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Influence of weld-induced residual stresses on the hysteretic behavior of a girth-welded circular stainless steel tube

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Abstract. The present study attempts to characterize the relevance of welding residual stresses to the hysteretic behaviour of a girth-welded circular stainless steel tube under cyclic mechanical loadings. Finite element (FE) thermal simulation of the girth butt welding process is first performed to identify the weld-induced residual stresses by using the one-way coupled three-dimensional (3-D) thermo-mechanical FE analysis method. 3-D elastic-plastic FE analysis equipped with the cyclic plasticity constitutive model capable of describing the cyclic response is next carried out to scrutinize the effects that the residual stresses have on the hysteretic performance of the girth-welded steel tube exposed to cyclic axial loading, which takes the residual stresses and plastic strains calculated from the preceding thermo-mechanical analysis as the initial condition. The analytical results demonstrate that the residual stresses bring about premature yielding and deterioration of the load carrying capacity in the elastic and the transition load ranges, whilst the residual stress effect is wiped out quickly in the plastic load domain since the residual stresses are nearly wholly relaxed after application of the cyclic plastic loading.

1. Introduction

Stainless steels are becoming an attractive choice of material in construction which includes bridges and offshore structures attributed to the established benefits over carbon steels, i.e., they present favourable mechanical properties, high durability and excellent resistance to corrosion and fire. Stainless steel circular tubes are, in particular, gaining increasing usage as exposed structural applications owing to the combination of corrosion resistance and structural efficiency as well as refined appearance. During their period of use, these tubes experience diverse load types such as axial tension or compression, bending, torsion and cyclic loading. In most tubular structures, connection of the circular members is mainly implemented by girth welding. In a girth-welded circular tube, the existence of inevitable welding residual stresses is well known [1-6], which result from the highly localized, non-uniform, transient thermal expansion and shrinkage imposed during welding process. Weld-induced residual stresses



increase the susceptibility to fatigue damage, stress corrosion cracking and brittle fracture [7-9]. It is well recognized that mechanical behavior of a girth-welded circular steel tube under monotonic loading is significantly affected by welding residual stresses [10, 11], i.e., the girth weld-induced residual stresses induce premature yielding and loss of stiffness and eventually lead to deterioration of the load carrying capacity.

A small number of research works have been devoted to examining the cyclic response of a girth-welded tubular member by experimental and/or numerical methods. Shao et al. [12, 13] investigated hysteretic performance of circular and square hollow section tubular T-joints under cyclic axial loading through the experiments and the corresponding finite element (FE) analyses. In the analyses, however, they did not consider the cyclic plasticity in the constitutive modeling and instead employed a bilinear stress-strain equation with isotropic hardening, even though the cyclic plasticity model is essential in the numerical reproduction of the cyclic behavior of the material, nor did they take account of the residual stresses generated by the girth welding due to the truly complex analytical procedure entailed in welding and subsequent cyclic mechanical loadings. Thus, quantitative assessment of the residual stress effect on the hysteretic behavior could not be attempted. Chang et al. [14] performed a numerical study on the hysteretic response of the welded joint in carbon steel pipe member under cyclic flexural loading taking welding residual stresses into account. Nevertheless, the accuracy of the result is doubtful since the performance of the cyclic constitutive model employed in the FE analysis, which is proposed based on the multi-surface hardening model, is not completely verified. Moreover, they failed to elaborate how the residual stresses affect the hysteretic behavior of the welded pipe joint. Hence, the structural response of a girth-welded tubular member subjected to cyclic loading has not been fully evaluated and is entitled to special attention.

This paper deals with hysteretic behavior of a girth-welded circular stainless steel tube under cyclic loading through the numerical investigation, focusing on the relevance of the weld-induced residual stresses to the cyclic performance. Thermal simulation of the girth butt welding process is first conducted to get the residual stresses by using the one-way coupled three-dimensional (3-D) thermo-mechanical FE analysis method. 3-D elastic-plastic FE analysis to scrutinize the residual stress effect on the hysteretic response of the girth-welded stainless steel tube subjected to cyclic axial loading is next carried out incorporating the residual stresses and plastic strains. A cyclic plasticity constitutive model for replicating the cyclic response is presented and its accuracy is confirmed by the experimental data, which is taken as the material constitutive equation in the FE analysis.

2. FE analysis of the residual stresses in the girth-welded circular stainless steel tube

FE thermal simulation of the girth butt welding process should first be carried out to obtain the weld-induced residual stresses and plastic strains, which are required input to the mechanical model for analysing the residual stress effect on the hysteretic behaviour of the girth-welded circular stainless steel tube under cyclic axial loading. In the present work, the process of welding was simulated by using the in-house FE code [15] developed by the authors based on the 3-D thermo-mechanical FE formulation, which has been extensively verified against experiments and numerical results found in the literature [5, 6]. The solution procedure for welding residual stresses and deformations is split into two parts:

- 1) A transient thermal analysis which solves for the temperature field and its history associated with the heating and cooling during welding.
- 2) A transient thermal-mechanical analysis that employs the temperature history solutions as the thermal loading for the evolution of residual stresses and deformations.

Since the thermal field has a strong effect on the mechanical field with little inverse influence, the two analyses are one-way coupled and thus can be performed in sequence. Specific details on the thermo-mechanical FE analysis are well described in the forthcomings [5, 6].

2.1. Model configuration

The FE analysis model configuration and dimensions are schematically shown in figure 1(a). The welding start/end position ($\theta = 0^\circ$) and the welding arc travel direction are also depicted in the illustration. Two circular steel tubes with V-groove between them were considered to be joined by a single-pass girth butt welding. The welding parameters employed for the present simulation were as follows: welding method, GTA

welding process; welding voltage, 22 V; welding current, 230 A and welding speed, 1.3 mm/s, respectively. The heat input and welding speed were derived from the experiment [16]. The 3-D FE mesh model is shown in figure 1(b). Note that only half of the tube geometry was modelled with eight-noded isoparametric solid elements due to the structural symmetry along the weld centreline. The adequate mesh density is achieved when an increase in the number of elements has a negligible effect on the global results. This results in the smallest element size of 0.9 mm (axial) $\times$ 1.5 mm (thickness) $\times$ 12.1 mm (circumference) in the weld region. The mesh in the regions far away from the girth weld is relatively coarse and equally refined along the axis to save computing time. In order to facilitate nodal data mapping between thermal and mechanical models, the same FE mesh refinement is used with respective element types. The FE element type used in the heat transfer model is the one which has single degree of freedom, temperature, on its each node, whilst in the mechanical model the element type is the other with three translational degrees of freedom at each node. As the tube is not clamped during the welding process, no boundary conditions except those to inhibit rigid body motion of the work piece are applied. The detailed boundary conditions adopted in the mechanical model are illustrated in figure 1(b) by the arrows.

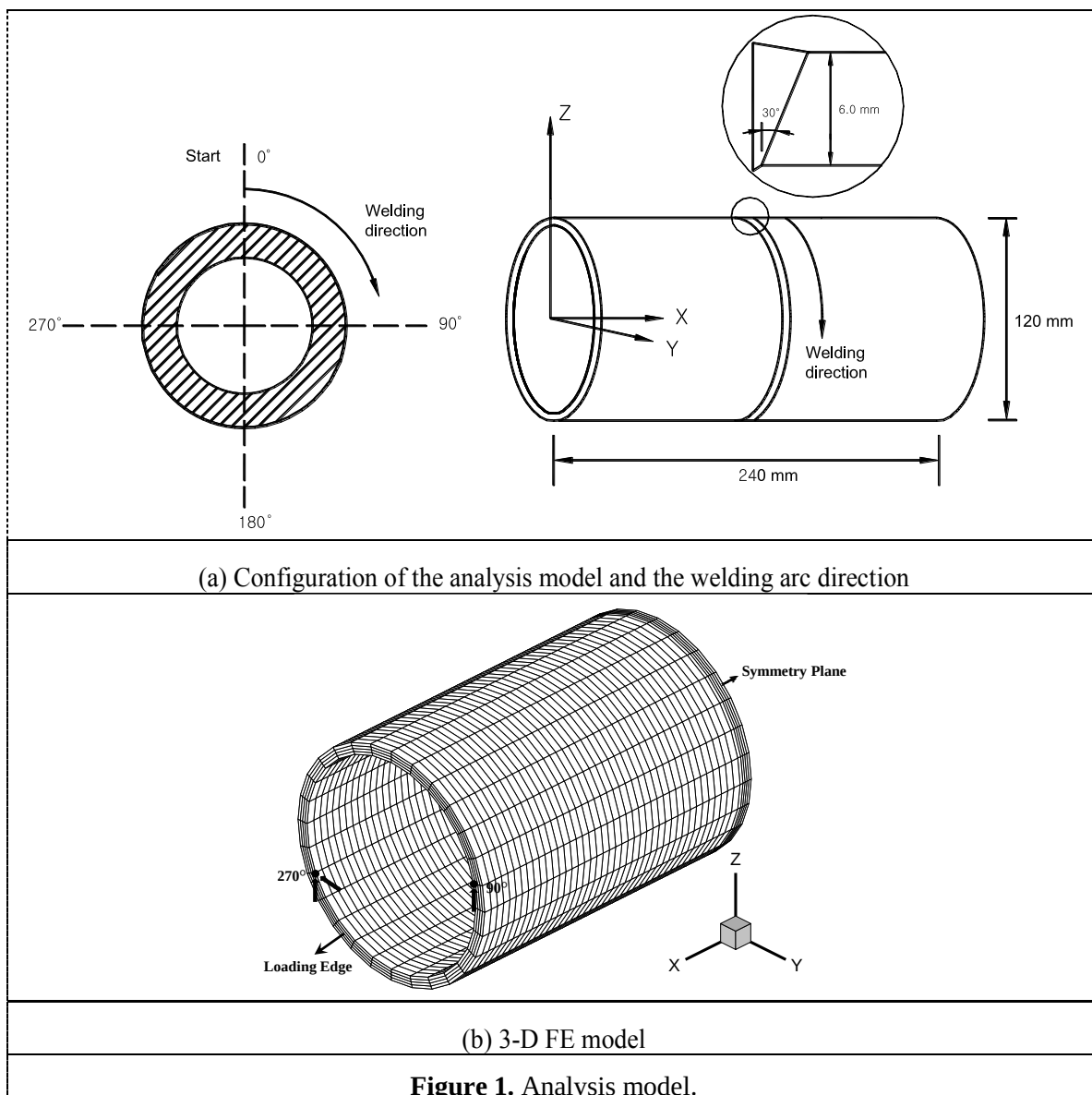


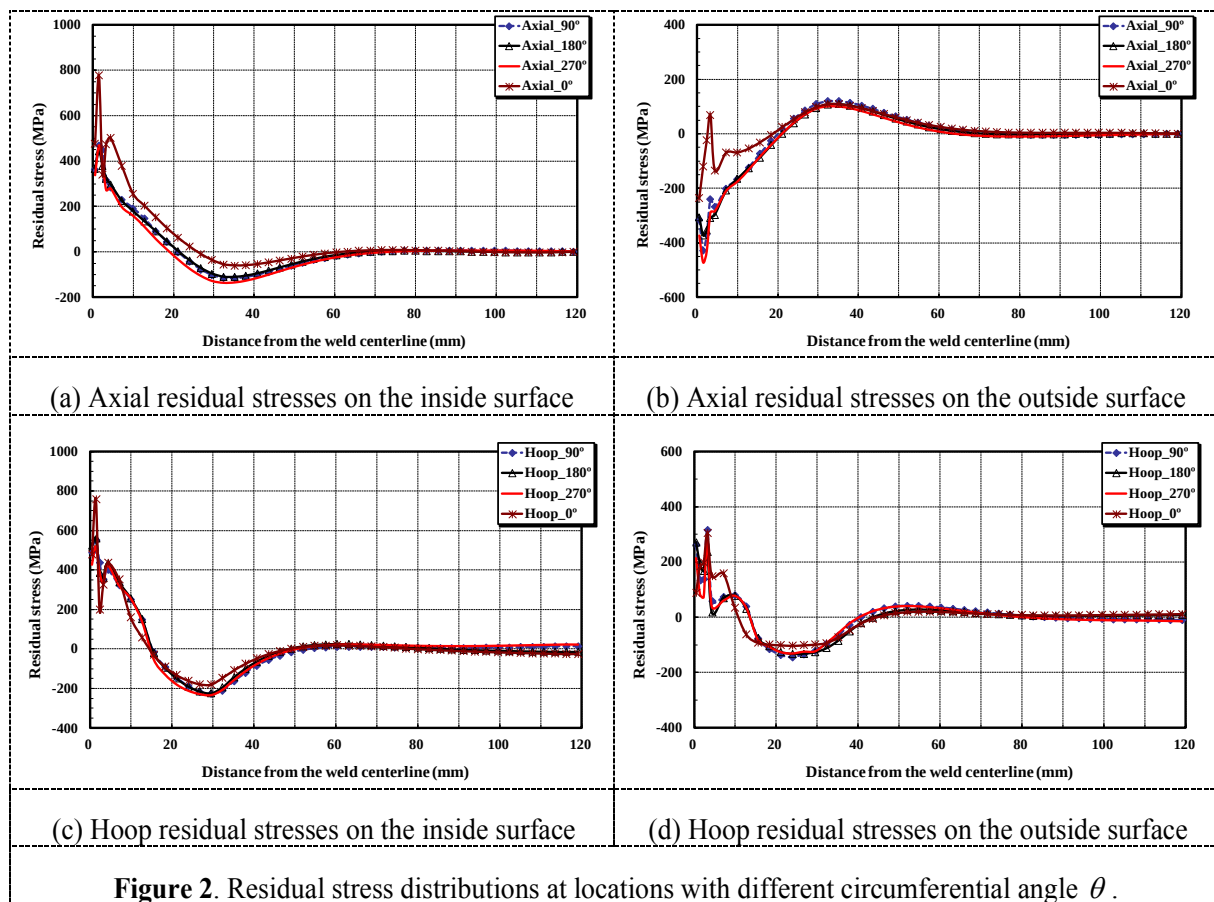
Figure 1. Analysis model.

2.2. Material model

The base metal chosen for this work is SUS304 austenitic stainless steel. Its physical (e.g. thermal conductivity, heat transfer coefficient, specific heat and density) and mechanical properties (e.g. yield stress, Young's modulus, Poisson's ratio and thermal expansion coefficient) are dependent on temperature. The variation of the thermal and mechanical properties with temperature is considered and is given in [5, 6]. In this analysis, autogenous weldment was assumed [17], i.e. the same material properties were used for the weld metal. The strain hardening produced by the cyclic thermal loading during welding in the weld region and its neighbourhood was also considered with the temperature-dependent strain hardening rule [5, 6].

2.3. Results and discussion

Figures 2(a) and 2(b) show the axial residual stresses along the axial direction at different circumferential angles from the weld start/end position (see figure 1(a)) on the inside and outside surfaces, respectively. From the predicted results, it can be found that in and around the weld region, the axial residual stresses are tensile on the inside surface and compressive on the outside surface due to the bending moment attributed to the circumferential shrinkage after welding. The tensile axial residual stresses level out in compression and converge to zero for self-equilibration as the distance from the weld region increases, and vice versa on the outside surface. Production mechanism for the residual stresses is well defined in the references [5, 6]. Figures 2(c) and 2(d) compare the hoop residual stresses along the axial direction at the different locations on the inside and outside surfaces, respectively. With regard to the hoop residual stresses, their formation is affected by the axial residual stresses. This accounts for why on the outside surface, which undergoes axial compression, the hoop residual stresses are less tensile at the weld area and its periphery compared to those on the inside surface. Detailed explanations on the axial and hoop stress distributions are given elsewhere [5, 6]. It should be recognized that the axial and hoop residual stresses vary depending on the circumferential



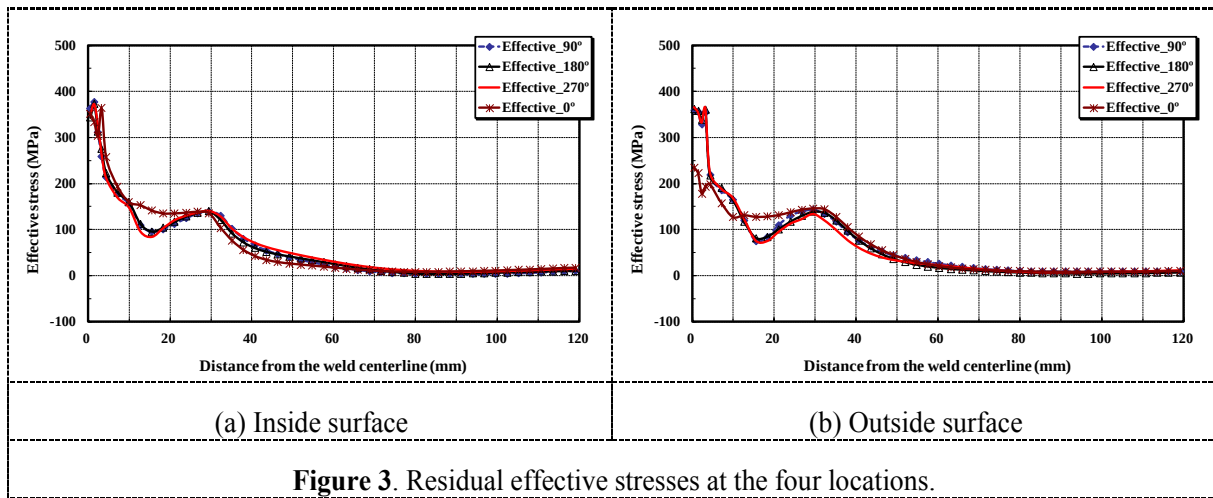


Figure 3. Residual effective stresses at the four locations.

position. This is due to the spatial variation of the internal restraint during the girth welding process. A considerable change of the stress profile is also seen at the welding start/end position. The residual effective stress distributions are also depicted in figure 3. It is noteworthy that the maximum residual effective stress at the girth weld exceeds the room temperature yield stress, which is also reported in an experimental work such as [18]. The higher strain hardening rate could be regarded as the main factor to explain the maximum residual stress. Nevertheless, it is much below the room temperature ultimate strength of the stainless steel. The effective stress distributions also exhibit the 3-D effects in and around the welded zone.

3. Hysteretic behaviour of the girth-welded circular stainless steel tube

3.1. Cyclic plasticity constitutive model

Detailed descriptions on the cyclic plasticity constitute model utilized to quantify the inelastic cyclic characteristics of the base material which displays cyclic hardening are made in [19]. In this section, only the key constitutive relations are given for completeness. The rate-independent cyclic plasticity constitutive model which assumes isotropic hardening and J_2 -type plasticity is considered and is based on the following three basic components:

(i) von Mises yield criterion: the yield criterion specifies the state of stress for which plasticity will occur. The yield surface is expressed by

$$f(\sigma - \alpha) = \left[\frac{3}{2} (\sigma' - \alpha') \cdot (\sigma' - \alpha') \right]^{1/2} - R - k^* = 0 \quad (1)$$

where f is the yield function, σ is the Cauchy stress tensor, α is the back stress tensor, σ' is the deviatoric stress tensor, α' is the deviatoric part of the back stress tensor, k^* is the initial size of the elastic domain and R is the isotropic hardening variable. The tensorial operator “ $\cdot$ ” indicates the inner product between second-order tensors A and B as $A \cdot B = A_{ij} B_{ij}$.

(ii) Flow rule: the total strain increment is additively decomposed into the elastic and the plastic strain increment. The plastic strain increment is given by

$$\dot{\varepsilon}^p = \dot{\lambda} \frac{\partial f}{\partial \sigma} = \frac{1}{H} \langle \dot{\sigma}' \cdot n \rangle n, \quad n = \sqrt{\frac{2}{3}} \frac{\partial f}{\partial \sigma} \quad (2)$$

where $\dot{\lambda}$ is a positive scale factor of proportionality, H is the plastic modulus, $\langle \cdot \rangle$ represents the MacCauley bracket. n is the unit vector normal to the yield surface at current stress point.

(iii) Hardening rule: the hardening rule describes the yield surface change due to plastic deformation. In general, the yield surface can vary in size (the yield surface expansion by isotropic hardening), shape (the yield surface distortion) and/or centre location (the yield surface translation by kinematic hardening)

in consequence of plastic deformation. In the present investigation, the yield surface variation with plastic loading is accommodated by considering the isotropic and the kinematic hardening rule. For the kinematic hardening rule which is the most favourite for simulations of a structural response induced by cyclic loading, the decomposed nonlinear kinematic hardening equation proposed by the authors [19] is adopted and incorporated into the cyclic plasticity constitutive model, which is expressed as

$$\dot{\alpha}'_{ij} = \sum_{k=1}^l (\dot{\alpha}'_{ij})_k = \sum_{k=1}^l \gamma_k \left\{ \frac{2}{3} c_k \dot{\epsilon}_{ij}^p - \left(\frac{\bar{\alpha}'_k}{c_k} \right)^m \left[\varphi(\alpha'_{ij})_k + (1-\varphi)((\alpha'_{rs})_k \cdot n_{rs}) n_{ij} \right] \dot{p} \right\} \quad (3)$$

where m , φ , c_k and γ_k are material constants. $\bar{\alpha}'_k = \left(\frac{3}{2} \alpha'_k : \alpha'_k \right)^{1/2}$ is the asymptotic value of the k^{th} back stress. The material parameters c_k and γ_k are determined using only the uniaxial stress-strain responses, while the additional constants m and φ are adjustable to fit the ratcheting experiment. In Eq. (3), $\dot{p}$ is the evolution of the accumulated plastic strain which can be expressed as

$$\dot{p} = |\dot{\epsilon}_{ij}^p| = \left[\frac{2}{3} \dot{\epsilon}_{ij}^p \dot{\epsilon}_{ij}^p \right]^{1/2} = \dot{\lambda} \left[\frac{2}{3} \frac{\partial f}{\partial \sigma_{ij}} \frac{\partial f}{\partial \sigma_{ij}} \right]^{1/2} \quad (4)$$

With regard to the isotropic hardening rule, the following equation is adopted [19].

$$R = Q(1 - e^{-bp}) \quad (5)$$

where Q is the saturated constant value of the isotropic hardening variable under a specific cyclic loading and can be obtained from experimental data. b is the material parameter which describes the rapidity of the isotropic hardening.

Simulation of a cyclic response primarily depends on the accuracy of the plastic modulus calculation. The plastic modulus can be derived from the kinematic hardening rule through the consistency condition as follows [19].

$$H = E_{ijkl} \frac{\partial f}{\partial \sigma_{ij}} \frac{\partial f}{\partial \sigma_{kl}} + \frac{2}{3} \sum_{k=1}^n \gamma_k c_k \frac{\partial f}{\partial \sigma_{ij}} \frac{\partial f}{\partial \sigma_{ij}} - \sum_{k=1}^n \gamma_k \frac{\partial f}{\partial \sigma_{ij}} \left(\frac{\bar{\alpha}'_k}{c_k} \right)^m \left[\varphi(\alpha'_{ij})_k + (1-\varphi)((\alpha'_{rs})_k \cdot n_{rs}) n_{ij} \right] \sqrt{\frac{2}{3} \frac{\partial f}{\partial \sigma_{kl}} \frac{\partial f}{\partial \sigma_{kl}}} + Qbe^{-bp} \sqrt{\frac{2}{3} \frac{\partial f}{\partial \sigma_{mn}} \frac{\partial f}{\partial \sigma_{mn}}} \quad (6)$$

where E_{ijkl} is the fourth-order elastic modulus tensor. The incremental total stress can then be obtained as

$$\dot{\sigma}_{ij} = E_{ijkl} \left(\dot{\epsilon}_{kl} - \dot{\lambda} \frac{\partial f}{\partial \sigma_{kl}} \right) = \left(E_{ijkl} - \frac{1}{H} E_{ijmn} \frac{\partial f}{\partial \sigma_{mn}} E_{opkl} \frac{\partial f}{\partial \sigma_{op}} \right) \dot{\epsilon}_{kl} \quad (7)$$

Eq. (7) can be rewritten as

$$\dot{\sigma}_{ij} = D_{ijkl} \dot{\epsilon}_{kl} \quad (8)$$

where the elasto-plastic modulus tensor is defined as

$$D_{ijkl} = E_{ijkl} - \frac{1}{H} E_{ijmn} \frac{\partial f}{\partial \sigma_{mn}} E_{opkl} \frac{\partial f}{\partial \sigma_{op}} \quad (9)$$

The path dependence on the plastic strain amplitude of the base material is not considered here owing to the lack of experimental data.

The cyclic plasticity constitutive model with three decomposed kinematic hardening rules ($l = 3$), which has three segments of a stable hysteresis loop, is used [20]. Therefore, the performance of the

cyclic plasticity model requires a total number of eleven material constants, i.e. the material constant for the initial size of the yield surface, the material parameters of c_1 , c_2 , c_3 , γ_1 , γ_2 , γ_3 , m , φ for calculating the kinematic hardening rate and those of Q , b for computing the isotropic hardening rule are needed to simulate the hysteretic response. To determine the kinematic hardening parameters, uniaxial test data of the stable stress-strain hysteresis loop with pure kinematic hardening are required. Assuming that the cyclic hardening is only induced by isotropic hardening, the isotropic hardening evolution with respect to accumulated plastic strain through the strain-controlled uniaxial symmetric cyclic loading test can be gained. The effect of isotropic hardening on the stabilized stress-strain hysteresis loop in which both isotropic and kinematic hardening are mixed can be excluded by using the isotropic hardening evolution function. Then, the kinematic hardening parameters c_1 , c_2 , c_3 and γ_1 , γ_2 , γ_3 are acquired in accordance with the procedures specified in the reference [20]. The material constants Q and b can also be obtained from the isotropic hardening evolution curve [19]. The additional kinematic hardening parameters m and φ are identified from the ratcheting experiments by the trial and error method [19].

In order to confirm the validity of the cyclic constitutive model used in this investigation and for direct comparison between the analytical prediction and the test data, numerical simulation of the experimental work by Kang et al. [21] was conducted by using the FE analysis method. They measured the stress-strain response of SUS 304 stainless steel under the strain-controlled uniaxial symmetric cyclic loading. Specific details on the test are presented in the reference [21]. Figure 4 compares the simulated and the experimental hysteresis curves for the strain-controlled cyclic loads with the strain amplitude of 0.6%. All the material parameters for the cyclic constitutive model were obtained from the experiment and are presented in Table 1. The predicted stress-strain response curves show a high correlation with the measured hysteresis loops, and it can also be observed that the cyclic plasticity constitutive model accurately duplicates the cyclic hardening behavior. As a result, the cyclic plasticity constitutive model is believed to be appropriate for describing the inelastic cyclic behavior of the material.

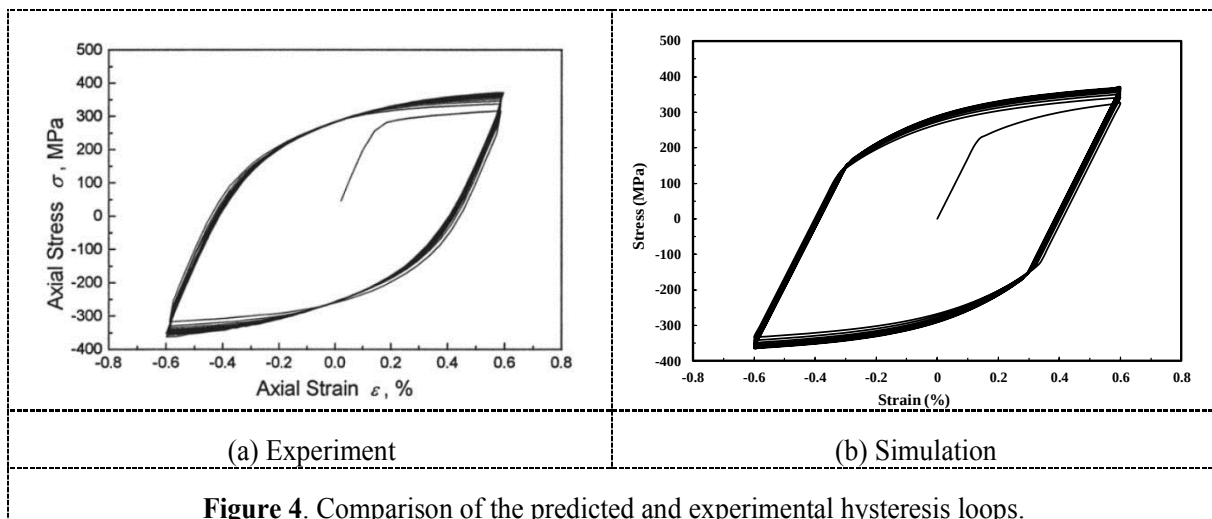


Table 1. Material constants for the kinematic and the isotropic hardening rate.

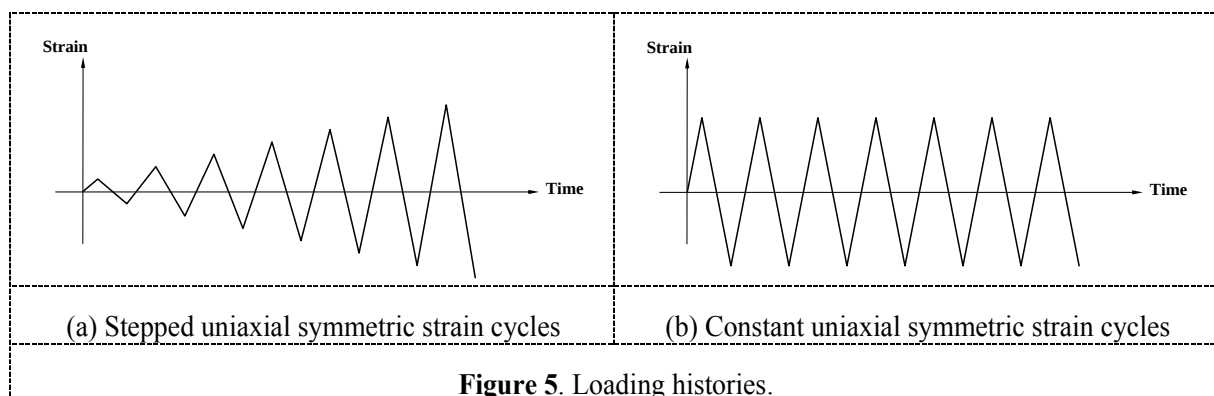
m	φ	c_1	c_2	c_3	γ_1
0.5	1.0	30.11	82.71	70.8	3.466
γ_2	γ_3	Q	b	k^*	
350.0	53.19	50.0	12.5	225.0	

3.2. 3-D FE analysis model

3-D elastic-plastic FE analyses were performed to explore structural responses of the girth-welded circular steel tube exposed to cyclic axial loading through the in-house FE-code [15, 22] equipped with the cyclic plasticity constitutive model and the material parameters. The same FE mesh refinement scheme as the thermal-mechanical model, with dissimilar loading and boundary conditions, was adopted to expedite data mapping between the two structural FE models. The computational domain was discretized by 3-D eight-noded isoparametric brick elements with three translational degrees of freedom at each node. The residual stresses and plastic strains obtained from the preceding FE thermal simulation were introduced as the pre-stress condition into the FE model. Then, symmetrical strain-controlled cycling was imposed on the edge of the girth-welded tube model (see figure 1(b)) parallel to the axial direction. Two loading patterns were considered, i.e. stepped uniaxial strain cycling in which the strain amplitude varies from 0.1 % to 0.6% and uniaxial strain cycling with constant strain amplitude of 0.6 %, which are shown in figure 5. The boundary conditions taken into consideration in the analysis assumed that the nodes at the loaded end were only free to move in the loading direction to allow for application of the strain cycling and were kinematically coupled to translate together in the same direction. As described earlier, autogenous weldment was employed during the girth welding. Therefore, the cyclic stress-strain relations for the base material can be used to capture the hysteretic response of the girth-welded circular stainless steel tube.

3.3. Results and discussion

Figure 6 compares the simulated cyclic strain-stress curves of the stainless steel tube with and without considering welding residual stresses for the stepped strain cycling with changing strain amplitude. It is immediately apparent that the cyclic behaviour is only affected by the residual stresses in the elastic (0.1%) and the transition load ranges (0.2 % and 0.3%), i.e., the residual stresses are not able to change the cyclic



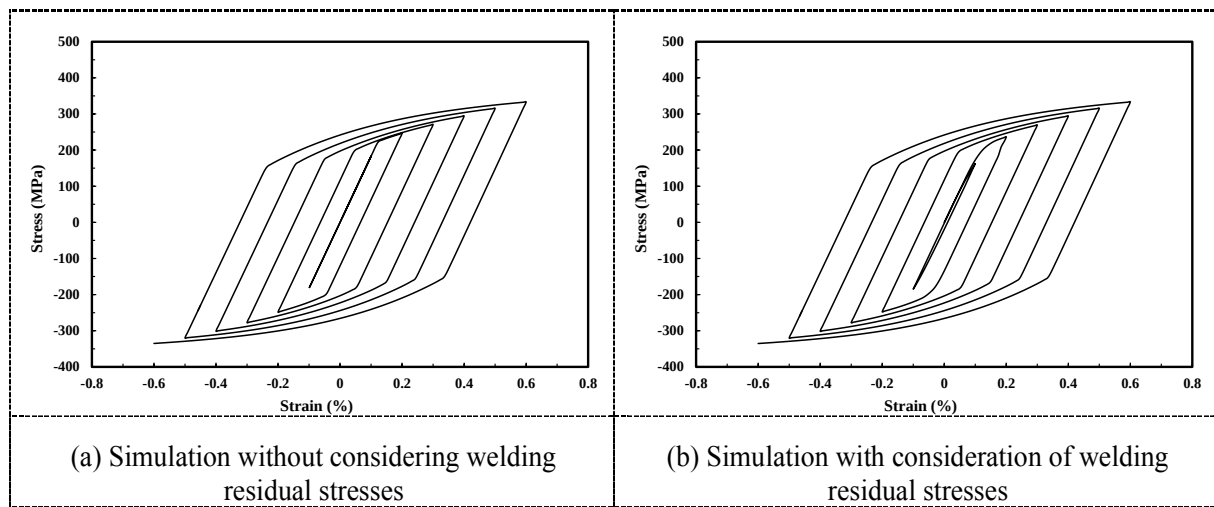


Figure 6. Cyclic strain-stress curves for the stepped strain cycling with changing strain amplitude.

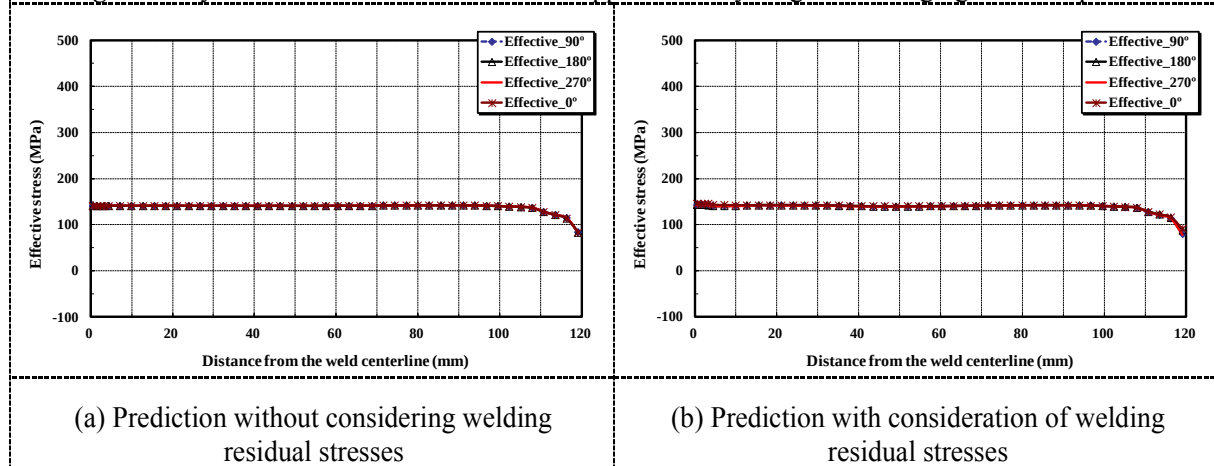


Figure 7. Comparison of the effective stresses on the inside surface after three cycles.

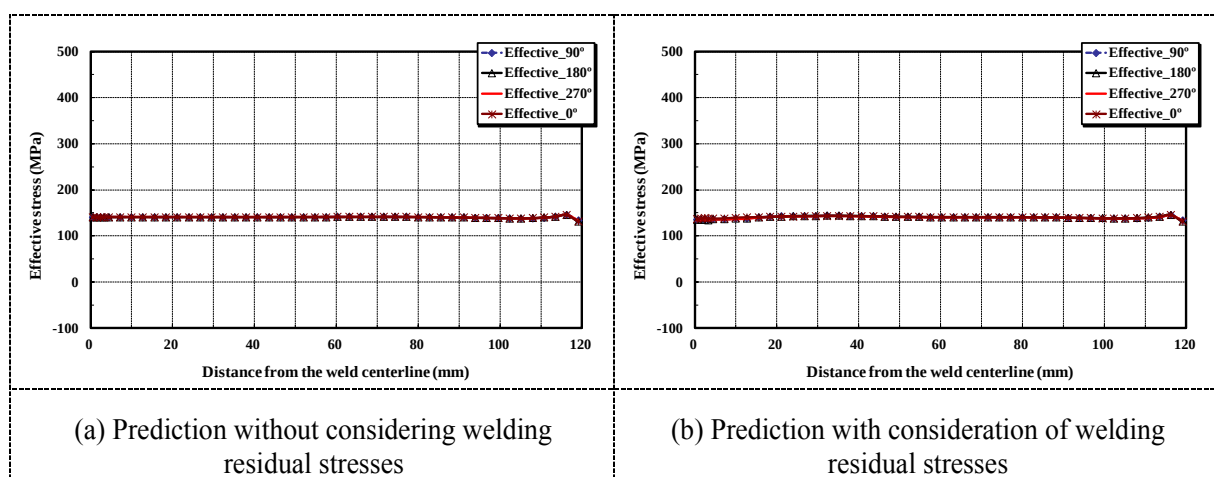
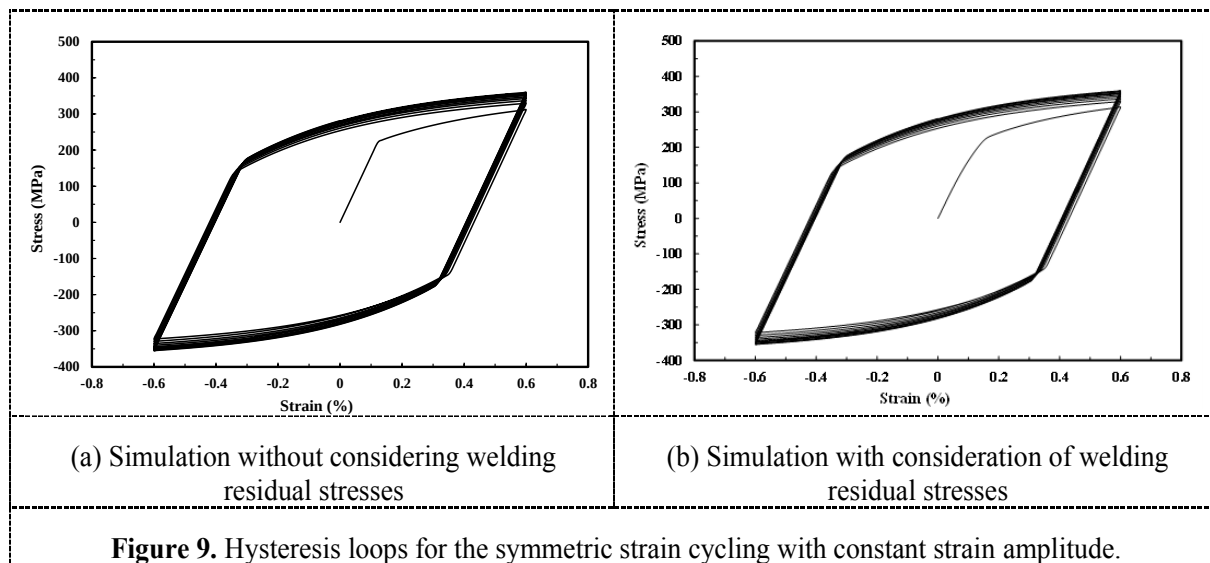


Figure 8. Comparison of the effective stresses on the outside surface after three cycles.



strain-stress histories in the fully plastic loading. In the elastic and the transition load domains, the residual stresses are not completely relaxed during the mechanical cyclic loading and the extent of the relaxation is mainly dependent on the stress amplitude applied [23]. The residual stresses cause premature yielding of the steel tube and result in deterioration of the load carrying capacity. In the plastic load range, however, the residual stresses are nearly wholly released by the cyclic plastic loading, thus do not influencing the hysteretic behaviour. Figures 7 and 8 represent the effective stress distributions after three cycles on the inside and outside surfaces, respectively with and without considering welding residual stresses. It can be recognized that both the effective stresses on the inside surface are nearly identical, and so do those on the outside surface. The simulated results corroborate the previous finding that the hysteretic behaviour of the steel tube is not affected by the residual stresses in the fully plastic load domain. Figure 9 depicts the predicted hysteresis loops of the tube model with and without considering weld-induced residual stresses for the symmetric strain cycling with the amplitude of 0.6 % which corresponds to the fully plastic load range. Careful observation of the analytical results reveals that effects of the residual stresses on the hysteretic behaviour of the girth-welded steel tube are confined to just the first cycle, i.e., the subsequent cyclic stress-strain curves are not altered in comparison with those of the tube model with no girth weld. The initial residual stresses bring about premature yielding and ensuing early onset of strain hardening, leading to a little higher load carrying capacity in the first loading phase. However, the residual stresses are almost completely relieved after the first cycle as a result of the cyclic loading, thus not capable of affecting the cyclic behaviour any more.

4. Conclusion

This study aimed to explore hysteretic behaviour of a girth-welded circular stainless steel tube subjected to cyclic mechanical loadings by numerical method and focused on characterizing the correlation of welding residual stresses to the cyclic behaviour. The one-way coupled 3-D thermo-mechanical FE analysis method was first utilized to simulate the girth butt welding process and hence to acquire the weld-induced residual stresses. Subsequently, the cyclic plasticity constitutive equation able to describe the cyclic response was presented and employed in the 3-D elastic-plastic FE analysis to scrutinize the effects of the residual stresses on the hysteretic performance of the girth-welded steel tube under cyclic axial loading. The weld-induced residual stresses and plastic strains gained from the thermal simulation were introduced as the initial condition for the FE analysis model. Two different loading types were considered to evaluate the influence that the residual stresses have on the hysteretic behaviour. Based on the results in this work, the following conclusions can be drawn.

- In the elastic and the transition load ranges, the residual stresses are not fully relaxed during the mechanical cyclic loading. The residual stresses induce premature yielding and deterioration of the load carrying capacity

- In the plastic load domain, the residual stresses are almost completely released by the cyclic plastic loading, thus do not affecting the hysteretic behaviour
- Accurate assessment of the residual stress effects on the hysteretic response under cyclic loading by the FE analysis method presented here can be helpful to understand the low-cycle fatigue behaviour of a girth-welded circular steel tube

Acknowledgments

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