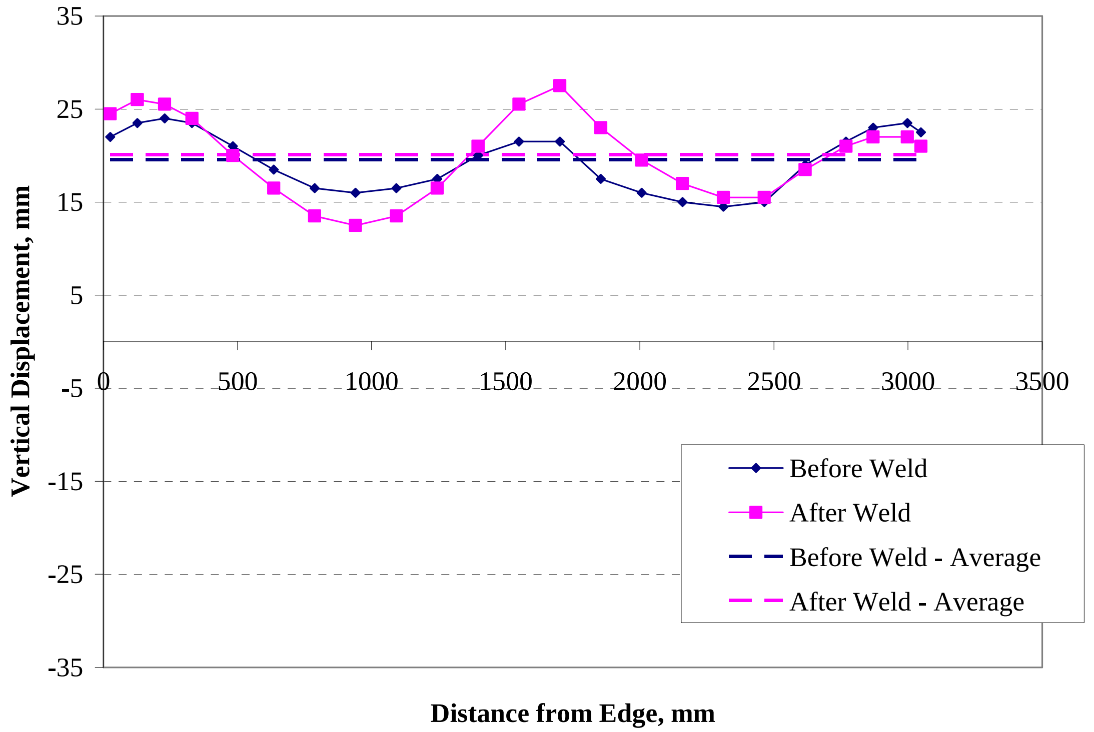


Figure J.12: Plate 7 Location A – Relative Displacement

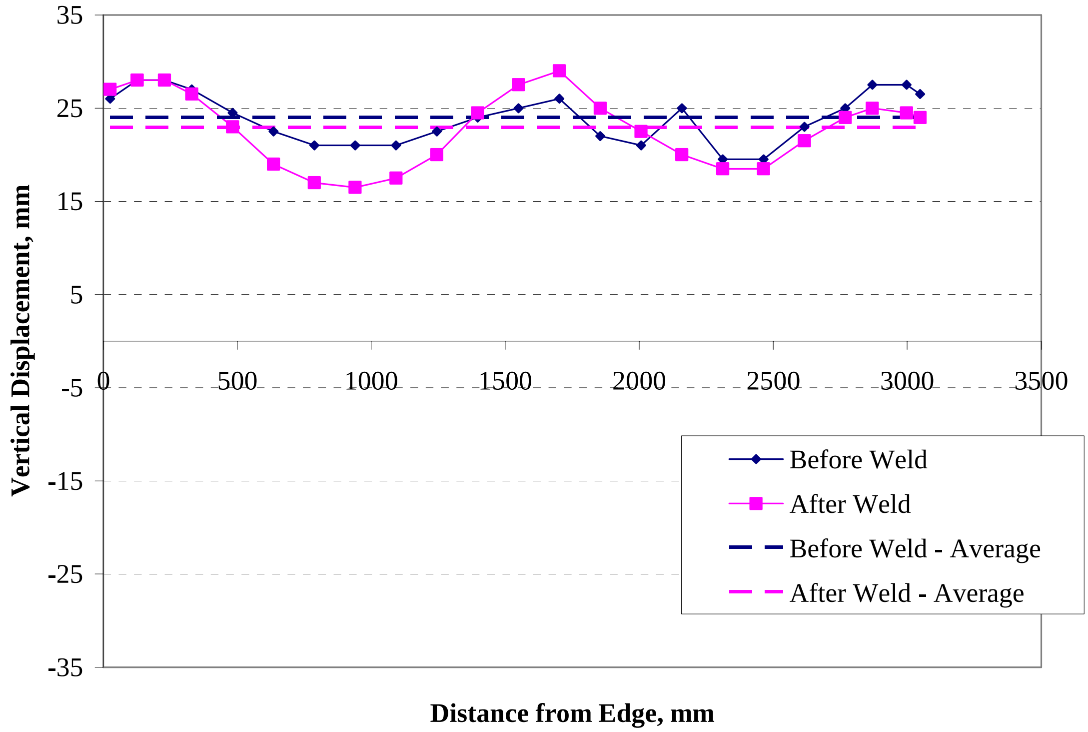


Figure J.13: Plate 7 Location B – Relative Displacement

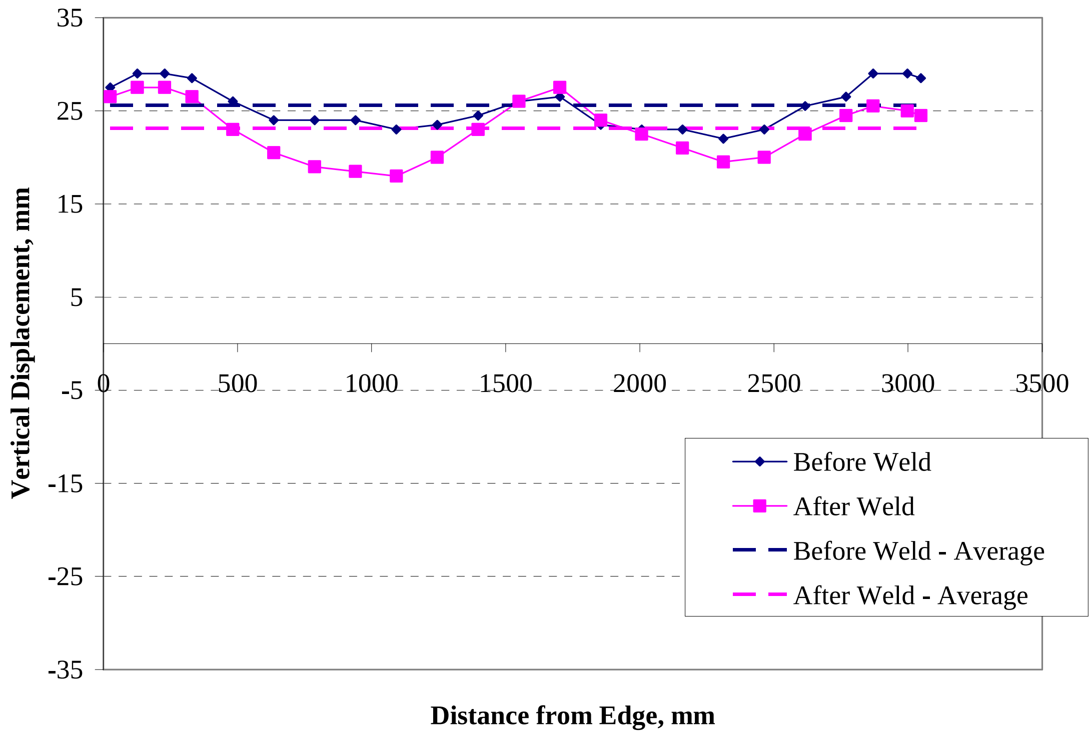


Figure J.14: Plate 7 Location C – Relative Displacement

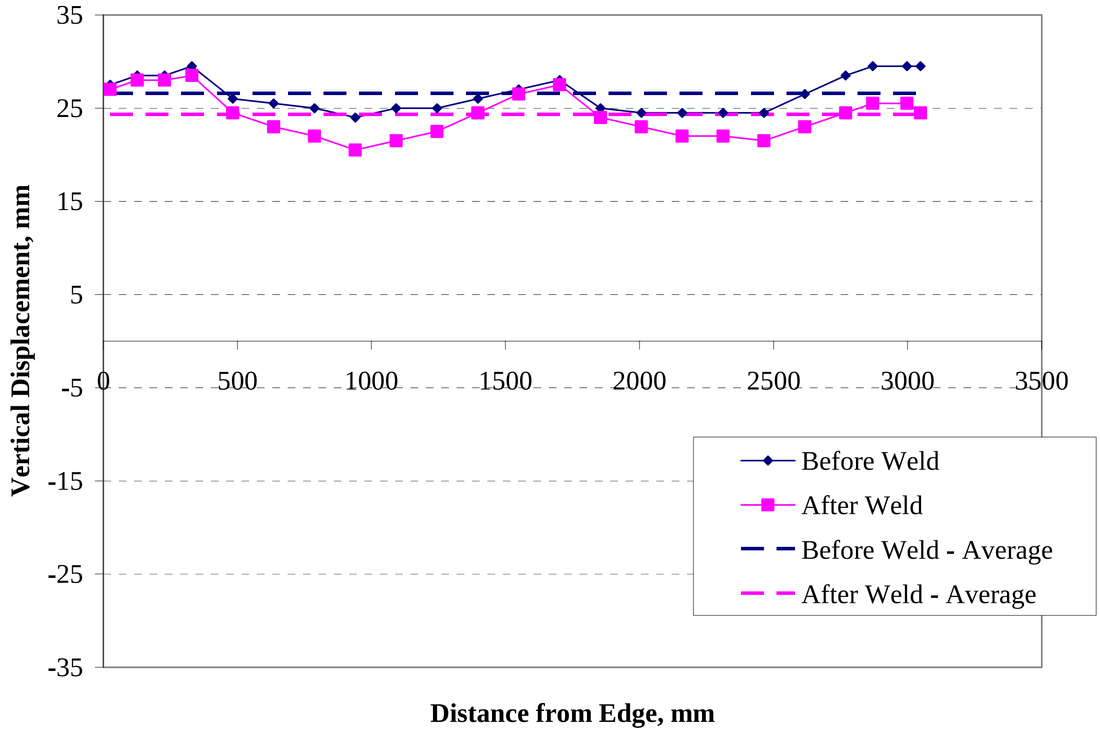


Figure J.15: Plate 7 Location D – Relative Displacement

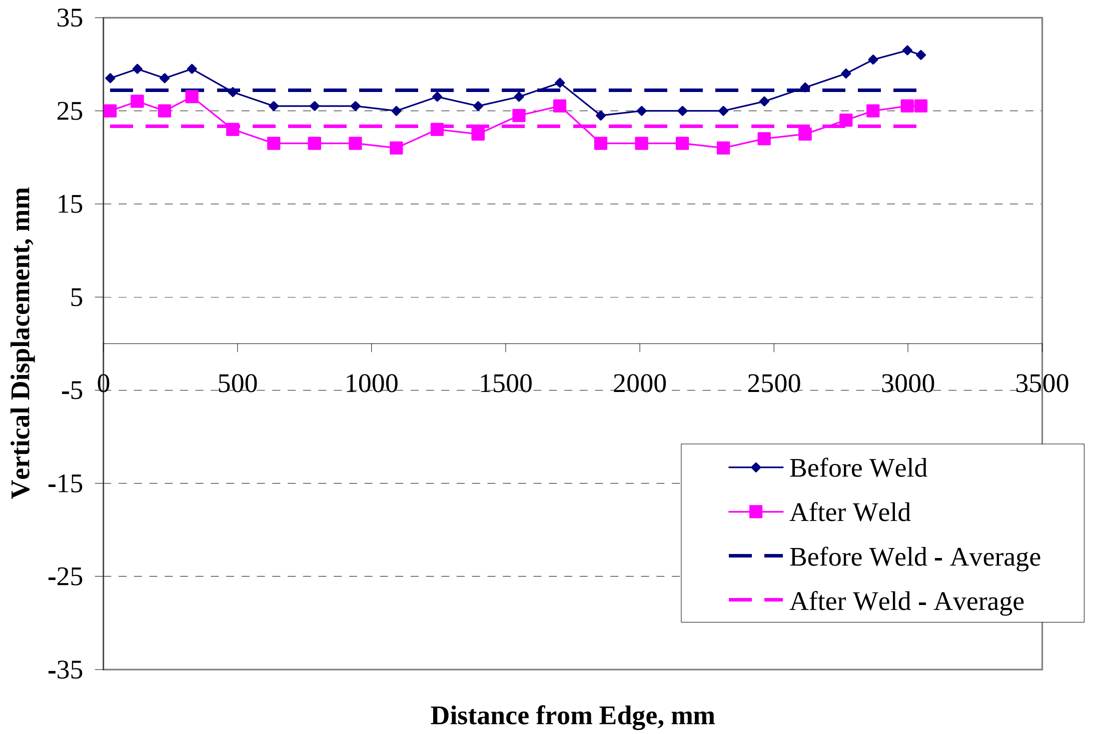


Figure J.16: Plate 7 Location E – Relative Displacement

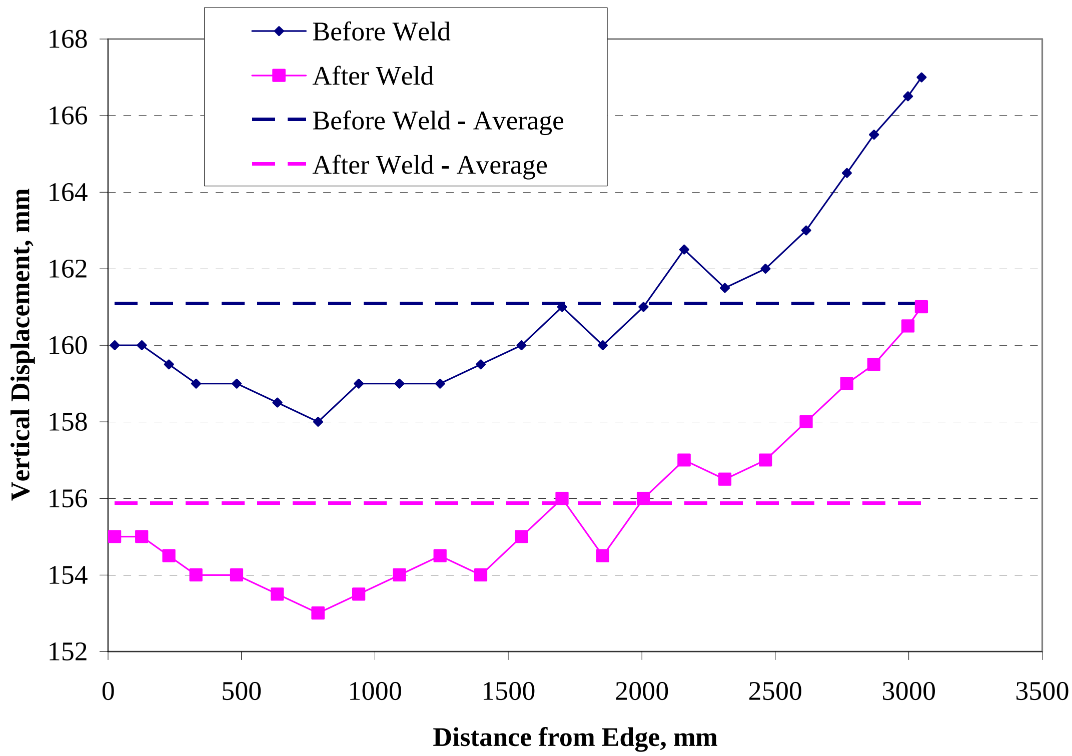


Figure J.17: Plate 7 At Stiffener – Relative Displacement

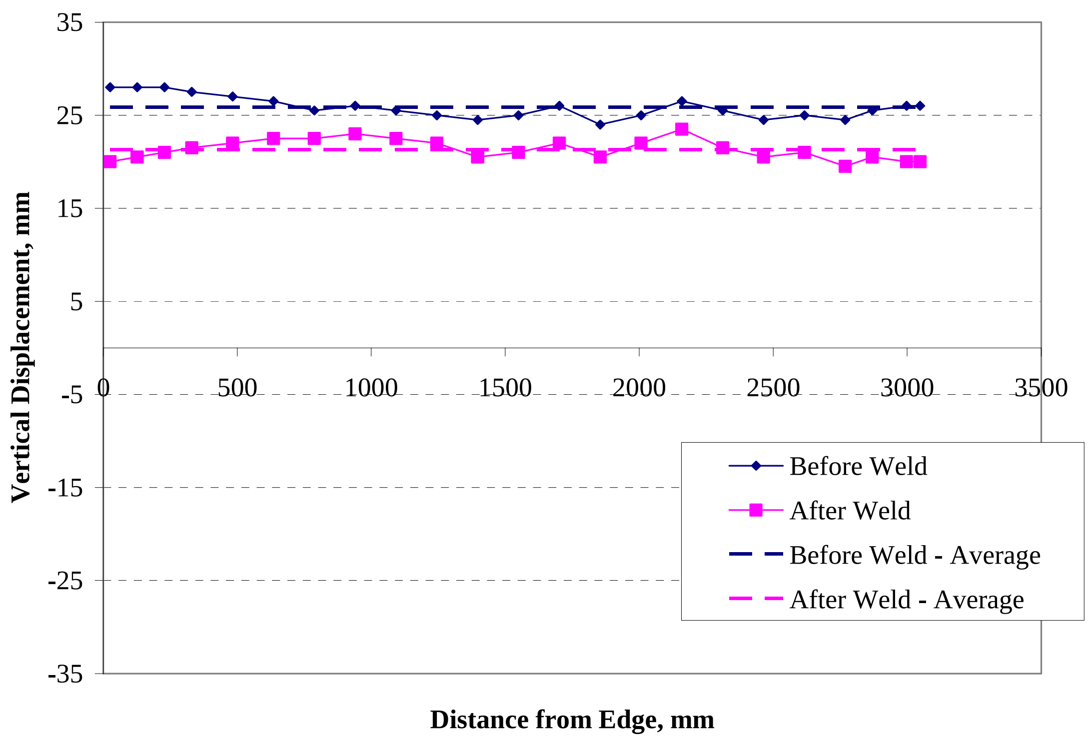


Figure J.18: Plate 7 Location G – Relative Displacement

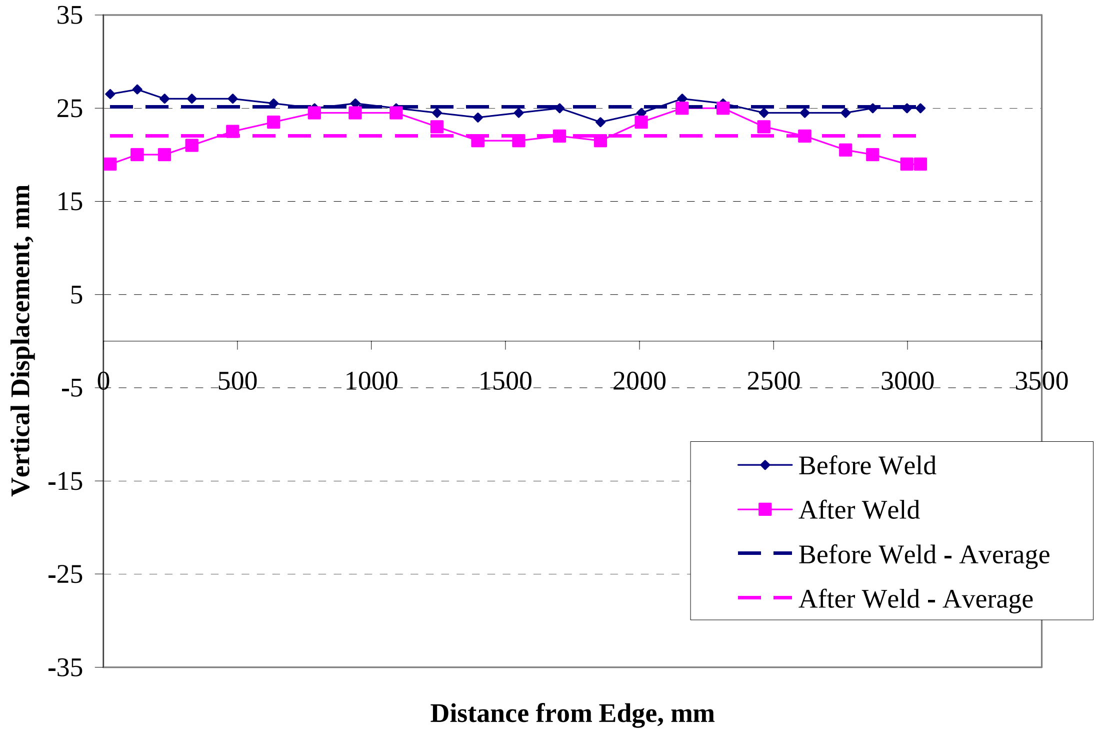


Figure J.19: Plate 7 Location H – Relative Displacement

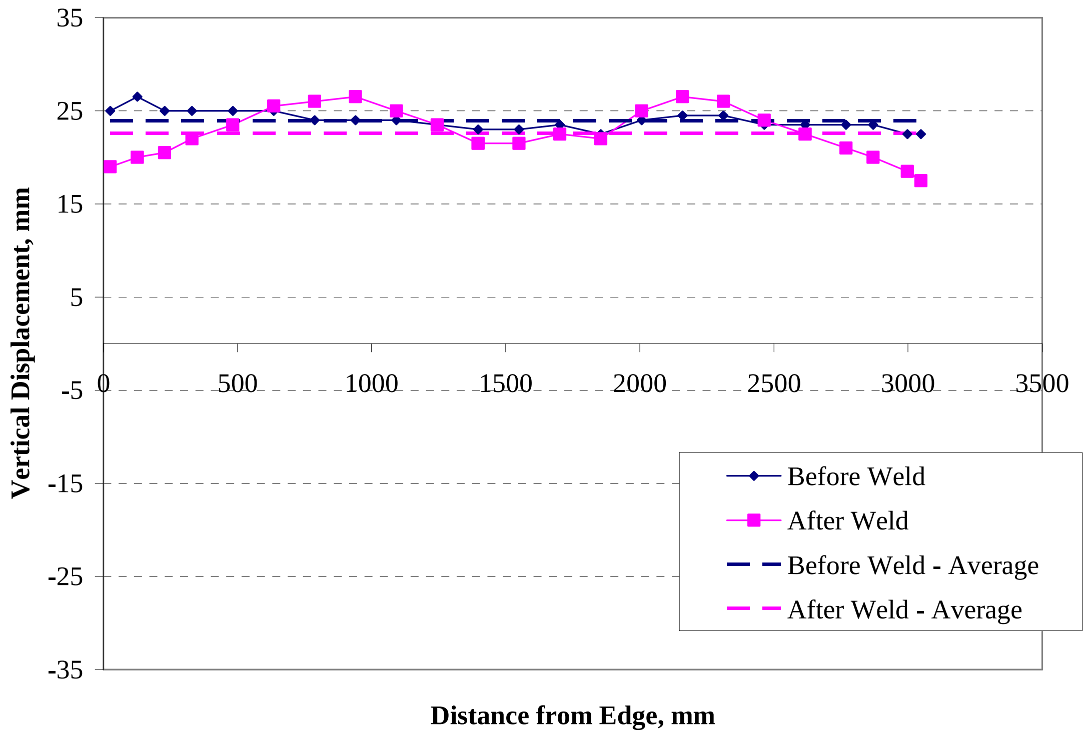


Figure J.20: Plate 7 Location I – Relative Displacement

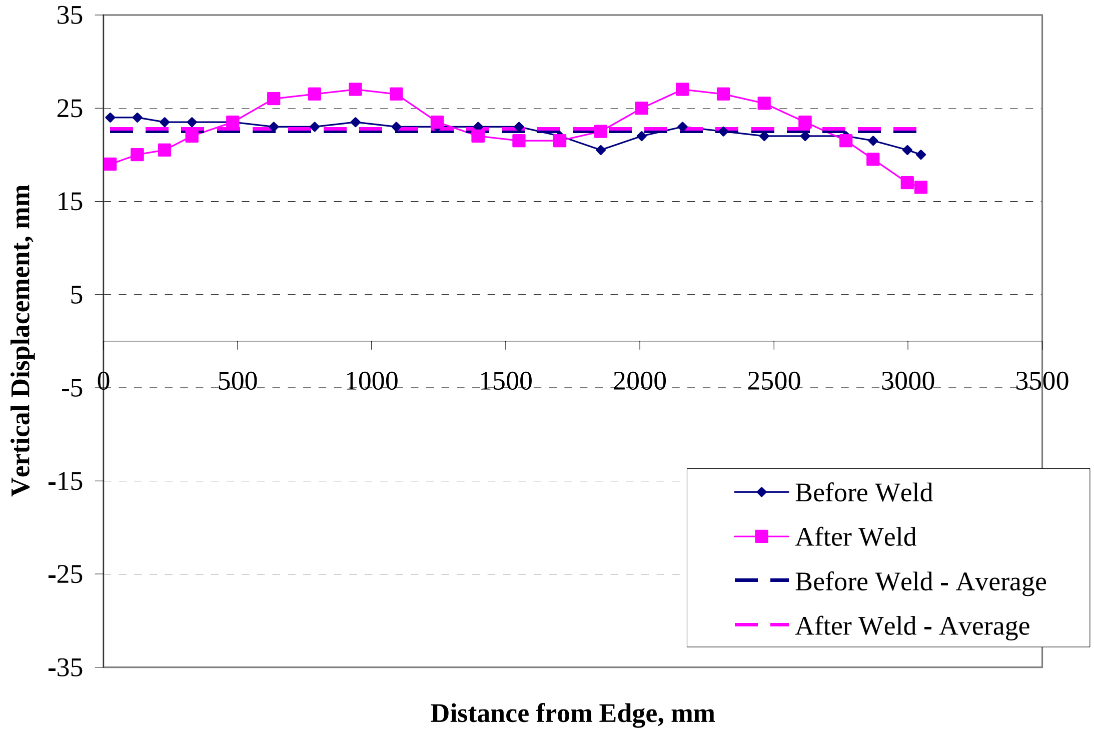


Figure J.21: Plate 7 Location J – Relative Displacement

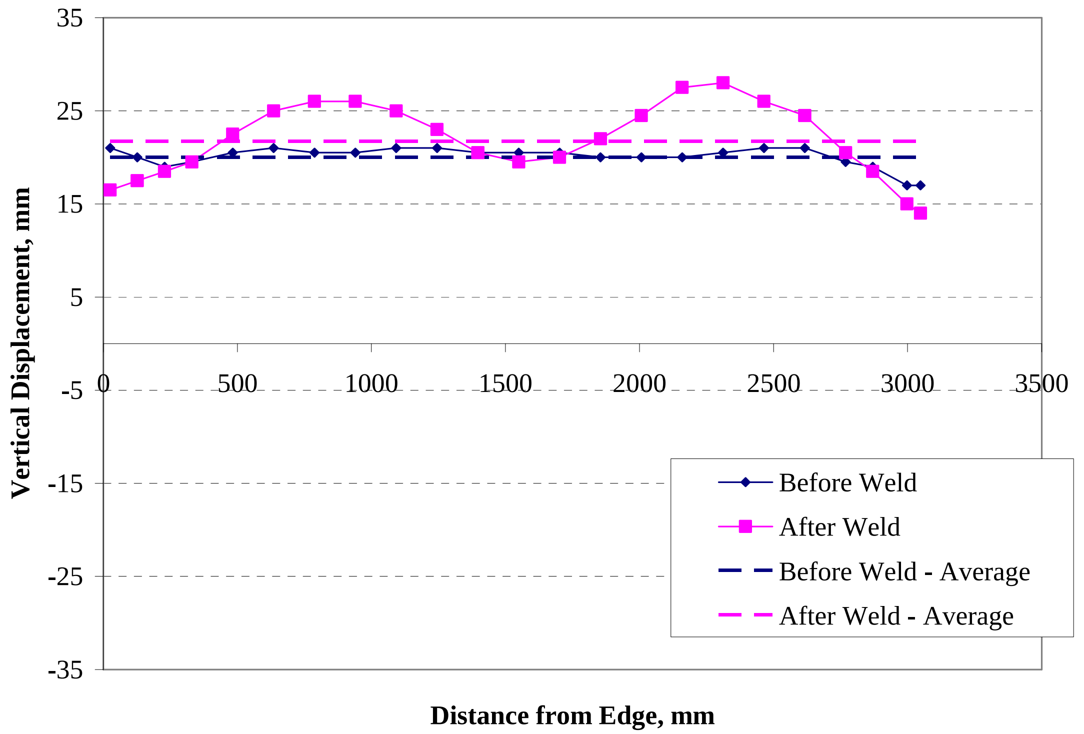


Figure J.22: Plate 7 Location K – Relative Displacement

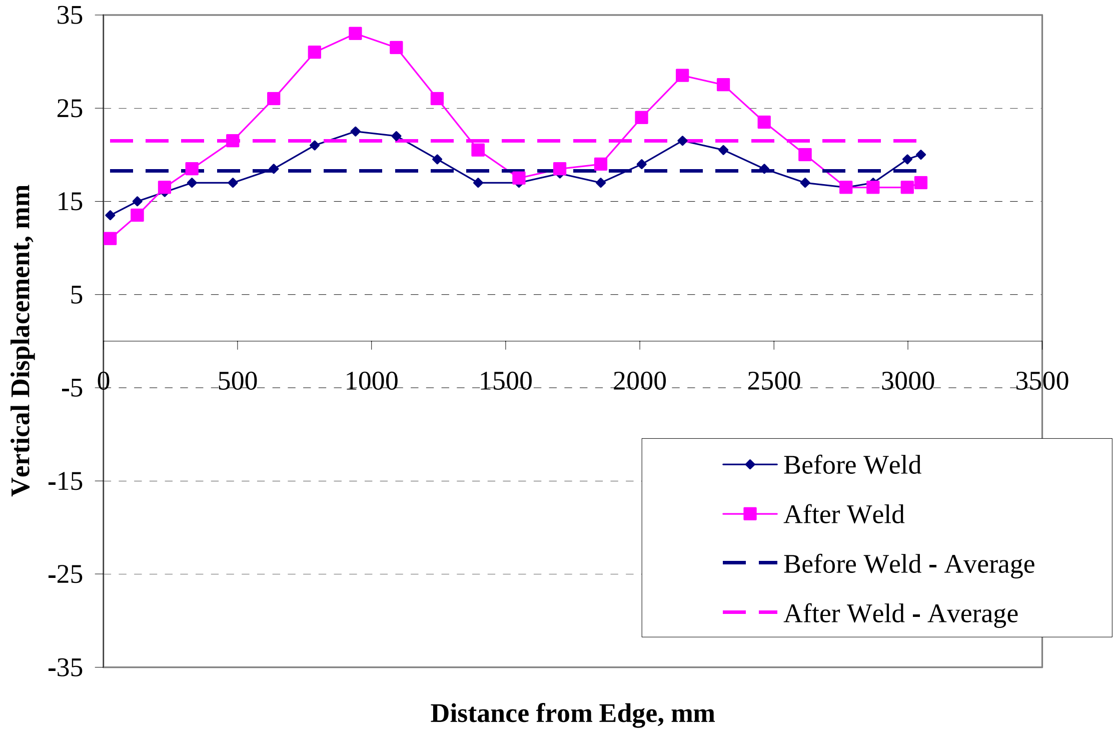


Figure J.23: Plate 8 Location A – Relative Displacement

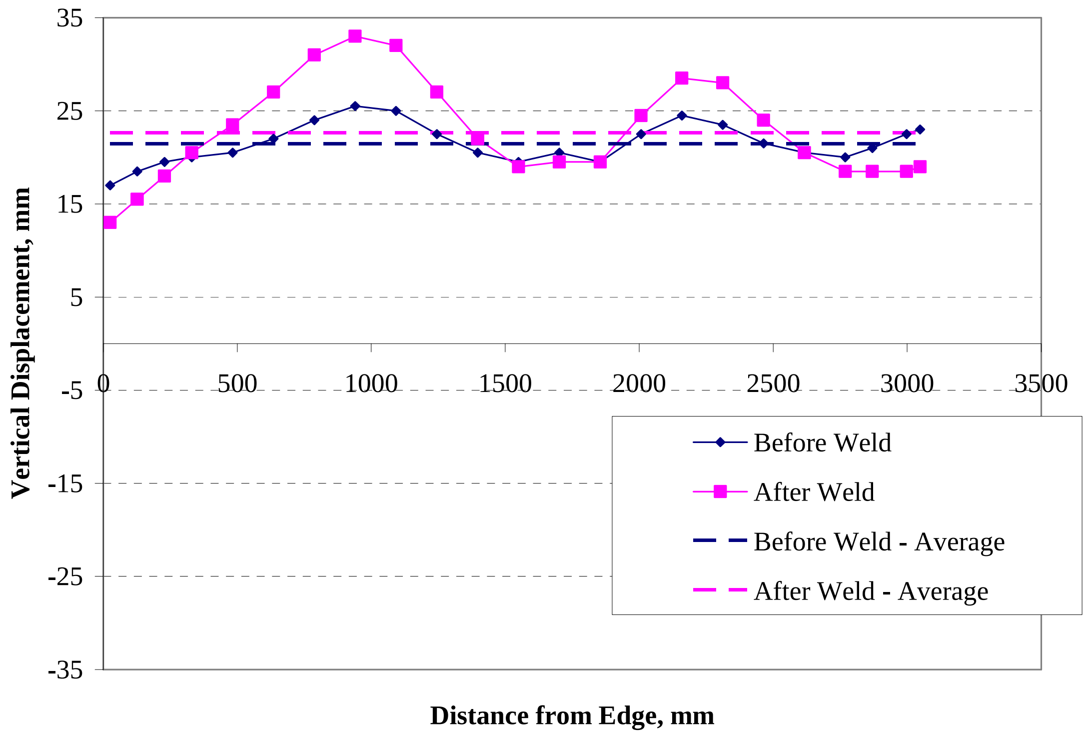


Figure J.24: Plate 8 Location B – Relative Displacement

Figure J.25: Plate 8 Location C – Relative Displacement

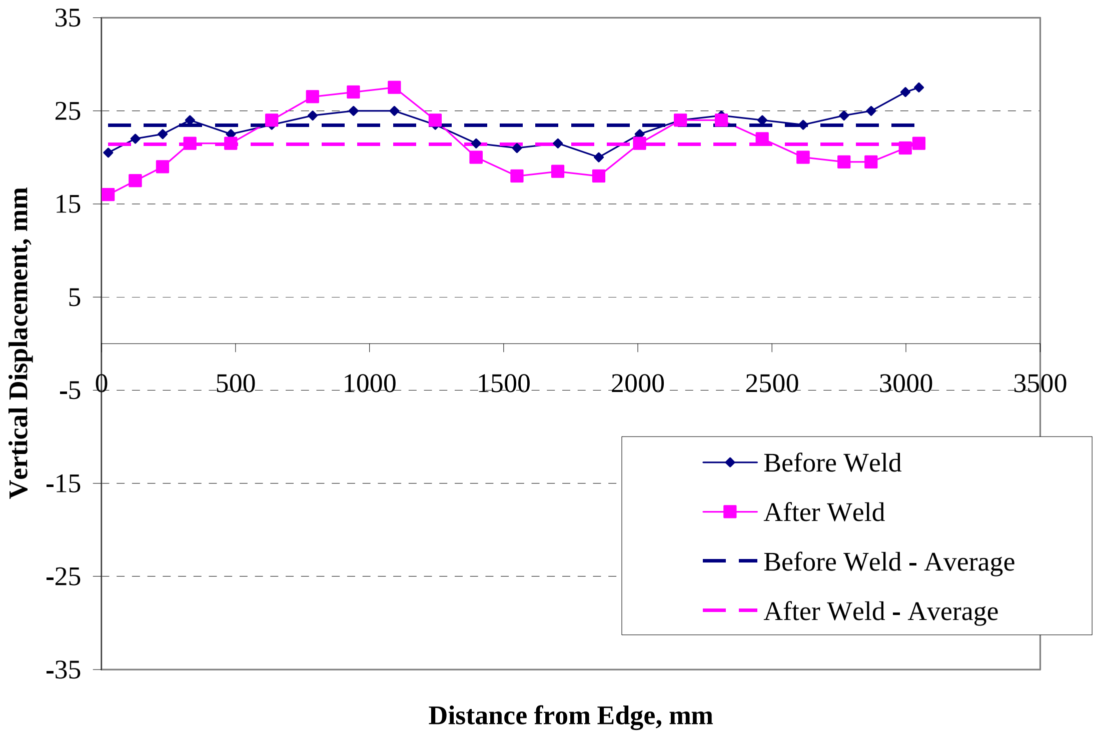


Figure J.26: Plate 8 Location D – Relative Displacement

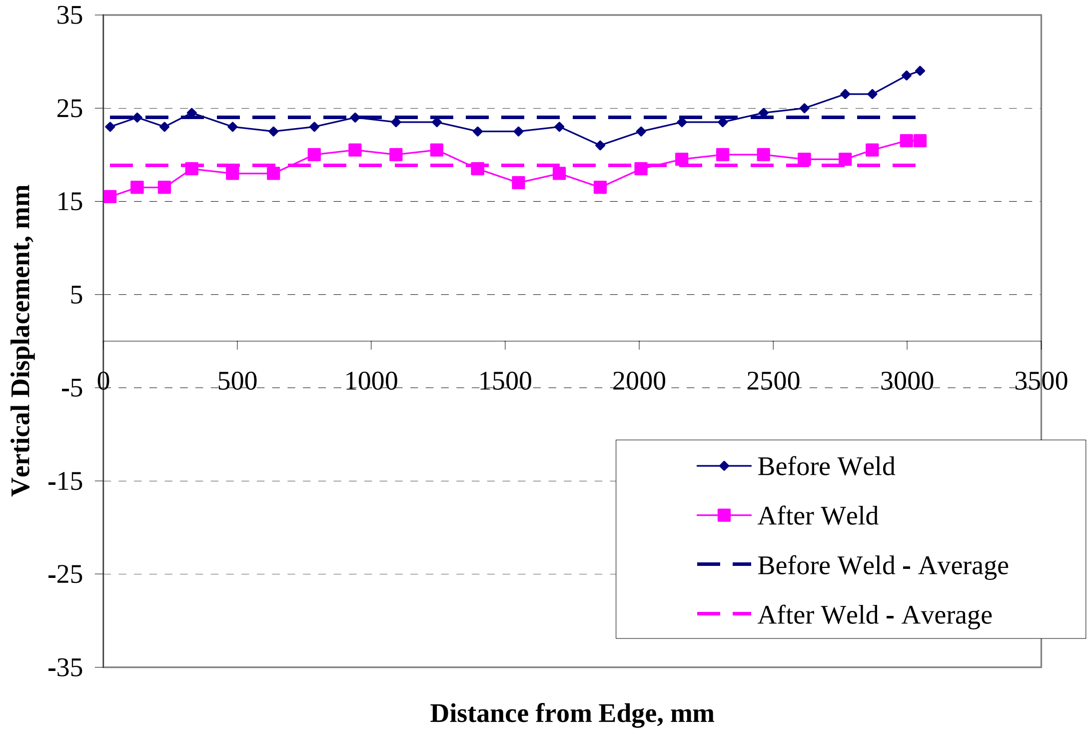


Figure J.27: Plate 8 Location E – Relative Displacement

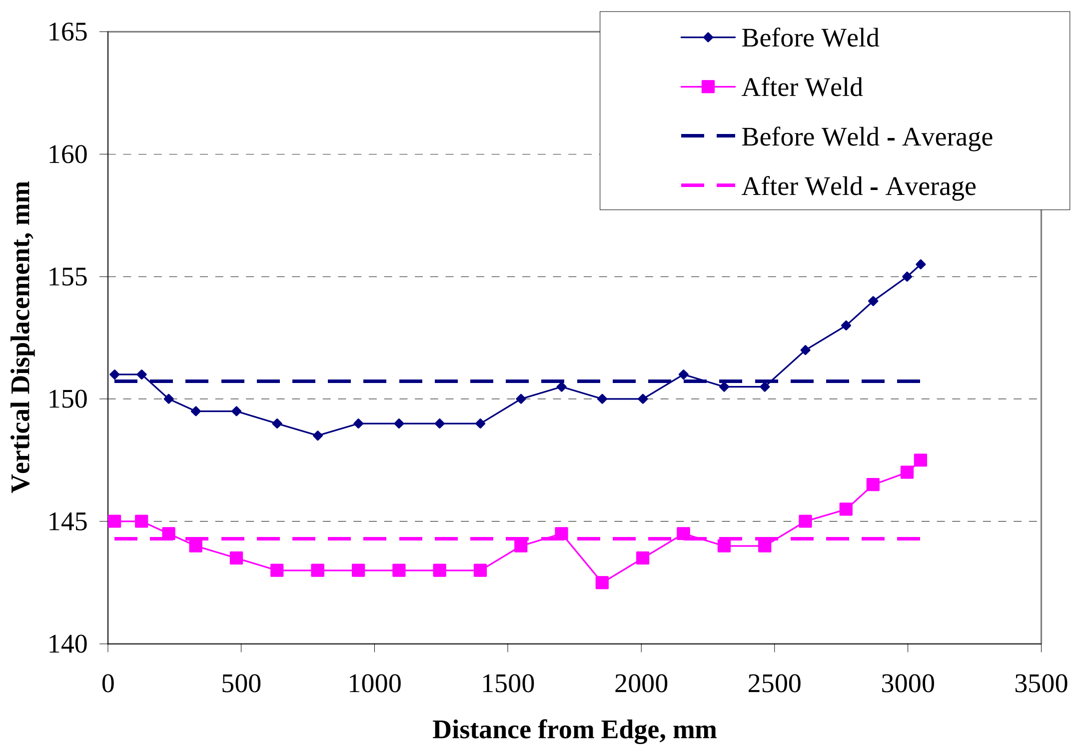


Figure J.28: Plate 8 At Stiffener – Relative Displacement

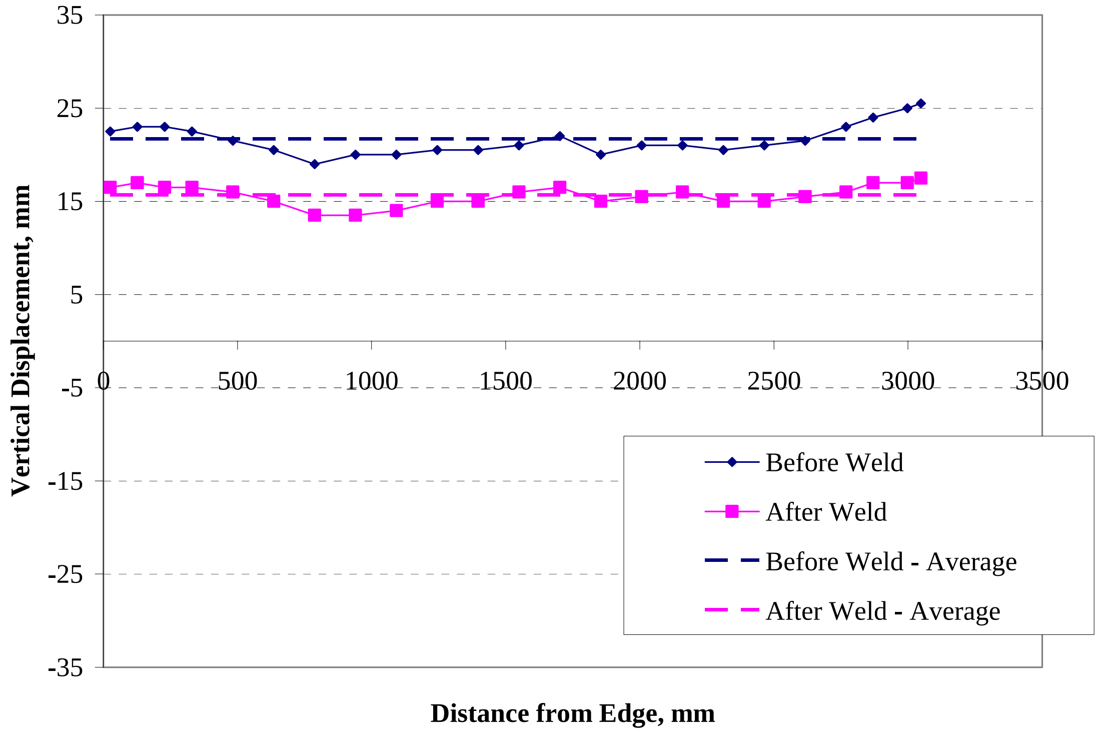


Figure J.29: Plate 8 Location G – Relative Displacement

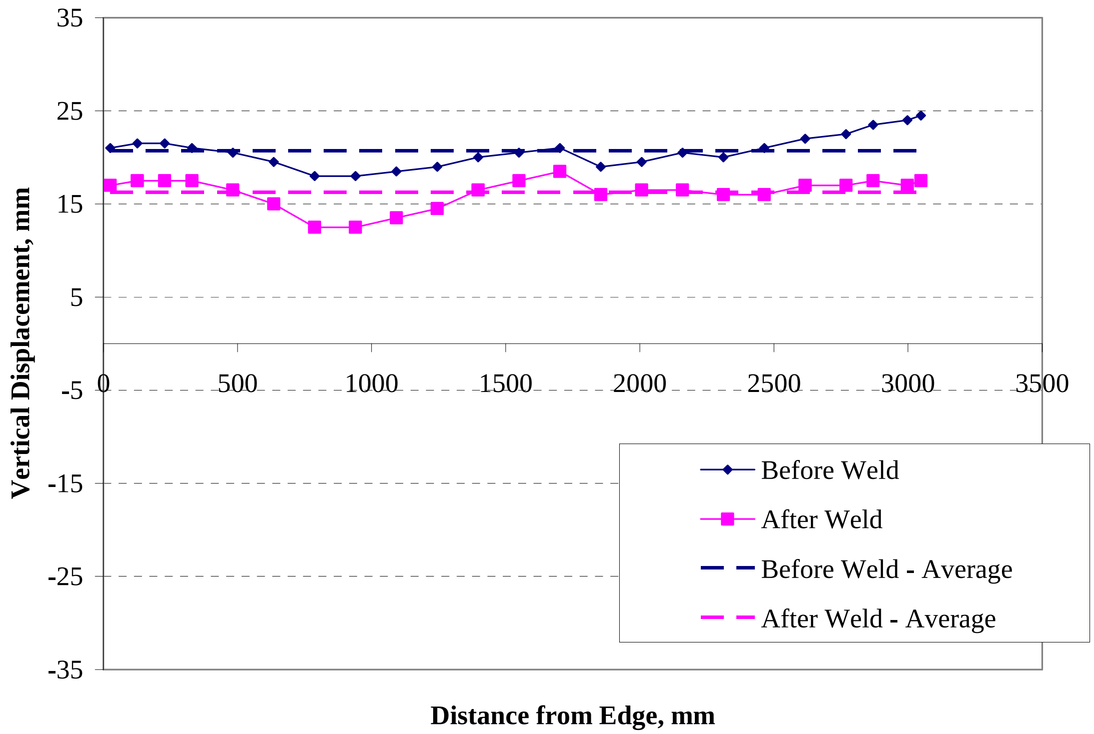


Figure J.30: Plate 8 Location H – Relative Displacement

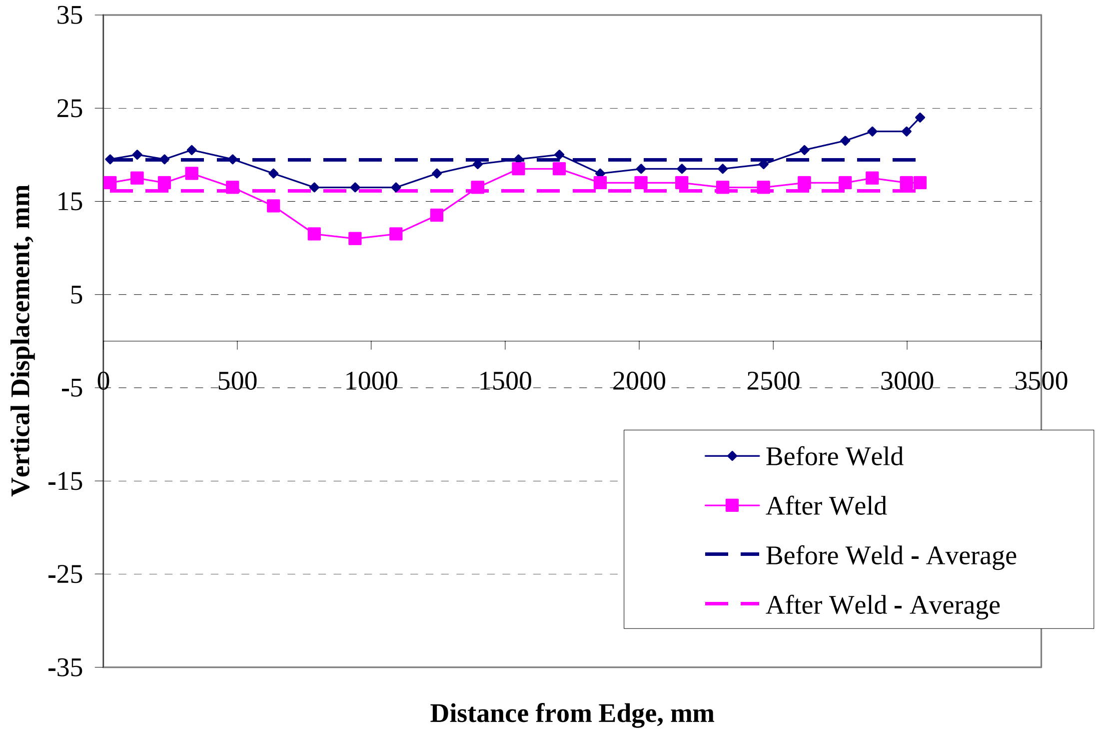


Figure J.31: Plate 8 Location I – Relative Displacement

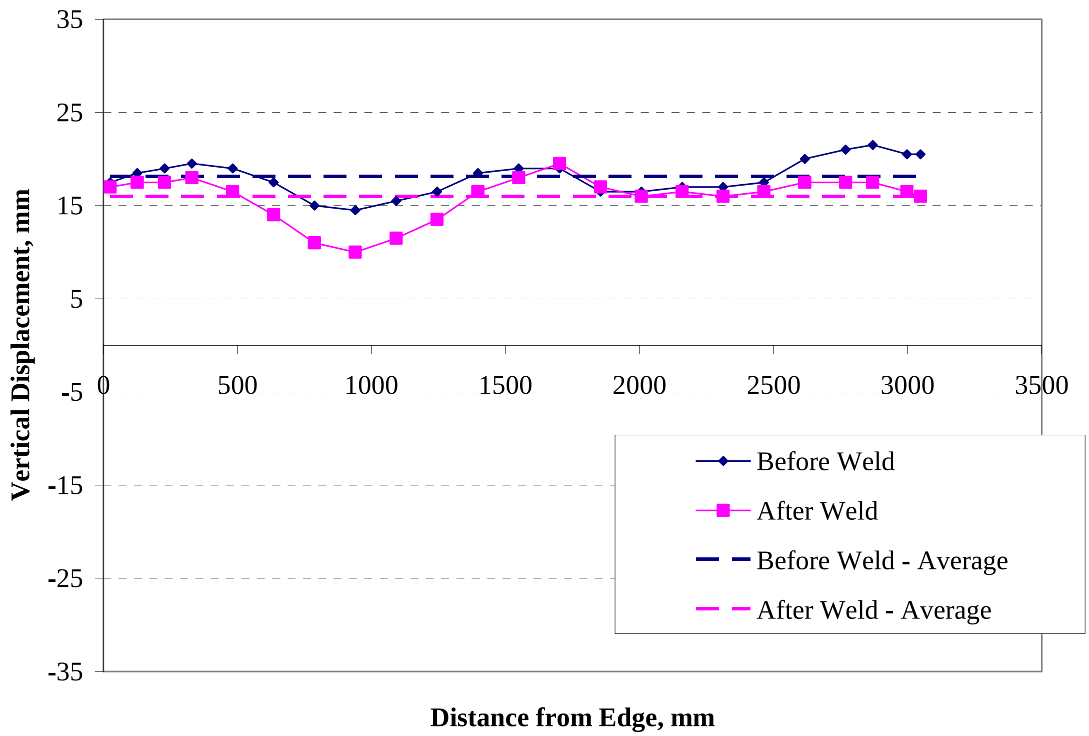


Figure J.32: Plate 8 Location J – Relative Displacement

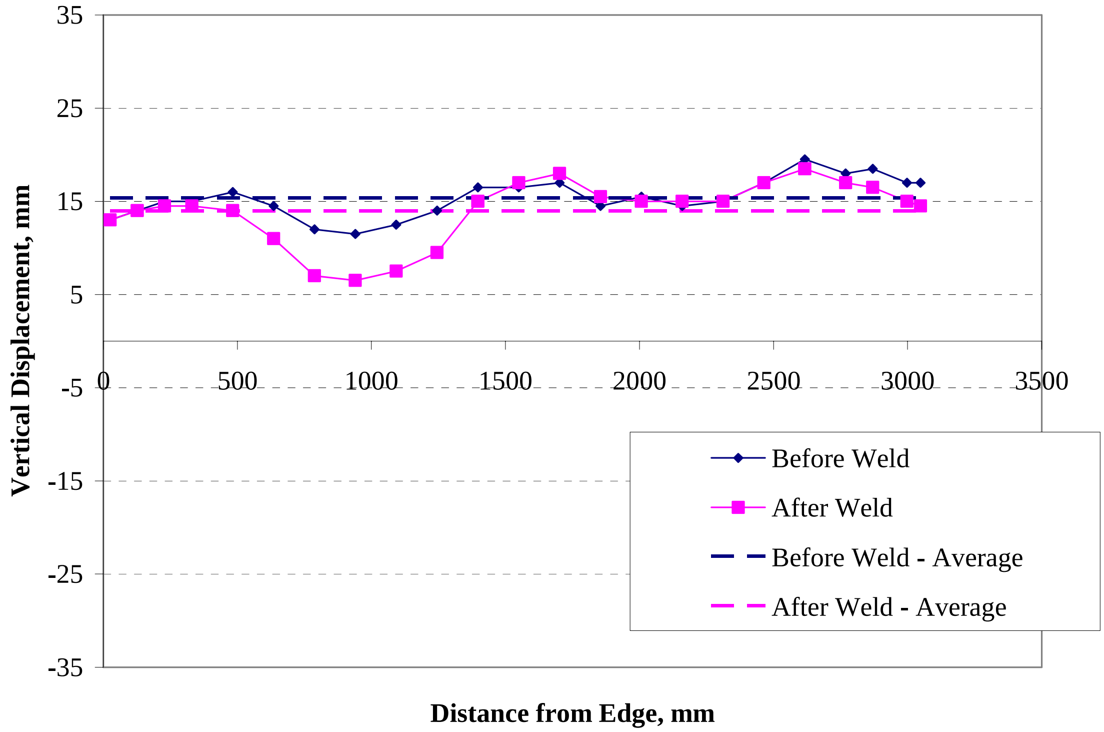


Figure J.33: Plate 8 Location K – Relative Displacement

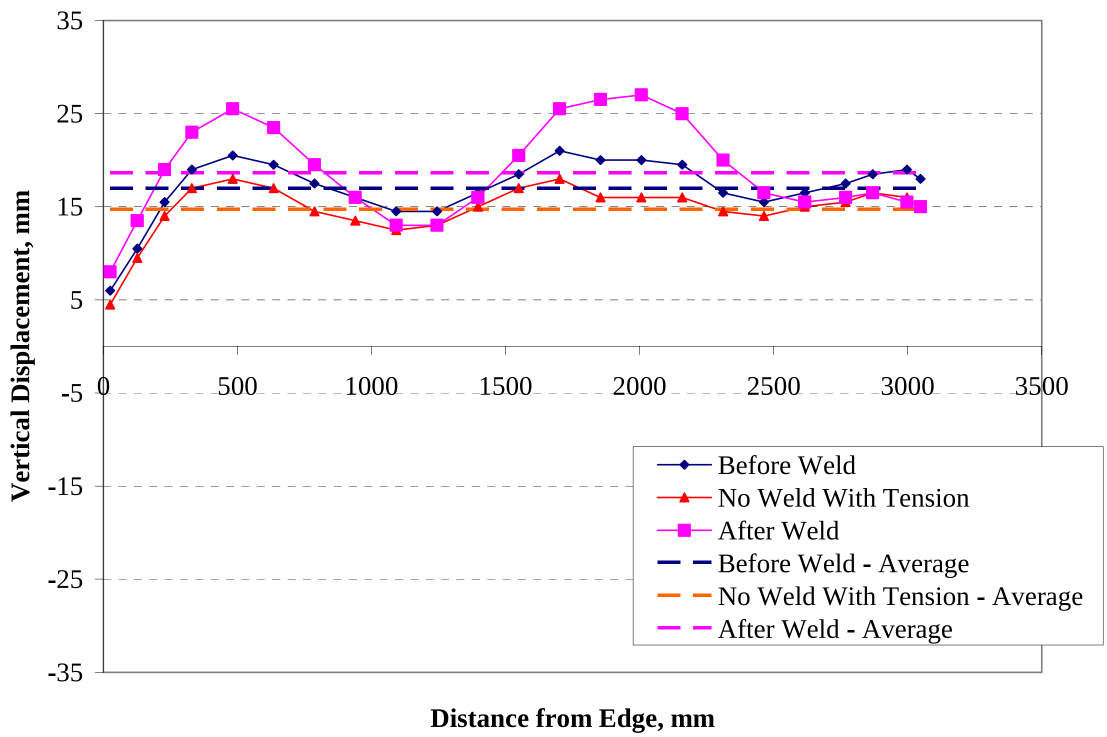


Figure J.34: Plate 9 Location A – Relative Displacement

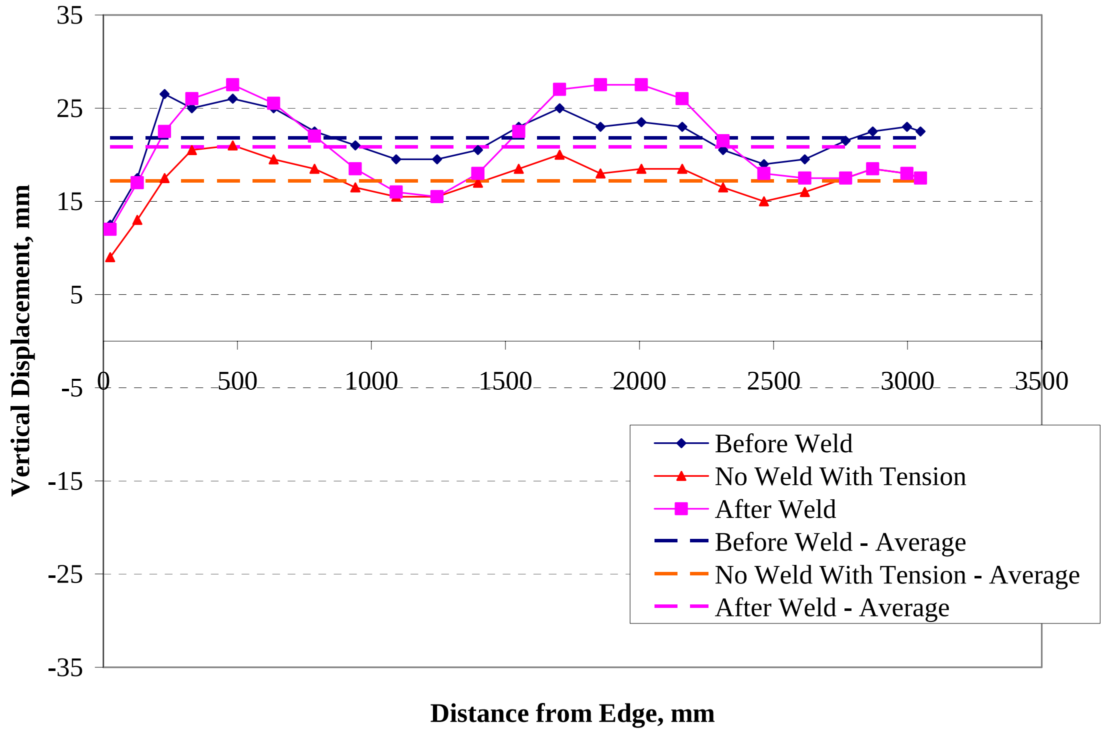


Figure J.35: Plate 9 Location B – Relative Displacement

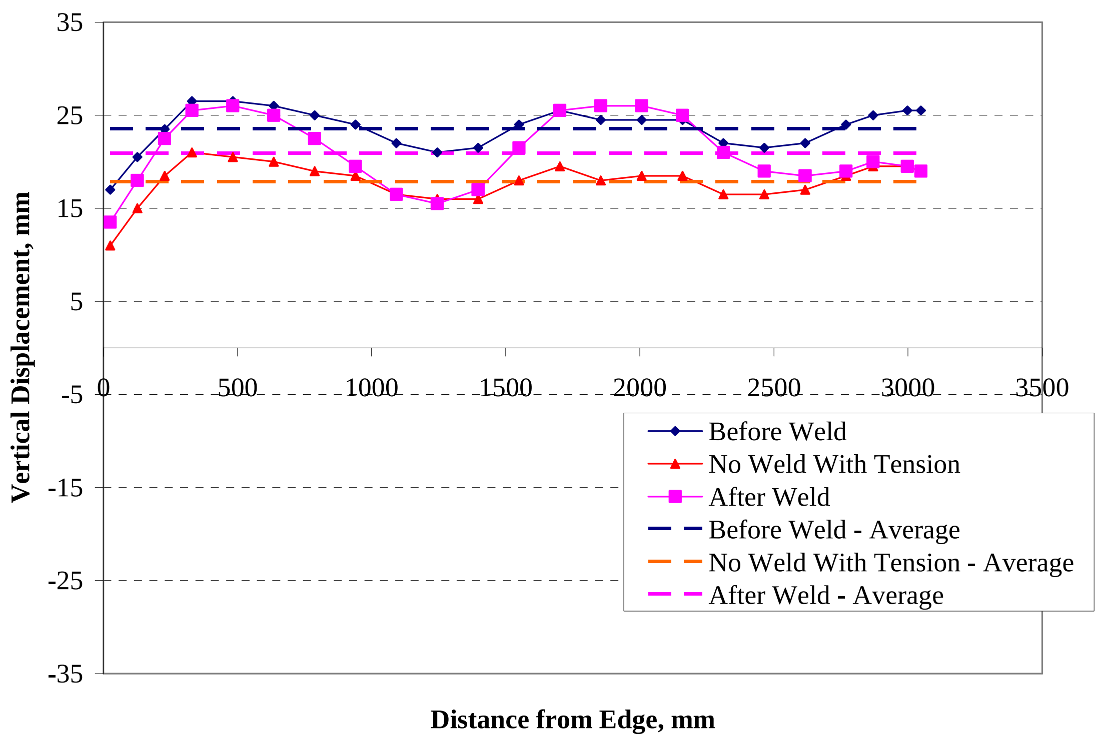


Figure J.36: Plate 9 Location C – Relative Displacement

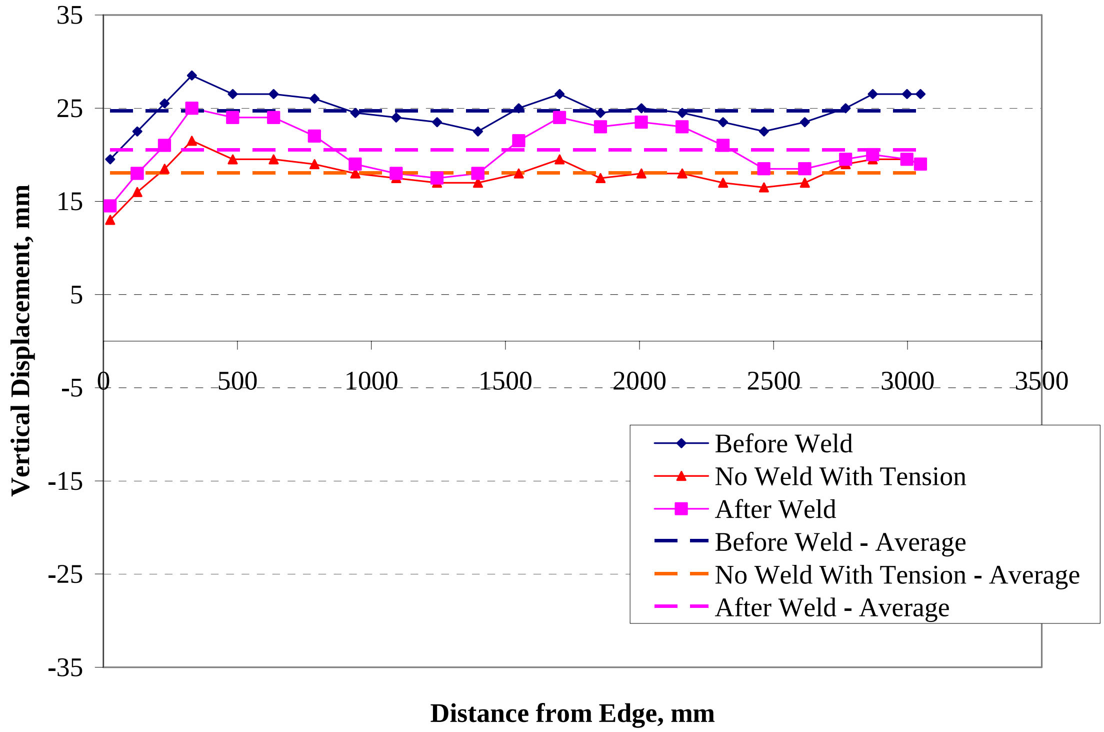


Figure J.37: Plate 9 Location D – Relative Displacement

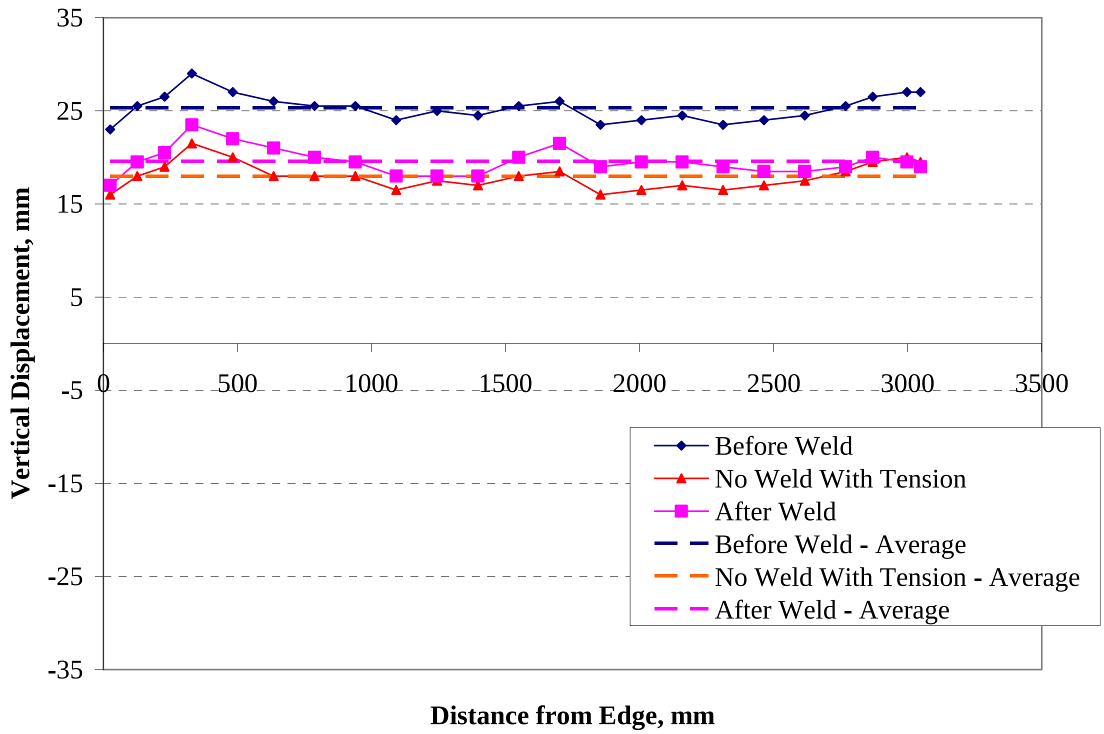


Figure J.38: Plate 9 Location E – Relative Displacement

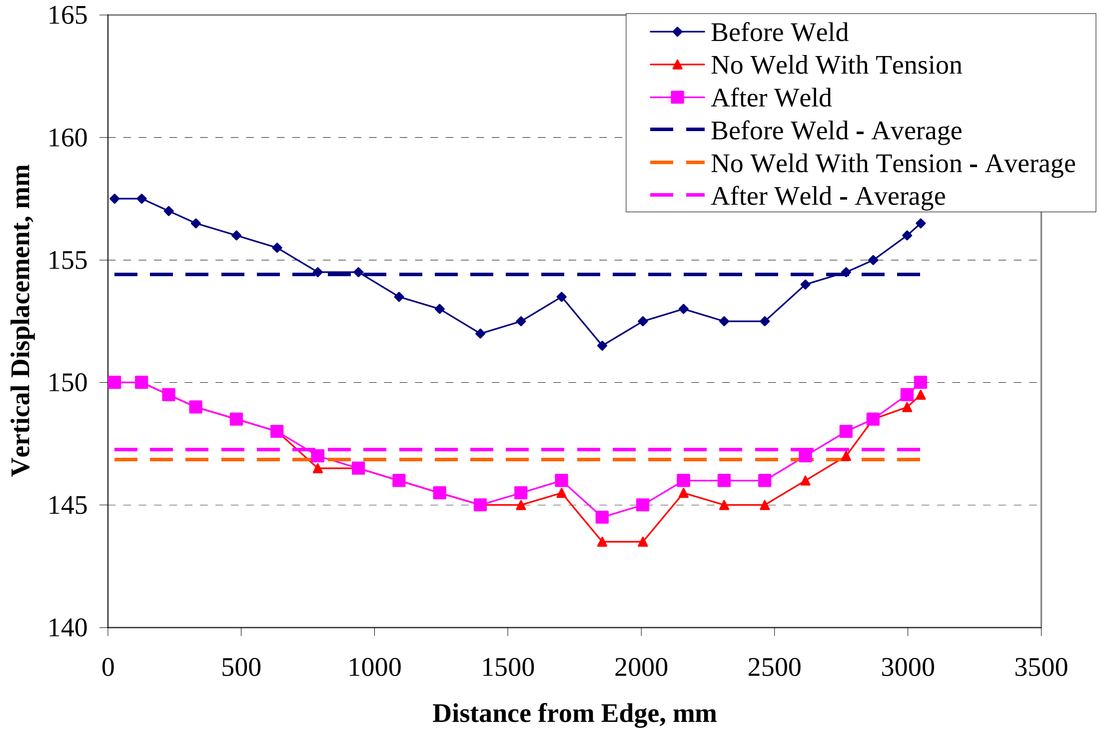


Figure J.39: Plate 9 At Stiffener – Relative Displacement

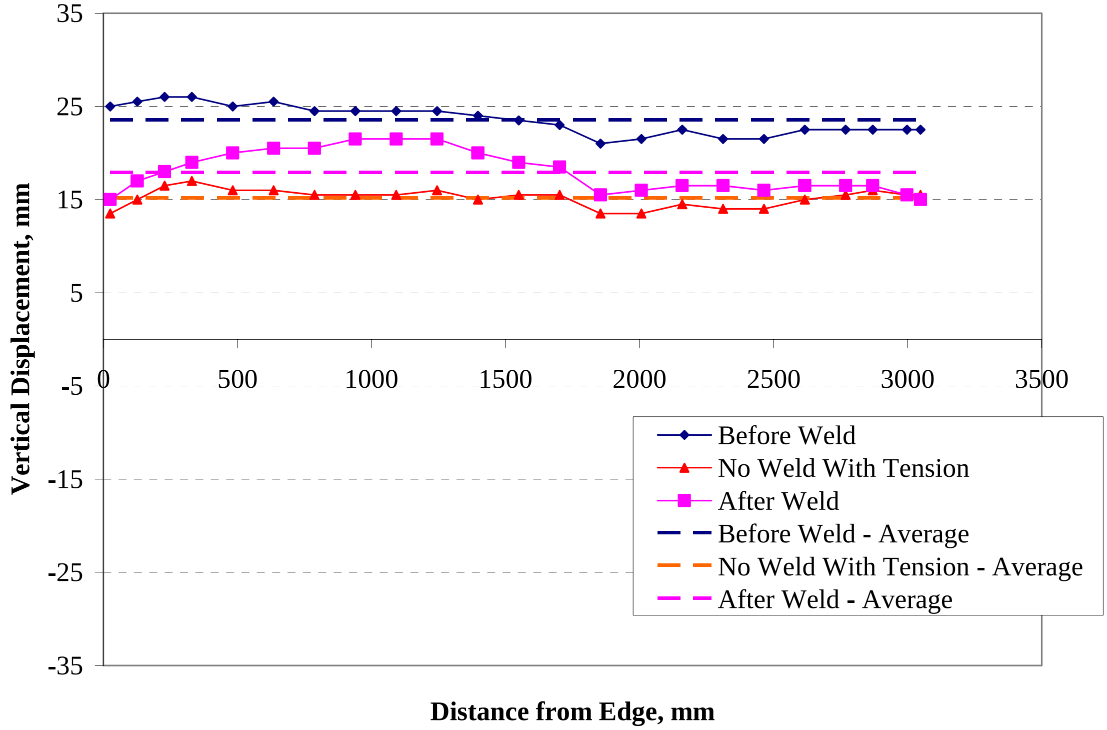


Figure J.40: Plate 9 Location G – Relative Displacement

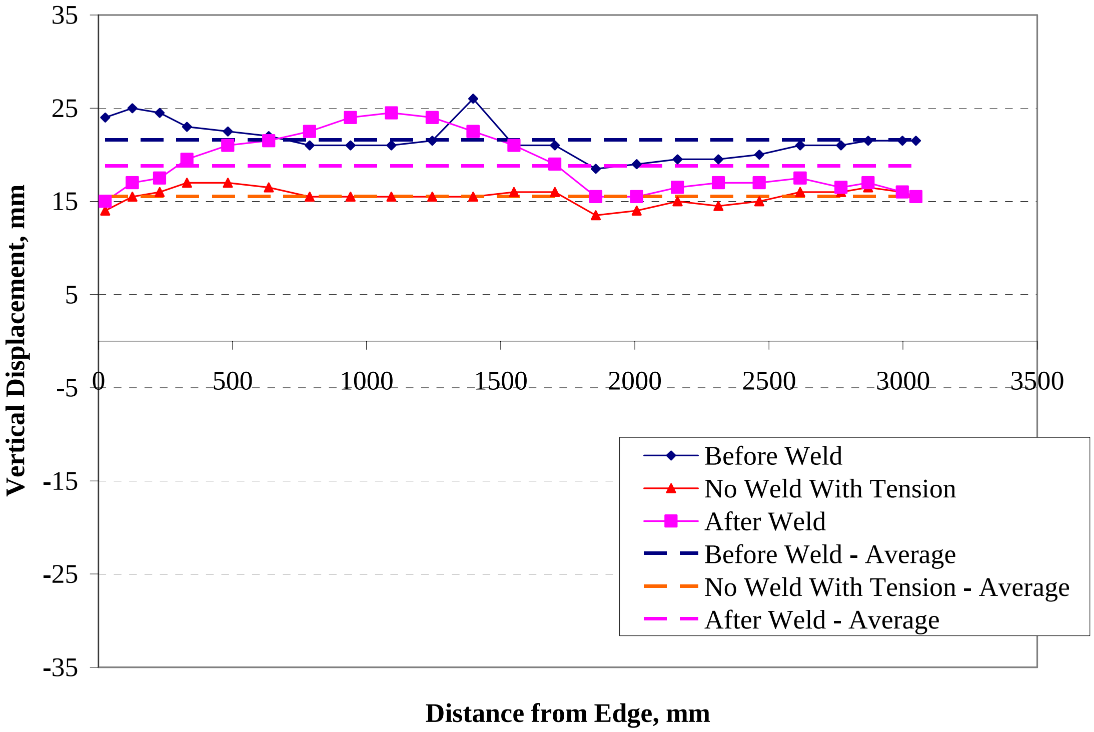


Figure J.41: Plate 9 Location H – Relative Displacement

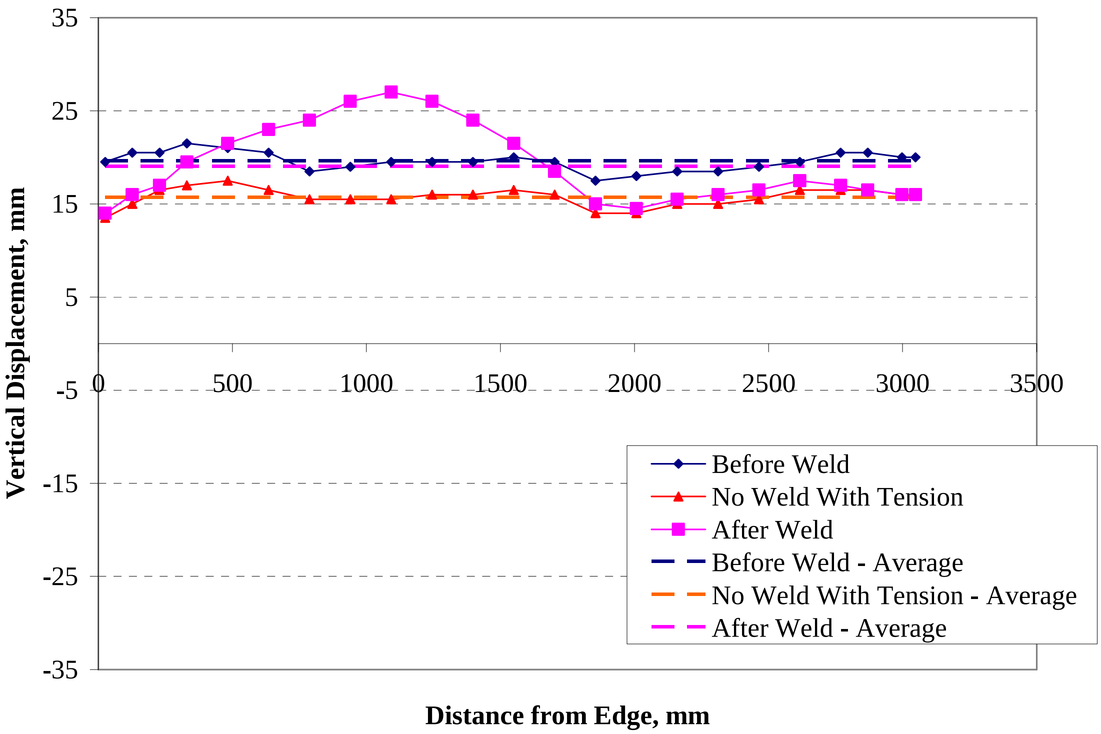


Figure J.42: Plate 9 Location I – Relative Displacement

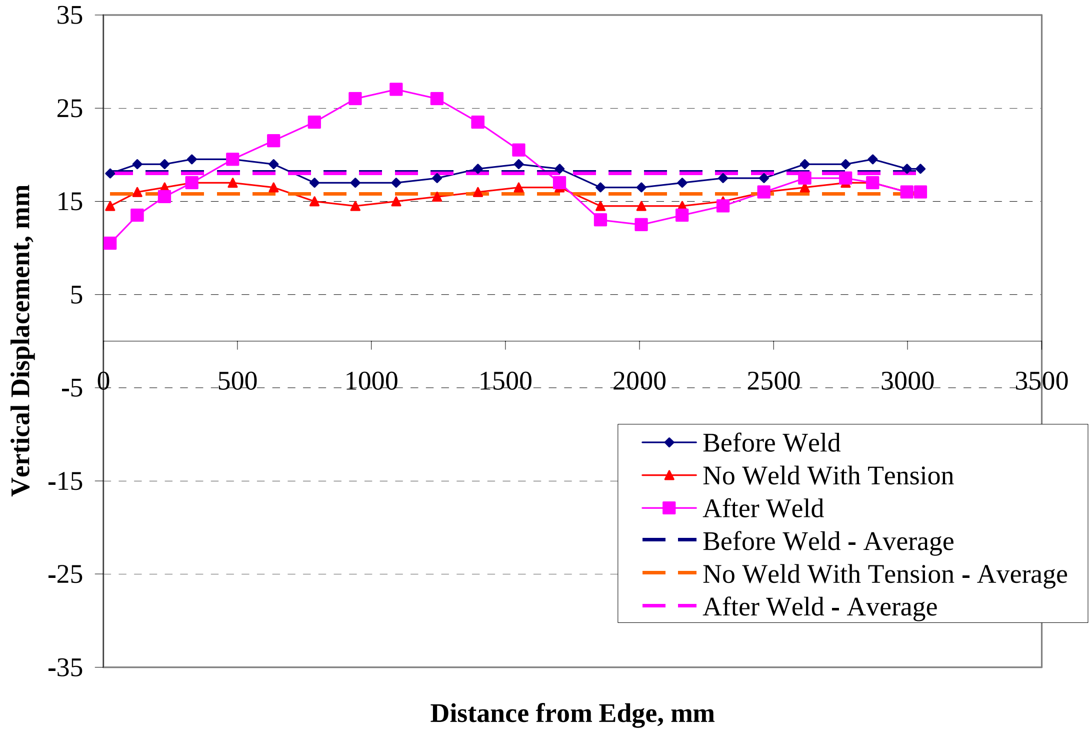


Figure J.43: Plate 9 Location J – Relative Displacement

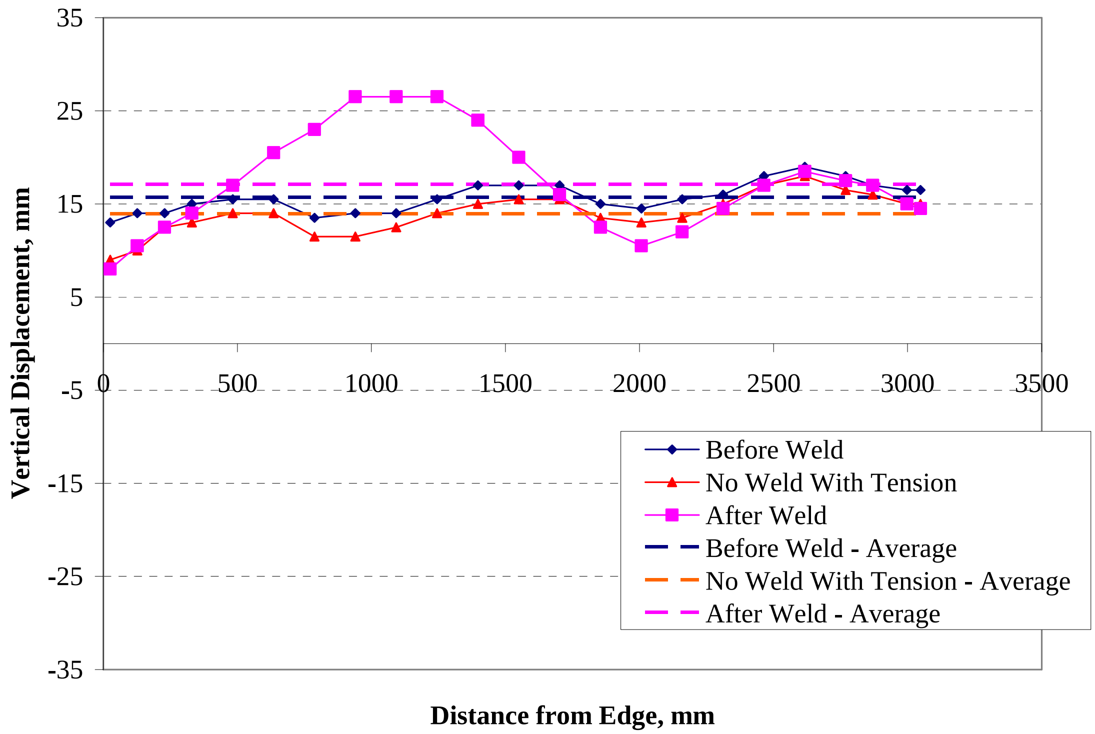


Figure J.44: Plate 9 Location K – Relative Displacement

APPENDIX K

DEVIATION FROM AVERAGE RELATIVE DISPLACEMENT FOR FCAW and T-MCAW (4’ x 10’ HSLA 80 BASE PLATES)

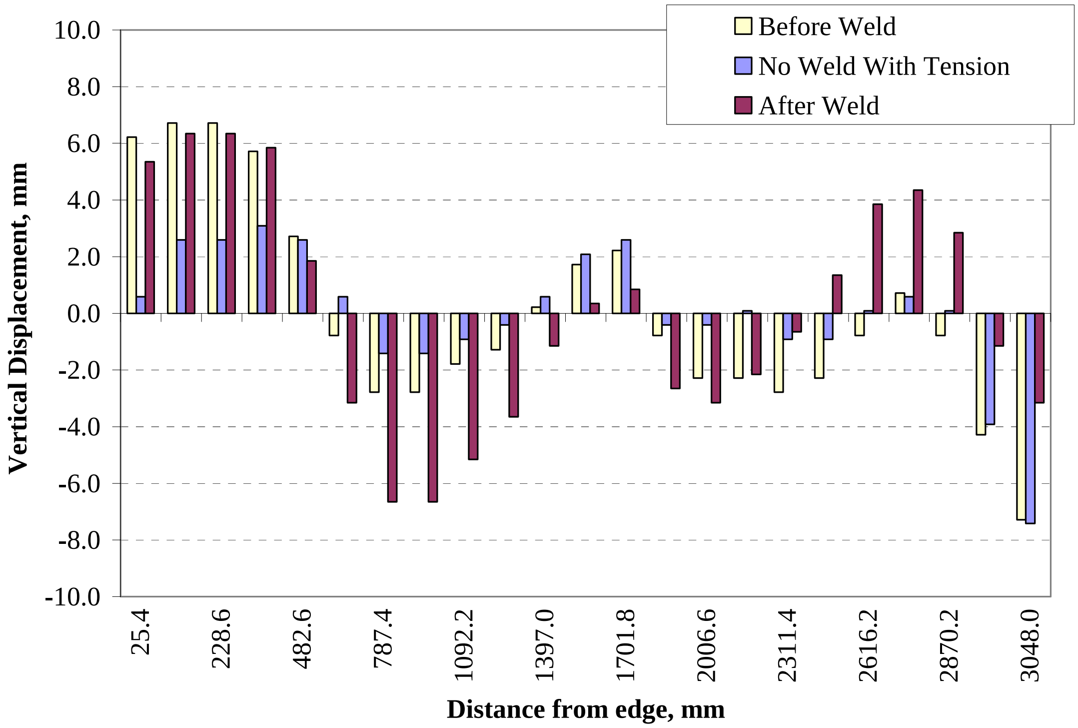


Figure K.1: Plate 3 Location A – Deviation From Average Relative Displacement

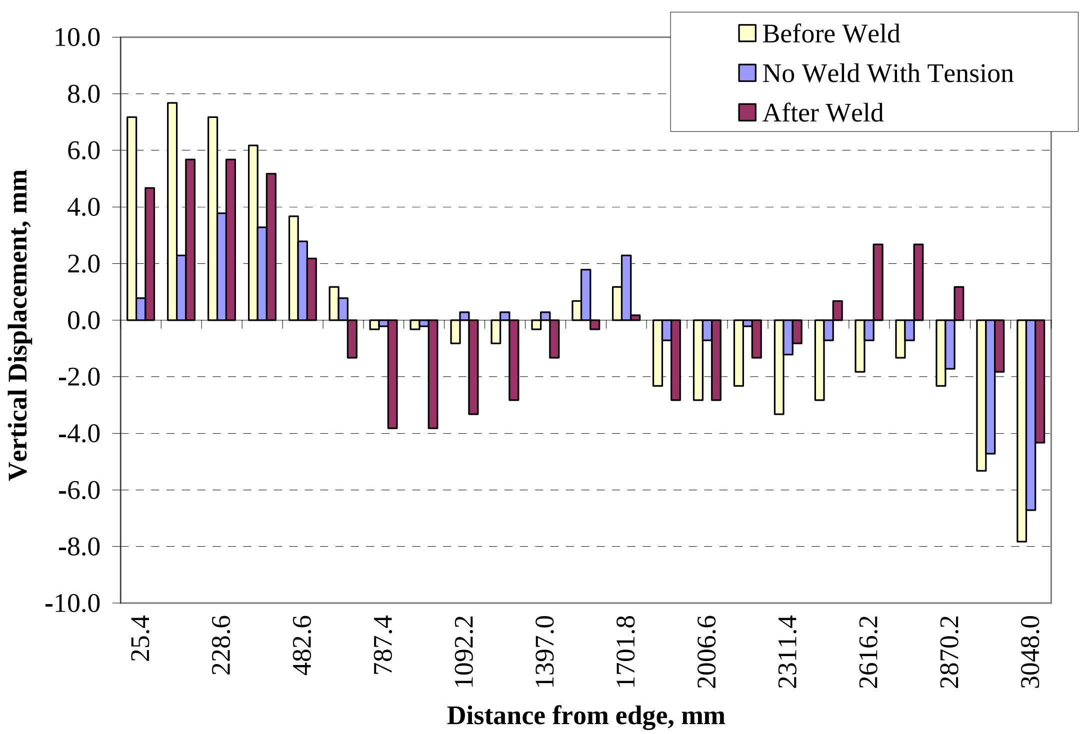


Figure K.2: Plate 3 Location B – Deviation From Average Relative Displacement

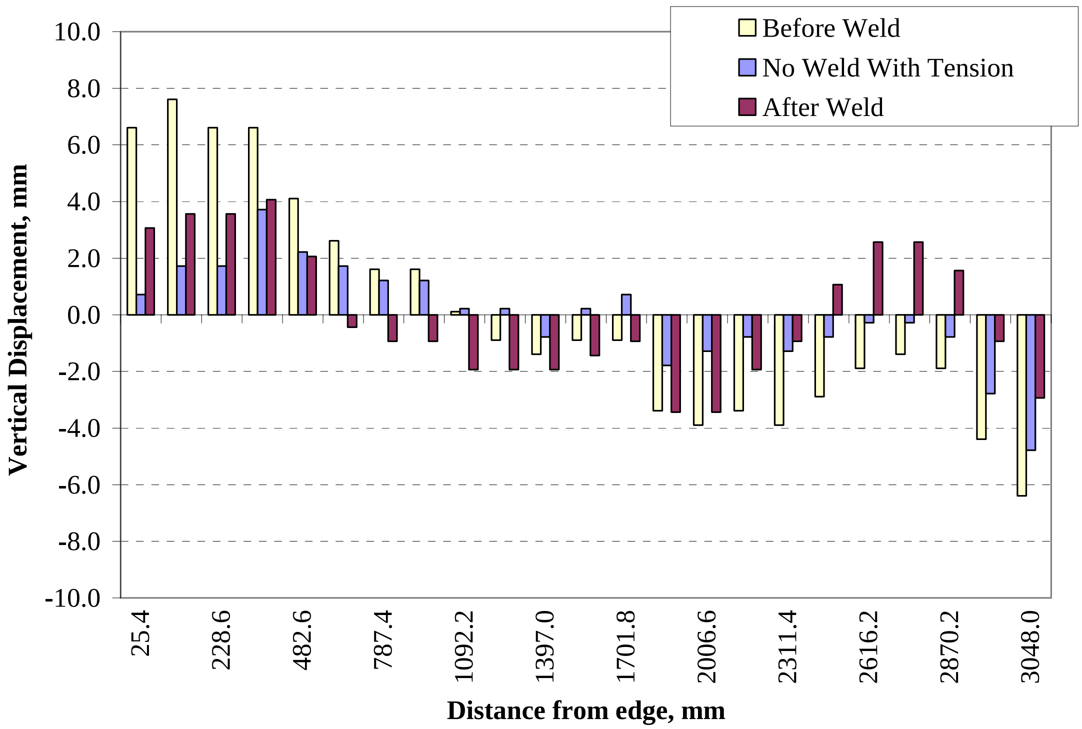


Figure K.3: Plate 3 Location C – Deviation From Average Relative Displacement

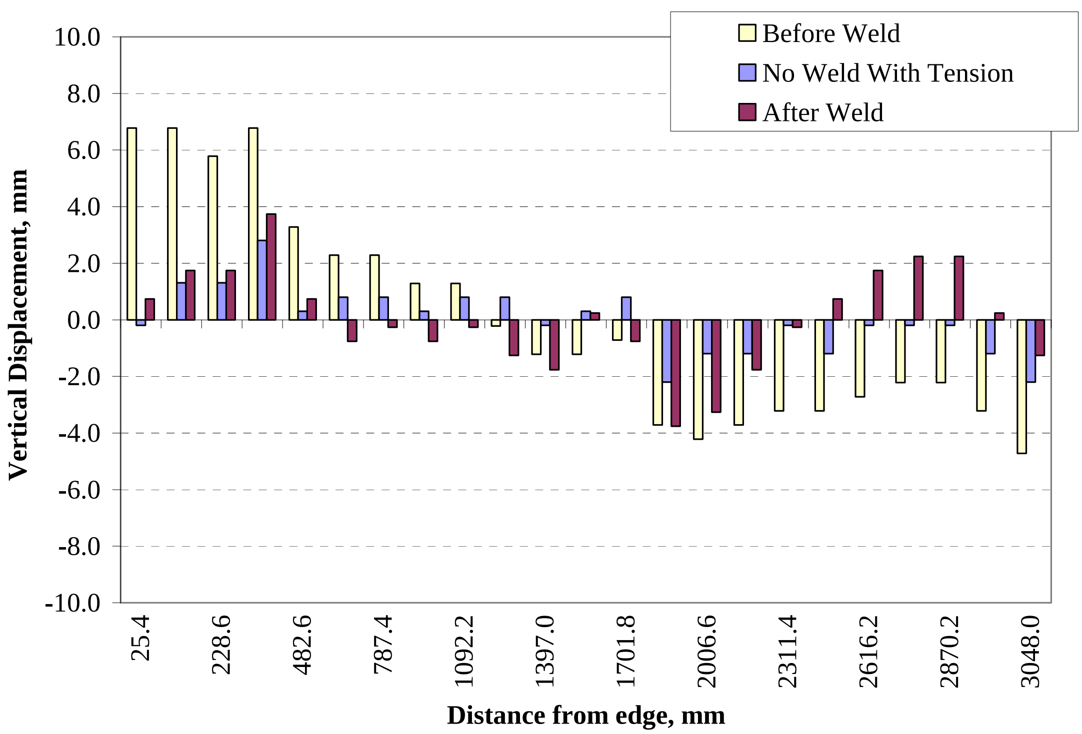


Figure K.4: Plate 3 Location D – Deviation From Average Relative Displacement

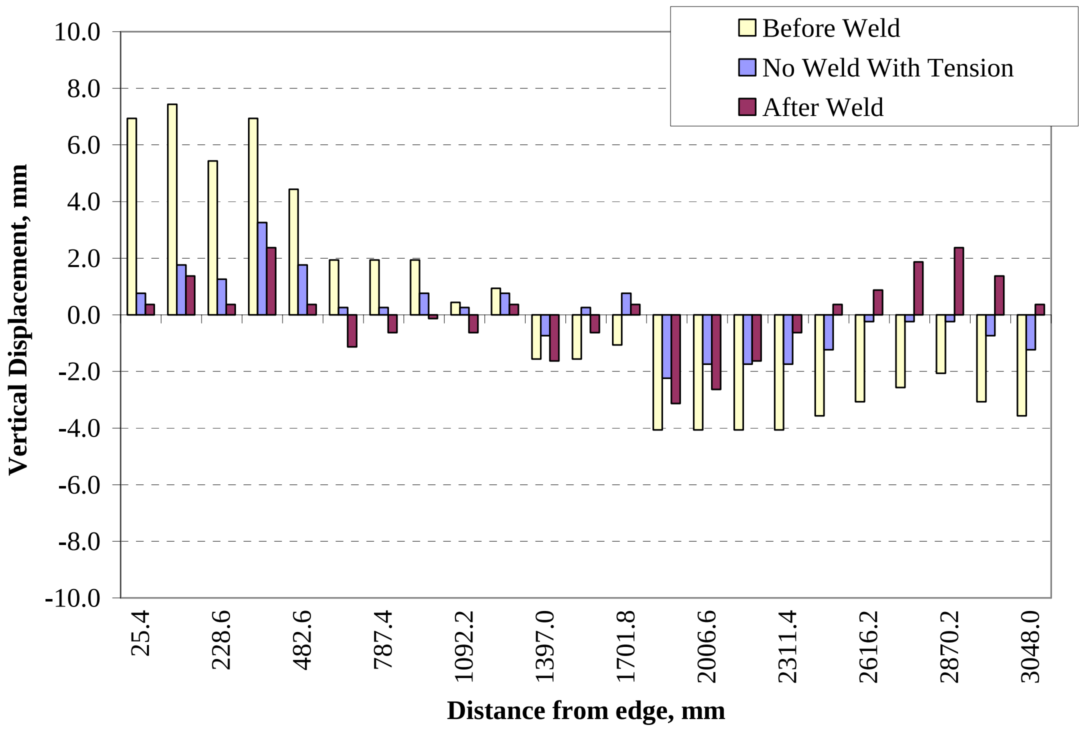


Figure K.5: Plate 3 Location E – Deviation From Average Relative Displacement

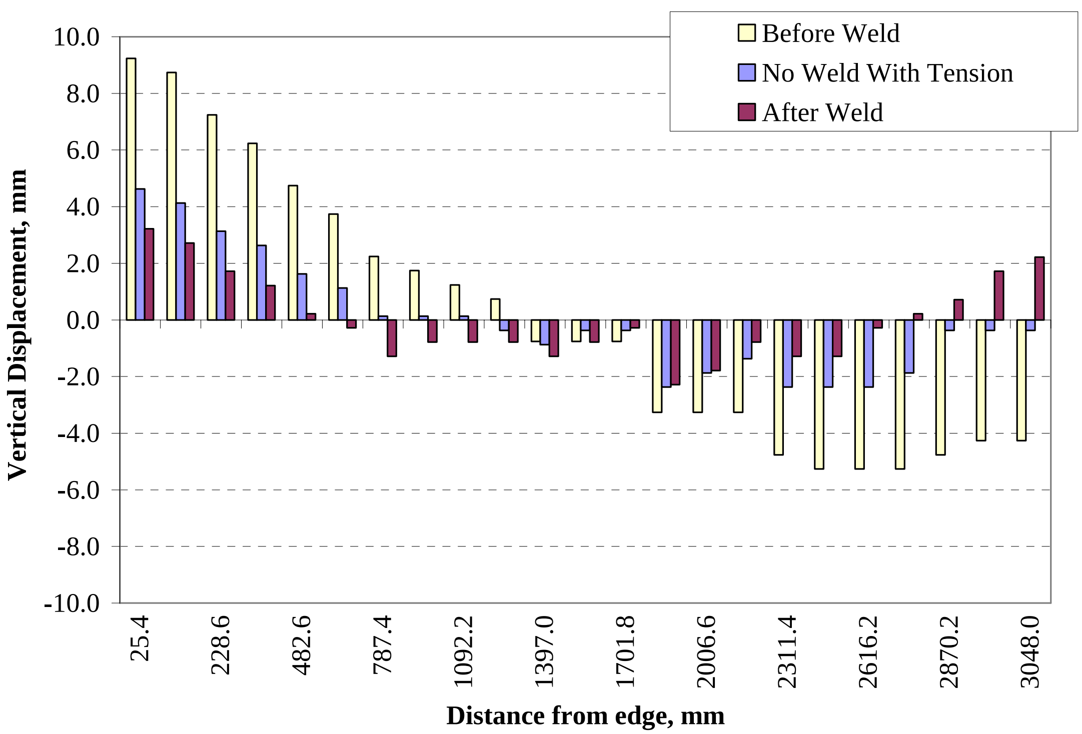


Figure K.6: Plate 3 At Stiffener – Deviation From Average Relative Displacement

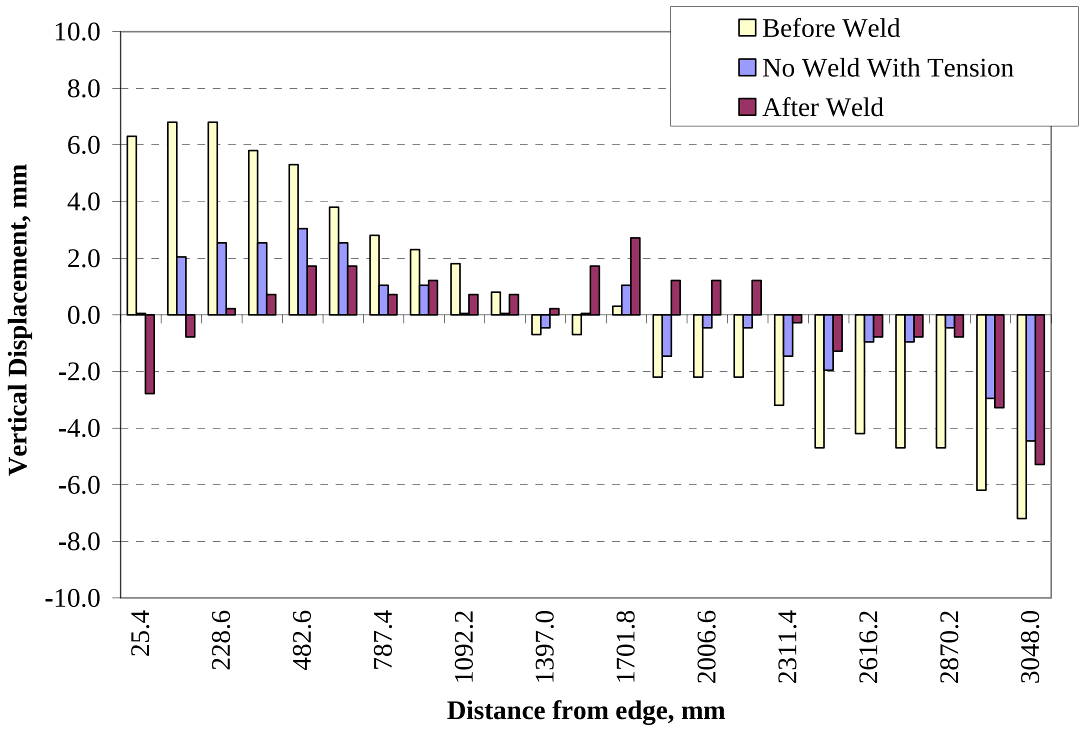


Figure K.7: Plate 3 Location G – Deviation From Average Relative Displacement

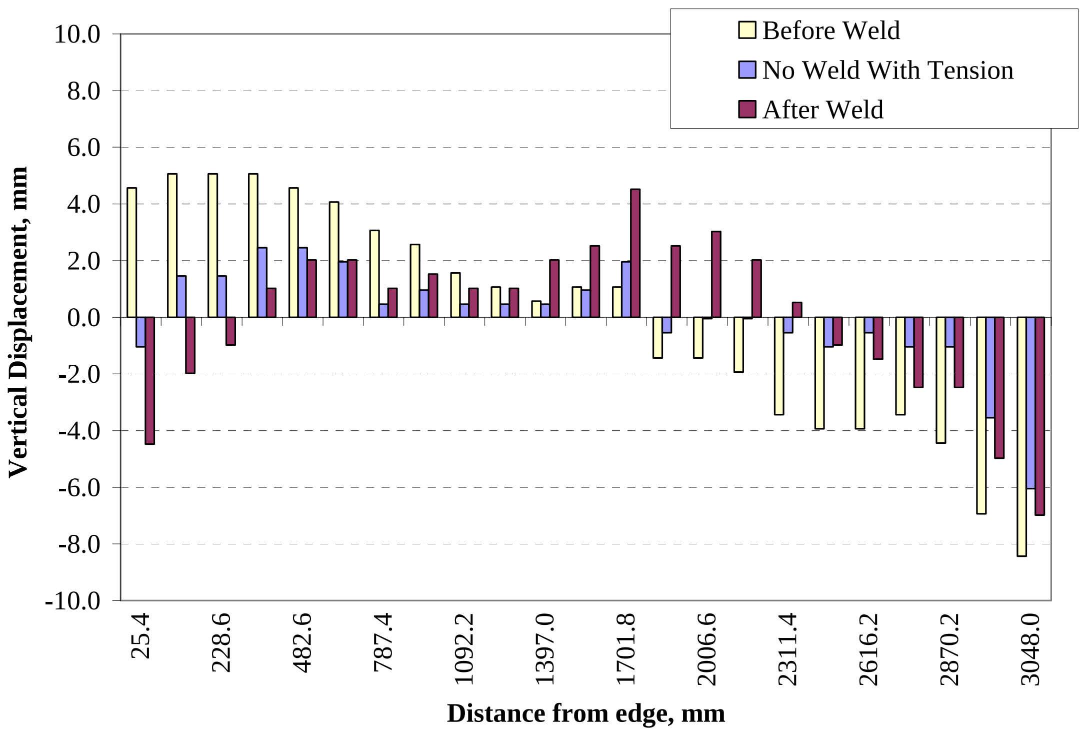


Figure K.8: Plate 3 Location H – Deviation From Average Relative Displacement

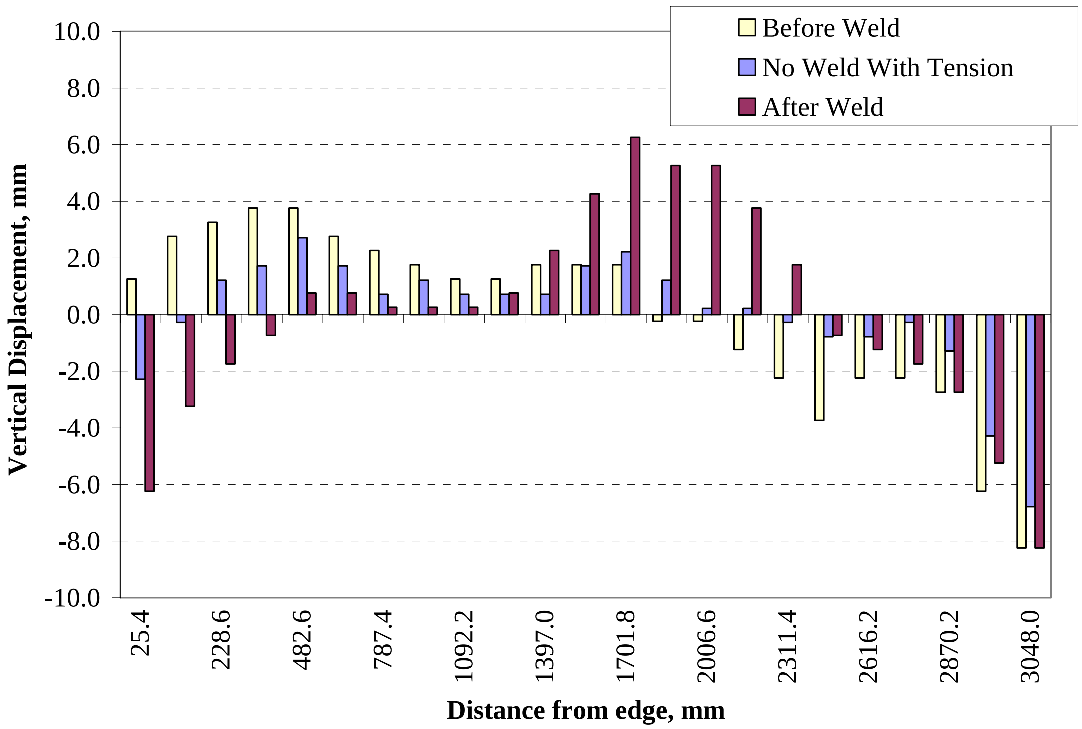


Figure K.9: Plate 3 Location I – Deviation From Average Relative Displacement

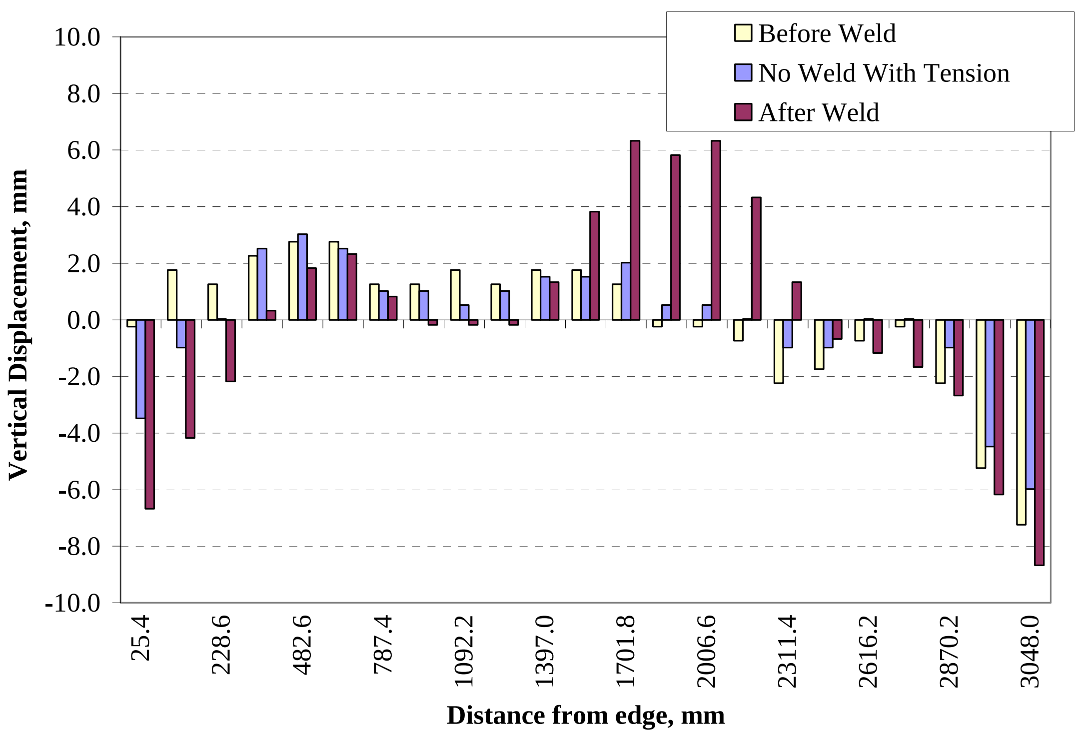


Figure K.10: Plate 3 Location J – Deviation From Average Relative Displacement

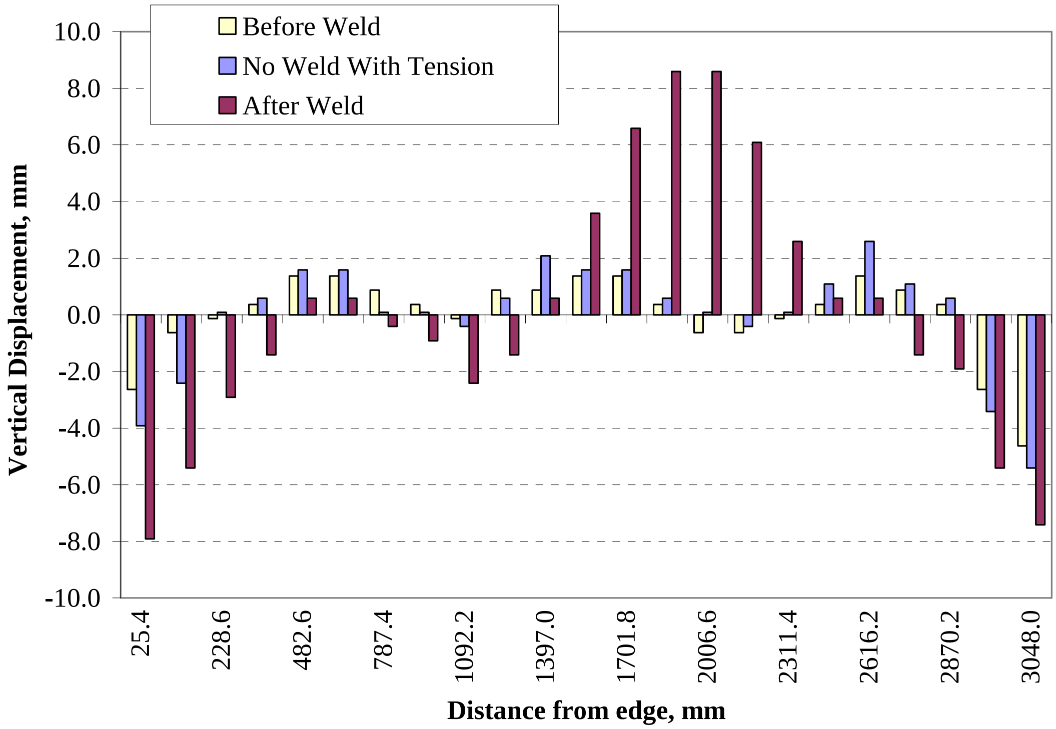


Figure K.11: Plate 3 Location K – Deviation From Average Relative Displacement

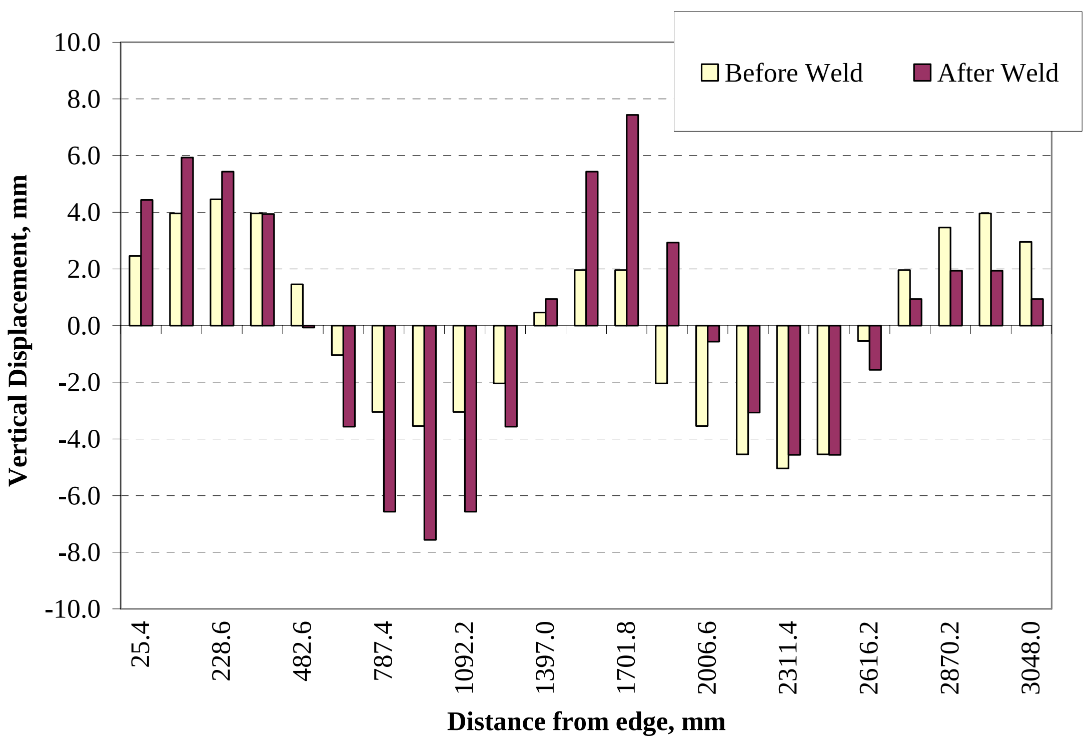


Figure K.12: Plate 7 Location A – Deviation From Average Relative Displacement

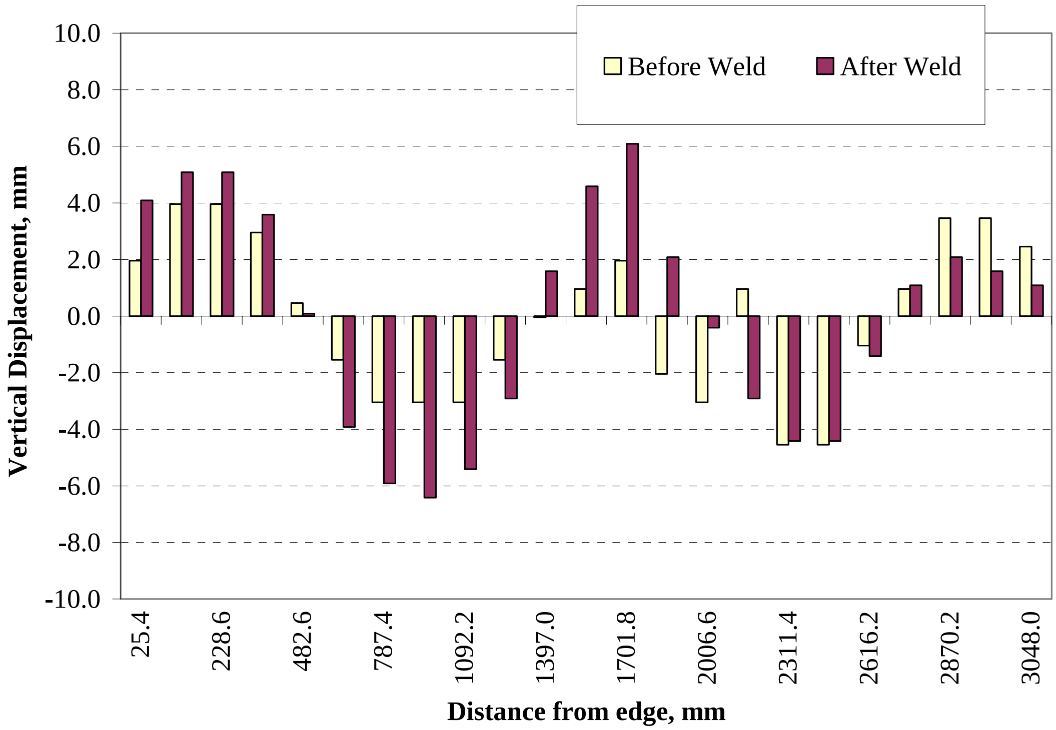


Figure K.13: Plate 7 Location B – Deviation From Average Relative Displacement B

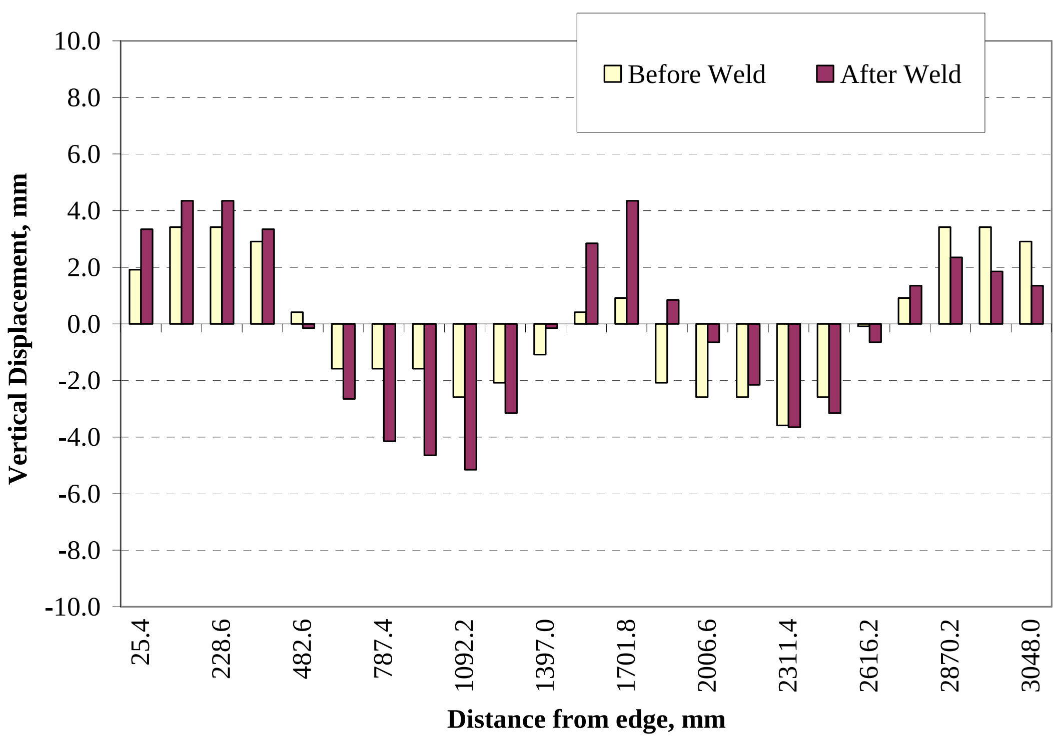


Figure K.14: Plate 7 Location C – Deviation From Average Relative Displacement

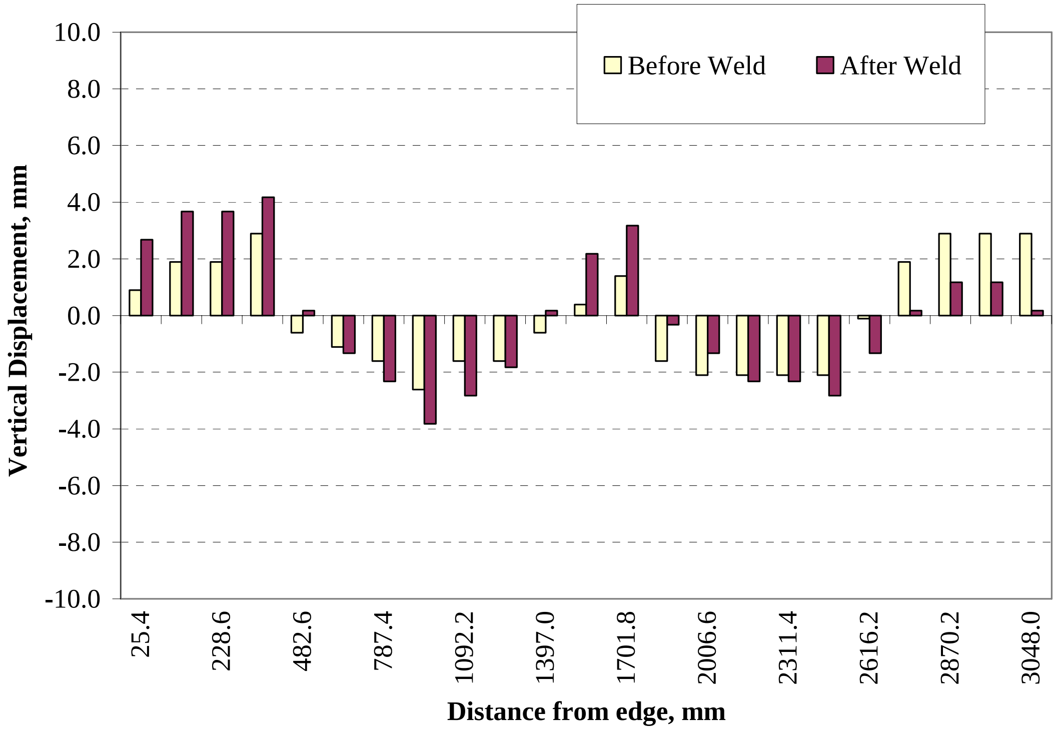


Figure K.15: Plate 7 Location D – Deviation From Average Relative Displacement

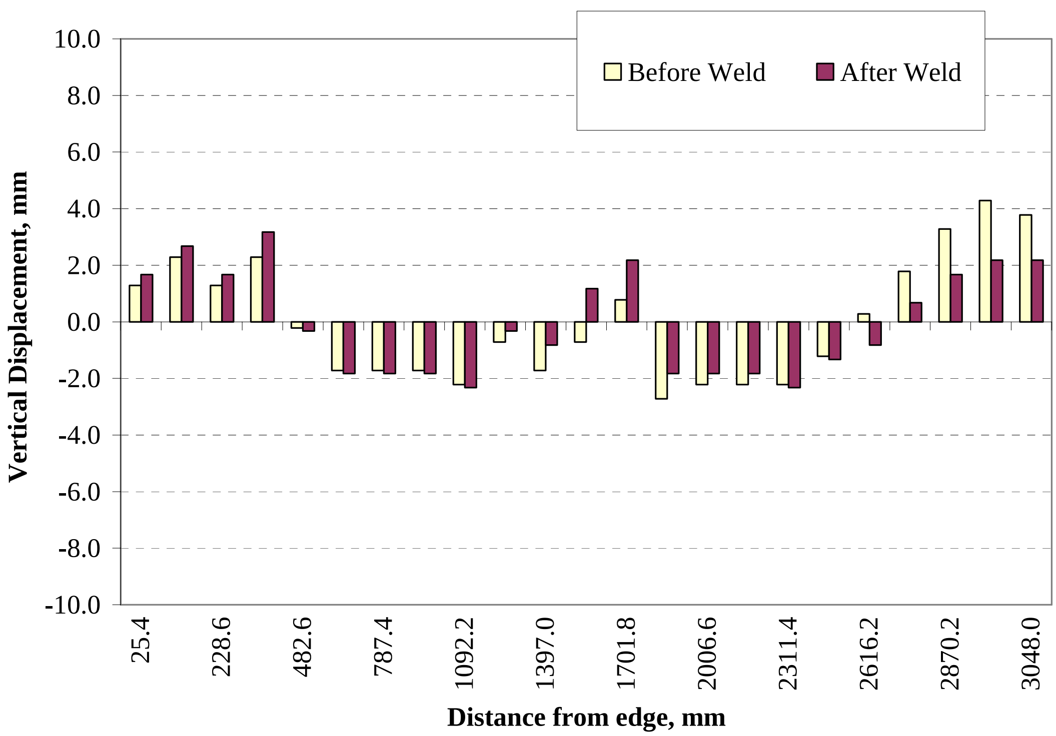


Figure K.16: Plate 7 Location E – Deviation From Average Relative Displacement

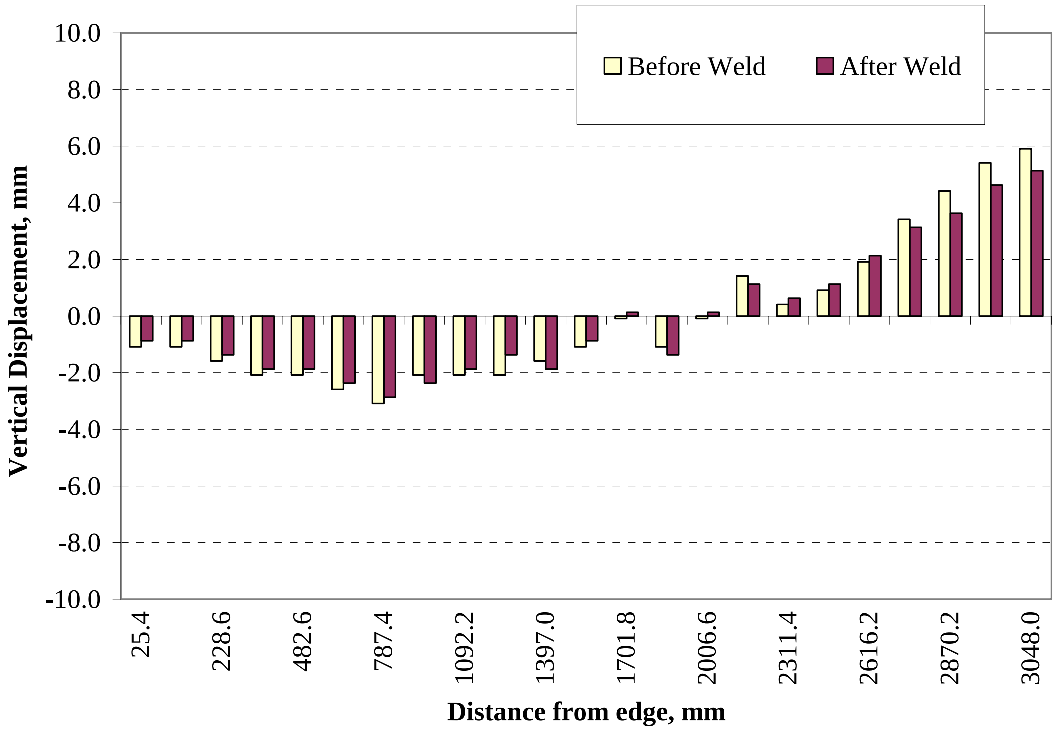


Figure K.17: Plate 7 At Stiffener – Deviation From Average Relative Displacement

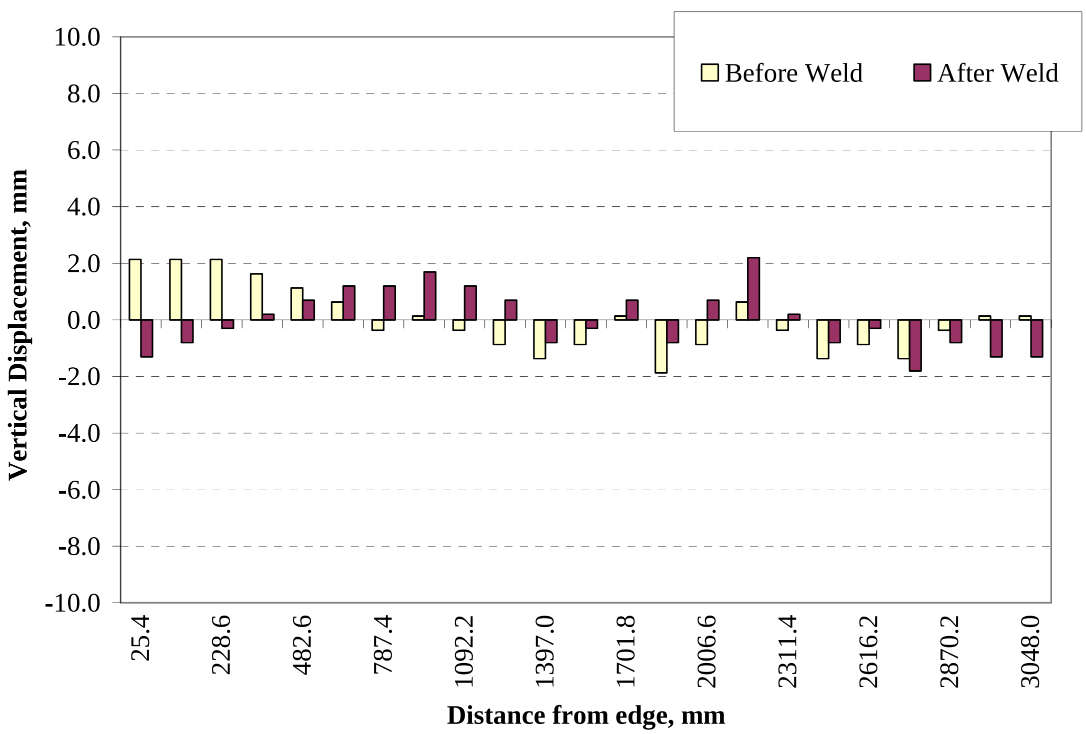


Figure K.18: Plate 7 Location G – Deviation From Average Relative Displacement

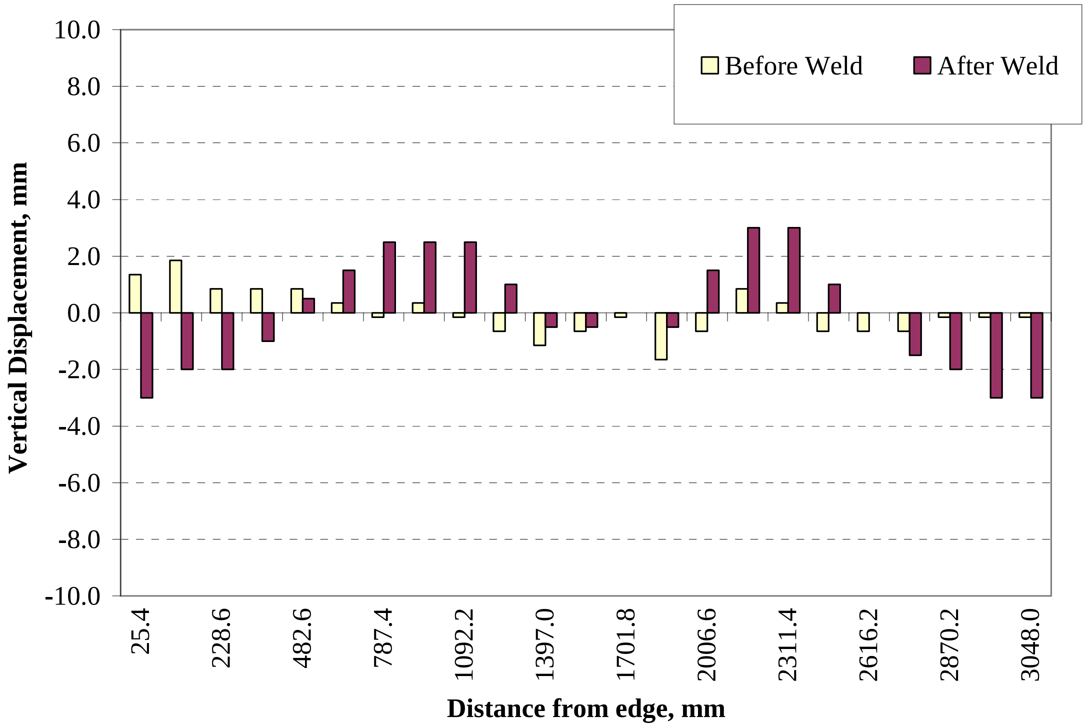


Figure K.19: Plate 7 Location H – Deviation From Average Relative Displacement

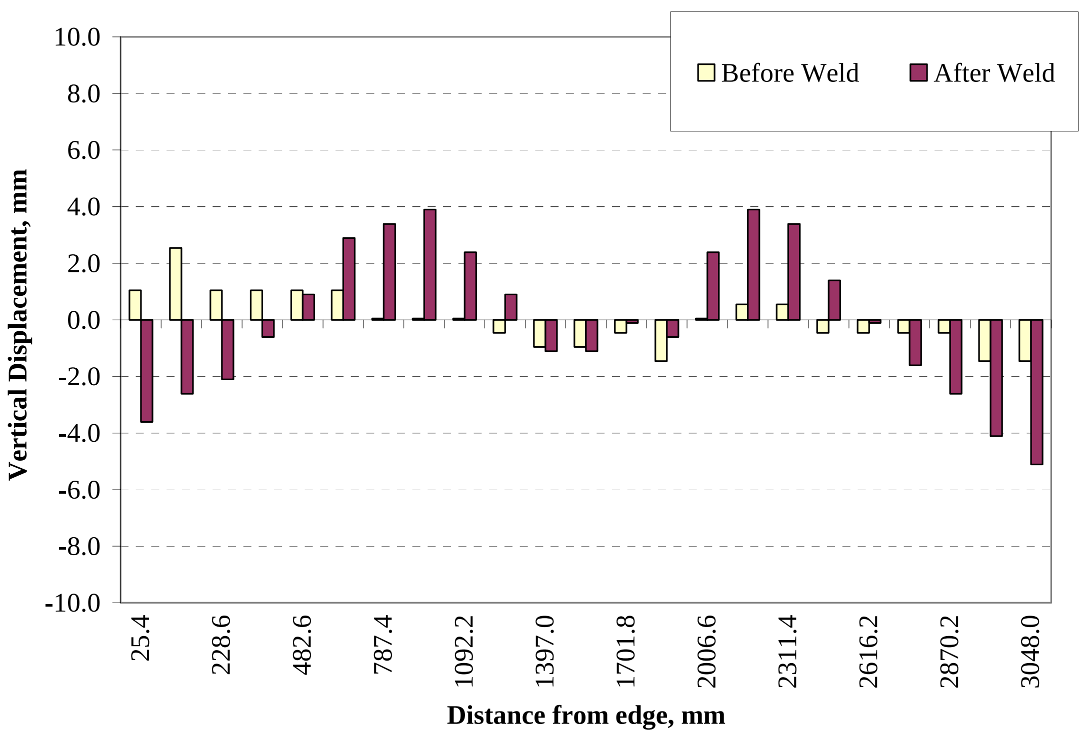


Figure K.20: Plate 7 Location I – Deviation From Average Relative Displacement

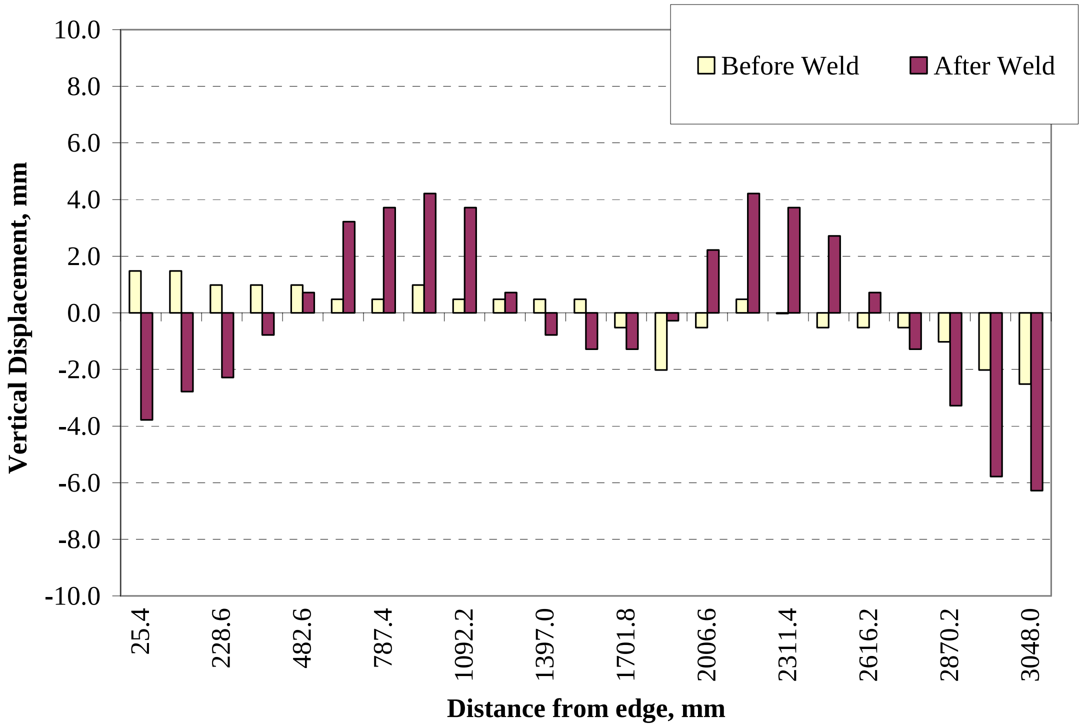


Figure K.21: Plate 7 Location J – Deviation From Average Relative Displacement

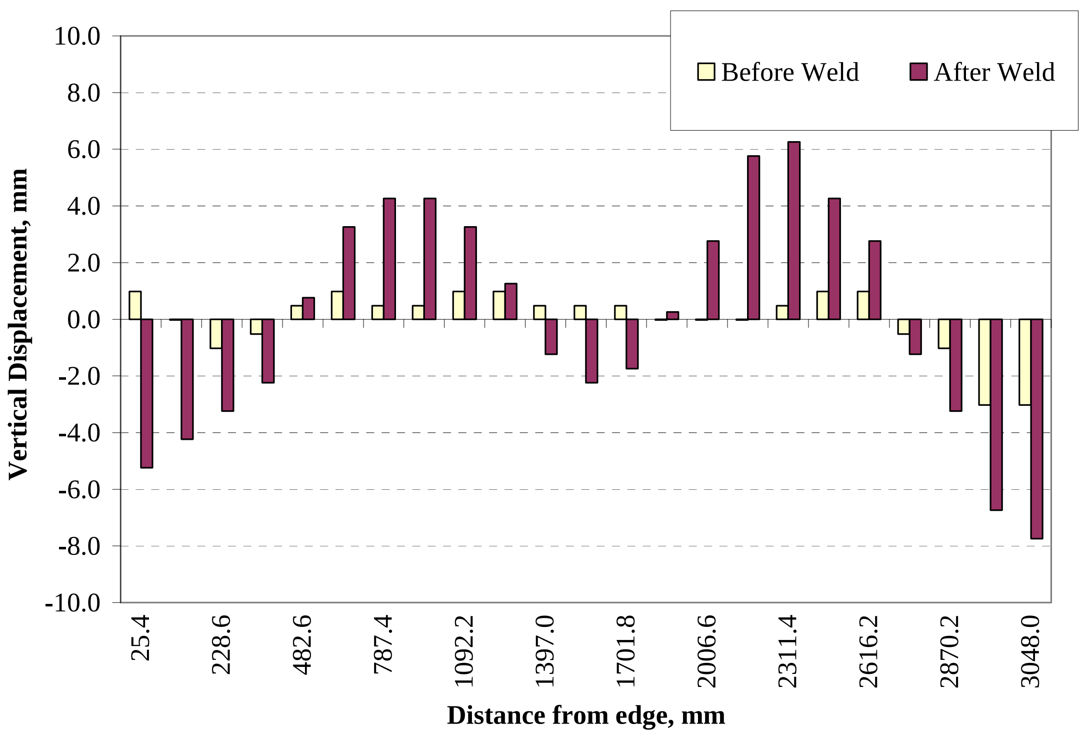


Figure K.22: Plate 7 Location K – Deviation From Average Relative Displacement

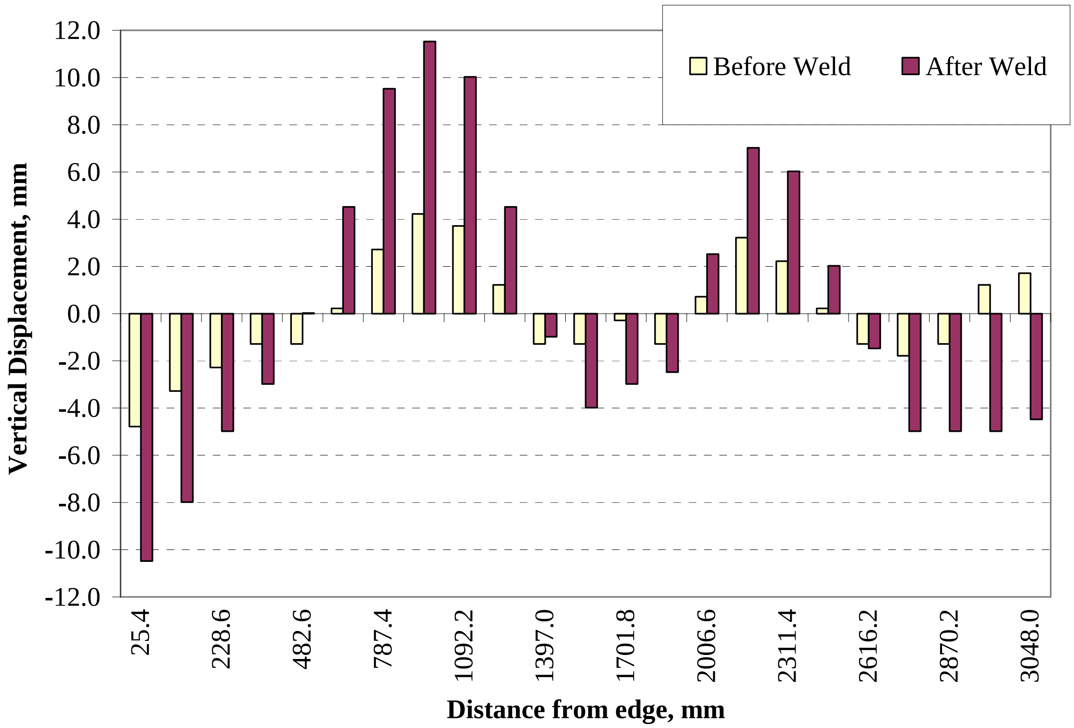


Figure K.23: Plate 8 Location A – Deviation From Average Relative Displacement

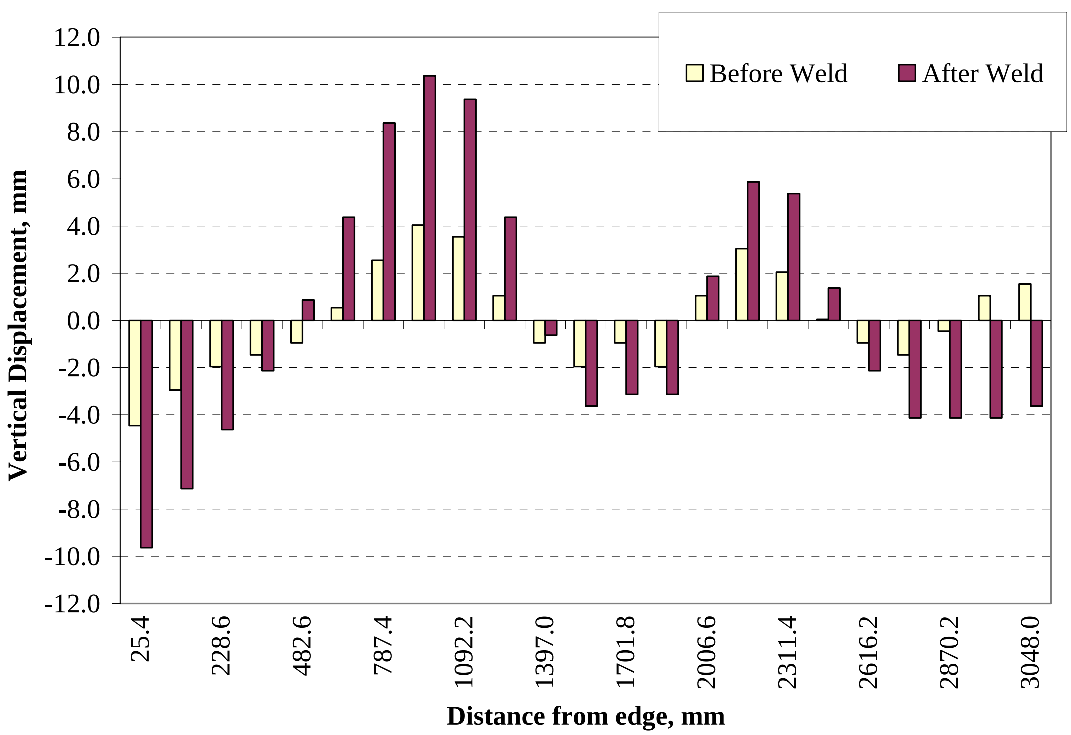


Figure K.24: Plate 8 Location B – Deviation From Average Relative Displacement

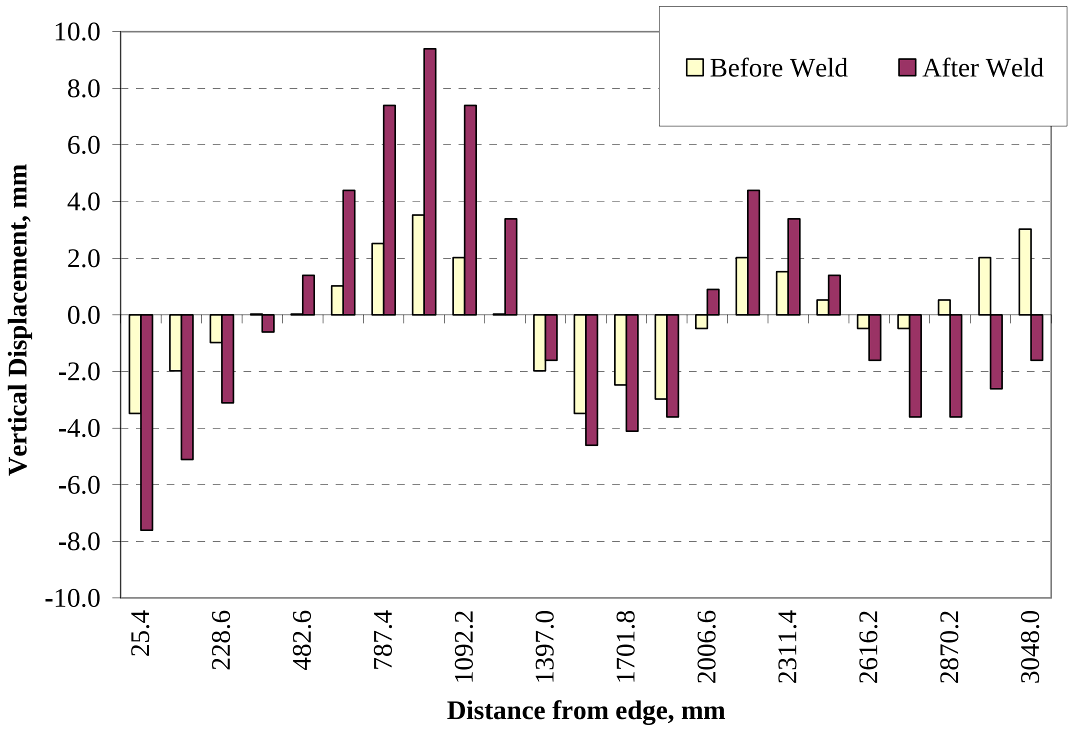


Figure K.25: Plate 8 Location C – Deviation From Average Relative Displacement

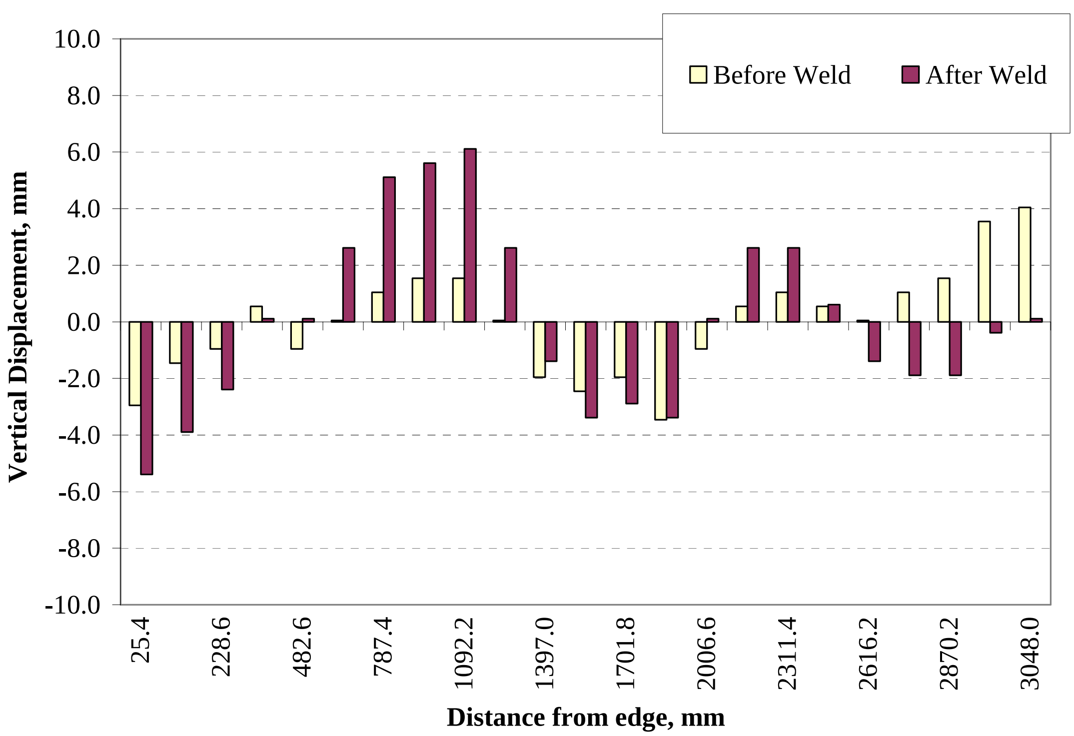


Figure K.26: Plate 8 Location D – Deviation From Average Relative Displacement

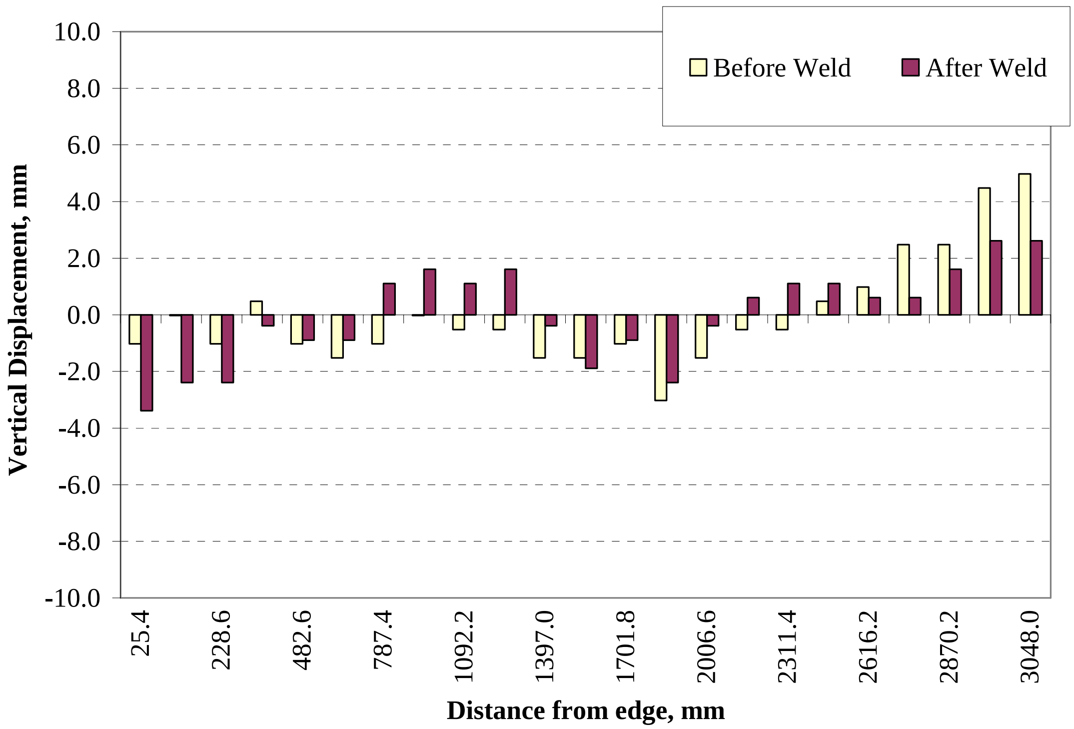


Figure K.27: Plate 8 Location E – Deviation From Average Relative Displacement

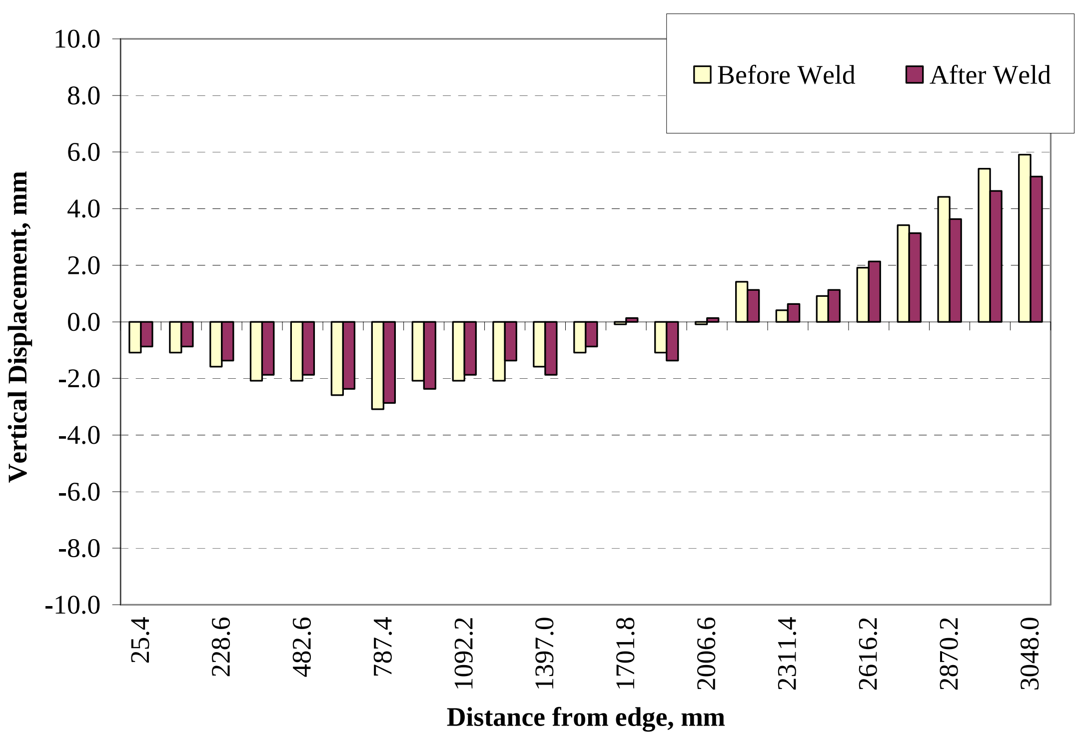


Figure K.28: Plate 8 At Stiffener – Deviation From Average Relative Displacement

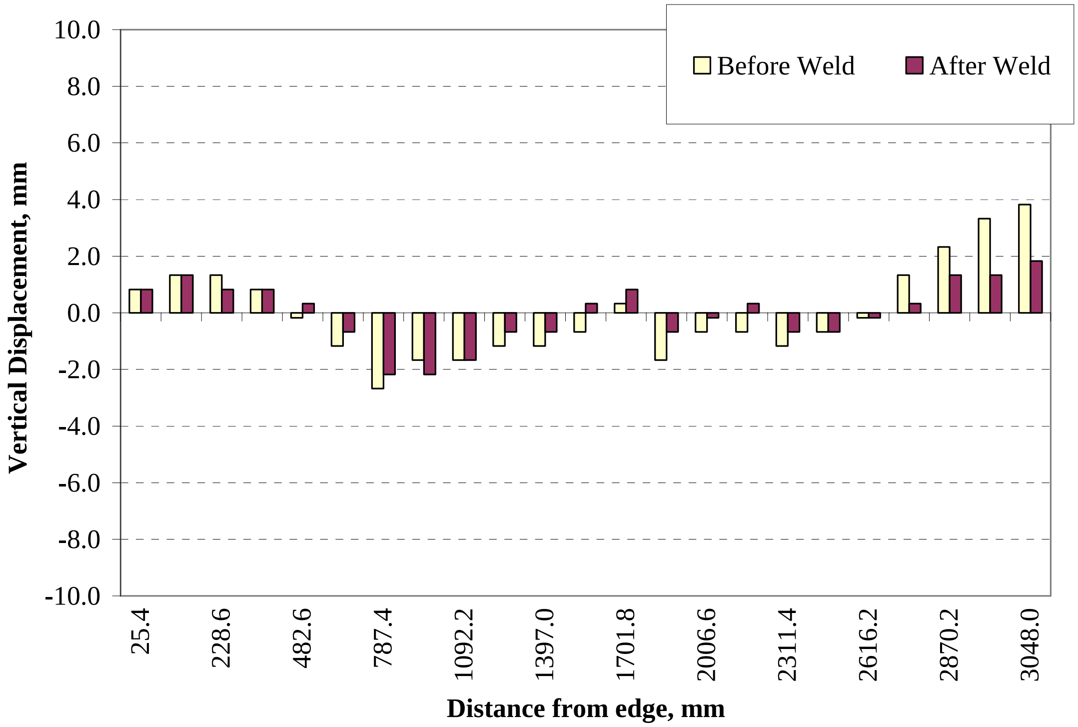


Figure K.29: Plate 8 Location G – Deviation From Average Relative Displacement

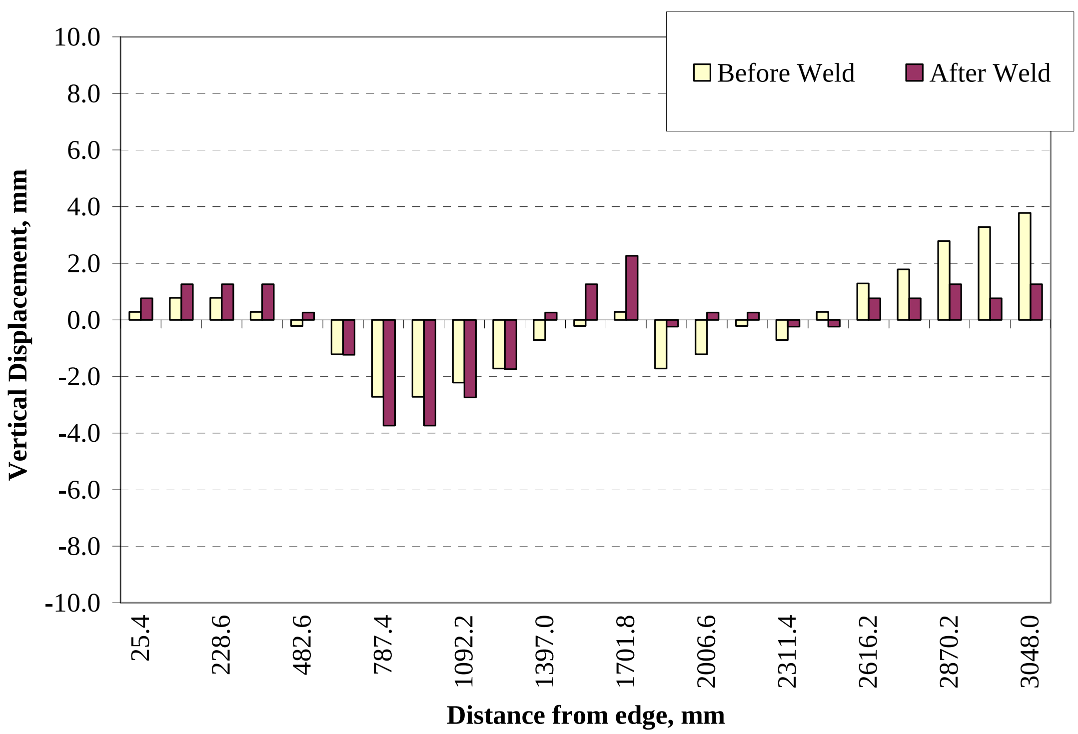


Figure K.30: Plate 8 Location H – Deviation From Average Relative Displacement

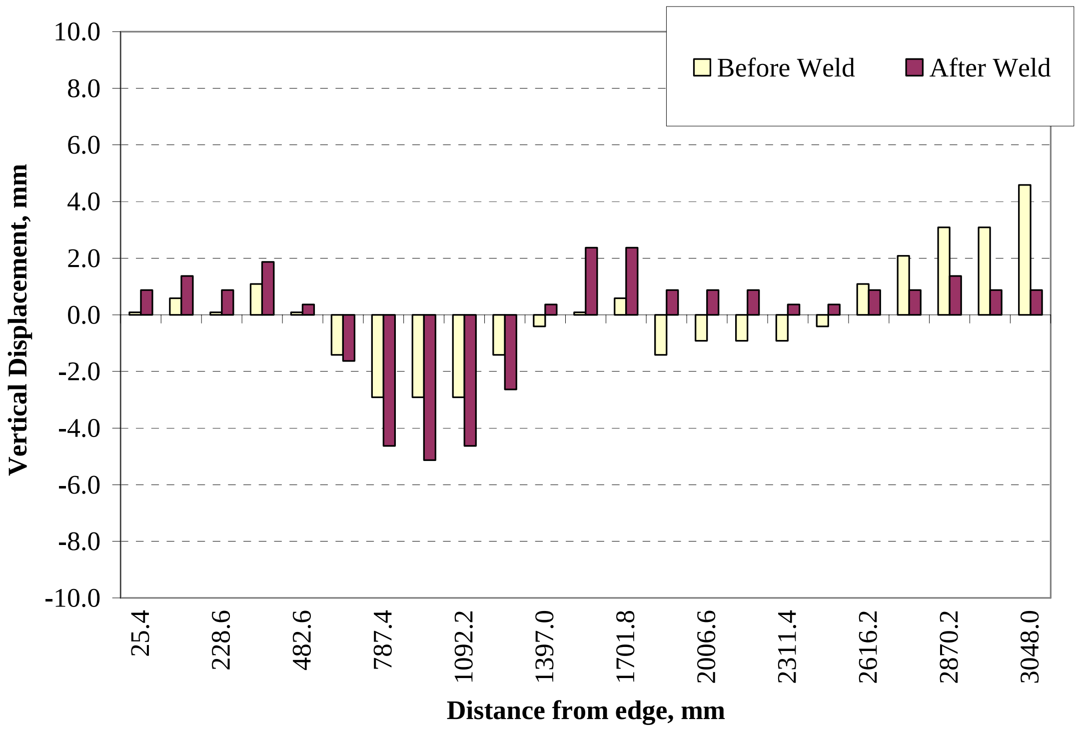


Figure K.31: Plate 8 Location I – Deviation From Average Relative Displacement

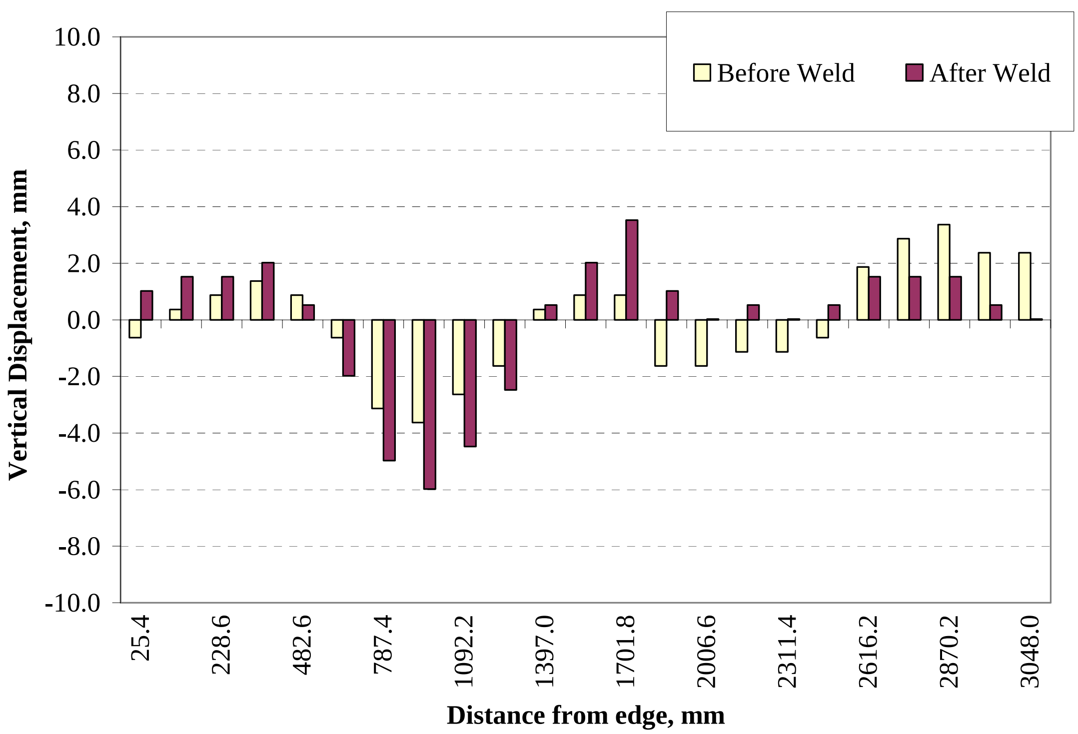


Figure K.32: Plate 8 Location J – Deviation From Average Relative Displacement

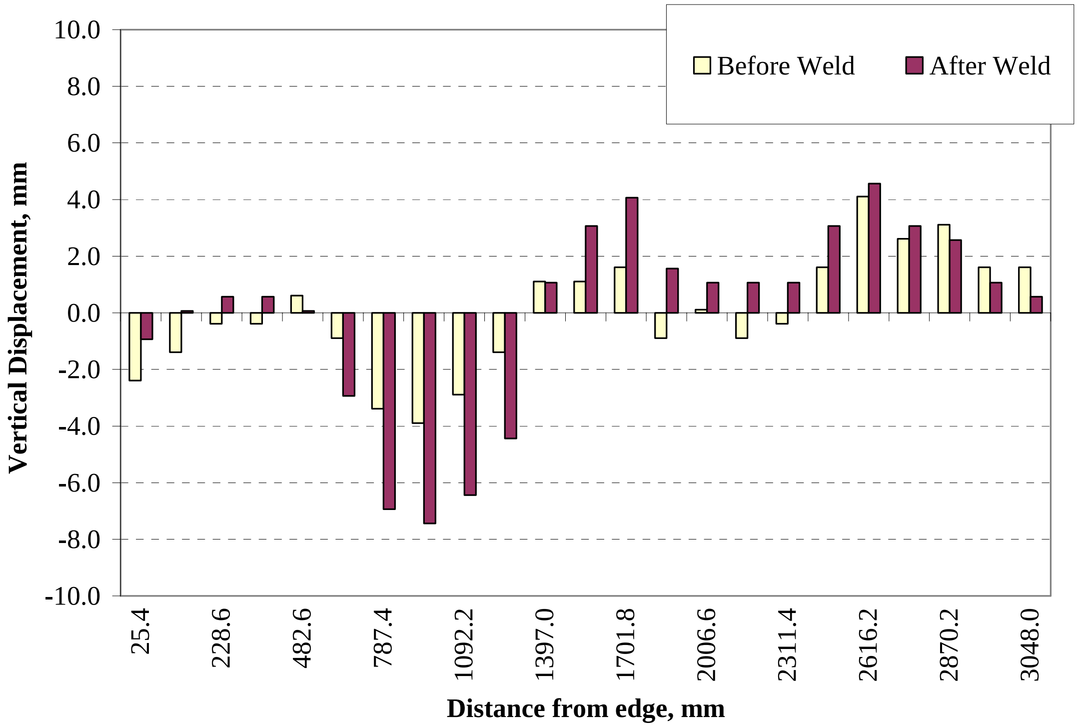


Figure K.33: Plate 8 Location K – Deviation From Average Relative Displacement

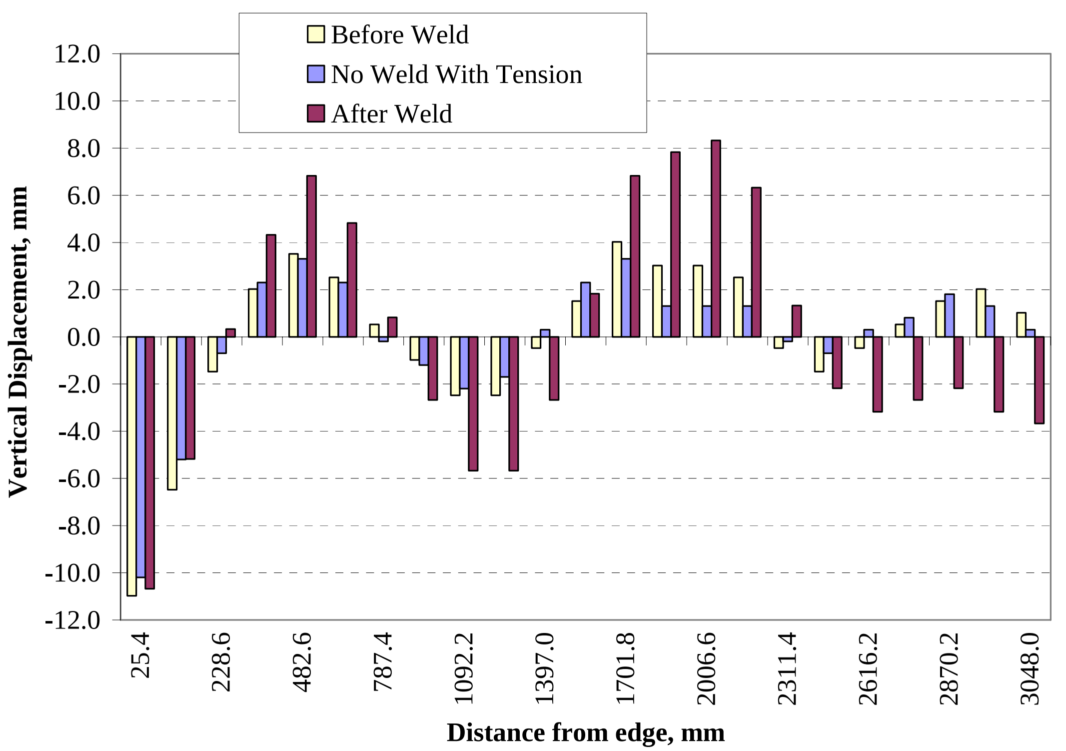


Figure K.34: Plate 9 Location A – Deviation From Average Relative Displacement

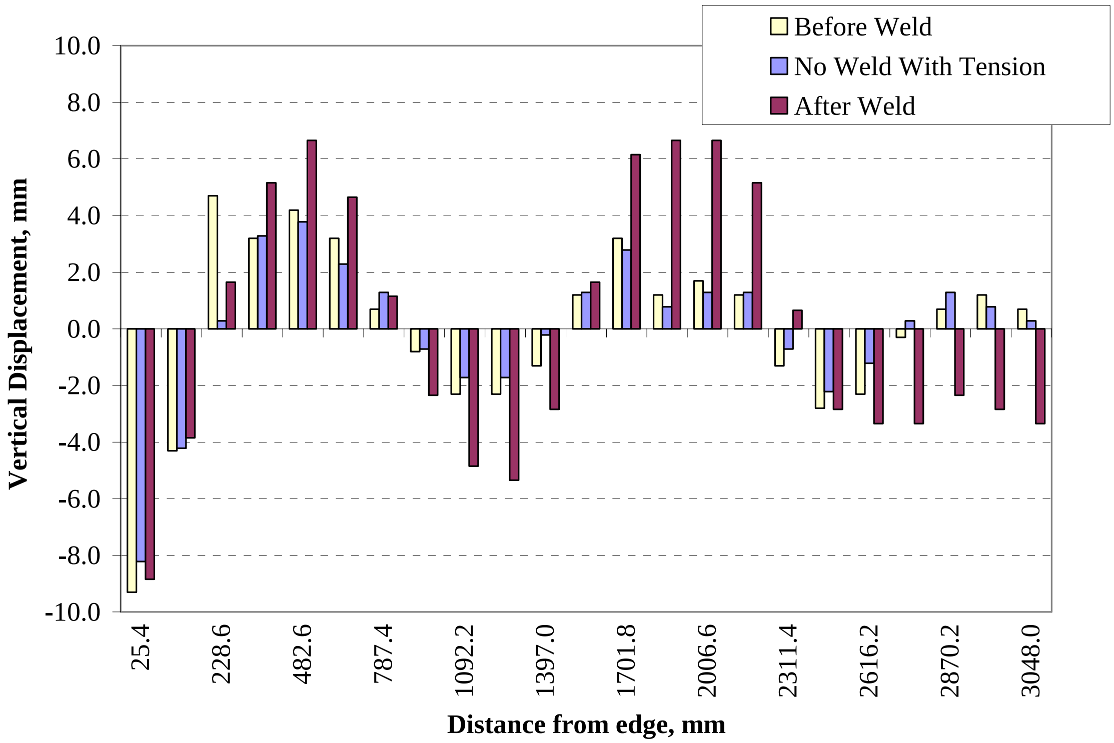


Figure K.35: Plate 9 Location B – Deviation From Average Relative Displacement

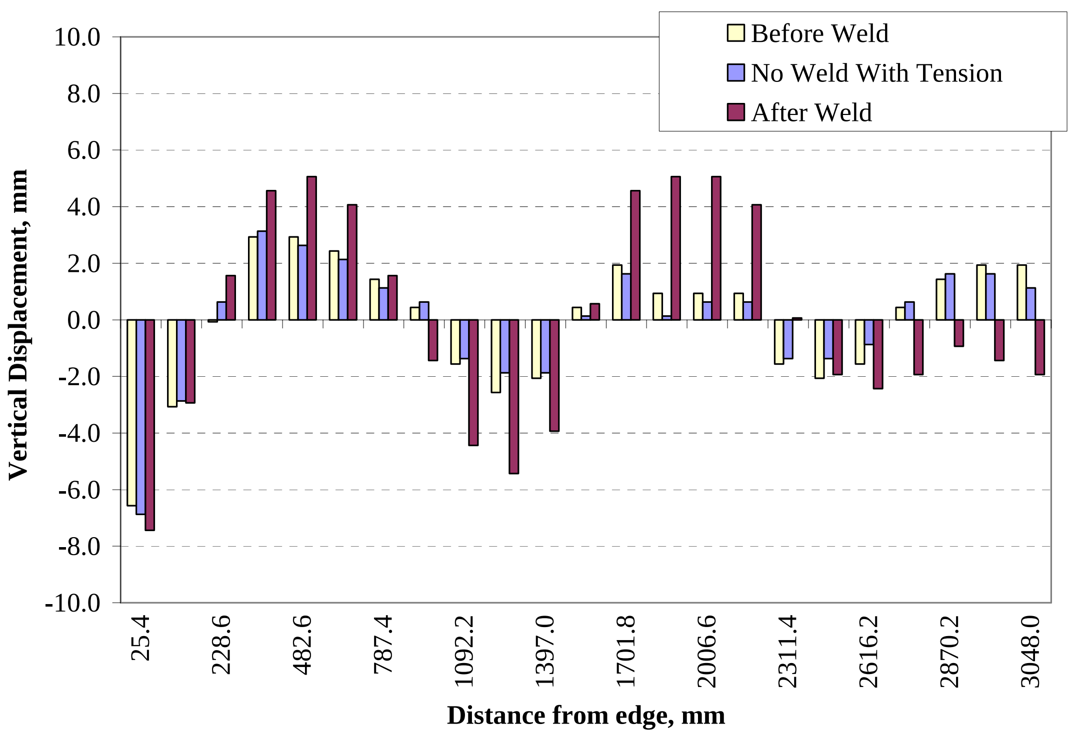


Figure K.36: Plate 9 Location C – Deviation From Average Relative Displacement

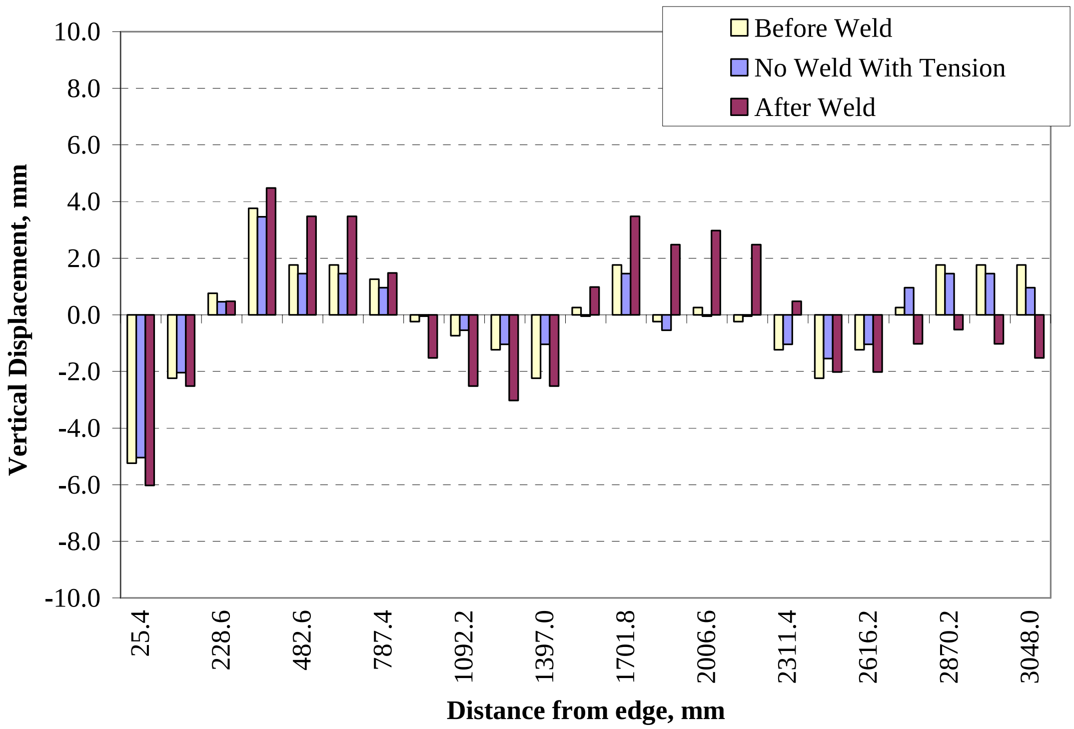


Figure K.37: Plate 9 Location D – Deviation From Average Relative Displacement

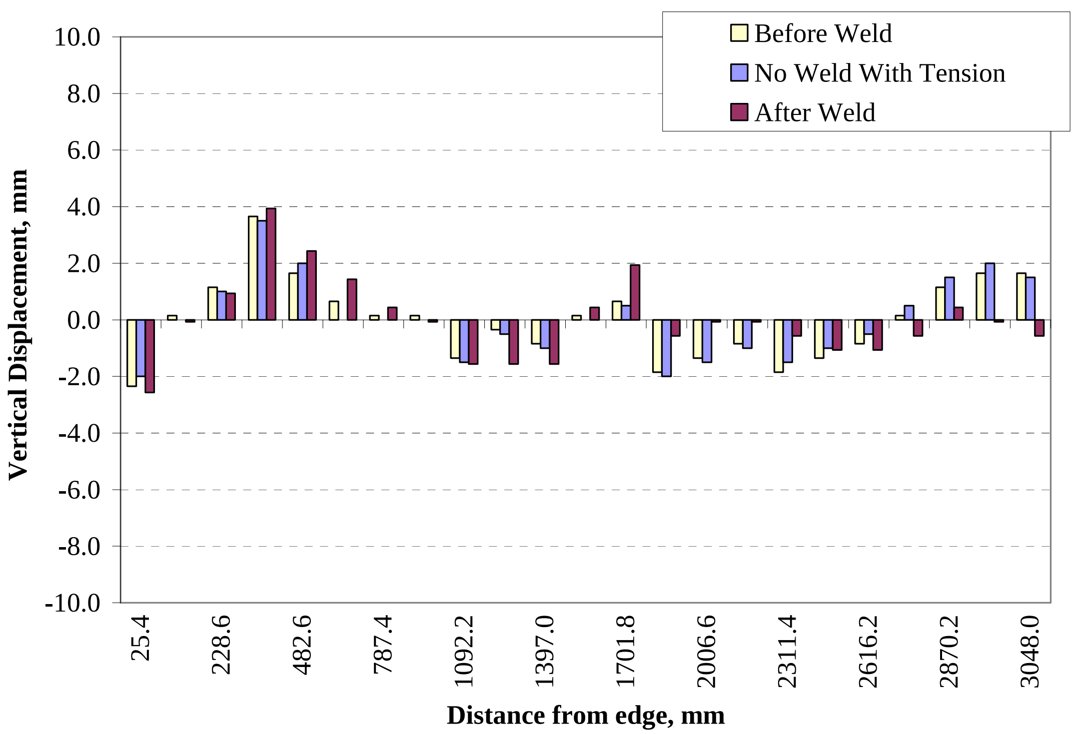


Figure K.38: Plate 9 Location E – Deviation From Average Relative Displacement

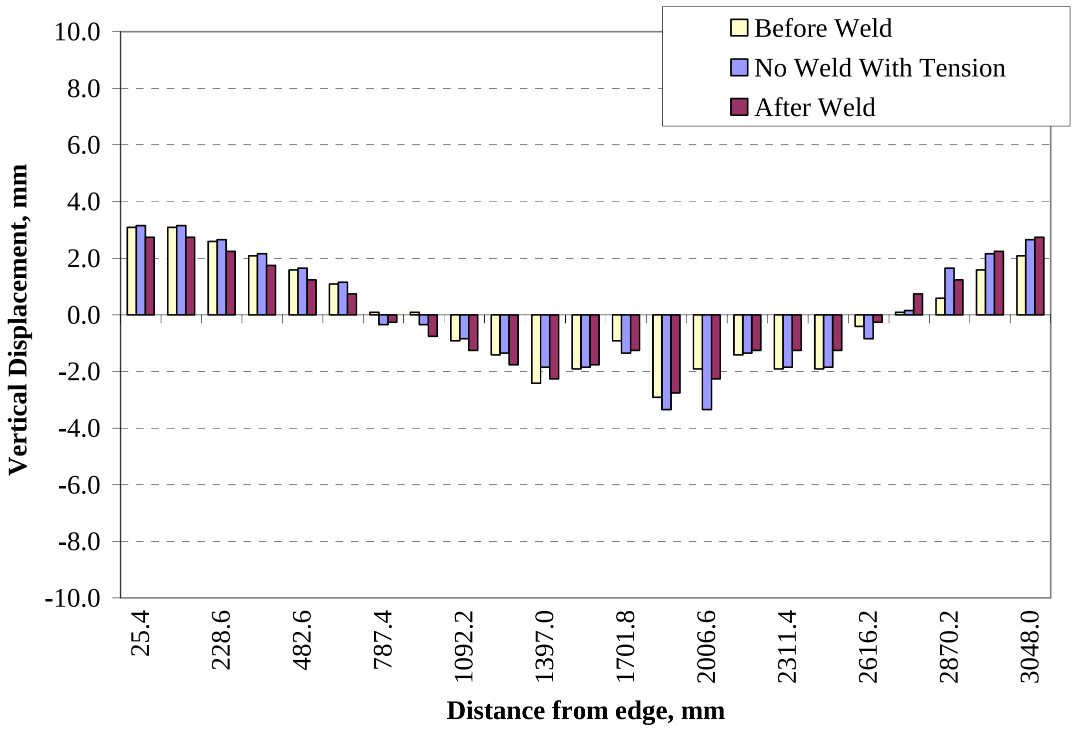


Figure K.39: Plate 9 At Stiffener – Deviation From Average Relative Displacement

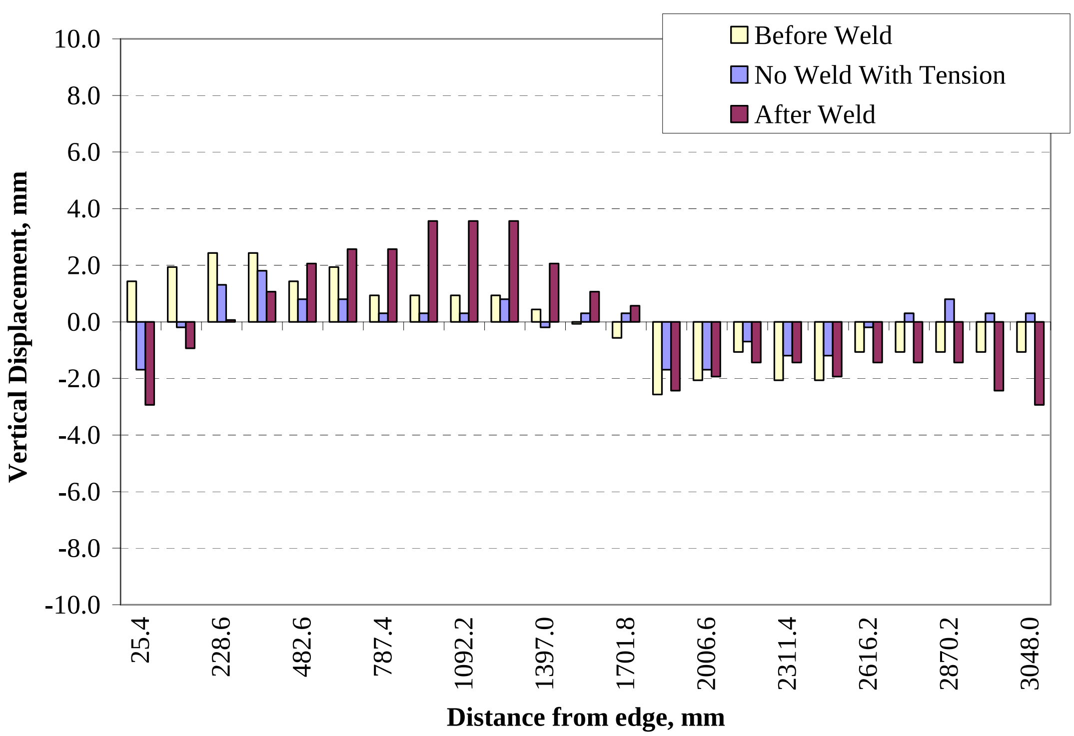


Figure K.40: Plate 9 Location G – Deviation From Average Relative Displacement

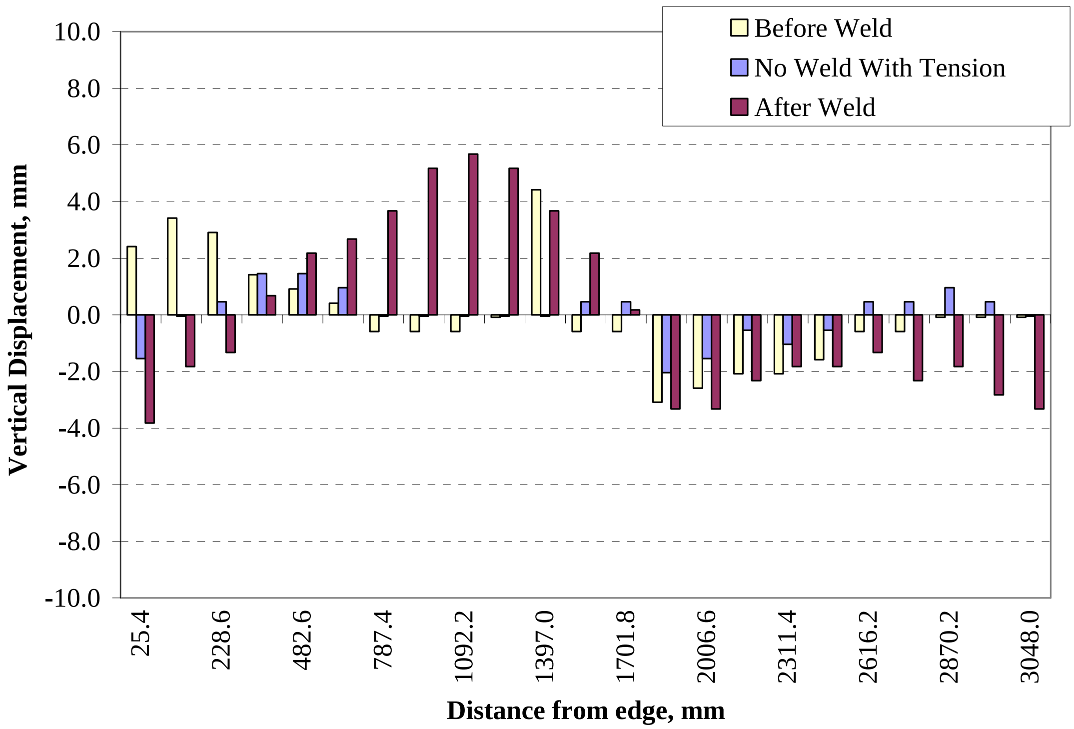


Figure K.41: Plate 9 Location H – Deviation From Average Relative Displacement

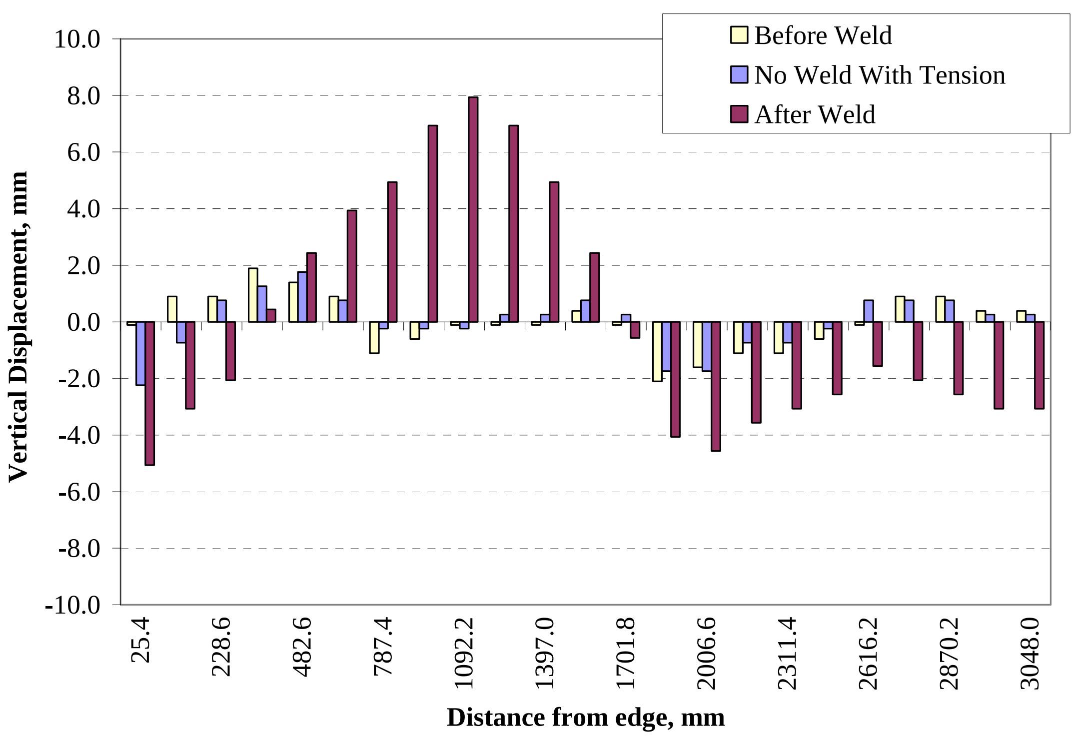


Figure K.42: Plate 9 Location I – Deviation From Average Relative Displacement

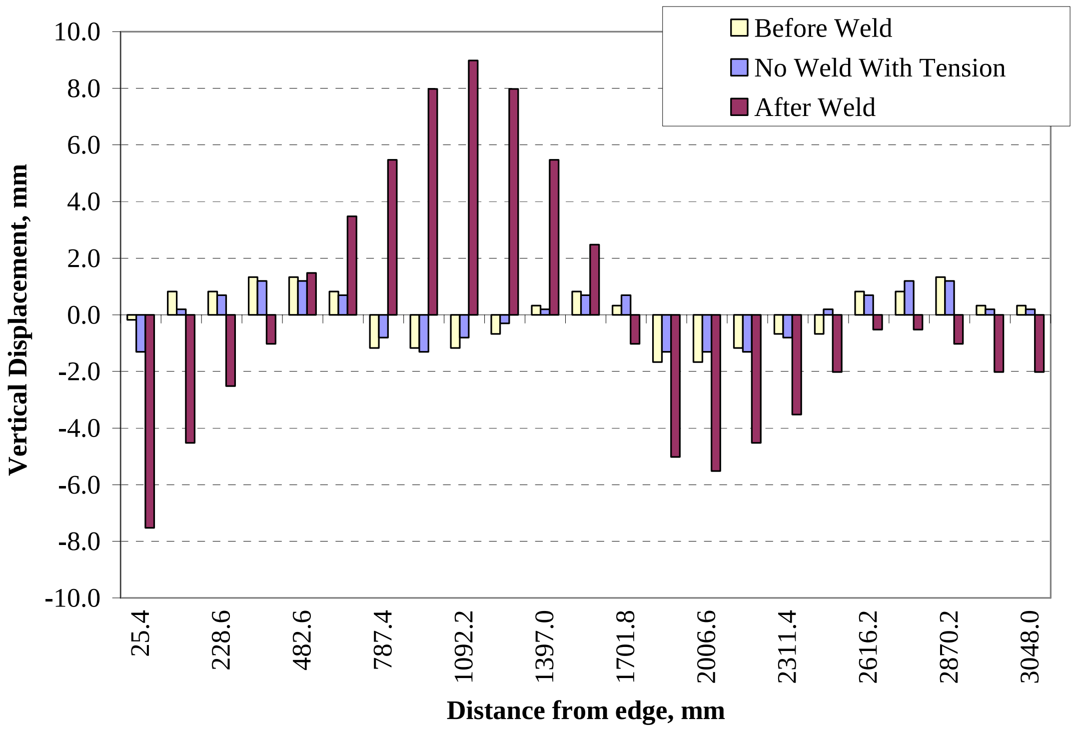


Figure K.43: Plate 9 Location J – Deviation From Average Relative Displacement

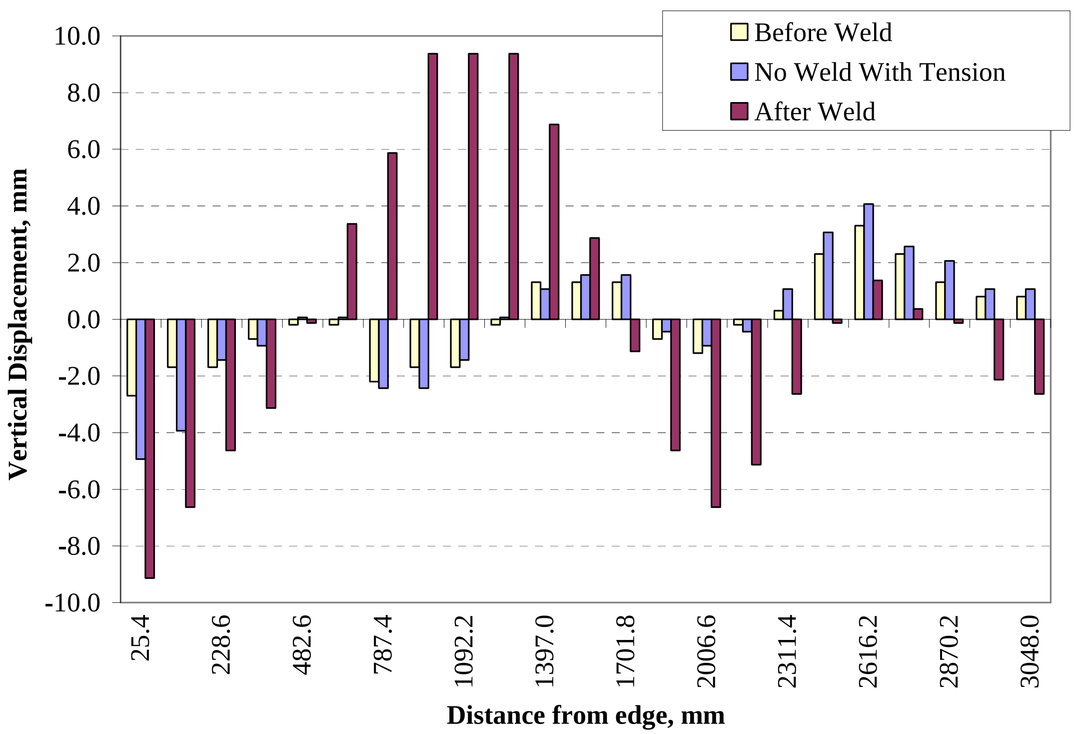


Figure K.44: Plate 9 Location K – Deviation From Average Relative Displacement

APPENDIX L

POROSITY ASSESSMENT FOR PLATE 3

Figure L.1: Plate 3 Start 1

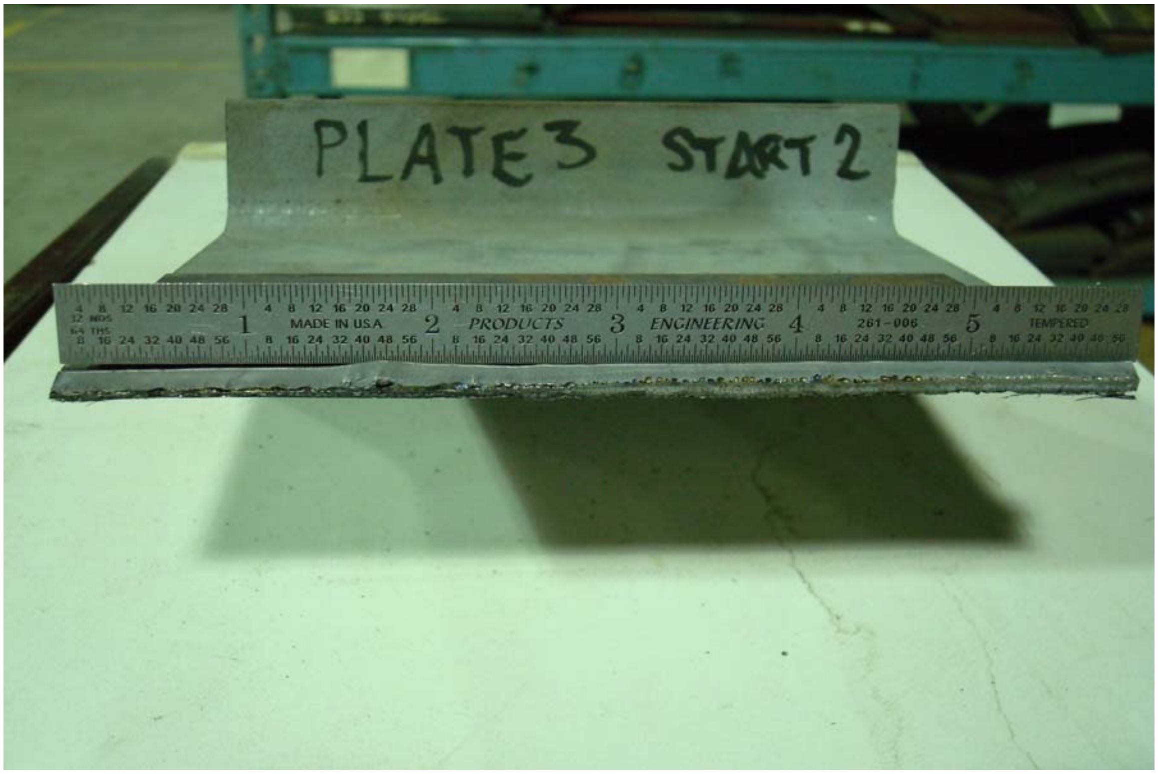


Figure L.2: Plate 3 Start 2

Figure l.3: Plate 3 Center 1

Figure L.4: Plate 3 Center 2

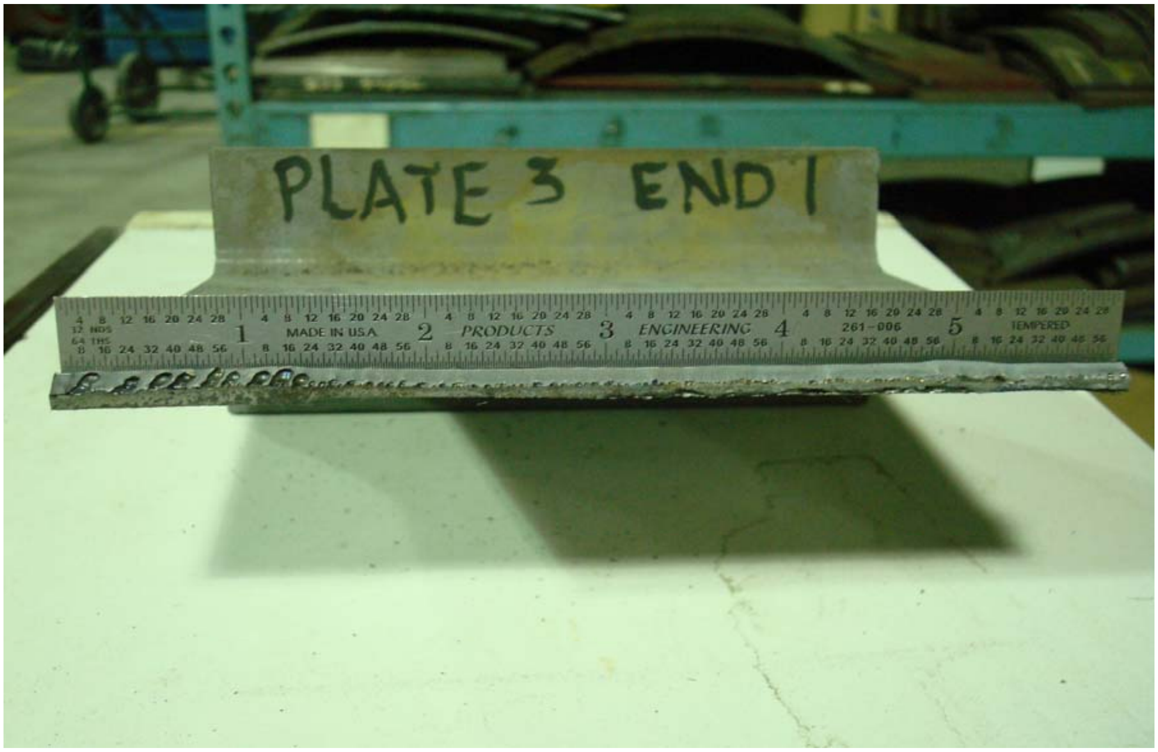


Figure L.5: Plate 3 End 1

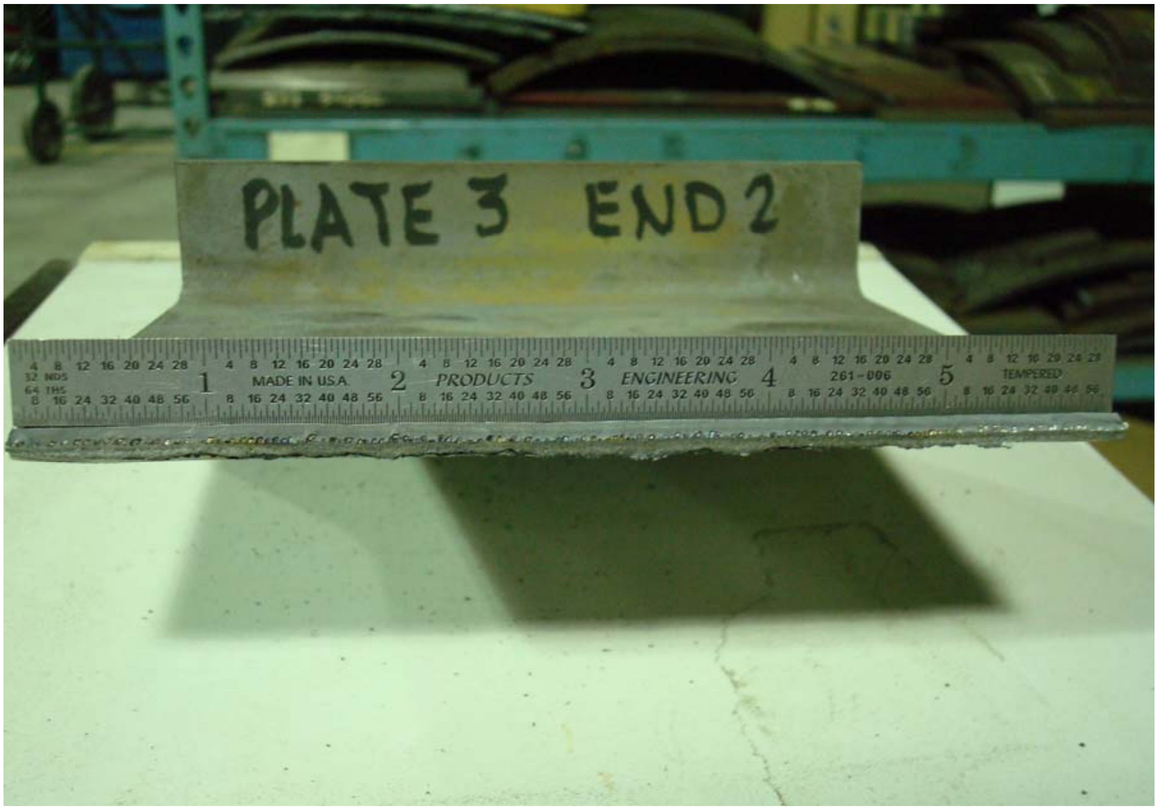


Figure L.6: Plate 3 End 2

APPENDIX M

POROSITY ASSESSMENT FOR PLATE 7

Figure M.1: Plate 7 Start 1

Figure M.2: Plate 7 Start 2

Figure M.3: Plate 7 Center 1

Figure M.4: Plate 7 Center 2

Figure M.5: Plate 7 End 1

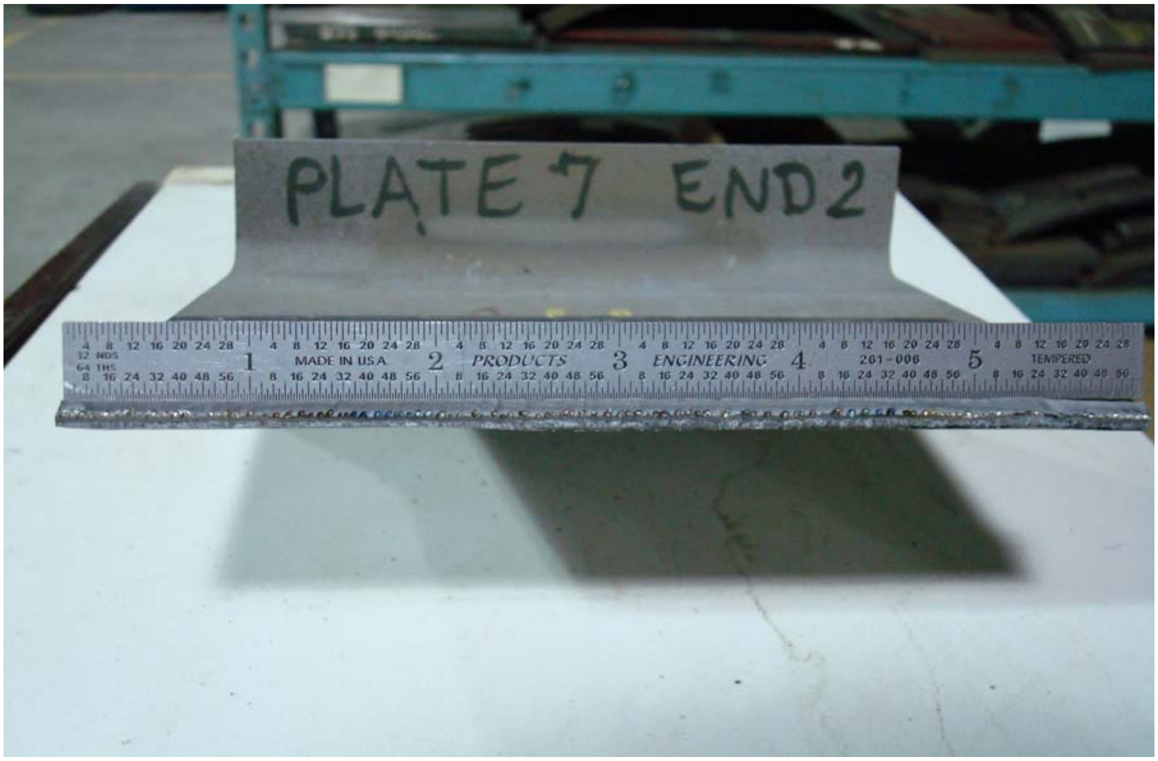


Figure M.6: Plate 7 End 2

APPENDIX N

POROSITY ASSESSMENT FOR PLATE 8

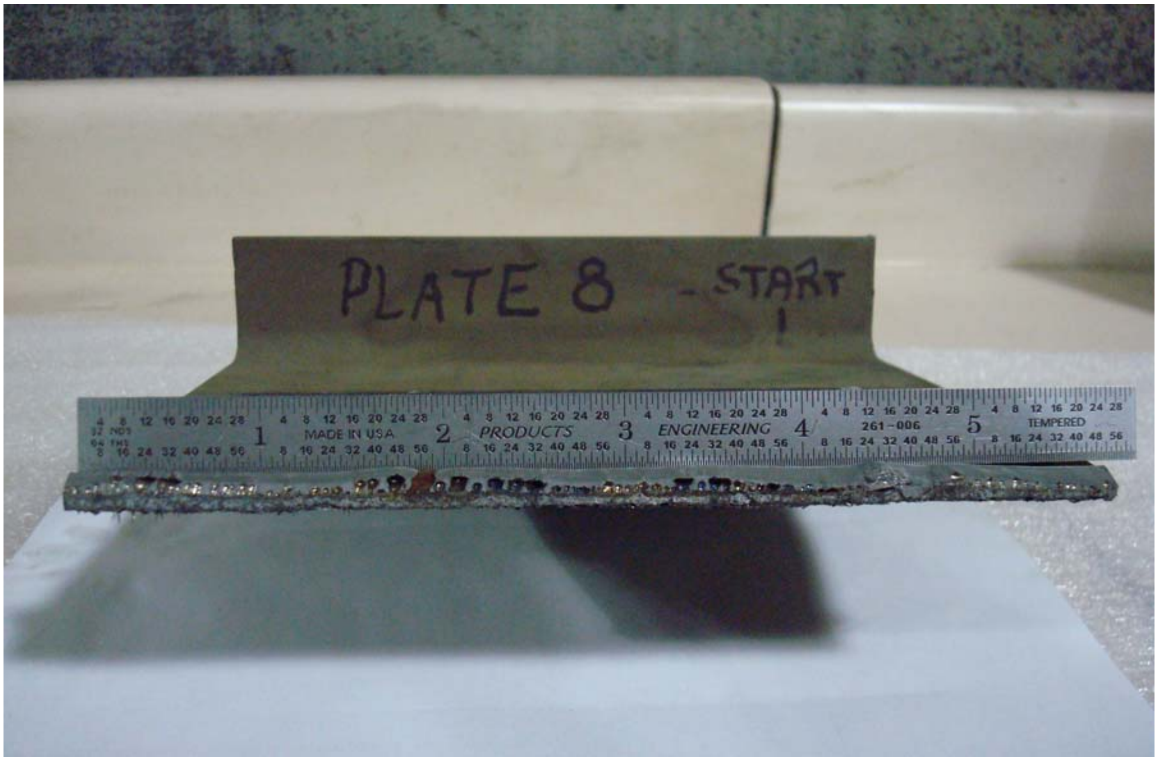


Figure N.1: Plate 8 Start 1

Figure N.2: Plate 8 Start 2

Figure N.3: Plate 8 Center 1

Figure N.4: Plate 8 Center 2

Figure N.5: Plate 8 End 1

Figure N.6: Plate 8 End 2

APPENDIX O

POROSITY ASSESSMENT FOR PLATE 9

Figure O.1: Plate 9 Start 1

Figure O.2: Plate 9 Start 2

Figure O.3: Plate 9 Center 1

Figure O.4: Plate 9 Center 2

Figure O.5: Plate 9 End 1

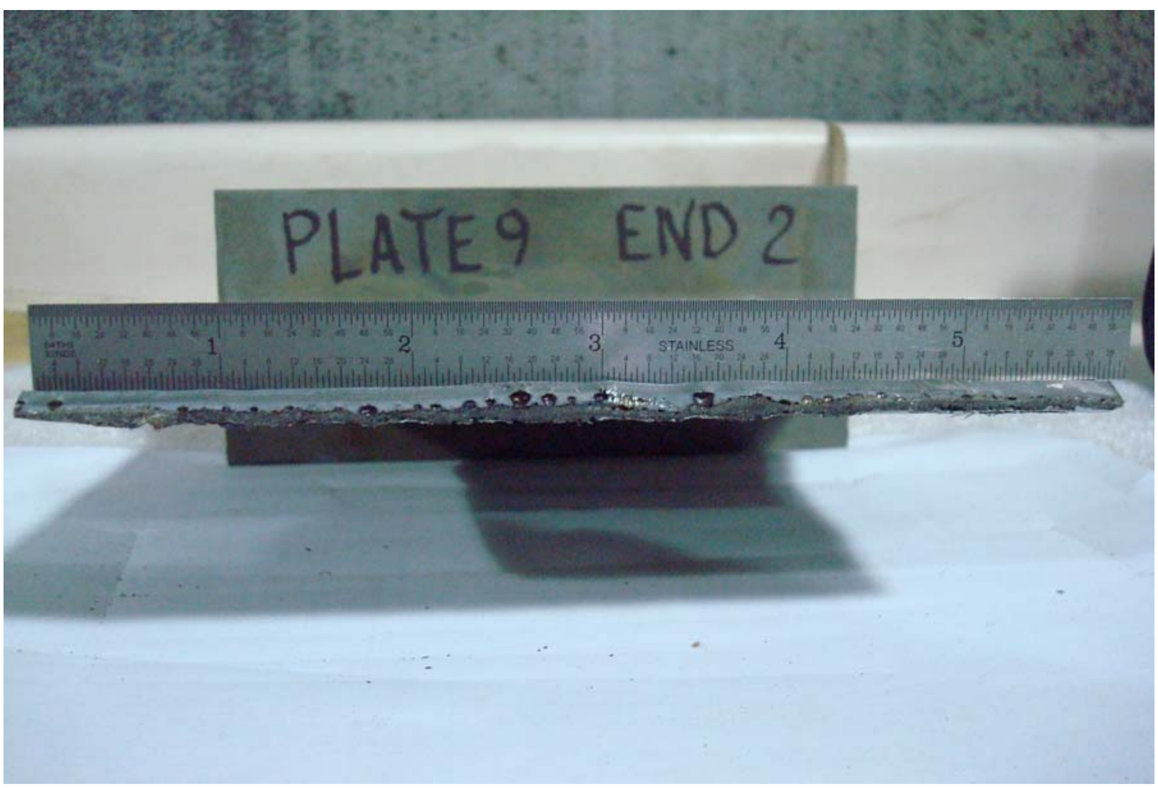


Figure O.6: Plate 9 End 2

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