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Characteristics of the residual stress distribution in welded tubular T-joints

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Abstract

Tubular T-joints are structural discontinuities that can be easily involved with stress concentrations. It is therefore necessary to estimate an internal stress distribution of T-joints. However, the complicated residual stresses are unavoidably produced adjacent to the joints by welding. In this paper, the residual stress distributions in welded tubular T-joints were analyzed by using a three-dimensional non-steady heat conduction analysis and a three-dimensional thermal elastic-plastic analysis. Characteristics of the residual stress distribution in welded tubular T-joints are investigated by the thermal-mechanical analysis results.

Keywords: Residual stress; Thermal-mechanical analysis; Welded tubular T-joint

1. Introduction

Steel structures, i.e. offshore structures, buried pipelines and steel trusses, consist of a large number of tubular members joined by the welding process. Tubular members are joined in a variety of geometrical forms such as T-type by welding. Tubular T-joints are structural discontinuities that can be easily encountered into stress concentrations. It is therefore necessary to estimate an internal stress distribution of the T-joints for safe construction of the welded structures. However, welding residual stresses are unavoidably produced at the welding joints as results of weld pool solidification, phase transformation and plastic deformation during welding. Furthermore, the distribution of welding residual stress is too complicated as affected by geometry of joints, weld conditions and etc. And the residual stresses in the tubular members are one of the important problems concerning with the buckling strength, the fatigue strength, crack propagation and so on [1-6]. It is therefore necessary to investigate the characteristics of the residual stress distribution in the welded tubular T-joints.

In this paper, characteristics of the residual stress distributions in welded tubular T-joints were investigated by an analytical approach. The residual stress distributions in welded tubular T-joints were computed by using an uncoupled three-dimensional thermal-mechanical finite element analysis. Thermal-mechanical analyses were sequentially performed; a three-dimensional non-steady heat conduction analysis and a three-dimensional thermal elastic-plastic analysis, respectively. In thermal-mechanical analyses, temperature-dependent thermo-physical and mechanical properties of the base metal used in the tubular members and weld metal were considered. Characteristics of the residual stress distribution in welded tubular T-joints are investigated by the thermal-

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mechanical analysis results.

2. Model for analysis

2.1 Analysis and welding conditions

It is assumed in analyses that round-to-round tubular members with a thickness of 10 mm and lengths of 500 mm and 1300 mm, respectively, are joined by arc welding as shown in Fig. 1 [1]. The welded joints are manufactured as T-type of round-to-round tubular joint. Analysis models are divided with a parameter of the diameter of members; 250 mm, 300 mm and 500 mm as shown in Table 1. In welding analysis, simple supported condition is applied at the horizontal member. Fig. 1 shows dimensions of the analysis model and observing parts to indicate residual stress distributions; upper, middle, lower parts of horizontal member and lateral part of vertical member.

It was assumed in the welding analysis that one-pass groove welding was conducted with welding velocity of 6 mm/sec, voltage of 30 V, current of 300 A, heat input of 1200 J/mm and heat efficiency of 0.8 [7, 8]. Material used in the tubular members is SM400, which is a structural steel for Korean Standards and equivalent to ASTM A527 Gr.42. And AWS E71T-1 is used for the weld metal. Temper-

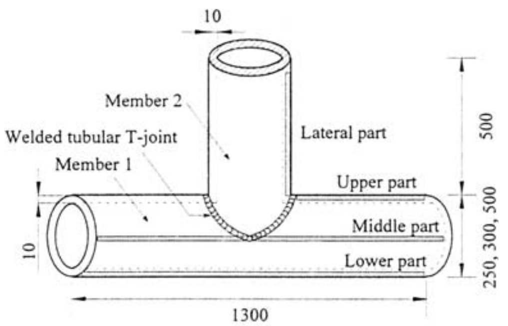
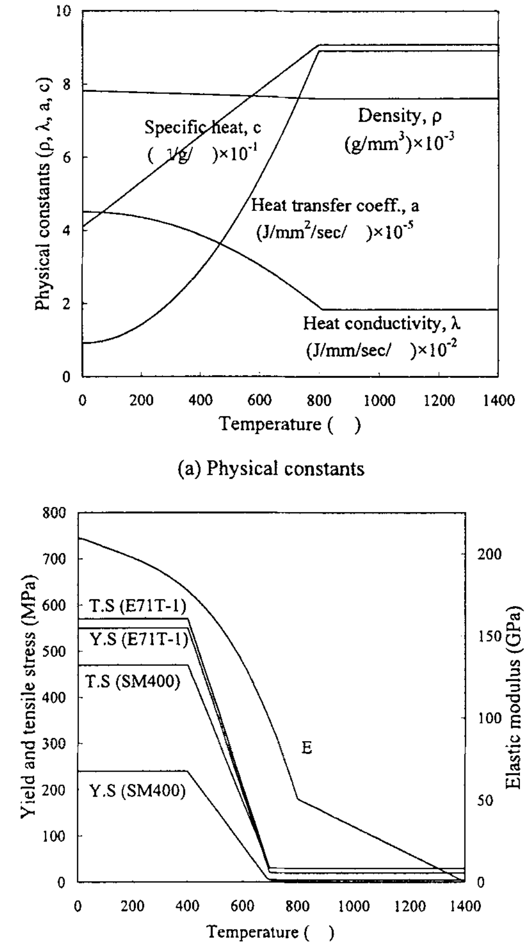


Fig. 1. Configuration of analysis model and observing parts.

Table 1. Model for the analysis.

Model	dimensions (unit=mm)				thickness-diameter ratio (t/D)
	diameters (members)	length (horizontal member)	length (vertical member)	thickness	
WT-250	250				0.040
WT-300	300	1300	500	10	0.033
WT-500	500				0.020



(a) Physical constants

(b) Mechanical properties

Fig. 2. Temperature-dependent physical constants and mechanical properties of base metal(SM400) and weld metal(E71T-1) (T.S = tensile stress, Y.S = yield stress).

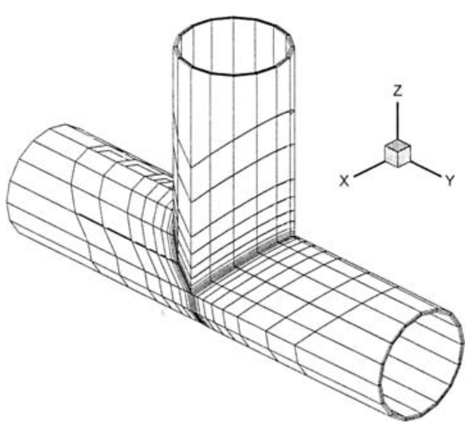


Fig. 3. Finite element discretization and coordinate system.

ature-dependent physical constants and mechanical properties of base and weld metals are shown in Figs. 2(a), (b) [9-13].

2.2 Thermal-mechanical analysis

The temperature and the thermal stress distribution are computed using an uncoupled thermo-mechanical finite element formation to incorporate the thermal and mechanical analysis. The computation employed a three-dimensional, eight-node, solid elements in an entire model and used temperature-dependent thermo-physical and mechanical properties of the used materials as shown in Figs. 2(a) and (b) [9-13]. The thermal analysis is based on the three-dimensional non-steady heat conduction formulation with the moving heat input. Thermal and mechanical analyses are uncoupled and conducted sequentially. First, the thermal analysis is carried out calculating the temperature distributions during welding. The three-dimensional thermal elastic-plastic analysis relied on the thermal analysis results and calculated the stress-strain distribution on the basis of the temperature history. The incremental form of stress-strain relationship can be written as

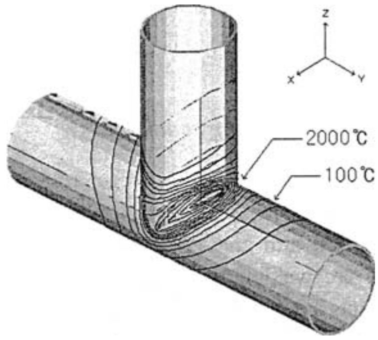
$$\{d\sigma\} = [D_d]\{d\varepsilon\} - \{c\}dT \tag{1}$$

where $[D_d]$ is divided into $[D_d^e]$ for the elastic range and $[D_d^p]$ for the plastic range, $\{c\}$ is a parameter to reflect the stress increment due to the dependence of the physical and mechanical properties of the materials on temperature, $d\sigma$ is the stress increment, $d\varepsilon$ is the strain increment and dT is the temperature increment. And the same finite element models as used in the thermal analyses are used in the mechanical analyses as shown in Fig. 3. Fig. 3 shows a finite element discretization and coordinate system.

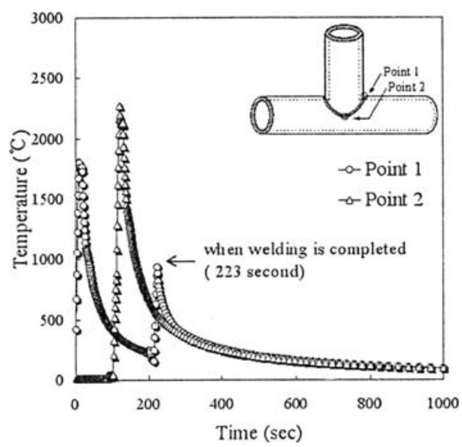
3. Analysis results and discussion

3.1 Temperature history

Fig. 4(a) shows an iso-thermal contour of WT-300 model at 223 seconds, when welding is completed, obtained by a three-dimensional non-steady heat conduction analysis. Fig. 4(b) shows thermal histories at outside element of each observing points. Where point 1 indicates a welding started element, and point 2 is the middle element on the weld line as shown in



(a) Iso-thermal contour at 223 second



(b) Temperature histories at each point

Fig. 4. Iso-thermal contour and temperature histories of WT-300 model.

Fig. 4(b).

It is known from thermal histories that temperature of point 1 increases up to approximately 1800 °C, when welding begins. Subsequently, temperature of point 1 decreases rapidly up to approximately 160 °C and re-increases up to approximately 940 °C , when welding is completed. The temperature of point 2 increases up to approximately 2270 °C at 120 seconds. Also, the temperature distributions of WT-250 and WT-500 models showed a similar tendency with that of WT-300 model.

3.2 Residual stress distribution

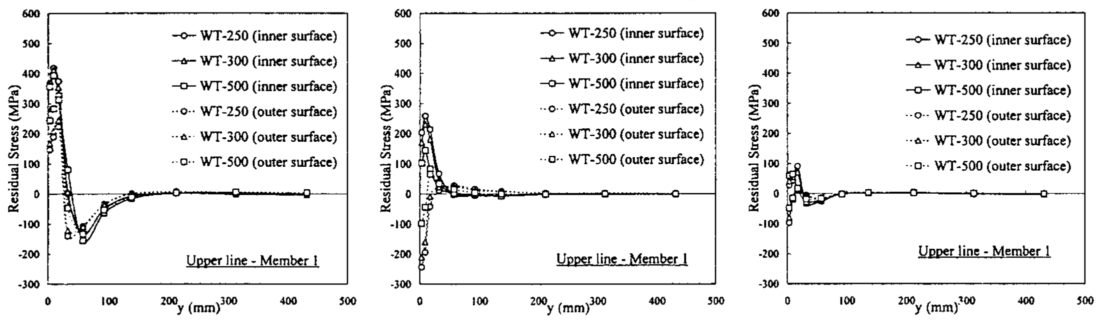
Figs. 5~8 show the residuals stress distributions of analysis models, obtained by a three-dimensional thermal elastic-plastic finite element analysis on the basis of the temperature histories. The residual stress distributions are presented at each observing parts as shown in Fig. 1.

Upper part – horizontal member

Fig. 5 shows the residual stress distributions of the upper part–horizontal member on the inside and the outside surface. Residual stresses of the circumferential direction near the welded T-joint are tensile on the inside and the outside surfaces in all analysis models. And the magnitude of stresses on the inside surface is larger than that on the outside surface. In case of residual stresses of the axial and the radial directions, tensile stress distributions show on the inside surface. On the outer surface, residual stresses near the welded T-joint are compressive. This difference of the residual stress distributions is due to geometry change during welding depending on thermal shrinkage [14]. The maximum residual stress occurs at the circumferential direction of the WT-250 model on the inside surface with a value of approximately 400 MPa.

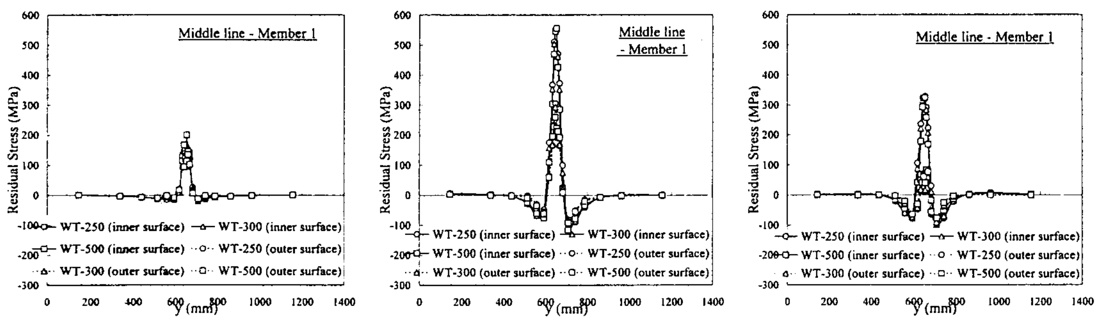
Middle part – horizontal member

Fig. 6 shows the residual stress distributions of the middle part–horizontal member on the inside and the outside surface. All residual stress distributions of analysis models show a similar tendency on the inside



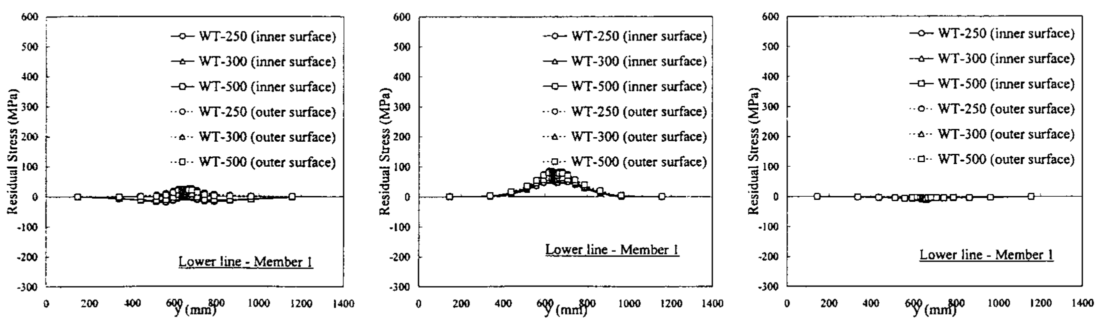
(a) Circumferential direction (b) Axial direction (c) radial direction

Fig. 5. Residual stress distribution of upper part-horizontal member on the inner and the outer surfaces.



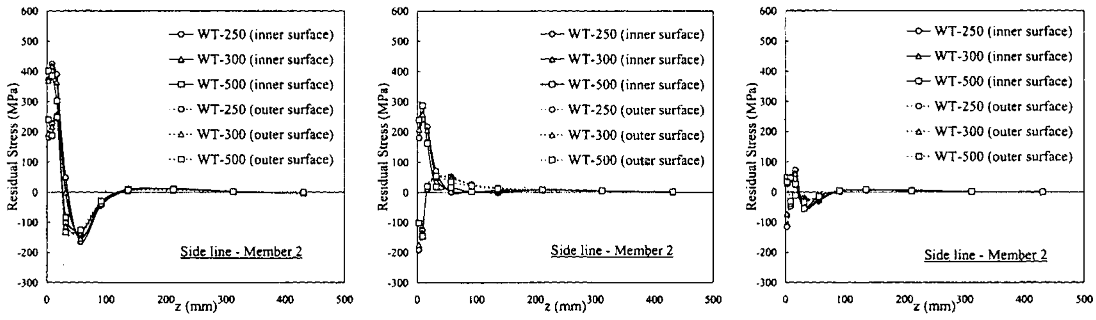
(a) Circumferential direction (b) Axial direction (c) radial direction

Fig. 6. Residual stress distribution of middle part-horizontal member on the inner and the outer surfaces.



(a) Circumferential direction (b) Axial direction (c) radial direction

Fig. 7. Residual stress distribution of lower part-horizontal member 1 on the inner and the outer surfaces.



(a) Circumferential direction (b) Axial direction (c) radial direction

Fig. 8. Residual stress distributions of lateral part-vertical member on the inner and the outer surfaces.

and the outside surface. The residual stresses near welded T-joint are tensile in all analysis models. The residual stresses of the axial direction are larger than those of other directions. And the residual stresses on the inside surface are relatively larger than those on the outside surface. It is seen from this tendency that production of the residual stress at the middle part – horizontal member is mainly dependent on the thermal history [14].

Lower part – horizontal member

Fig. 7 shows the residual stress distributions of the lower part–horizontal member on the inside and the outside surface. The residual stresses of the circumferential and the axial directions near welded T-joint are tensile, and these magnitude do not exceed approximately 50 MPa and 100 MPa, respectively. In case of the residual stresses of the radial direction, insignificant value is observed in an overall region.

Lateral part – vertical member

Fig. 8 shows the residual stress distributions of the lateral part–vertical member on the inside and the outside surface. The residual stress distributions of the lateral part–vertical member are similar with those of the upper part–horizontal member in respect of the magnitude and the tendency. It is known therefore that production mechanism of residual stress at the lateral part–vertical member is equal to that at the upper part–horizontal member consequently.

4. Conclusions

In this paper, characteristics of the residual stress distribution in welded tubular T-joints are presented by a three-dimensional thermal-mechanical finite element analysis considering temperature-dependent physical constants and mechanical properties of the base metal (SM400) used in the tubular members and weld metal (E71T-1). And conclusions can be summarized as follows;

It is concluded from three-dimensional non-steady heat conduction analyses that temperature distribution on the weld line increases up to approximately 940 ~2270 during welding.

Residual stresses of the circumferential direction of the upper part–horizontal member near the welded T-joint are tensile on the inside and the outside surfaces. And the residual stresses of the axial and the radial directions are tensile on the inside surface. However, on the outer surface, residual stresses near the welded T-joint are compressive. This is due to geometry change during welding depending on thermal shrinkage.

All residual stress distributions of the middle part–horizontal member show a similar tendency on the inside and the outside surface. And residual stresses on the inside surface are relatively larger than those on the outside surface.

The residual stresses of the circumferential and the axial directions of the lower part–horizontal member near welded T-joint are tensile, and the residual stresses of the radial direction are insignificant.

The residual stress distributions of the lateral part–vertical member are similar with those of the upper part–horizontal member in respect of the magnitude and the tendency. It is concluded therefore that production mechanism of residual stress at the lateral part–vertical member is equal to that at the upper part–horizontal member.

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