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Investigation on the Effect of Initial Welding Imperfection on Fatigue strength of Tubular Member by FEM

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Abstract. Steel tube structure is used for steel structure such as offshore platform, bridges and so on. Also, all circular members of tubular structures are mainly connected by welding. When the steel tubular structures are subjected to repeated loading, not only the load carrying capacity is reduced but also fatigue cracks may develop at the joint part of steel tubular members which are connected by welding.

Carrying out welding, welding initial imperfection such as welding deformation and residual stress are inevitably generated at weld part. It was well known that the effect of welding residual and welding deformation on fatigue strength. However, It's not clear which affects fatigue strength more. However, it's difficult to clear the effect on fatigue strength by experiment. To clarify these effect, fatigue analysis was carried out by FEM which is based on continuum damage mechanics. On the other hand, coupled three-dimensional non-steady heat conduction analysis, and the thermal elastic-plastic analysis was carried out to reproduce the initial weld state of tubular member. From the result, not only the fatigue strength of welded tubular member but also the fatigue life could be found by FEM fatigue analysis.

1. Introduction

Steel Pipe members such as K-type and T-type are widely used in civil and offshore construction and plant field. Also, pipe structure has longer length than its diameter and thickness. Thus, pipe structure needs weld joint. The initial imperfections such as welding residual stress and welding deformation of weld joint affect the fatigue performance of the structure. Also, it is well known as that mechanical behavior of a welded steel pipe under monotonic loading is significantly affected by welding residual stresses [1~7]. A few research works have been studied to examine the mechanical behavior of a welded T-joints pipe member under cyclic loading by experimental or numerical methods. In the analysis, even though a cyclic plasticity model is essential in the numerical study, however, they did



not employ the cyclic plasticity in the constitutive modeling. They used a bilinear stress-strain equation with isotropic hardening rule [8]. Also, nor did they consider the welding residual stresses. Thus, the mechanical behavior of a welded pipe subjected to cyclic loading has not been fully evaluated.

In this paper, it proposes a 3D fatigue high cycle damage analysis method. There are many parameters such as thickness, diameter, size, which affect fatigue performance of pipe member. This paper deals with fatigue behavior of a pipe subjected to cyclic loading through the numerical investigation, focusing on the effect of the welding imperfection such welding deformation and welding residual on the fatigue performance. The numerical investigation is carried out to clarify the effect of the initial imperfection on the fatigue life in the T-type steel pipe welding joint. Also, 3D analysis was carried out to obtain the welding residual stresses and welding deformation by using sequentially coupled three-dimensional non-steady heat conduction analysis and the thermal elastic-plastic analysis. Then, a FEM fatigue analysis was carried out to calculate the fatigue strength and fatigue life of the welded steel pipe. As a result, the fatigue behavior of the T-type steel pipe was clarified.

2. T-type Pipe Welding Analysis Model and Conditions

3D analysis is carried out to obtain the welding residual and welding deformation by using sequentially coupled three-dimensional heat conduction analysis and the thermal elastic-plastic analysis based on the in-house FE-code. The validity of 3D in-house FE-code has extensively been published by author [1~18].

2.1 Thermal conductivity, thermal elasto-plastic analysis

Chord diameter is D 500mm and its thickness t is 16mm. Brace diameter D is 400mm and its thickness t is 10mm. The FE analysis model geometry and dimensions are schematically shown in Fig 1. A V-groove butt welding of T-type circular which is made of carbon steel was considered. The 3-D FE mesh type with eight-noded isoparametric solid elements is used. The base material is SM490 steel used in civil engineering field. Temperature dependent thermo-physical and mechanical properties shown in Fig 2 were considered in the FE analysis. In welding analysis, a relatively fine mesh is used in near the weld centerline. The validity of these heat conduction analysis and thermal elastio-plastic analysis method are already verified by the published papers of author [9~18].

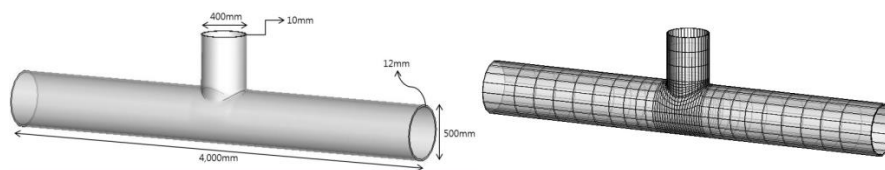


Fig 1. Configuration of T-type pipe welding

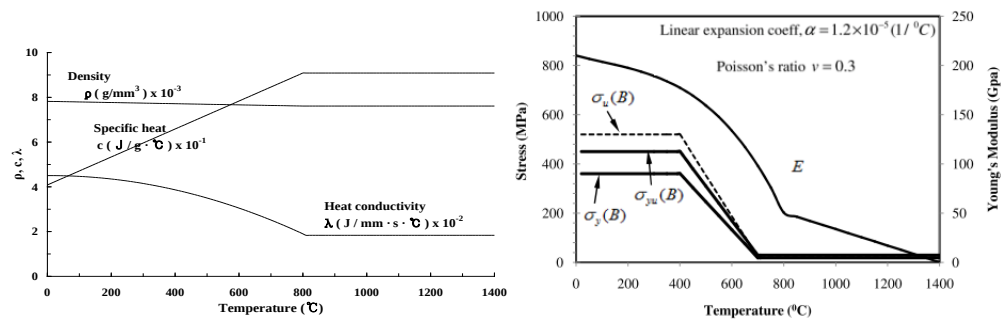


Fig 2. Temperature-dependent thermo- physical constants and mechanical properties.

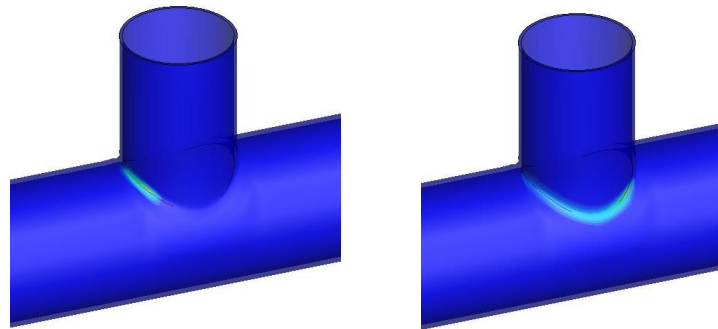


Fig 3. Thermal heat conduction analysis

2.2 Residual Stress Distribution

Table 1 shows the mechanical properties of SM490 steel. These parameters are obtained by tensile and cyclic tests according to ASTM standard with smooth round bar [9].

Table 1. Mechanical properties of SM490 steel

Material	E (GPa)	ν	σ_y (MPa)	σ_u (MPa)	Elongation (%)	ε_{st}
SM490	204	0.3	365.	549.	30.6	0.0124

First, coupled three-dimensional heat conduction analysis was carried out to obtain temperature history in Fig 3. Then, the thermal elastic-plastic analysis was performed to get the residual stresses and welding deformation. The results are the residual stress of the inner and outer surface in Fig 4 and Fig 5. Fig 4 shows the residual stress distribution at inner surface of the upper thickness part in pipe. The residual stress distribution from the weld line is in three directions distribution of longitudinal, circumference and thickness. Circumferential stress generated a tensile stress in the welding joint.

Compressive stress was generated away from the welding joint. Longitudinal stress is tensile stress in the welding joint. In comparison with three direction stress, thickness direction stress generated tensile stress in the welding joint. However, its absolute value is very small. Fig 5 is a residual stress distribution at outside surface of the upper thickness. Circumferential stress showed a similar distribution to the inner side. But, tensile stress in the joint showed a relatively low value compared to the inner side. The axial direction residual stresses were generated small tensile stress on the outside surface compared to inside axial direction tensile stress. This is because the circumferential shrinkage during the welding process increases to a local inward deformation near the weld area, resulting in compressive stresses is acting on the outside surface. Considering this, it concluded that the axial direction residual stresses are sensitive to the circumference shrinkage. The overall thickness stress distribution is similar to the inner side.

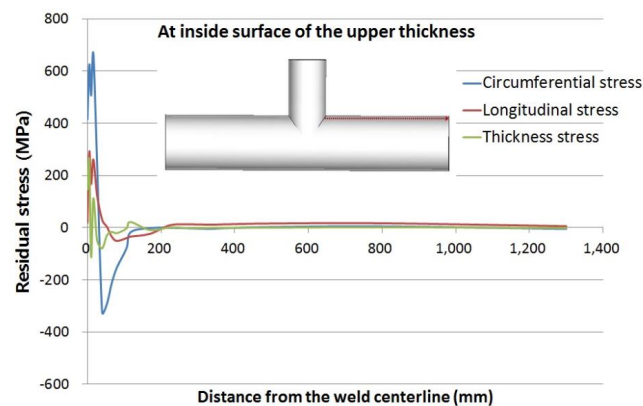


Fig 4. The residual stress distribution at inside surface of the upper thickness.

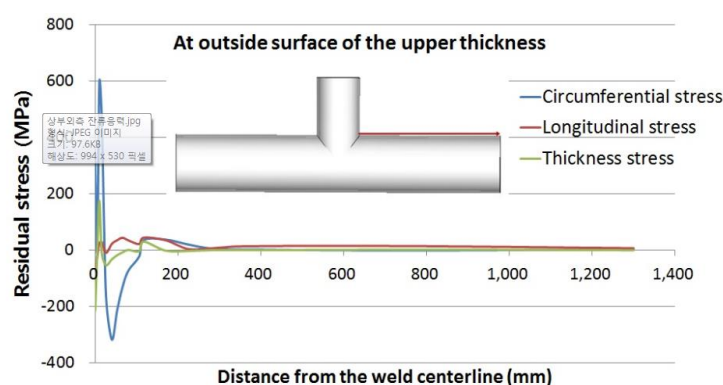


Fig 5. The residual stress distribution at outside surface of the upper thickness

2.3 Fatigue strength of Steel pipe in weld joint under cyclic loading.

To consider the effect of stress concentration and residual stress generated during welding process, the

initial stress and deformation should be incorporated with the FE model as an initial state. In the case of residual stresses are superposed into internal stress generated by external loading. In fatigue analysis, continuum damage mechanics was considered [19~32]. The damage variable is given : $D = 1 - \frac{A_D}{A_T}$, where, A_D is damaged area(micro-crack). The damage variable leads to the concept of effective stress, which can be expressed as following : $\bar{\sigma} = \frac{\sigma}{1-D}$, where, coefficient (1-D) is a reduction factor associated

with the amount of damage in the material. The value $D = 0$ indicates the undamaged state, $D = D_c$ indicates the complete local rupture and $D = [0 \sim 1]$ indicates the partial damage state. Under the number of cycles, the stress-plastic strain upgrade and damage variable was accumulated until reaching to critical value, at this time the crack initiation will occur in the structure. The damage at the cycle N :

$$D = 1 - \left[1 - \left(\frac{n}{N_f} \right)^{1/(1-\alpha)} \right]^{1/(1+\beta)} . \text{ where, } N_f = \frac{1}{(\beta+1)(1-\alpha)} \left(\frac{A_{pl}}{M} \right)^{-\beta} . \text{ The damage is given an incremental form :}$$

$D_{N+\Delta N} = D_N + \Delta D$, where, D_N is the damage value at the cycle N , ΔD is the damage increment corresponding to the increment of the number of cycle ΔN . Let us define $D = 0$ corresponding to $N = 0$ and $D = 1$ corresponding to rupture of a material point.

$$\text{The number of cycles to failure : } N_f = \begin{cases} \frac{q(1/2(1-R))^{2q}}{C(1+R^{2q})} \frac{1}{(2q+1)(1-\alpha)} \sigma_{af}^{-2q}, & R < 0 \\ \frac{q(1/2(1-R))^{2q}}{C(1-R^{2q})} \frac{1}{(2q+1)(1-\alpha)} \sigma_{af}^{-2q}, & 0 \leq R < 1 \end{cases}$$

For fully reverse loading case, $R = -1$: $N_f = \frac{q}{2(2q+1)(1-\alpha)C_{-1}} \sigma_{-1}^{-2q}$, where, C_{-1}, q, σ_{-1} are the parameters

determined from the experimental fatigue test [33~38]. The FE analysis was continuously repeated until the crack go through the entire length at cross-section of weld structure. All variables in FE code were simultaneously updated for every cycle. The fatigue life of welded structure under the cyclic load was determined by the number cycles of repetition until the calculation is finished. Related detailed analysis theory was published by author [33~38].

To analyze the deformation and stress behavior of the T type pipe welding joint under cyclic loading, 3D fatigue high cycle damage analysis was carried out. The welding residual stresses and welding deformation were obtained by the FE welding simulation as an initial condition. Figure 6 shows a load condition of the T type pipe. A load is given by the displacement control. A displacement magnitude is from 0.0(mm) to 10.0 (mm).

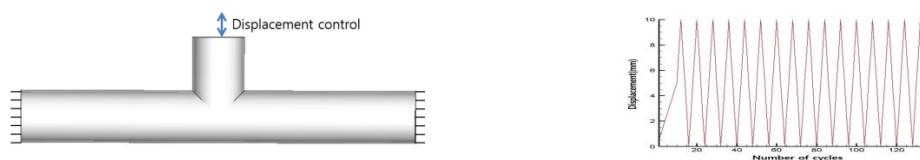


Fig 6. Load condition and Boundary conditions.

Fig 7 shows the fatigue behavior accompanied by crack. Initial crack is generated at the welding

joint and crack is propagated. Because, it is the most important thing to find the position of crack initiation, crack propagation and fatigue life. Therefore, when crack is generating, maximum load displacement and number of cycles are compared as shown in Fig 8. Fig 8 shows Fatigue life comparing with or without residual stress and welding deformation. The effect of welding deformation on fatigue strength is greater than the effect of residual stress on fatigue strength.

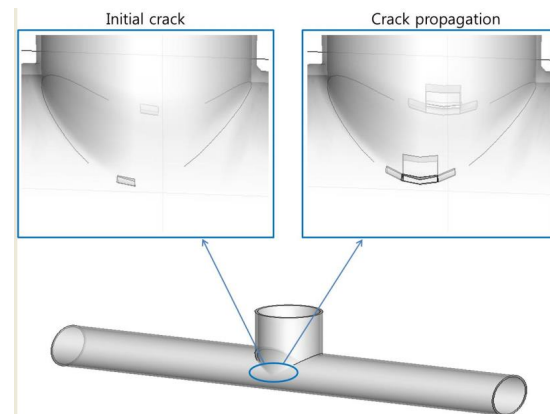


Fig 7. Fatigue behavior of the steel pipe accompanied by the crack.

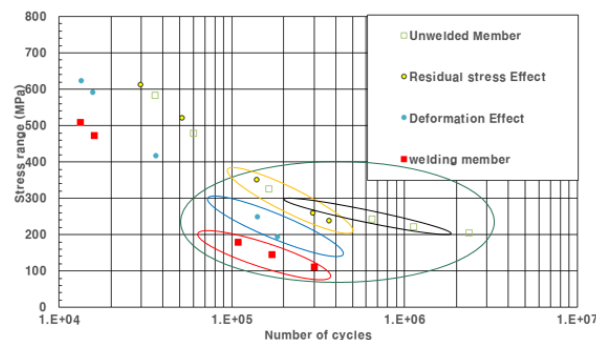


Fig 8. Fatigue strength comparing with or without residual stress and welding deformation

3 Conclusions

In this paper, a 3D fatigue analysis method was proposed from in-house codes based on continuum damage mechanics. To calculate the fatigue life of welded member, coupled three-dimensional heat conduction analysis, the thermal elastic-plastic analysis and 3D high cycle fatigue analysis was carried out. Also, there were many parameters such as stress concentration, residual stress, welding deformation, thickness, diameter, size, which affects fatigue performance of tube member. This paper dealt with fatigue behavior of a tube member subjected to cyclic loading through the numerical investigation, focusing on the welding deformation and residual stresses effect to the fatigue performance. Based on

the results in this work, the following conclusions can be drawn.

- 1) It clarified the effect of the welding deformation and residual stress on the fatigue strength in tube weld member.
- 2) Also, it clarified a fatigue life of the T-type tube welding joint.
- 3) It clarified the initial crack position and crack progress direction in the steel member.
- 4) FE analysis method presented here is helpful to understand the fatigue strength of steel tube.

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