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The behavior of welded joint in steel pipe members under monotonic and cyclic loading

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Abstract

Most steel pipe members are joined by welding. The residual stress and weld metal in a welded joint have the influence on the behavior of steel pipes. Therefore, to accurately predict the behavior of steel pipes with a welded joint, the influence of welding residual stress and weld metal on the behavior of steel pipe must be investigated.

In this paper, the residual stress of steel pipes with a welded joint was investigated by using a three-dimensional non-steady heat conduction analysis and a three-dimensional thermal elastic–plastic analysis. Based on the results of monotonic and cyclic loading tests, a hysteresis model for weld metal was formulated. The hysteresis model was proposed by the authors and applied to a three-dimensional finite elements analysis. To investigate the influence of a welded joint in steel pipes under monotonic and cyclic loading, three-dimensional finite elements analysis considering the proposed model and residual stress was carried out. The influence of a welded joint on the behavior of steel pipe members was investigated by comparing the analytical result both steel pipe with a welded joint and that without a welded joint.

Keywords: Hysteresis model; Residual stress; Steel pipe members; Welded joint; Weld metal

1. Introduction

Most steel pipe members are joined by welding—for example, steel piles, pressure vessels, pipe laying structures, water supply facilities, etc. As these structures are relatively slender and long, welded joints are required during construction. Therefore, when designing steel pipes with welded joints, the influence of the welded joint must be investigated.

In welding to make a welded joint, residual stress is inevitably generated. And this influences on the behavior of steel pipes under monotonic and cyclic loading. The weld metals used in welding process have different characteristics than structural steels in regard of the hysteretic behavior and mechanical characteristics. Thus, the residual stress distribution and characteristics of weld metal are very important factors to determine the behavior of steel pipes with a welded joint. Therefore, to accurately design steel pipe members with a welded joint, the research for the residual stress distribution and hysteresis model for weld metal is necessary.

In this paper, to investigate the residual stress distribution of steel pipes with a welded joint, a three-dimensional non-steady heat conduction analysis and a three-dimensional thermal elastic-plastic analysis were carried out [1,2]. To formulate a hysteresis model for SM490 and E71T-1 welded metal, monotonic and cyclic loading tests were performed. The hysteresis model was proposed by the authors and formulated considering the finite deformation, geometry and material non-linearities [3–5]. The formulated hysteresis model was applied to three-dimensional elastic–plastic finite element analysis using an 8-node cubic element.

The objective of this paper is to investigate the influence of a welded joint on behavior of steel pipe under monotonic and cyclic loading by using a three-dimensional elastic-plastic finite elements analysis. In this analysis, a

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hysteresis model for weld metal and welding residual stress was considered. The influence of a welded joint on the behavior of steel pipe was investigated by comparing analytical results for both steel pipe with a welded joint and that without a welded joint.

2. Experimental procedure and results

2.1. Experimental procedure

To formulate a hysteresis model for base and weld metal, monotonic and cyclic loading tests were performed. Base metal is SM490 (according to Korean standard) which is steel for welded structure corresponding to ASTM A572 Grade 50 specification. Weld metal is E71T-1 weld metal (AWS A5.20 specification). Based on ASTM specification, two kinds of round type specimens were manufactured as shown in Fig. 1; one is for the monotonic loading test and the other is for the cyclic loading test [6,7]. For weld metal specimen, a weld pad was manufactured by FCAW on the mold as shown in Fig. 2. Weld metal specimens were obtained from the manufactured weld pad.

2.2. Experimental results

Fig. 3 shows the test results of SM490 and E71T-1 weld metal. Mechanical properties of SM490 and E71T-1 weld metal are shown in Table 1 where $\varepsilon_{st}^{\mathrm{P}}$ and E_{st}^{P} are the initial plastic modulus and initial plastic strain of strain hardening. These test results were used to obtain the parameters of the hysteresis model for SM490 and E71T-1 weld metal.

3. Three-dimensional elastic-plastic finite element analysis

In this paper, to investigate the behavior of steel pipe with a welded joint, a three-dimensional elastic-plastic finite element analysis was carried out. A hysteresis model and finite deformation theory were applied to the finite element analysis.

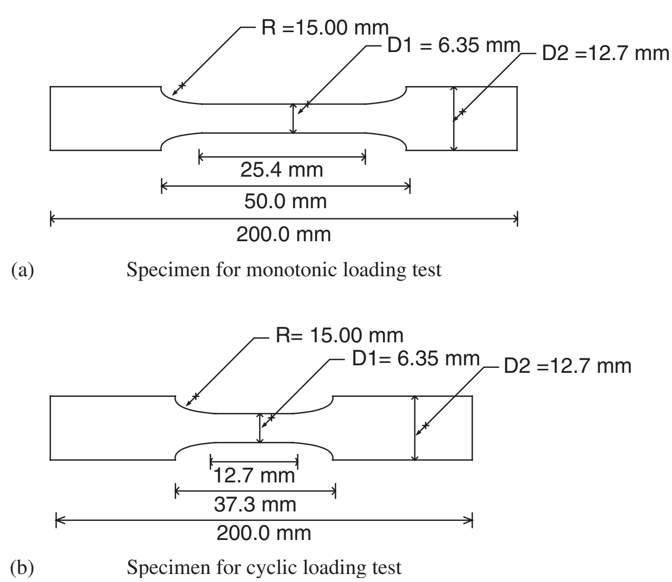

Fig. 1. Configuration of test specimens (round type).

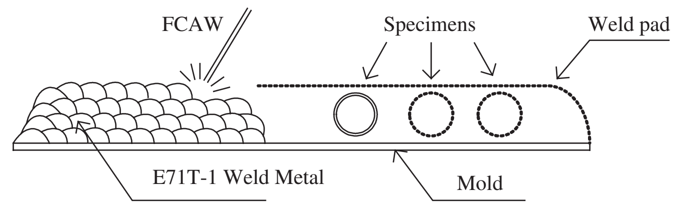

Fig. 2. Course of weld metal specimens.

3.1. Finite deformation theory

To describe the large deformation behavior, finite deformation theory was applied to the finite element analysis [8,9]. In displacement–strain relationship in finite deformation theory, Green strain tensor is used on the updated Lagrangian description and is defined as follows:

$$E_{ij} = \tfrac{1}{2}(u_{i,j} + u_{j,i} + u_{k,i}u_{k,j}). \tag{1}$$

The stress–strain relationship in finite deformation theory is defined by using a Jaumann rate of Kirchoff stress tensor (σ_{ij}^{J}) as follows:

$$\sigma_{ij}^{\mathrm{J}} = \sigma_{ij}^{*} - \omega_{ik}\sigma_{kj} + \omega_{jk}\sigma_{ki}, \tag{2}$$

where σ_{ij}^{*} is time derivative of the Kirchoff stress component and ω_{ij} is the spin tensor.

3.2. Formulation of hysteresis model

Based on test results, a hysteresis model for SM490 and E71T-1 weld metal was formulated. The hysteresis model was proposed by the authors and verified by comparing both analytical and test results [3–5]. In the proposed model, cyclic strain hardening, reduction of the elastic range, the Bauchinger effect and the yield plateau are considered. The logic function (ln) is used to precisely describe the non-linearity of the hysteretic curve. The formulated model on the uni-axial stress state is extended to the multi-axial stress state based on the two-surface plasticity theory [10,11].

A hysteresis model can be classified as a loading and unloading state based on the Von Mises yield criteria as shown in Fig. 4(a). A loading state is defined as yield surface and memory surface contact and movement according to the kinematic hardening rule. The plastic modulus ($E_{\mathrm{L}i}^{\mathrm{P}}$) in a loading state is based on a monotonic loading curve obtained by testing and formulated as follows:

$$E_{\mathrm{L}i}^{\mathrm{P}} == E_{st}^{\mathrm{P}} + \beta_{\mathrm{L}i} \ln\left(1 + \frac{x}{\alpha_{\mathrm{L}i}}\right), \tag{3}$$