Military Technical College
Kobry El-Kobbah,
Cairo, Egypt.

13th International Conference
on Applied Mechanics and
Mechanical Engineering.

COMPUTER SIMULATION TECHNIQUE TO REDUCE RESULTED RESIDUAL STRESSES AND DISTORTION IN HIGH STRENGTH THIN BUTT WELDED SHIP PANELS

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ABSTRACT

Welding of thin-plate ship structures often results in warping of finished fabricated panels. Some manufacturers use preheating and/or pre-stressing the plates during assembly or post heating after assembly as a mitigation method to reduce final product distortion with variably satisfactory results. The current paper aims to study the effect of tensile force application (on the plates undergoing welding) on the residual stresses and distortion behaviours of butt welded thin ship panels using the finite element method. The effects on the butt welded thin panel applying several components of different magnitudes of tensile forces before and during welding are shown. Those external forces are released after the welded joint has reached the room temperature. The stretching force leads to a reduction in the longitudinal residual stresses, consequently reduced the buckling deformation. All those diagnostics will demolish the welded plate distortion making it close to zero.

KEYWORDS

Thin plates, plastic zone, tensile loads, welding distortion and longitudinal residual stresses.

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NOMENCLATURE

	Latin letters
A	Cross section area (mm^2).
AWL	Applied Welding Load.
A_s	The Percentage of the applied external stress as a ratio from the yield strength of the parent material.
B_w	The percentage of the applied external stress zone as a ratio of the width of the plate.
b	Width of plate (mm).
CBL	Critical Buckling Load.
C_p	Volume specific heat capacity.
d_p	Thickness of plate (mm)
E	Elastic modulus (N/m^2) .
I	Current amperage at the arc
K_b	(Buckling coefficient) depends on the length-to-width ratio (a = b).
Q	Heat input per unit length.
U	Gross energy input per unit volume of plate .
V	Arc voltage (V).
V_s	Welding velocity mm/sec.
	Greek Symbols
ΔT_1	A unit temperature load = 0.56^0 C.
ΔT_{APP}	Temperature loading.
α	Thermal expansion coefficient.
η	Arc welding efficiency from 0.7 – 0.9.
δA	Change of area under curve (driving force (N)).
$\delta ep_n'$	Change in plastic zone at each case (mm).
λ	Minimum positive eigen value.
λ_i	Ith eigenvalue.
σ_{crit}	Critical buckling stress (Pa)
σ_r	Longitudinal Residual stresses of welded plate without any stretching force (Pa).
σ_y	Yield stress (Pa)
υ_s	Electrode speed.
υ	Poisson's ratio.
φ_i	i^{th} eigenvector.

INTRODUCTION

Light weight structures' applications in shipbuilding have increased dramatically over the past decade. Both military and commercial vessel owners have tightened the design requirements in strength, stiffness and fitness to meet more stringent performance specifications. So, ship designers have been forced to incorporate thinner, lighter weight steel structures to reduce topside weight, improving fuel economy and enhancing mission capability. By this modification, shipyards rose savings in weight of hull structures to over 90% per vessel, as shown in Fig.1 [1].

This trend has been adopted by shipyards lately where the production ratio of thin steel panels (≤10mm) to thick plate structures has been increased. It has been seen in

Europe, where destroyers/frigates are using significant proportions of 4 and 5mm thick plate to reduce top side weight and control centre of gravity. Commercial vessels are also using thin steel plates on upper superstructures and aluminium alloys [2]. Significant warping emerged as a commonly experienced problem in the welding fabrication of thin walled panel structures creating a major obstacle to the cost effective utilization of these structures.

Factors influencing distortion magnitude are both design-related and process-related variables. Significant design-related variables include weld joint details, plate thickness, and the transition zone if the joint consists of plates of different thickness, stiffener spacing, and number of attachments, corrugated construction, mechanical restraint conditions, assembly sequence and overall construction planning. Welding process variables include heat input, travel speed and welding sequence [3].

RESULTANT DISTORTION AND RESIDUAL STRESSES

Welding stresses and deformations are closely related phenomena [4]. During heating and cooling, thermal strains due to plastic deformation of the metal occur in the welding and adjacent constrained areas. Non-uniform heating of material during the welding process produces residual stresses and plastic strains due to differential thermal expansion of the weld and surrounding material. The lower temperature material away from the weld restrains the weld from expanding and produces plastic deformation. Upon cooling, the region attempts to contract against the same restraints of the surrounding material. This restraint produces residual stresses in the weld region. The residual stress and plastic strain interact to produce distortion in the panel [5]. The mismatch of the transient thermal strains during the passage of the heat source adds to the insult.

The dominant outcome in thin plate structures is typically an angular deformation across the line of weld, as in Fig. 2 [6]. In addition, a longitudinal contraction force gives rise to bending and may indeed cause buckling. So, the deviated shape of the work pieces from the ideal perfectly flat or regular forms is caused by the combined effect of angular deformation and contracting forces.

As welds are non-linear, the accumulated resultant distortions add to the final residual deformation. Residual deformations introduce severe problems in assembling the welded structure and reduce its quality. Distorted shape and dimensions of the work piece limits its usefulness. Its repair imposes extra costs for additional man-hours needed for difficult unit fit-ups, flame straightening and rework.

MEANS OF MITIGATION OF WELDING DISTORTION

Several mechanical/thermal or thermal only means of mitigating welding distortions during the fabrication process have been utilized leading to reduced distortion and warping of thin plate panels [7]. These include temperature gradients achieved by applying a controlled temperature field in two strips parallel to the longitudinal welds devised by Holzbaur, by using the heat-sink welding process devised by (Barber et al), use of induction heating (Groom et al), use of trailing heat sink (Guan et al), use of thermal tensioning introduced by Michaleris, mechanically compressing the weld during cooling and in process thermal stretching introduced by Dong et al. [1].

The complexity of ship structures makes the development of such techniques in assembly rather difficult and dependent on individual welding configurations and materials. A better approach to find a strategy to control distortion would be to predict the amount of distortion associated with the different welding techniques available through a simulation programme and then select the best welding configuration and pre-processing techniques to achieve a final acceptable panel shape. Significant advances have been made in this field, and many comprehensive methods like SYSWELD, VFT, and SimManTec have been developed that can simulate the entire physical process of welding which includes metal deposition, melting/remelting, and microstructure evolution [8]. Better determination of welding characteristics could share in sorting out distortion and residual welding stresses.

METHODS

The present study aims at introducing a new mechanical only technique for reducing the final distortion of thin welded metal plates. This technique depends on applying a tensile force on the welded plates during the welding process and all through the cooling stage till the plates reach the ambient temperature, when the pressure will be released gradually. A simulation software (SimManTec) introduced by Goldak [8] was utilized for application of the technique and predictions of longitudinal residual stresses levels produced at different magnitudes of tensile forces applied.

For conducting this study, two virtual rectangular plates of AH36 material were selected. Dimensions utilized were 600 mm x 250 mm x 4mm. All edges were simply supported. Butt welding (using GMAW (Co_2)) was done along the 600 mm edge to produce a weld joint longer than the critical 450 mm needed to produce maximum longitudinal residual tensile stresses in the centre with uniform distribution. [5]. Welding plates were divided into elements by SimManTec finite element software where the No of elements was 8592 and that of nodes was 10115 . After finishing the welding, the plate was left to cool down to ambient temperature.

The simulator program then measured the longitudinal residual stresses on the plate at the mid point of the weld line which gives its maximum level as is shown in fig.3.[5]. The results were analyzed and recorded as the base line for future comparisons. They were also compared to longitudinal residual stresses curves available in the literature for similar conditions in order to validate the programme measurements and predictions [5].

Experimental work was done using the same materials, dimensions, welding technique and welding conditions as in the simulation and the resultant deformations were measured and recorded.

The same welding procedure was then repeated on the simulation programme after the application of external tensile force to the two opposite edges of the welded plates perpendicular to the welding line on either side of it as shown in Fig.4.

Sixteen cases were run on the programme and studied. Four different magnitudes of stretching tensile forces were applied to four different central widths of the plates to be welded and the resultant longitudinal residual stresses were calculated for each case. The magnitudes utilized were percentage from σ_y (0.25, 0.5, 0.75 and 1) multiplied to the projected area. These were applied to the central one fourth, half, three quarters as well as to the whole width of the plate sequentially.

Calculation of the applied tensile force was done according to Eqn. (1). Comparison between residual longitudinal stresses resulting from each case was done in order to select the most optimum applicable conditions of tensile force on specific projected area giving a satisfactory relief of residual stresses and reduction of deformation .

BUCKLING ANALYSIS

The deformation in butt-welded structures utilized in this study was assumed to be mainly due to initiation of buckling. The primary force leading to buckling deformation is the longitudinal contraction force. On the other hand, the transverse contraction mechanisms, arising from the weld pool shape, are assumed to be constant for the different welding head configurations as was found by Michaleris and DeBicarri, Hinrinchsen , Conrardy and Dull [9], They concluded that the angular distortion when compared to the buckling distortion was small enough to be neglected and so they did not consider the transverse shrinkage effect. Hence, in the current study, buckling analyses Eigenvalue solutions corresponding to the longitudinal contraction forces were utilized. The classical analytical buckling formula for rectangular plates under equal uniform compression on two opposite edges (Eqn. (2)), is an appropriate benchmark to identify the critical buckling load, where K_b (buckling coefficient) depends on the length-to-width ratio (a=b) [9]. Further information on a linearly distributed compression on two opposite edges of large length to width ratios, could be found in Ref. [9].

The ambiguity in the contraction force distribution and boundary conditions assumed in the analytical buckling, Eqn. (1), may be clarified by a finite element buckling analysis, carried out in two stages. First, a small deformation, zero gravity, initially flat shape, with a thermal load corresponding to the sequentially welded case was being used to evaluate a stiffness matrix [K] and a stress stiffness matrix [S]. Secondly, ANSYS, Block Lancoz [9], Eigenvector extraction method is being applied, following Equation (3), to identify the critical buckling loads and buckling modes associated with the weldment. This has been done in similar way to that carried out in Ref. [9]. Appendix A. gives the mathematical analysis of the problem in detail. The following is a discussion of the running cases for different external applied loads and different acting zone widths.

RESULTS

Comparing the basic longitudinal residual stresses curve resulting from welding without tensile forces application produced in the current work (fig. 5) with that found in the literature [5], showed no significant differences**.** So the use of the SimManTec software was substantiated. Again the maximum longitudinal stress at the point of measurement was 350 MP which was comparable to literature.

On experimental work using the same conditions, maximum measured buckling deformation was 15mm (corresponds to calculated longitudinal residual stress of 350 MP) as shown in fig.6. After applying the tensile stretching forces, different measurements of longitudinal residual stresses were obtained. Shown are some of the important cases' results in Fig. 7 up to Fig. 10., to indicate the change of longitudinal residual stresses associated with the change of tensile forces applied and width of applications. Summary of the values of applied external forces and the predicted resultant residual longitudinal stresses are shown in Table 1.

CASE (1)

The tensile external applied force is 0.25 σ_y acting at the central half of the plate edge as shown in Fig. 7. Comparing between Figs. 5 and 7 shows a definite reduction in the values of longitudinal tensile residual stresses from 350 to 280 MPa.

CASE (2)

Applied external tensile force of 0.25 σ_y on central 0.25 of the edge, Fig. 8, gives the same trend as in Case 1. The resultant residual stresses were reduced from the basic 350 MPa in Fig. 5b to 240 MPa shown in Fig . 8b.

CASE (3)

The tensile external applied stress of 0.75 σ_y, acting at 0.5 side, Fig. 9, showed the same trend as in Cases 1 and 2.

CASE (4)

The tensile external applied force of 0.75 σy, acting at 0.25 side, Fig. 10, gives the same trend but with more effective reduction of magnitudes of longitudinal residual stresses (190MPa), Table 1.

Figure 11, summarizes all predicted results for the sixteen studied cases. Table 1 lists the various associated values.

DISCUSSION AND APPLICATION

It is to be noted from the table that the least residual stresses ranging from 125-175 MPa were produced either by applying high tensile forces (1.0 σ_y) to small projected areas (0.25 of the width) or from applying small tensile forces (0.25 σ_y) to large projected areas (whole width of the plate). Both cases will require a total stretching force of high magnitude that will require the availability of very large costly and space occupying hydraulic machines in order to be able to provide it, especially when applied to plates of large dimensions (e.g. 6-10 m length and 2 to 2.5 m breadth) as those utilized in shipyards.

Therefore, economical and engineering aspects necessitate applying such stretching forces on small parts of the plate's width. The applicable optimum applied tensile stress value was found to be 0.75 σ_y acting on the central 0.25 of the plate width of the weldment. This will produce relief of residual stresses from 350 to 190 MPa , i.e. (54.2

% reduction) consequently the welded plate distortion would be reduced , as indicated in curve (1) of Fig. 11. The total force required for applying such parameters (0.75 x σ_y x t (0.25 x b)) Newton could be easily achieved in shipyards with reasonable costs. It is to be noted that the HAZ (Heat Affected Zone) which is the area of the plate closest to the welding line in which the maximum strains are present, is the most important target area for applying the stretching forces and it is completely included within the central 0.25 of the welded plate breadth.

CONCLUSIONS

From the presented analysis and the investigated cases, the following are the main concluding remarks:

1. Basic welding conditions in thin metal plates results in significant longitudinal residual stresses and buckling deformations.
2. Applying stretching tensile force during the welding and cooling down stages was able to significantly reduce these longitudinal residual stresses and consequently the deformations.
3. The stretching forces direction is opposite to the longitudinal shrinkage direction, eliminating and reducing the resulting deformation.
4. The most cost effective parameters for tensile forces application was to apply 0.75 σ_y on the central 0.25 of the width of the plate on either sides of the welding line.
5. The proposed procedure has special merits and advantages over the line heating method currently applied in most of the world shipyards. This method is very cheap and time saving.

ACKNOWLEDGEMENT

The authors acknowledge the assistance and the generous support given by Prof. Dr. J. Goldak , University of Carlton, Canada. Thanks are due to Prof. Goldak for allowing the use of PC- SimManTec software which was run and used in the study of the 16 presented cases.

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EQUATIONS

Tensile force on each plate (F_t) = A_S *σ_y * B_W (b * t) (1)

$$\sigma_{crit} = K_b \frac{E}{1-\nu^2}\left(\frac{d_p}{b}\right)^2 \quad (2)$$

where K_b of 3.5 has been assumed.

$$[K]\{\phi_i\} = \lambda_i[S]\{\phi_i\} \quad (3)$$

FIGURES AND TABLE

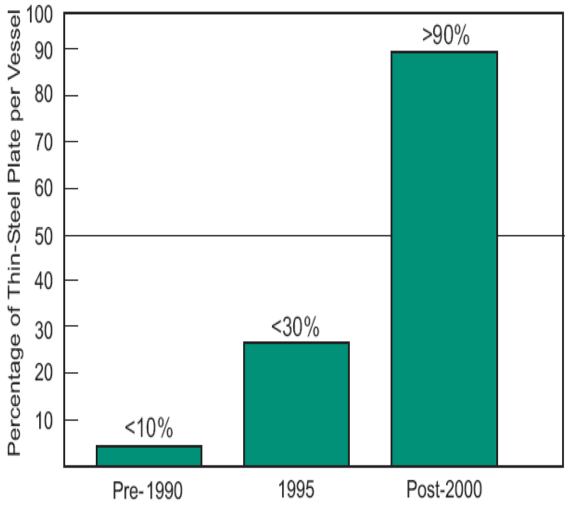


Fig.1. Increasing percentage of thin-steel plate ordered per vessel at Northrop Grumman Ship System Avondale Shipyards. [1]

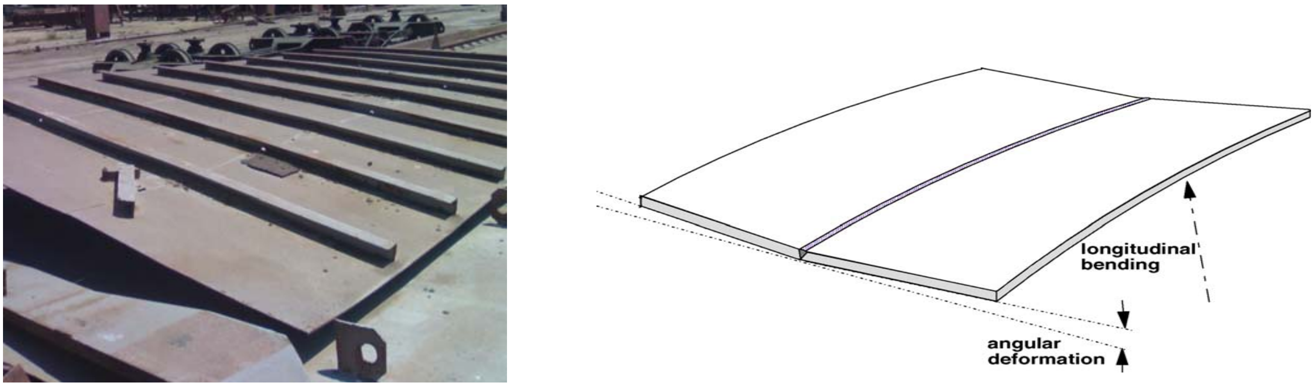
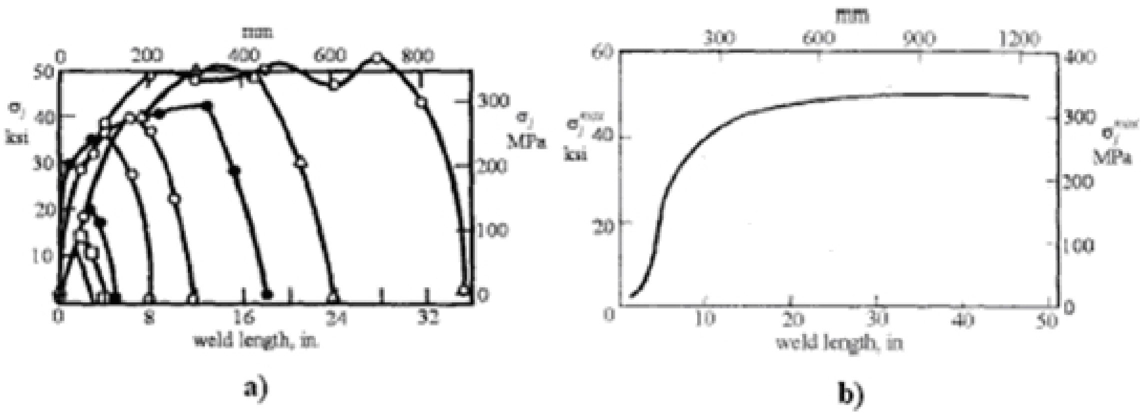


Fig. 2. The resulted warping distortion and deformations in a weldment.



Effect of length of weld on: (a) – longitudinal residual stress distribution; (b) – maximum longitudinal stress distribution.[50]

Fig. 3 : Maximum longitudinal stress distribution [5].

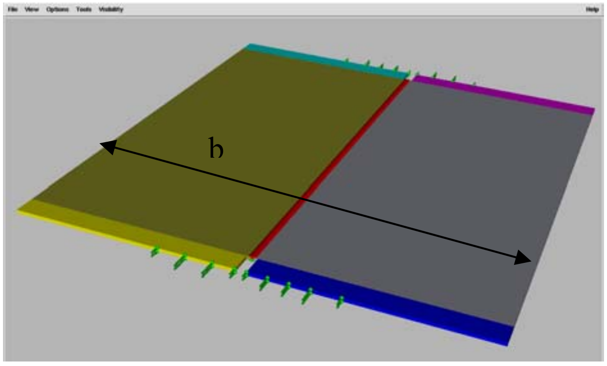


Fig. 4: Tensile forces (F_t) acting on 1/4 width panel

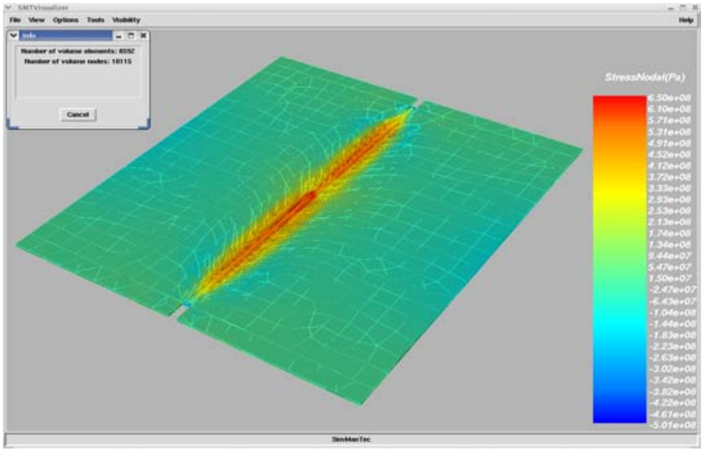


Fig. 5(a). Graph of longitudinal residual stress distribution on welded plate

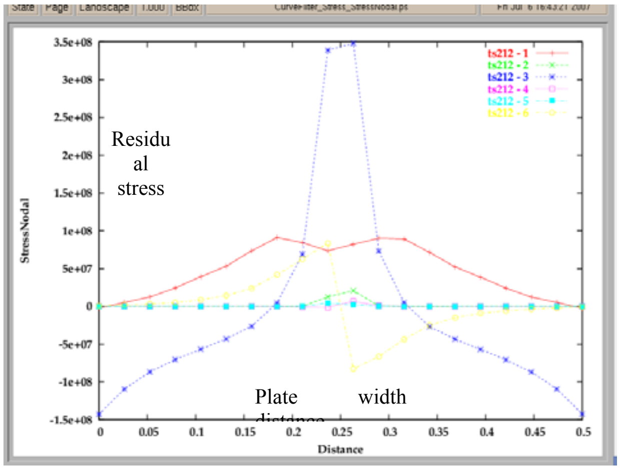


Fig. 5(b). Longitudinal residual stress distribution as measured at the central line of plate crossing the weld line

Fig. 6 : plate buckling deformation after welding and cooling (AH36) (experimental work)

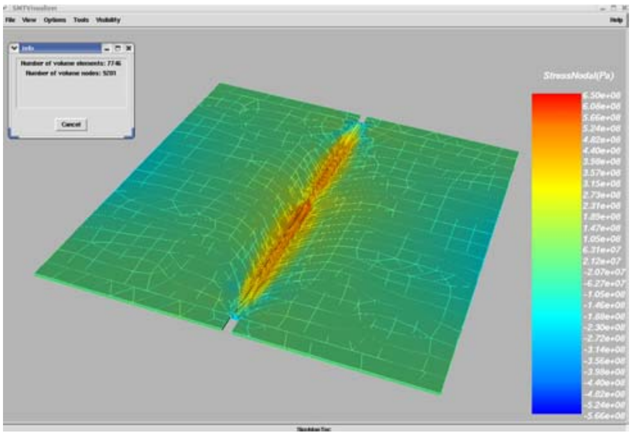


Fig. 7(a). Graph of longitudinal residual stress distribution on welded plate after releasing the tensile force

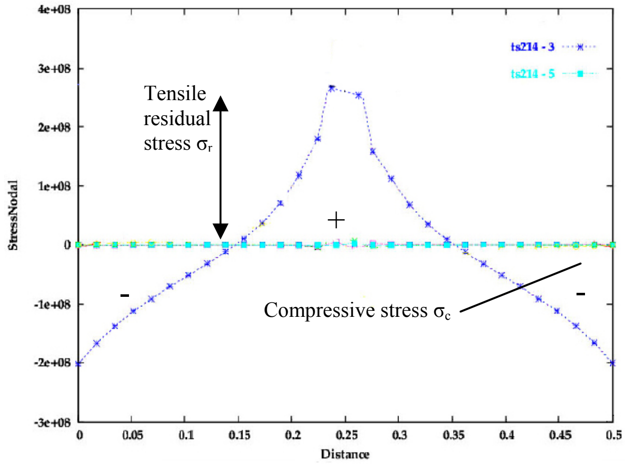


Fig. 7(b). Longitudinal residual stresses distribution across the width (b) of the two welded plates

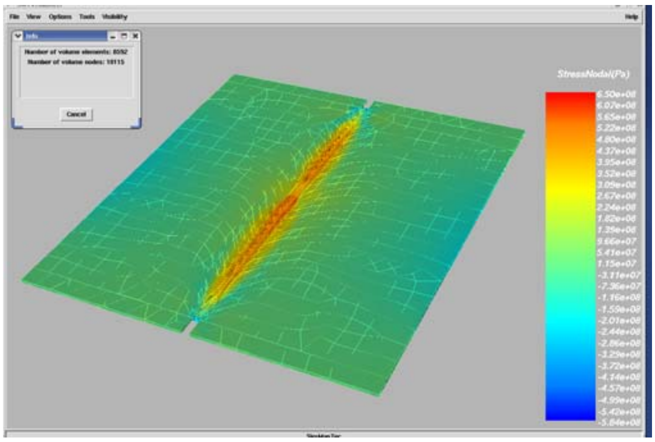


Fig. 8(a). Graph of longitudinal residual stresses distribution

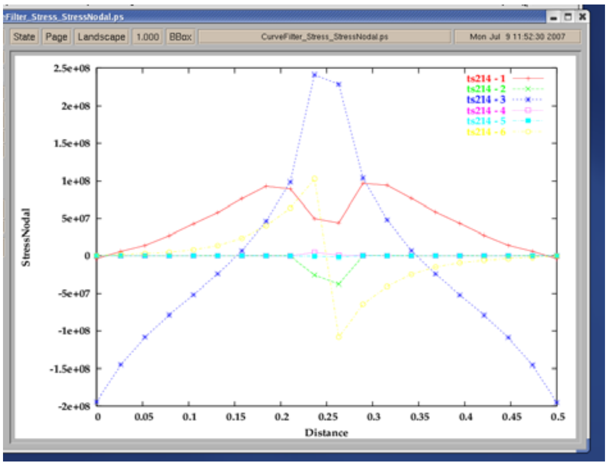


Fig.8 (b). Longitudinal residual stresses distribution on welded plate across the width (b) of the two-welded plate

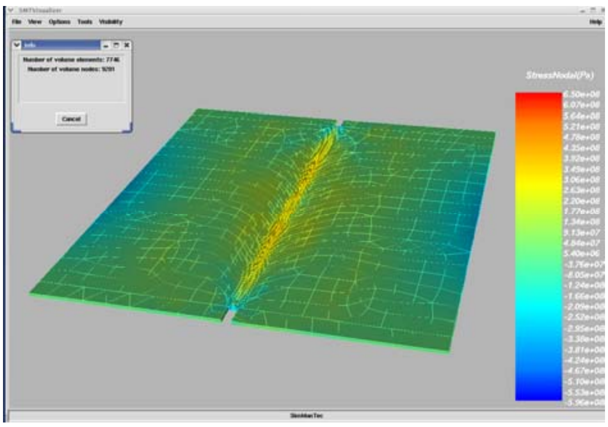


Fig. 9(a).Graph of longitudinal residual stress distribution on welded plate

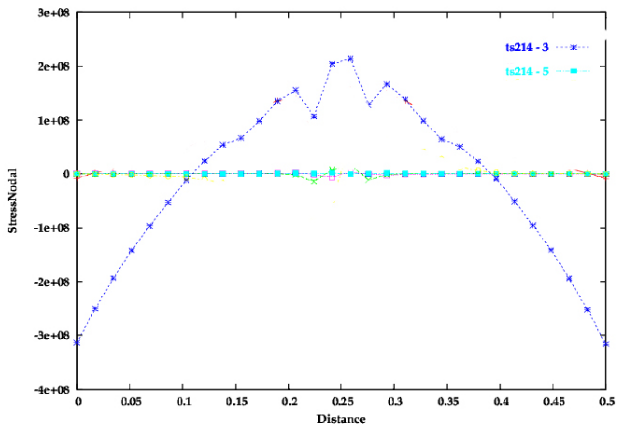


Fig. 9(b). Longitudinal residual stresses distribution across the width (b)of two welded plate

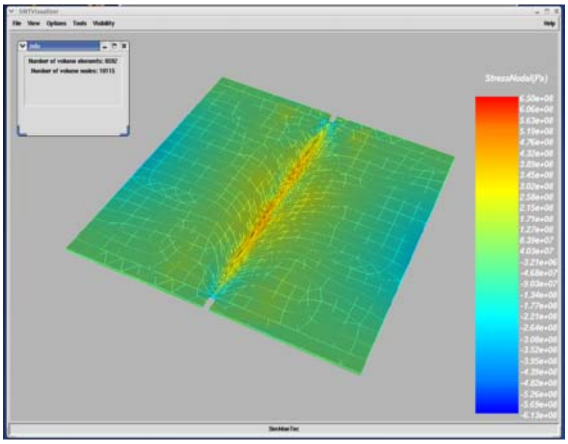


Fig. 10 a. Graph of longitudinal residual stress distribution on welded

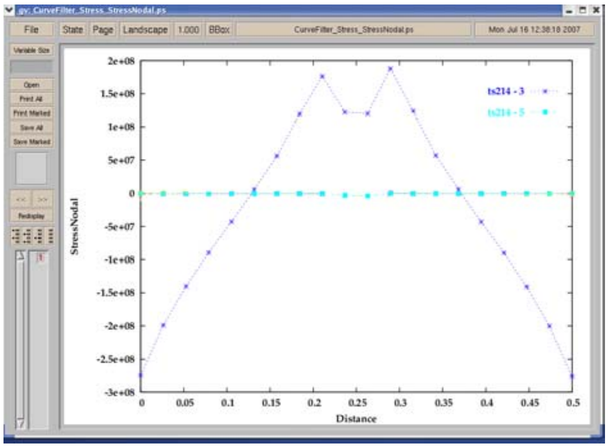


Fig. 10b. Longitudinal residual stresses distribution across the width (b) of two-welded plate

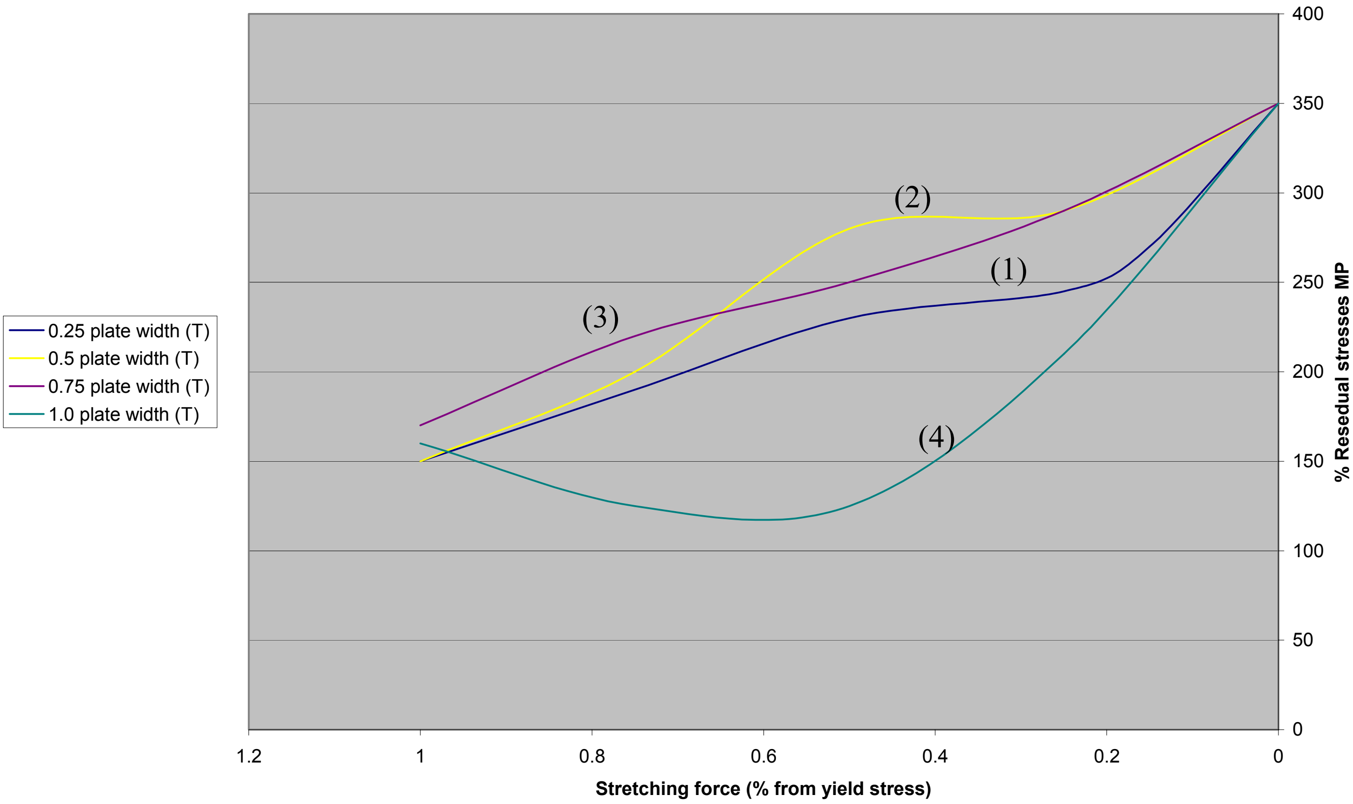


Fig.11. Summarizes all predicted results .

Table 1.

Stretching Force % (σ_y)	0.25 width	0.5 width	0.75 width	100% of the width
Plate thickness, 4mm	σ_r	σ_r	σ_r	σ_r
Zero	350	350	350	350
0.25 σy	245	280	250	125
0.5 σy	230	200	220	125
0.75 σy	190	150	170	160
1.0 σy	150	350	350	350

APPENDIX A : INDICATES THE DERIVATION OF THE BUCKLING DISTORTION RESULTED FROM THIN PLATES WELDED PANELS.

The types of deformation for butt welding are Longitudinal shrinkage and transverse shrinkage shown in Fig. A-1. A compressive residual stress in a thin plate caused by the longitudinal shrinkage of the seams may also produce an unstable transverse deformation .The welding induced distortion can be estimated from simple analytical or empirical formula for many types of common welds and fabrication processes [10].

Theory of longitudinal shrinkage

Analysis of longitudinal shrinkage is based on some assumptions that are:

a- Material is elastic /perfect plastic.
b- Yield stress is constant up to T = 200 ^{0}C and then falls linearly to zero at T = 1200^{0}C.
c- Diffusivity , conductivity and Young's modulus stay constant .

we propose the following simple formula for practical calculations of residual stress σ_r

$$\sigma_r = 0.2\eta U \quad \text{(A-1)}$$

$$U = Q/(V_s\ b\ t) \quad \text{(A-2)}$$

The tendon force F , which when resisted by the total plate area , b t, gives the correct σ_r is therefore given by

$$F = 0.2\ \eta\ Q/V_s \quad \text{(A-3)}$$

When this tendon force is increased, the longitudinal shrinkage is increased too. According to Okerblom (1958), the longitudinal shrinkage ΔL of plates , bars or girders of length L and total cross-sectional area a with centric longitudinal weld follows the equation [10]

$$\frac{\Delta L}{L} = \ln 2\sqrt{\frac{2}{e\pi}}\frac{q_w}{A}\frac{\alpha}{c_p} = 0.335\frac{\alpha}{c_p}\frac{q_w}{A} \quad \text{(A-4)}$$

The longitudinal shrinkage depends on the cross-sectional area A and on the heat input per unit length weld q_w defined by

$$q_w = \eta\frac{VI}{\upsilon_s} \quad \text{(A-5)}$$

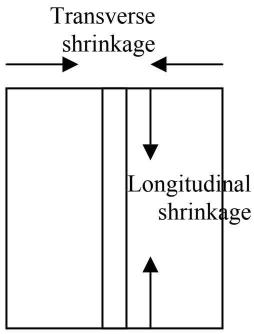


Fig. A-1. Type of welding deformation

When thin plates are welded , residual compressive stresses occur in areas away form the weld and cause buckling . Buckling distortion occurs when the Applied welding load AWL exceeds the critical buckling load CBL [11]

$$AWL = EA\alpha\Delta T_{APP} \quad \text{(A-6)}$$

$$CBL = \lambda EA\alpha\Delta T_1 \quad \text{(A-7)}$$