Effects of Welding Procedures on Residual Stresses of T-Joints†

Aiping Wu*, Ning Xu Ma**, Hidekazu MURAKAWA*** and Yukio UEDA****

Abstract

The residual stress distributions of T-joints and the effects of welding procedures are analyzed with the aids of ABAQUS. The main results are described as follows.

1) In T-joints the weld toe and root are subjected to serious tensile residual stresses.

2) Simultaneous welding in same direction has some beneficial effect on the reduction of the longitudinal residual stress.

3) The undermatching weld has unfavorable effects on the transverse residual stress at the weld toe of the flange.

4) Preheating is beneficial for the transverse residual stress of the weld toe.

5) The welding sequence has some effects on the residual stresses of the weld toe. The later welds can release the residual stresses of the former welds to some extent, especially for the transverse stress.

6) Backstep welding can reduce some of the longitudinal residual stress of the weld.

7) For the transverse residual stress of the transverse weld toe, longer transverse welds are better than short welds.

KEY WORDS: (T-joint) (Residual Stress) (Welding Procedure) (Numerical Analysis) (ABAQUS)

1. Introduction

The residual stresses in metal constructions, such as ships, offshore structures, heavy cranes, trunks and pressure vessels, have important effects on the qualities of these structures. The residual stresses have influences on fracture strength and fatigue strength and sometimes they can be the driving force for crack initiation and propagation themselves[1]. For this reason, residual stresses have always been one of the most important research subjects[2]. Unfortunately, it is difficult to investigate residual stresses, especially in 3-dimension, with experimental methods, but the numerical simulation method has been well developed and with the use of computer technology is widely used in these studies[3].

During the last 20 years, most of the research about welding residual stresses has been on butt welded joints and only a few researches have been conducted on T-joints. However, there are many T-joints in ship and bridge structures and some failures in these structures are related to the residual stresses, and there are various welding procedures for constructing T-joint in practice[4]. For example, in order to prevent the cold cracking of high strength steel weld structures, it is necessary to preheat the base metal. On the other hand, it is commonly believed that the welding joint with undermatching weld has a better fracture toughness[5], and it is possible to use undermatching weld in practical welding structures for the prevention of cracking. But the effects of these welding procedures on the residual stresses of T-joint are not thoroughly investigated. For these reasons, the aims of this work are to study the residual stresses in T-joint and clarify the effects of welding procedures.

In this paper, the residual stresses distributions in T-joint and the effects of welding procedures (including welding sequence, welding direction, weld length, preheating, undermatching weld and backstep welding) on the residual stresses were analyzed as 3-D thermal elasto-plastic problems using ABAQUS[6].

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2. Modeling and Welding Conditions

The T-joint investigated is composed of a web with its dimensions 200 x12 x100 mm (length x thickness x height) and the flange of 500 x 250 x 16 mm (length x width x thickness). The standard welding procedure for comparison is a circle along the corner between the web and the flange, as shown in **Fig.**1.

The conditions of standard and other welding procedures are described briefly in **Table** 1. The welding parameters used in all procedures are the same. The welding current I and the voltage V are 260A and 27V and the welding speed is 5 mm/sec. The efficiency of arc heat input is assumed to be 75%. The weld is single pass and its penetration is about 2 mm and the fillet size is 8 mm. There is a gap between the web and the flange except for the penetration parts.

The mesh division of model is shown in **Fig.**2. The element type used in thermal analysis is a 3-D, 8-node linear heat transfer brick and that used for the stress analysis is 3-D, 8-node linear brick element employing reduced integration and hourglass control.

The material used in analysis is assumed to be low alloy high strength steel. Its temperature dependent thermal and mechanical properties are shown in **Fig.**3.

3. Computed Results and Discussions

3.1 Residual stress distributions in T-joints welded with the standard welding procedure

3.1.1 General distributions of residual stresses in the flange of the T-joint

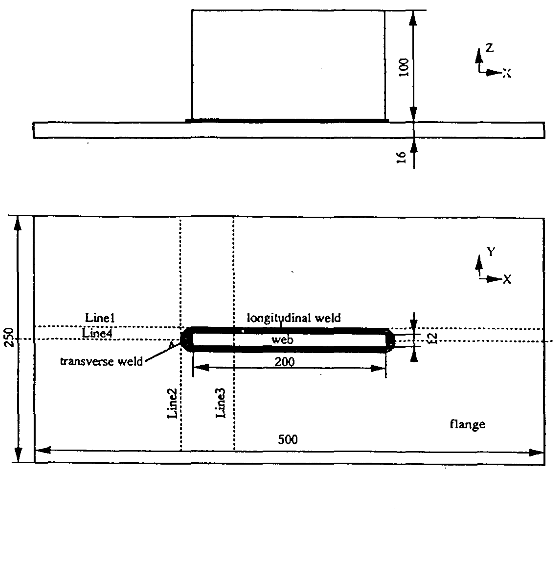


Fig.1 T-joint model

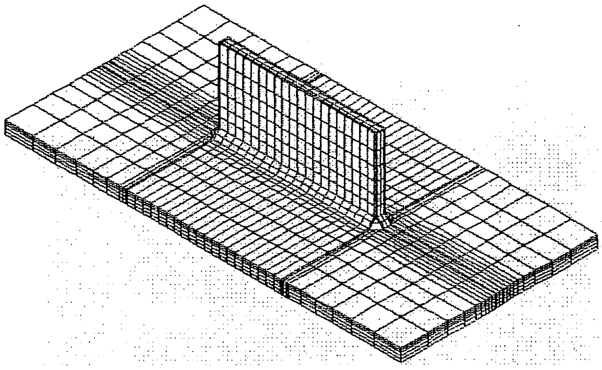
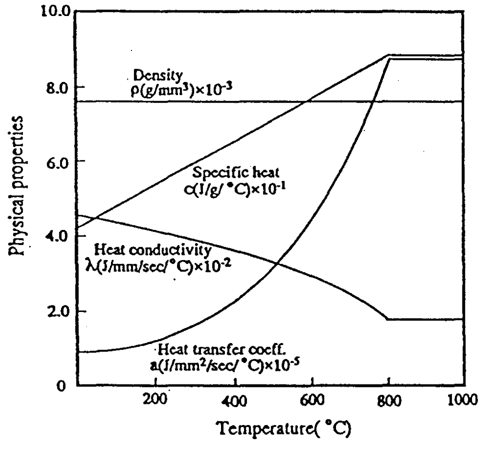
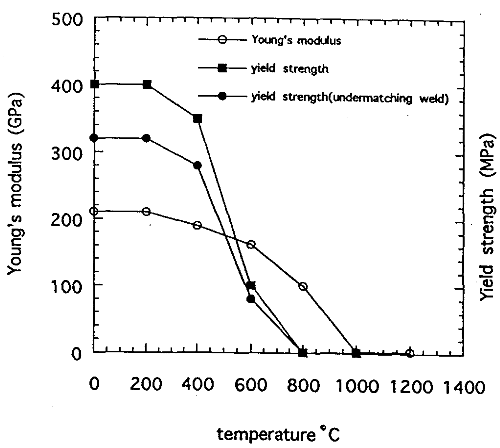


Fig. 2 Mesh division of model



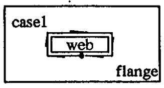
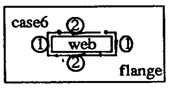
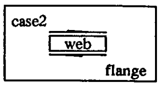
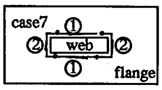
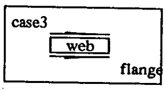
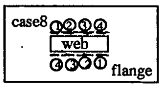
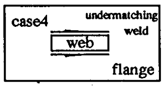
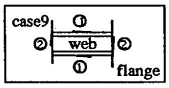
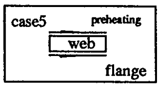
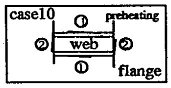
a. Physical properties

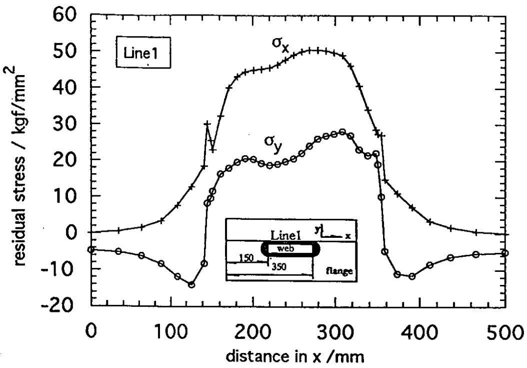


b. Mechanical properties

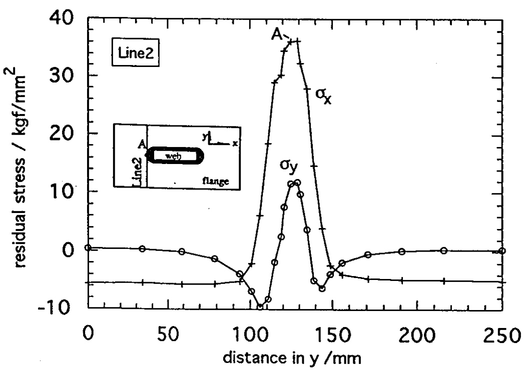
Fig. 3 Properties of mesh division

Table 1 the conditions of welding procedures

case No.	schematic	description	case No.	schematic	description
case1		general procedure, the weld starts and ends at the middle part	case6		the corner welds are welded first, after they cool to room temperature, the longitudinal welds are welded
case2		two longitudinal welds are welded simultaneously in different directions	case7		first to weld the longitudinal welds, then the corner welds
case3		two longitudinal welds are welded simultaneously in the same direction	case8		backstep welding, the length of step weld is 50mm
case4		the yield strength of the weld metal is 80% of the base metal, other conditions are similar to case3	case9		the length of transverse weld is 100mm, first to weld the longitudinal welds, then the transverse welds
case5		preheating temperature is 200°C, other conditions are similar to case3	case10		preheating temperature is 200°C, other conditions are similar to case9



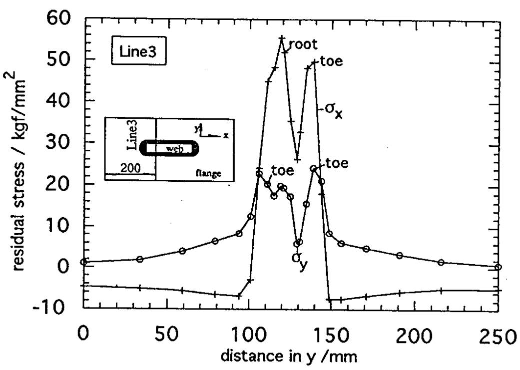
a. along Line 1



b. along Line 2

Fig. 4 Residual stress distributions along weld toe and the surface line of cross section

The residual stresses σ_x and σ_y along the Lines 1, 2, 3 in Fig.1 are shown in **Fig.**4. On the Line 1(along the weld toe), the residual stresses are tensile both in transverse and longitudinal directions in the weld part. The maximum σ_y is up to 280 MPa. In the center of Line 2 (namely A point), the residual stresses are maximum tensile stresses both in transverse and longitudinal directions. Its transverse stress σ_x (for the transverse weld σ_x is its transverse stress, but for the longitudinal weld σ_x is its longitudinal stress) is about 360 MPa. It can be seen from the residual stress distribution along the Line 3, the maximum value of the transverse tensile residual stress is located on the



c. along Line 3

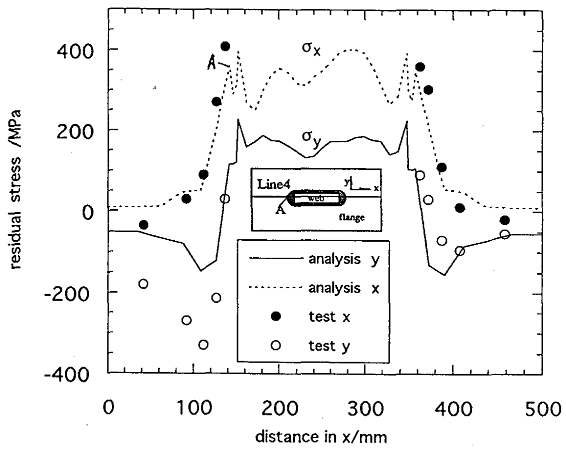


Fig. 5 Comparisions between the results of simulation and measurement

weld toe or close to it and that of the longitudinal stress σ_x is on the toe or close to the root.

3.1.2 Comparisons between the results of simulation and measurement

The results of the simulation and the measurement of residual stresses along the Line 4 are shown in **Fig.**5. It can be seen that for the residual stress σ_x, the results of the analysis are in a good agreement with the results of the test. But for the residual stress σ_y, the tendency is similar but the values show some differences.

According to the results mentioned above, it can be seen that

(1) the residual stresses at the weld toe are all tensile stresses and their values are the maximum or close to the maximum in the distribution. Moreover, the weld toe is subjected to stress concentration. Thus, it is the most dangerous part in a T-joint. Consequently, the attention is paid to the residual stresses at the weld toe in the following studies of the effects of welding procedures.

(2) the comparison between the results of simulation and measurement indicates that the analysis model used here is reliable for studying the general characteristics of the 3 dimensional welding residual stress in T-joint.

3.2 Effects of welding direction

The results of Case 2 and Case 3 are shown in **Fig.**6. In Case 2, the welds are welded simultaneously along the different directions and in Case 3, they are welded simultaneously in the same direction. The maximum longitudinal stress along the weld toe can be reduced by about 50 MPa when welded in the same direction compared with the case when welded in the different directions. There is no distinct effect on the maximum transverse residual stress at the weld toe.

3.3 Effects of under-matching weld

When the yield strength of weld metal is 80% of the yield strength of the base metal, the transverse residual stress σ_y at the weld toe on the flange surface is 60 MPa higher than that of equal strength joint as shown in **Fig.**7. There is no effect on the longitudinal stress at the weld toe. Therefore, no beneficial effect can be expected from the undermatching weld for reducing transverse residual stress at the weld toe.

3.4 Effects of preheating

In order to prevent cold cracking of high strength steel weld structures, preheating is commonly employed. The effects of preheating on the residual stresses at the weld toe are shown in **Fig.**8. Preheating to 200°C can decrease the transverse residual stress σ_y about 60 MPa, from 280 MPa to 220 MPa, and has little effect on the longitudinal stress. This result indicates that preheating has some beneficial effect for decreasing the transverse residual stress at the weld toe.

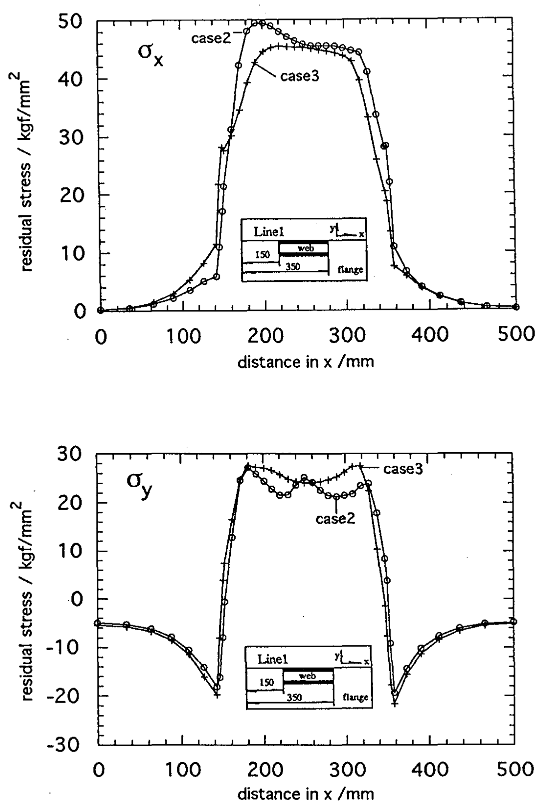


Fig. 6 Effect of welding direction

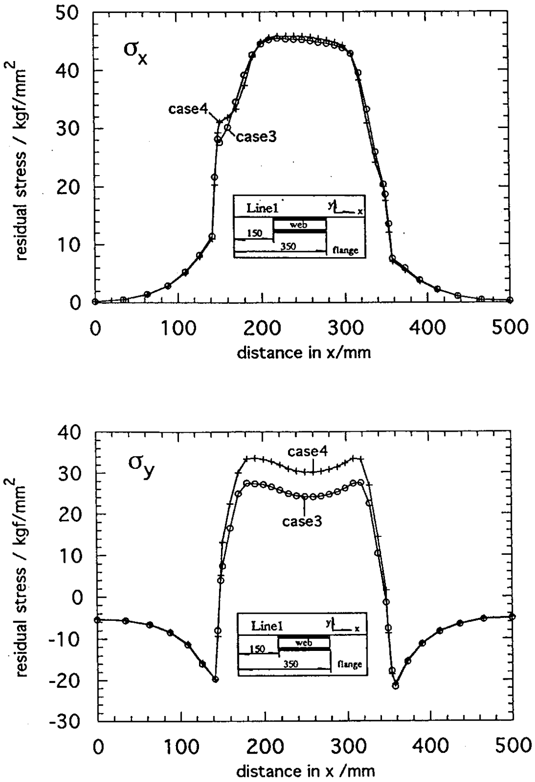


Fig. 7 Effect of undermatching welds

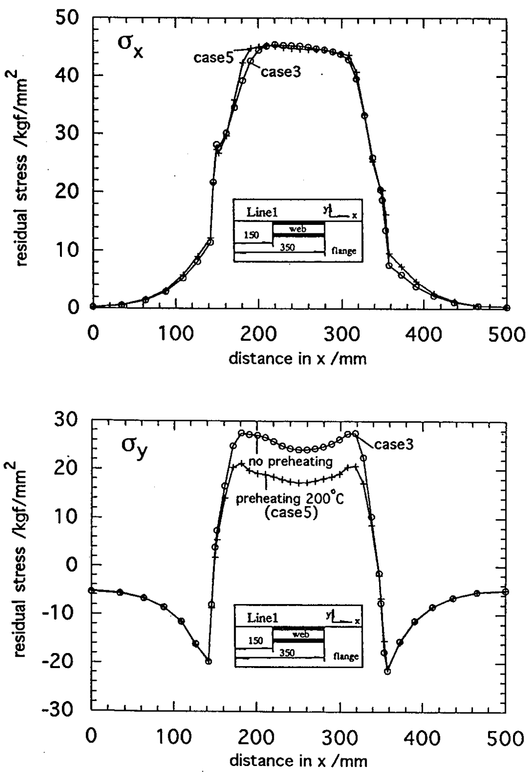


Fig. 8 Effect of preheating

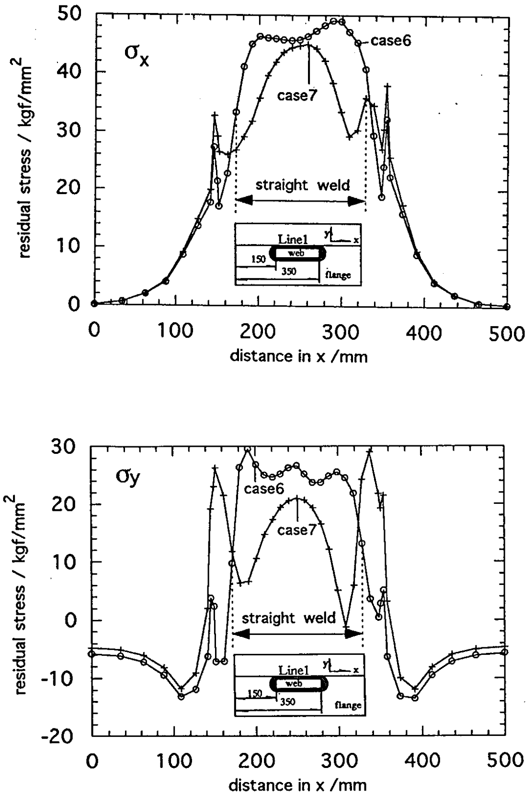


Fig. 9 Effect of welding sequence on the residual stresses of longitudinal welds

3.5 Effects of welding sequence

In Case 6 the corners are welded first and then the straight parts are welded. In Case 7 the sequence is contrary: the straight parts are welded first and then the corners are welded. The distributions of the residual stresses along the weld toe of the longitudinal weld(Line 1) are shown in **Fig.**9. When the corner welds are welded first, the residual stresses are smaller than those of Case 7, especially for the transverse residual stress σ_y. Along the toe of the transverse weld(Line 2, **Fig.**10), this effect is only distinct for σ_y while for σ_x there is little difference between Case 6 and Case 7. It means that the later welds can reduce the residual stresses of preceding welds to some extent, especially for transverse residual stresses. This effect can be confirmed from the results of first and final steps of Case 6 which is shown in **Fig.**11. Especially for transverse stress σ_y, the effect is distinct and the residual stress is reduced (from 260 MPa to 40 MPa). It can be concluded from these results that it is better to first weld the part where the transverse residual stress is required to be reduced.

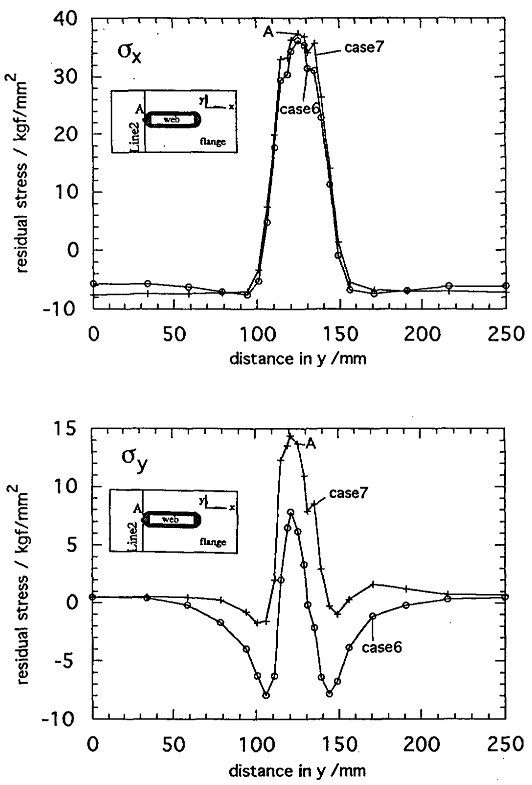


Fig.10 Effect of welding sequence on the residual stresses of transverse welds

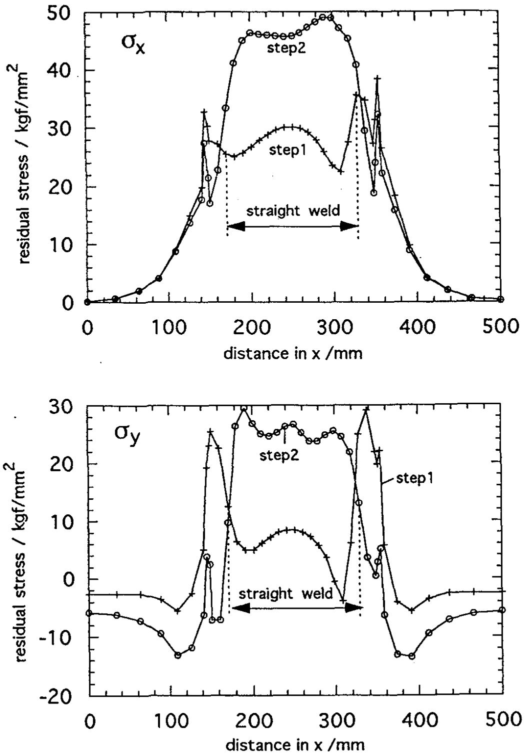


Fig. 11 Effect of later welds on the residual stresses of former welds

3.6 Effects of backstep welding

The residual stresses at the weld toe (along Line 1) of a backstep welding procedure are shown in **Fig.**12. Compared with the results of Case 2, it can be seen that backstep welding has no beneficial effect on the reduction of transverse residual stress σ_y. Although the later step weld has some releasing effect on the former one, the residual stress of the last part of the weld is larger than that of the standard welding procedure. But for longitudinal stresses, backstep welding can reduce the maximum tensile stress from 500 MPa to 425 MPa.

3.7 Effects of extended weld

The residual stresses along Line 1 and Line 2 when the transverse weld is extended and long are shown in **Fig.**13. It can be seen that the long transverse weld has little effect on the residual stresses at the toe of the longitudinal weld, except on the parts close to the transverse welds. But at the point A on Line 2, the transverse residual stress σ_x can be reduced by 250 MPa(from 370 MPa to 120 MPa) and the longitudinal residual stress σ_y is increased by about 200 MPa(from 140 to 340 MPa). It means that a long weld is beneficial to reduce the transverse residual stress but is unfavorable to the longitudinal residual stress.

As for the results along the Line 2, the residual stresses at the middle part are small. The reason may be that in this part, the maximum temperature is lower than that of the other part of the transverse weld, because the heat input is same but in the middle part the heat is transferred in 3 directions instead of 2 directions (some of the heat is transferred into the web). For this reason, preheating has no beneficial effect on the transverse residual stress σ_x at the middle part, but can reduce it at the other part (in which the weld is a bead on plate, as shown in **Fig.**14).

3.8 Discussions

3.8.1 Transverse residual stress at the toe of a longitudinal weld

For a longitudinal weld, the weld toe is a potentially dangerous point and the transverse residual stress σ_y (on the flange surface) is more important than the longitudinal one for failures of T-joints. One reason may be that, in a T-joint welding structure, longitudinal defects occur more often than transverse defects. According to the results mentioned above, the following welding procedures are beneficial to decreasing the tensile transverse residual stress at the toe of the longitudinal weld.

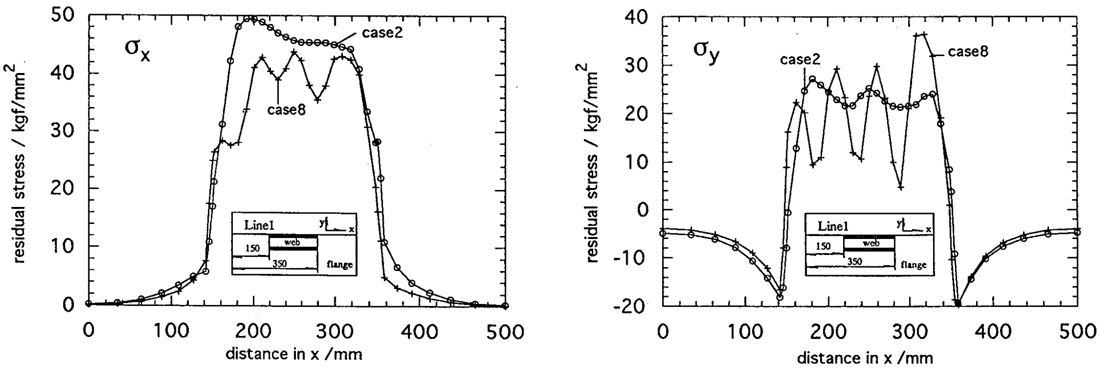


Fig. 12 Effect of backstep welding

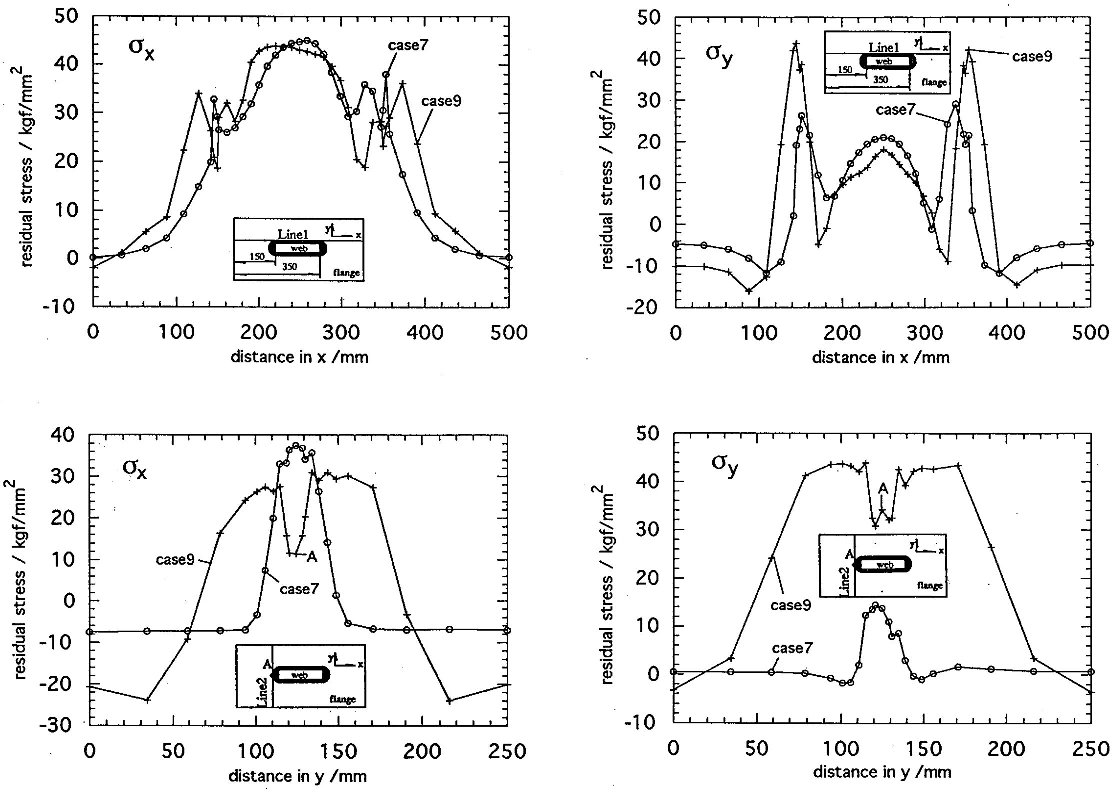


Fig. 13 Effect of weld distribution

1. Preheating to 200°C can reduce the transverse residual stress of longitudinal welds by about 60 MPa (maximum tensile stress can be decreased from 275 MPa to 212 MPa).

2. When the longitudinal welds are welded first and followed by the corner welds, the transverse residual stress of the longitudinal welds can be reduced by about 70 MPa (from 281 to 207 MPa).

3. On the other hand, the undermatching weld has an unfavorable effect on the transverse residual stress at the toe of a longitudinal weld on the flange side.

3.8.2 Transverse residual stress σ_X at point A

For the transverse weld, point A (at the toe of transverse weld on the flange side) is a dangerous point and its transverse residual stress σ_X is more important than the longitudinal stress. The residual stresses of various welding procedures are listed in **Table** 2. It is observed that for the transverse residual stress σ_X at point A, the best welding procedure is that of Case 9, in which extended transverse welds are employed. When the transverse welds are long, preheating is not necessary for reducing the transverse residual stress at point A.

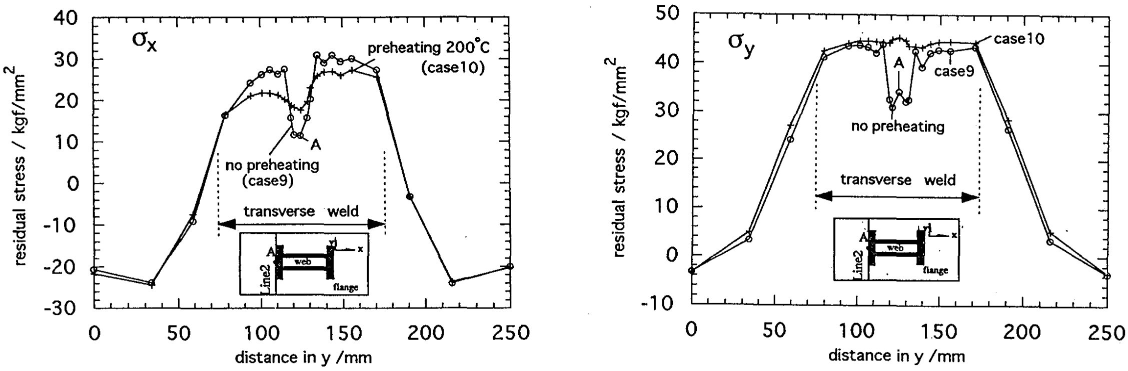


Fig. 14 Effect of preheating when the transverse welds are long welds

Table 2. Residual stresses at point A

case No.	case1	case6	case7	case9	case10
σ_x (MPa)	361.0	362	374.2	114.7	176.4
σ_y (MPa)	116.0	61.6	137.2	342.2	454.0

These results can be explained by the reason that when the transverse welds are short, the residual stresses at point A are mainly dependent on the long longitudinal welds. The transverse residual stress are strongly influenced by the longitudinal ones of the long welds, which have a large value(greater than 300 MPa). However, when the transverse welds are long, the residual stresses at point A are practically dependent on these long transverse welds, which have a smaller transverse residual stress than longitudinal stress. Another reason is that when the weld is short, its transverse residual stress will be larger than that of long weld. That is the reason why in Case 9 the transverse residual stress of point A is smaller than the longitudinal residual stress and is the smallest one amongst these cases.

4. Conclusions

The residual stress distributions of T-joints and the effects of welding procedures, including weld length, welding direction, undermatching weld, preheating and welding sequence, are analyzed using ABAQUS. The main results are summarized as follows.

1) In T-joints, the weld toe and root are subjected to serious tensile residual stresses both in transverse and longitudinal directions. It follows that the weld toe and root are the most dangerous positions in T-type welding joints.

2) When the two longitudinal welds are welded simultaneously in the same direction, the longitudinal residual stress at the weld toe is 50 MPa smaller than that of the case in which the welds are welded in the different directions. The welding direction has little effect on the transverse residual stress.

3) The undermatching weld has an unfavorable effect on the transverse residual stress at the weld toe of the flange and has little effect on the longitudinal residual stress.

4) Preheating can reduce the transverse residual stress of the weld toe but has little effect on the longitudinal stress.

5) The welding sequence has some effects on the residual stresses of the weld toe. The later welds can release the residual stresses of the earlier welds, especially for the transverse stress.

6) Backstep welding has no beneficial effect on the transverse residual stress but can reduce some of the tensile longitudinal residual stress of the weld toe.

7) For reducing the transverse residual stress of the transverse weld toe at point A, it is better to extend the transverse welds.

References

1) Welding Handbook, Vol.1, Welding Technology, 8th edition,AWS,1987

2) Yukio Ueda and Hidekazu Murakawa: New Trends of Research on Mechanics in Welding and Fabrication in Japan,Trans. of JWRI(1993),Vol.22,No.2,189-200.
3) Yukio Ueda and Hidekazu Murakawa: Applications of Computer and Numerical Analysis Techniques in Welding Research, Trans. of JWRI(1984),Vol.13,No.2,165-174
4) Ning Xu Ma, Yukio Ueda, Hidekazu Murakawa and Hideaki Maeda: FEM Analysis of 3-D Welding Research Stresses and Angular Distortion in T-type Fillet Welds, Trans. of JWRI(1995), Vol.24, No.2, 115-122.
5) F. Minami, Y. Nakano, S. Suzuki, et al: Fracture Toughness Evaluation of Multipass Weld HAZ with Focus on Mechanical Mismatching Effect, Quarterly Journal of Japan Welding Society (1994), Vol.12, No.4, 568-574
6) ABAQUS/Standard User's Manual, Vol.I and II, and ABAQUS Theory Manual, Version5.4