Investigation of the 3-D Response of Thick Plates under the Multipass Welding Using Anand's Viscoplastic Model

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Abstract- A 3-D finite element model is presented to study the thermo-mechanical response of thick plate weldments under different multi-pass welding sequences. The Anand's Viscoplastic Model is applied to simulate the mechanical response of weldments. The thermal modelling of welding zone is also carried by applying the isothermal melting pool approach. In this research the temperature dependency of thermal and mechanical properties of material is considered and the welding parameters such as arc movement, welding speed and welding lag between each sequence are simulated. Finally, in the FE model the addition of filler material into the welded zone is modeled using the Element Rebirth Technique (ERT). The accumulated results show that, on specific point as the number of layers of weld increases, a noticeable change occurs in the magnitude of maximum temperature and its time of reach. For the points near to the weld line, this change affects the amount of distortion, and the through thickness stress components but it has no significant effect on the residual stress components which may arise in the plane of plates.

Keywords: welding Sequence, multipass welding, thick plates, viscoplastic.

1. Introduction

Temperature and its distribution strongly affects distortions and residual stresses in weldments. The determination of thermal history of weldments is the first step to analyze distortions and residual stresses. On the other hand, the welding sequence is a parameter, which has a major effect on thermal history of weldments.

Investigators have used different mechanical models to simulate the thermo-mechanical behavior of weldments [1-9]. Because of time dependency of applied loads (thermal) in welding, different viscoplastic (rate dependent plastic) models have been developed and used in the recent researches on welding. In 1982, Argyris et al. [6] used a typical viscoplastic model for their study on welding. Anand et al. (1989) [7] however presented an experimental relation to predict the viscoplastic behavior of hot working metals. Ronda et al. in 1998 [9], compared the applicability of various viscoplastic models for welding and stated that the results are sensitive to the selection of material parameters for a chosen viscoplastic model.

Hong et al. [10] also presented a 2D model to simulate the effect of multi-pass welding in thick plates in 1998. They used a symmetric-ramp model for the inserted arc power as well as a plastic model for the mechanical behavior of weldments.

In joining thick plates with long strip of welds, the movement of arc and the layer wise joint cause a three dimensional distribution of temperature in weldments. The distribution, magnitude and time rate of change of temperature also affected by the number of passes in welding. Therefore, a 3-D thermo-mechanical model, which has the capability of simulating the effect of arc movement and welding speed, is fully in demand.

2. Thermo-Mechanical Modeling

Compared to the arc power in welding, the other kinds of energy such as latent heat due to phase change or plastic work done by stresses and strains are very small. By neglecting the effect of these kinds of energy, at first we solved the uncoupled and transient heat problem to find the thermal history in weldments. The calculated temperature was then applied into the model as the loading function for thermo-mechanical analysis.

In the present research, the welded zone is modeled by an isothermal welding pool (melting temperature). In addition, heat is assumed to be transferred by conduction into the plates and by convection into the surrounding. The effect of radiation is negligible [1,6,10] and ignored in this research. For both base plate and filler material, temperature dependent properties are incorporated into the model. The welding time and speed are also obtained from the welding characteristic data table. The term "welding lag" is defined here to introduce the effect of lag time that welders apply to examine the condition of welds after each sequence. An approximate value of 10% of welding time is used for welding lag in the present work. To introduce the effect of filler material into the FE model, the birth and rebirth technique is applied [10]. Therefore, using this approach, the elements of welded region are deactivated first by changing their material properties, and activated by considering the normal value for their properties, while welding is in process

The rate dependent plastic (viscoplastic) model is considered to simulate the thermo-mechanical behavior of the weldments. The Anand's viscoplastic model [7], incorporated in the present study, is a single-scalar internal variable viscoplastic model for large, isotropic, viscoplastic material with small elastic deformations. There are two basic features in this model. First, this needs no explicit yield condition and no loading/unloading criterion. Second, this model employs a single scalar as an internal variable, the deformation resistance s, to present the averaged isotropic resistance to plastic flow.

The following functional form for the flow equation was presented by Anand [7]:

$$\dot{\varepsilon}_p = A\exp(-\frac{Q}{R\theta})[\sinh(\xi\frac{\sigma}{s})]^{1/m} \qquad (1)$$

where $\dot{\varepsilon}_p$ is the inelastic strain rate, A is the pre-exponential factor, Q is the activation energy, m is the strain rate sensitivity, ξ is the stress multiplier, R is the gas constant, θ is the absolute temperature and σ is the applied stress.

The evolution equation for the internal variable s is derived as

$$\dot{s} = \{h_0\left|1-\frac{s}{s^*}\right|^a .sign(1-\frac{s}{s^*})\}.\dot{\varepsilon}_p \,;\, a>1 \qquad (2)$$

with

$$s^* = \hat{s}\left[\frac{\dot{\varepsilon}_p}{A}\exp(\frac{Q}{R\theta})\right]^n \qquad (3)$$

where h_0 is the hardening/softening constant, a is the strain rate sensitivity of hardening/softening, s^* is the saturation value of s, $\hat{s}$ is the coefficient and n is the strain rate sensitivity for the saturation value of deformation resistance.

There are nine material parameters in the above mentioned Anand's viscoplastic model: A, Q, ξ, m, h_0, $\hat{s}$, n, a and s_0; the last one is the initial value of the deformation resistance [7]. These parameters are directly obtained from experimental data.

3. Computational Model

The multi-pass (multi-layer) welding is one of the most important and common types of welding sequences, which welders apply in joining thick plate weldments. The present research is focused on the effect of number of passes in multi-pass welding. To accomplish this, the following FE model has developed and solved for two different numbers of passes.

In the FE model, two 300×300×12 mm steel plates are assumed to be welded with different passes of welds (three and five). Fig.1, 2 and 3 show the overall view, fixtures and layer configurations that were used in the computational model.

Here, the temperature of welding pool was assumed as 1500°C (melting) while the ambient temperature was taken as 27°C. Heat convection into surrounding was considered to take place from all external surfaces of the plates with a constant coefficient of 10.0 W/m^2 K.

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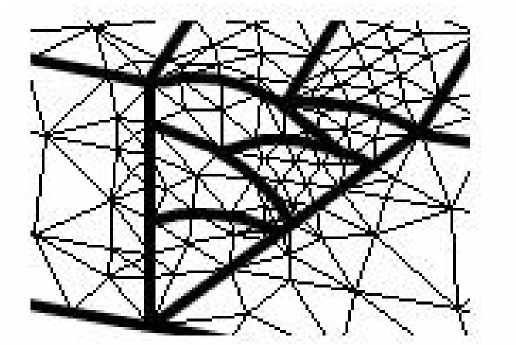


Fig. 1 FE meshes used for welded region.

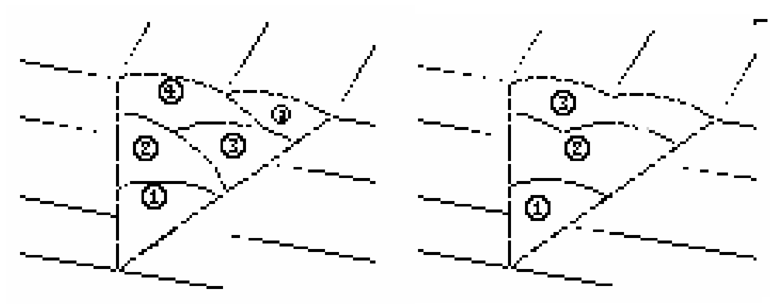


Fig. 2 Two welding passes used in the analyses.

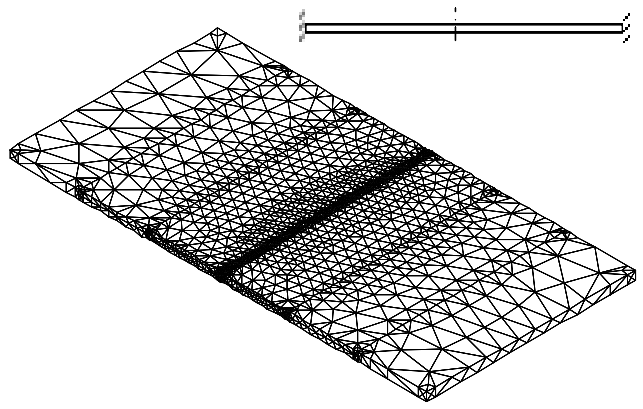


Fig. 3 Fixture configuration and the overall FE model used in the analyses.

The welding parameters such as welding speed and time for each sequence were obtained from the operational welding characteristic data [10] which are shown in Table 1.

Table 1 Welding characteristc data used in analyses[10].

Pass No.	Current (A)	Voltage (V)	Speed (mm/min)
1	215	24	366
2	205	25	366
3	215	26	366
4	210	24	366
5	210	24	366

The temperature dependent properties of selected material are also listed in Table 2 [5].

In addition, the constants of viscoplastic Anand's model, which are obtained from the literature [7] are shown in Table 3.

4. Validity of Model

Based on the experimental data of Ruud *et al*. [8] as well as analytical work of Ronda et al. [9], the applicability of the present model in welding of thick plates has been thoroughly verified [12].

Table 2 Variation of thermo-mechanical properties of material vs. temperature [5].

T (°C)	Thermal conductivity *k*(W/m.°K)	Specific heat, C_p (J/kg.°K)	Coefficient of thermal expansion $\alpha(10^{-6}$ 1/C)	Young's modulus E(Gpa)
0	51.9	450	10	200
75	-	486	-	-
100	51.1	-	11	200
175	-	519	-	-
200	49	-	11.5	200
275	-	557	-	-
300	46.1	-	12	200
400	42.7	-	-	-
450	-	-	13	150
475	-	662	-	-
500	39.4	-	-	-
550	-	-	14	110
575	-	749	-	-
600	35.6	-	14	88
675	-	846	-	-
700	31.8	-	-	-
725	-	1432	14	20
775	-	950	-	-
800	26	-	14	20
1000	27.2	-	14.5	11
1200	-	-	15	2
1500	29.7	400	15	0.2

Table 3 Constants of Anand's viscoplastic model for selected material [7].

A	Q	ξ	m	$\hat{S}$	n	h_0	*a*	s_0
6.346×10^{11}	312.35	3.25	.1956	125.1	.06869	3093.1	1.5	102.7

By X-ray diffraction, Ruud *et al.* in 1993 measured the magnitude of residual stress on the surface of two thick multipass-welded plates. In 2004, Nami [12] applied the present model in welding thick multipass-welded plates and compared the results with Rudd's experimental data. The comparison showed that there exists a good compatibility between the experimental data of Rudd *et al.* and the results of the present model.

For example, the variation of residual stress in the X_1 direction along a specified path on the top surface of thick welded plates, presented in Fig. 4. As the figure illustrates, the variation of computed stress has a pattern similar to the pattern of experimental data and shows a good compatibility between the results. Ronda *et al.* [9] also applied the present model (Anand viscoplastic model) in their analysis of welding and thoroughly studied the applicability of this viscoplastic model in the welding of thick plates. Thus, by these comparisons, the validity of the model was checked and the results were encouraging.

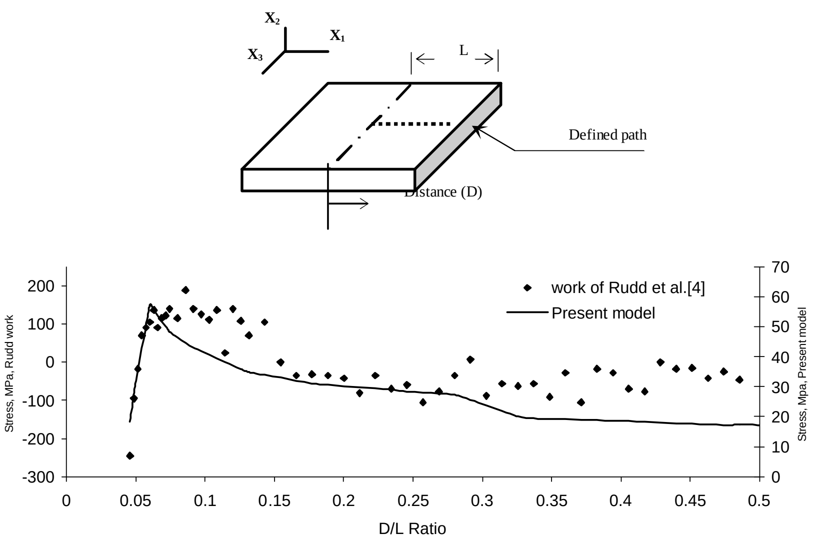


Fig. 4 Variation of residual stress in X_1 direction along the specified path located on top surface of thick welded plates

5. Numerical Results

Fig. 5 shows the temperature variation at a point near the weld line on top surface of the plates. As the figure shows, the temperature and its time of reach are greatly affected by the number of passes at that point. This effect for points, which are far from the weld line, is negligible and is not shown here [11].

The variation in different components of stress along the three paths (through thickness) located near the welded region is also shown in Fig. 6. It demonstrates that the changes in different components of stress through thickness and width of the plates are considerable and these variations are sensitive to the selection of number of passes of welds.

Further, Fig. 7 also presents the variation of stresses at other horizontal path (in plane). The selected path is on the top surface of the plates and located in middle of the weld line. The results reveal that, the effect of number of passes on the stress components is mainly significant in regions near the weld line and for the other points is very minimal that can be neglected.

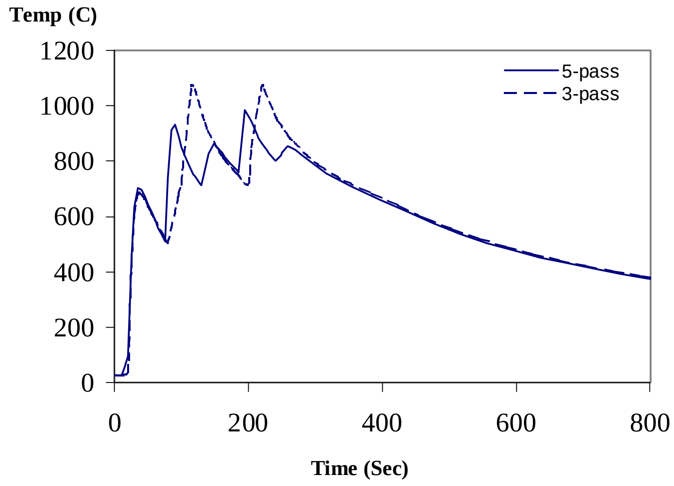


Fig 5 Variation of temperature versus time for different number of passes. The point is located near the welded region, 5 mm from the weld toe on top surface of the plates (dashed line).

Finally, Table 4 lists the maximum values of various modes of distortion and their locations in weldments. From the results one can see that the number of passes has major effect on amount and location of all modes of distortions. For example, total distortion (U_{sum}) is changed by an amount of 40% when the number of passes varies from three to five. It also shows that the maximum distortion always occurs in the region near the welded zone.

6. Concluding Remarks

Based on the computed results, the following conclusions can be ascertained:

1. As we know the thermal strain, which is the main loading function in thermo-mechanical analysis, is directly affected by temperature. The material constants and viscoplastic strains are temperature dependent too. Hence, one can estimate that if the number of passes of welds which has considerable effect on thermal loads in welding varies, significant changes occur in the amount of different modes of distortions. The results of the present analyses strongly support this conclusion which has been further experimentally proofed by Masubuchi [1].

2. Number of layers of weld mainly affect the amount of stresses in the region near the welded zone. This effect is more significant in distribution and amount of stresses, which arise through the thickness of the plates.

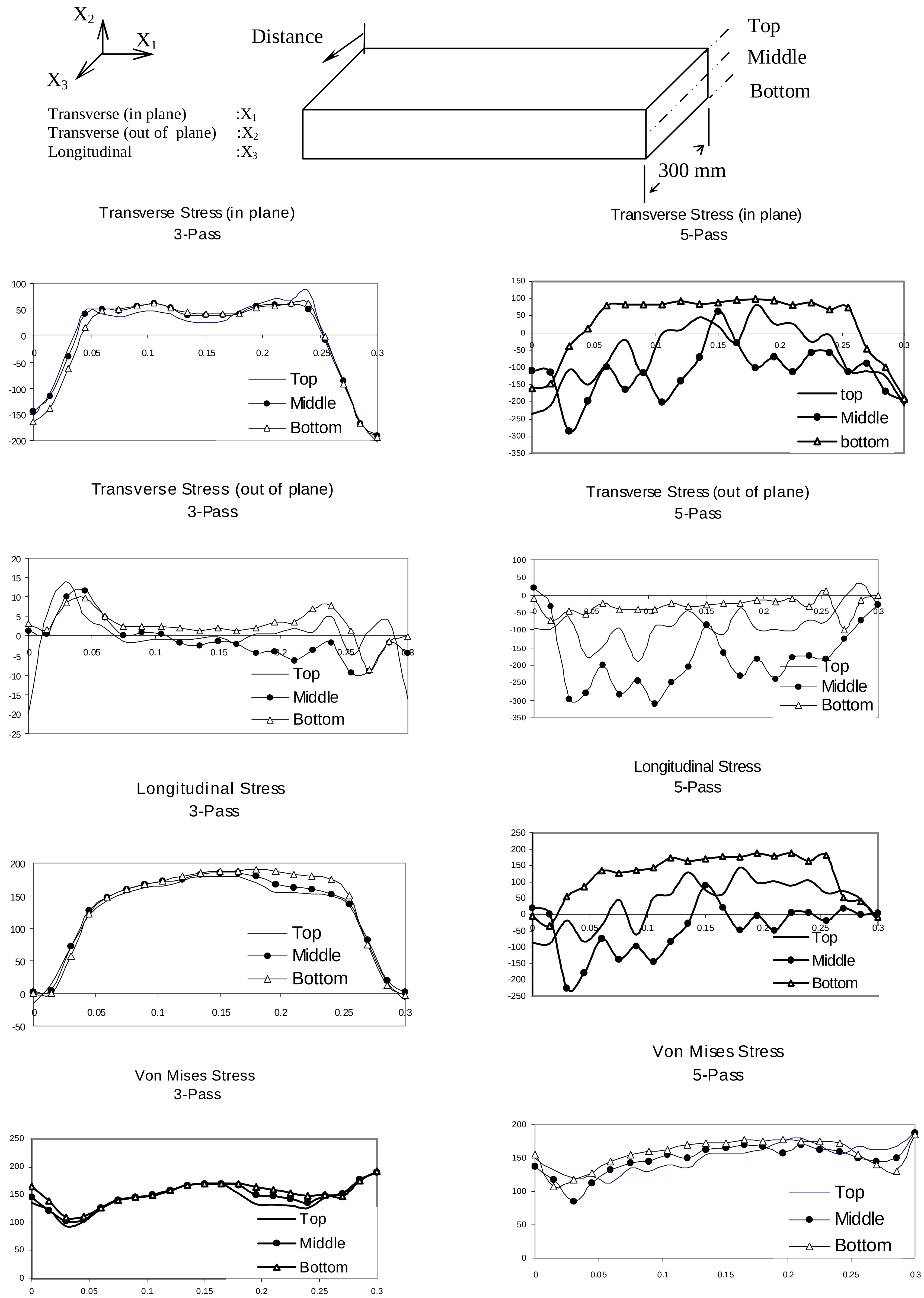


Fig. 6 Variation of different components of residual stresses through the thickness of plates (stresses and distance are measured in Mpa and meter respectively).

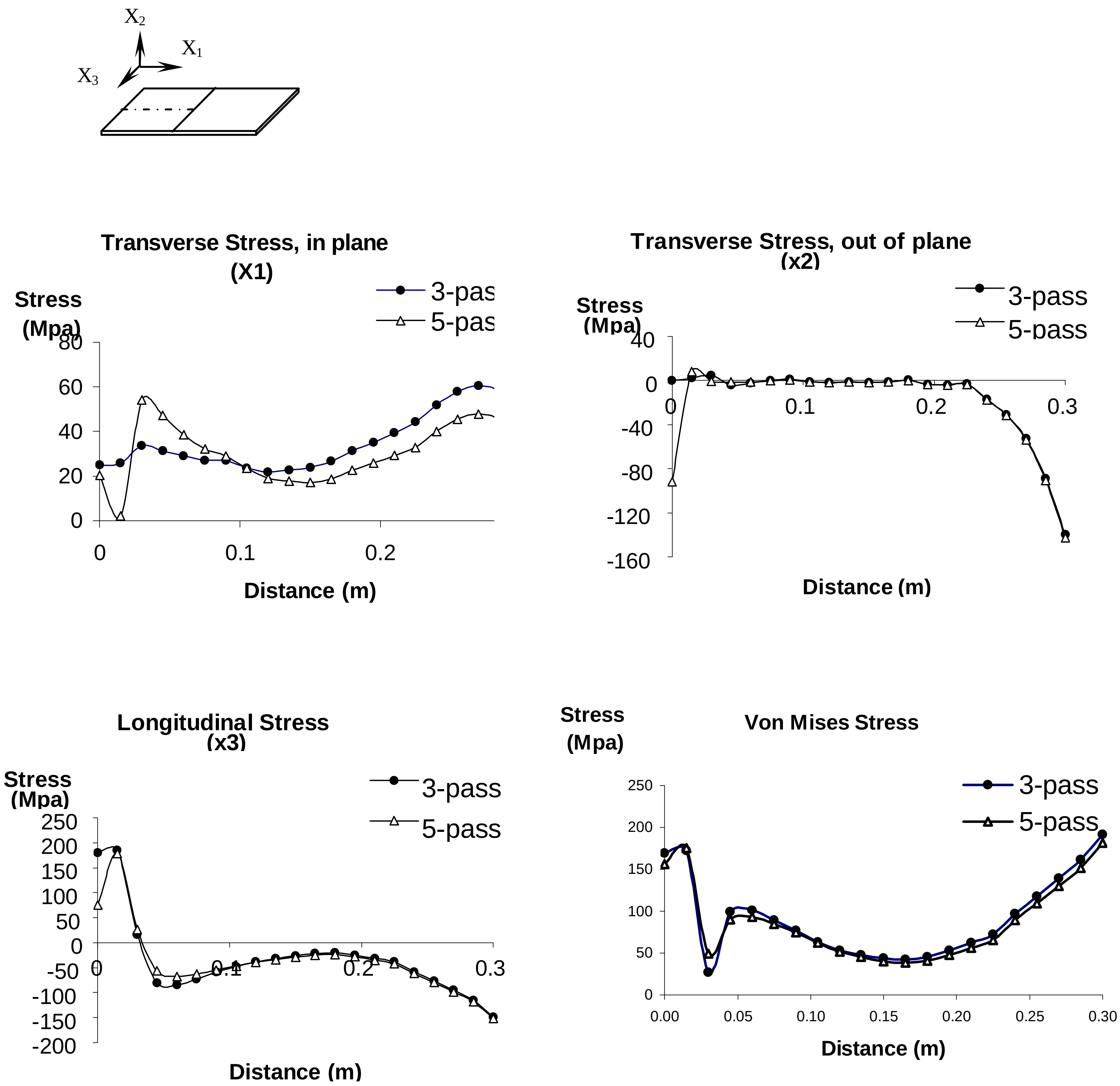
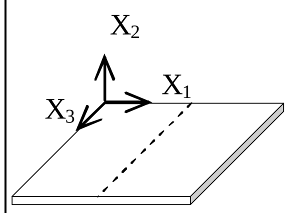


Fig 7 Final residual stress components along the defined path [dashed line]. (Distance measured from weld toe).

Table 4 The maximum values and their location of various modes of distortions generated by the different number of welding passes in the plates. U_i and U_{sum} are the distortions in the i^{th} direction and the total distortion of point respectively (measured in meters).

	No. of passes	**Distortion modes**				**Coordinates of points**		
		U_1	U_2	U_3	U_{sum}	X_1	X_2	X_3
	3-pass	-0.00111				0.310	0.0099	0.214
			0.001672			0.304	0.0127	0.211
				-0.001		0.304	0.0125	0.0
					0.001716	0.304	0.0127	0.211
	5-pass	-0.00742				0.319	0.012	0.147
			0.000806			0.306	0.0121	0.088
				- 0.00095		0.303	0.0128	0.0
					0.001002	0.308	0.0	0.300

As the number of layers of welds increases, the amount of all components of these stresses also increased. This effect is small for stresses produces in horizontal planes and would be negligible for the points far from the weld line.

3. The most important effect of number of passes in the welding of thick plates are the changes that might occur in the distortion of weldments. In assembling large structures, the choice of number of passes play an important role in generating all types of welding shrinkages [1]. As the analyses show, the change in the number of passes greatly affects the amount of distortion but it does not but same effect on the different modes of distortion. In other words the number of passes might increase or decrease the amount of different distortion components. For that reason, depending on the condition of joints such as the fixtures, the geometry of welds etc. in industrial constructions, one must be more careful in the selection of welding sequences.

4. In comparison with the cost of experimental approach, the use of a computational model to predict the relative response of weldments to the changes in number of passes may be more economical. Based on the obtained results and the verification, it is found that there exists good compatibility between the experimental and the analytical results. Therefore, the presented model can be recommended for the analyses of thick plate weldments and the accuracy and reliability of results will be acceptable.

7. References

[1] Masubuchi, K.; *Analysis of Welded Structures*; Int'l Series on Mat. Sci. & Tech.; Vol. 33; Pergamon Press; 1980.

[2] Rosenthal, D.; "Mathematical Theory of Heat Distribution during Welding and Cutting"; *Welding Journal;* 20(5); pp. 220s-234s; 1941.

[3] Paley, Z. and Hibbert, P.D.; "Computation of Temperatures in Actual Weld Designs"; *Welding Journal*; 54(11); pp. 385s-392s; 1975.

[4] Shim, Y., Feng, Z., Lee, S., Kim, D., Jaeger, J., Papritan, J.C. and Tsai, C.L.; "Determination of Residual Stresses in Thick-Section Weldments"; *Welding Journal*; pp. 305s-312s; Sept. 1992.

[5] Brown, S.B., Song, H.; "Implications of Three-Dimensional Numerical Simulations of Welding of Large structures"; *Welding Journal*; pp. 55s-62s; Feb. 1992.

[6] Argyris, J.H., Szimmat. J., William, K.J.; "Computational Aspects of Welding Stress Analysis"; Comput. Methods Appl. Mech. Engrg.; 33; pp. 635-666; 1982.

[7] Brown, S.B., Kim, H.K., Anand, L.; "An Internal Variable Constitutive Model for Hot Working of Metals"; International *Journal of Plasticity*;Vol. 5; pp. 95-130; 1989.

[8] Rudd, C.O., Josef, J.A. & Snoha, D.J.; "Residual stress characterization of thick-plate weldments using X-ray diffraction"; *Welding Journal;* pp. 87s-91s; 1993.

[9] Ronda, J., Oliver, G.J; "Comparison of Applicability of Various Thermo-Viscoplastic Constitutive Midels in Modeling of Welding"; *Comput. Methods Appl. Mech. Engrg*.; pp. 153, 195-221; 1998.

[10] Hong, J.K., Tsai, C.L., and Dong, P.; "Assessment of Numerical Procedure for Residual Stress Analysis in Multi-pass Welds"; *Welding Journal*; pp. 372s-382s; Sept. 1998.

[11] Nami, M.R., Kadivar, M.H, Jafarpur, K. ; "Three-dimensional thermal response of thick plate weldments: effect of layer-wise and piece-wise welding"; Modelling Simul. Mater. Sci. Eng. 12 ; pp. 731–743; 2004.

[12] Nami, M.R., Kadivar, M.H, Jafarpur, K.; "3D Thermo-Viscoplastic Modeling of Welds: Effect of Piece-Wise Welding on Thermo-Mechanical Response of Thick Plate Weldments"; *Iranian Journal of Science* & Technology; Transaction B; Vol. 28; No. B4; pp. 467-478; 2004.