A Simplified Method to Estimate Welding Induced Crack of Weldments with Initial Structural Restraints

J. M. Lee, J. K. Paik, M. H. Kim, S. W. Kang, and H. Y. Heo

Abstract

A practical method for evaluating the possibility of the occurrence of cracking in actual thick-plate T-joint weldments is presented in this study. Systematic experiments based on the method of the design of experiment are conducted in order to investigate the crack tendency in relation to typical welding parameters such as diffusible hydrogen, restraint intensity, preheating temperature and so on.

The elastic analysis using the finite element techniques is employed to quantify the restraint intensities of the specimens. The defined restraint intensities are treated in numerical way for the sake of considering the most uncertain factor among some major factors that govern the cracking phenomena due to welding.

The critical plane for judgment of the crack occurrence or crack density is presented as a function of typical welding parameters including determined restraint intensities. The results of numerical estimation by the proposed method for the experimental specimens show the usefulness as a practical tool in welding induced crack problem having extensive uncertainties.

Key Words : Restraint intensity, Crack density, Finite element analysis, Design of experiment, T-joint weldments.

1. Introduction

While it is well known that the welding is very commonly employed for making metallurgical joints for ships, offshore structures, and steel structures because of the advantages such as high joint efficiency, air and water tightness and so on, it is also important to realize that the welding is subject to many strict requirements in order to ensure the structural strength .[1] In general, latent damage or micro crack in welding joints can degrade the product performance, increase manufacturing costs due to the renewal process, and reduce structural integrity due to the relatively poor performance. Therefore, several cases of structural collapse caused by fatal defects in welded joints have been reported, and these have necessitated rigorous evaluations associated with welded joints.

Over the past decades, a number of studies have been performed on the clarification or verification of the relationship between welding-induced cracks and several welding parameters, but few are useful in the design process. As a demand for highly cost-efficient design criterion for preventing cracks increases, it would be attractive to be able to establish a relationship between the mechanical characteristics of weldments and the various welding parameters. This type of relationship should be determined on the basis of experience, engineering judgment or calculation such as simple and empirical formula for the prediction of

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J. M. Lee, J. K. Paik, M. H. Kim, and *S. W. Kang* : Department of Naval Architecture and Ocean Engineering, Pusan National University, Busan, Korea
E-mail : jaemlee@pusan.ac.kr
H. Y. Heo : Shipbuilding & Plant Research Center, Samsung Heavy Industries, Co., Ltd., Koje, Korea
E-mail : heeyoung.heo@samsung.com

shrinkages or angular distortions due to welding that are commonly found at shipyards.[2)]

It is evident that there are several crucial influence factors on the welding induced crack - including diffusible hydrogen - preheating temperature and residual stress. Among these factors, it is well recognized that high tensile residual stresses, set up in the region close to the welding, will promote fracture or failure. However, in practice an accurate prediction of this residual stress is difficult to obtain, especially for complex welded structures. A number of contributors previously investigated the validity of finite element methods for predicting the residual stress due to welding, thus considerable efforts have been put into the development of numerical technique.

It has also been recognized that the boundary condition, i.e. constraint or restraint condition of weldments, could significantly affect the welding induced crack. However, it is almost impossible to determine this restraining effect by a numerical way such as the finite element analysis since it may require a considerable amount of computational cost. Therefore, in spite of a number of successful examples using FEA on welding problems, the determination or evaluation of restraining effect for various actual weldments by a numerical way is still an open problem.

The intention of this study is to set up the relationship between crack and welding parameters especially in terms of the restraining effect in T-joint thick weldments. A practical method using the combination of systematic experiments, finite element analyses and analytic analyses is implemented to investigate the possibility of crack occurrence. This method is particularly useful for the cases where design is fixed and rigorous safety requirements are in place.

2. Numerical analysis

In this study, the welding induced residual stresses are calculated by finite element analysis using a commercial finite element package SYSWELD+[3)]. The calculated residual stress values are used to quantify the restraining effect of corresponding structures in a numerical way. After investigating residual stress characteristics and verifying numerical results, a simplified numerical method using another commercial finite element package NASTRAN is proposed to model the mechanical behavior of structure during welding process. The numerical results, i.e. strain distribution obtained by NASTRAN, are chosen as restraint factors. The restraint intensities are calculated from the restraint factors for various boundary types of the corresponding structure.

At first, the thermo-mechanical FE analysis was carried out for T-joint profile shown in Fig. 1 using SYSWELD+. The finite element mesh subdivision for T-joint is shown in Fig. 2. The model contents the basic material and 39 welding beads. In the actual analysis, a multi-pass welding process was fully simulated in order to investigate the variation of stress distribution with respect to welding beads.

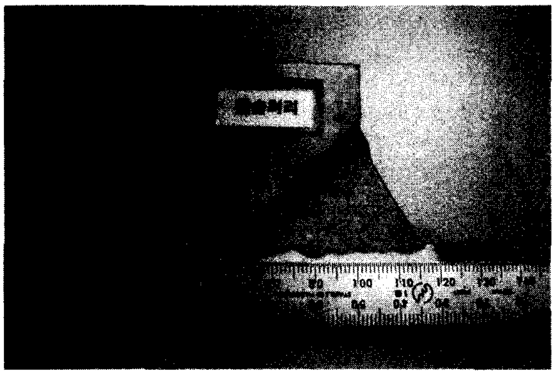

Fig. 1 Cross-sectional view of T-joint

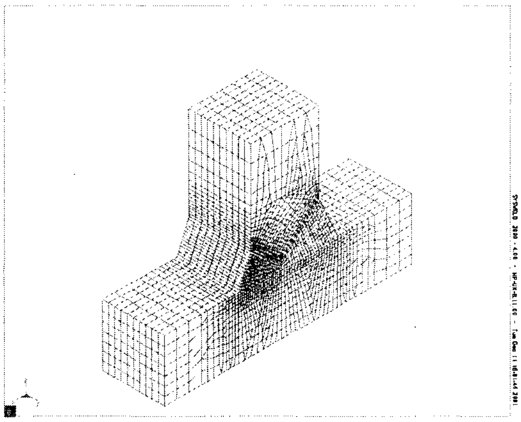

Fig. 2 Finite element mesh sub-division

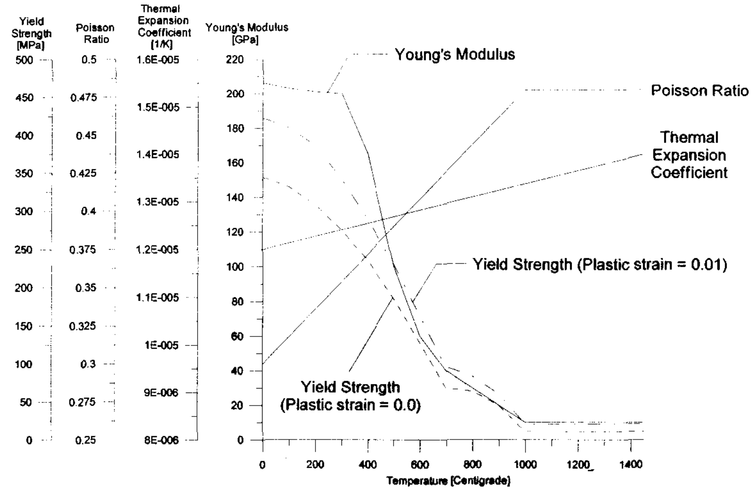

Fig. 3 Temperature dependent material properties

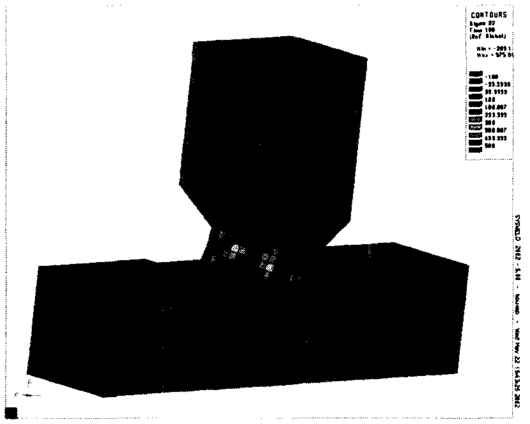

Fig. 4 Equivalent stress distribution after 4th bead laid down

Fig. 5 Residual stress characteristics for each welding bead

The temperature dependent material properties shown in Fig. 3 are considered during the whole calculation steps. For a description of heating process the double ellipsoidal moving heat source is used. Activation and deactivation of elements for welding bead during process is carried out. The temperature distribution is calculated by assuming a steady-state condition since the heat source does not change its shape at each calculation step. However it is important to note that the problem itself is treated as a transient.

Fig. 4 shows the von Mises equivalent stress distribution after the 4th bead was laid down. The maximum and average stress values at the time after each welding bead was laid down are demonstrated in Fig. 5.

It is evident that welding induced cracks are likely to be sensitive to welding conditions of corresponding structure. Therefore, it is important to have a good understanding of the effect of these conditions on the mechanical response. However, the parametric analysis for various welding conditions, i.e. welding length, boundary condition etc., is almost practically impossible. But as shown in Fig. 5, it can be found that the difference of residual stress magnitude for each bead could be negligible. Therefore, a simple welding simulation such as single pass welding etc. is considered to be sufficient and efficient to investigate the effect of welding length on the welding residual stress. In this study, bead-on plate problem is chosen for investigating the effect of welding length on the

Table 1 Details of analysis conditions and numerical solutions

case	Geometry of model (mm)			Boundary condition	Longitudinal average residual stress (MPa)
	width	welding length	thickness		
1	300	50	8	Free	274.2
2	300	50	8	Fix (L=0, 50)	352.5
3	300	100	8	Free	293.4
4	300	100	8	Fix (L=0, 100)	335.0
5	300	200	8	Free	325.4
6	300	200	8	Fix (L=0, 200)	331.8
7	300	300	8	Free	326.2
8	300	300	8	Fix (L=0, 300)	329.3

welding residual stress. After verifying the quantitative evaluation for numerical results for bead-on plate with the dimension 310×1380×8 (B×L×t, mm) as shown in Fig. 6 and 7, a parametric analysis was performed for 8 cases with different welding conditions.

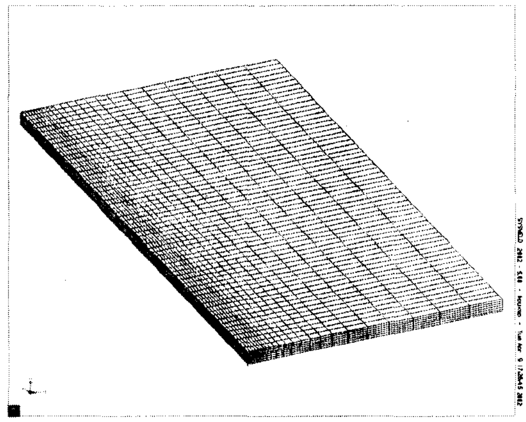

Fig. 6 FE mesh subdivision for bead-on plate (1/2 model)

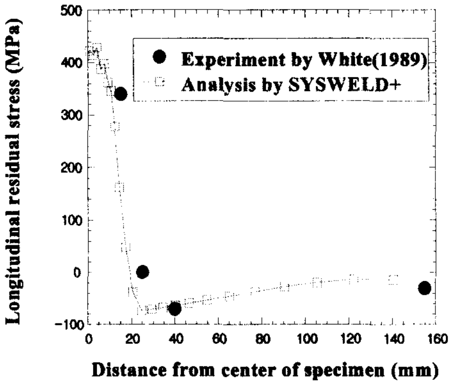

Fig. 7 Longitudinal residual stress at top surface of plate

The details of analysis conditions and some numerical solutions are listed in Table 1. The "Fix" means that 3 translation components of DOF are fixed at both edge sides, i.e. welding starting and end sides. The physical and mechanical properties of material are the same as T-joint model. Fig. 8 shows the effect of boundary condition on the residual stress as a function of welding length.

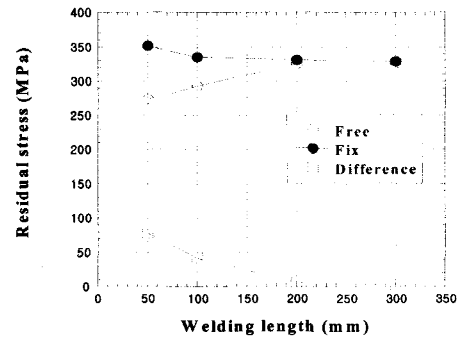

Fig. 8 The effect of welding length on the residual stress characteristics

It is interesting to note that the residual stress reaches a same value with the increase of the welding length. For the free boundary condition, the residual stress increases as the welding length increases. This reveals that the internal restraining effect such as dead weight can exist even under the fully free constraint condition. On the other hand, the residual stress decreases with the increase of welding length for fixed boundary. In general, if the welding length is relatively short between rigid boundaries, for instance repair welding case, the value of residual stress are high.

These residual stresses may cause the cracking in welding joints in many cases. This is due to the influence of restraint conditions. If the residual stress characteristics, for example the difference shown in Fig.8, produced by welding can be used for quantifying a restraint conditions, the determined restraint intensity can be used as an influence factor for welding induced cracks.

Although the FE analyses for welding have gained an increasing interest, numerical experiences have shown that some difficulties may arise with respect to the computational cost. In practice, the computational method has rarely been applied to analyze real weld structures because of the computational efficiency. Therefore, it can be more efficient to carry out simplified analysis for welding problem for the case of real weld structures, not test coupons. In this study, a simplified elastic finite element analysis using NASTRAN is carried out for real T-joint weldments.

The most representative mechanical behaviors of structures subjected to welding may be shrinkage or distortion. In this study, the shrinkage of the weld seam is focused, then it is assumed that the internal mechanical status of the structure, which was produced by rigid boundary for preventing free shrinkage, affect crack occurrence. Based on this assumption, shrinkage of the seam due to a welding is modeled as mechanical shrinkage, and then the mechanical responses were investigated. In order to induce mechanical shrinkage in model, the concentrated compressive unit load was applied to analysis model, shown as Fig. 9.

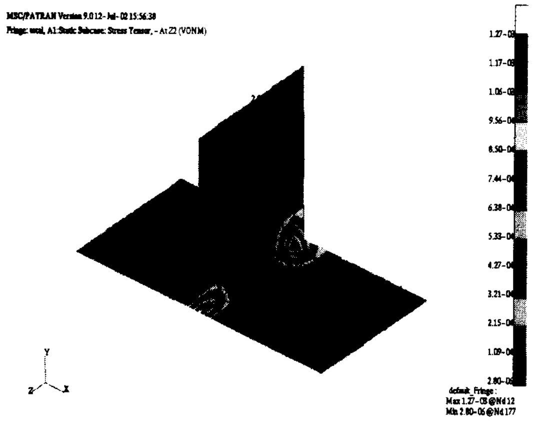

Fig. 9 Equivalent strain distribution of T-joint subjected to concentrated compressive unit load

Equivalent strains are selected at discrete elements of flange on the cross line between flange and web in the finite element mesh, as shown in Fig. 9. The restraint factor of corresponding structure is taken from the effective equivalent strain calculated by the following[4) :

$$RF = \overline{\varepsilon_{eq}} = \frac{\sum_{i=1}^{n} \varepsilon_{eq}^{i} \times l^{i}}{L} \tag{1}$$

where, the subscript i denotes reference element, l and L are the length of element and the entire model, respectively.

The restrain intensity is defined using the above restraint factor for free and fully fixed boundary conditions, i.e. RF_{free} and RF_{fix}.

$$RI = RF_{free} - RF_{fix} \tag{2}$$

According to the above definition, the restraint intensity could be determined by simple analysis for a given structure. The variation of restraint intensity due to different boundary conditions is shown in Fig. 10.

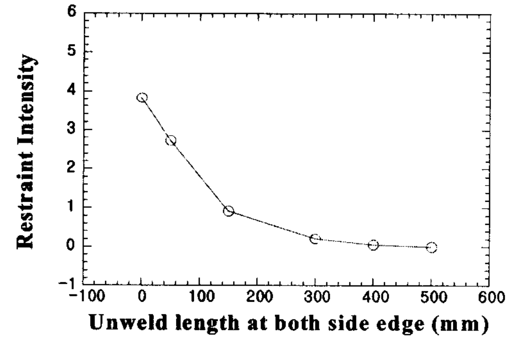

Fig. 10 The relationship between the restraint intensities and restraint conditions

3. Crack initiation experiment

In this study, crack occurrence characteristics of actual weld structures, as shown in Fig. 11, with various weld lengths and restraints associated with weld conditions are investigated. For the uniform weld

Photo 1 Photograph of the experiment set-up

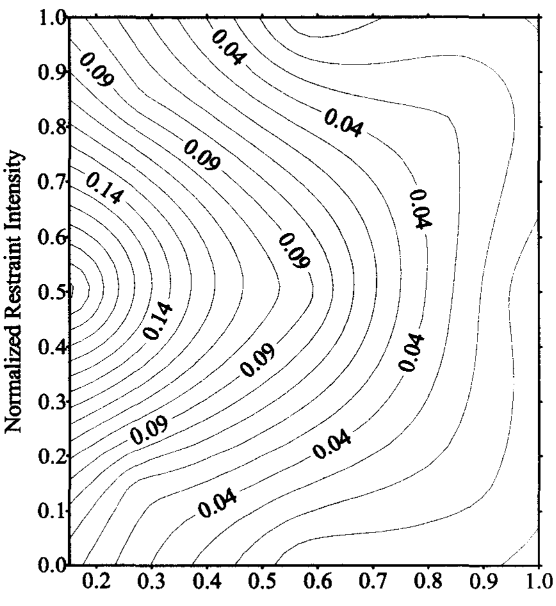

Fig. 11 The contour diagram of crack density as a function of the preheating temperature and the restraint intensity

condition, an automated weld is carried out using "Bugo tractor" as shown in Photo 1, and hydrogen contents of weld materials are also measured. Photo 2 illustrates a weld completed specimen.

For the measurement of hydrogen contents, Gas-chromatography (AWS A4.3-93, JIS Z3118) methods is adopted, and cracks are measured using ultrasonic test. The restraints are computed based on the method described in chapter 2, and the actual measurement values such as preheating temperature, hydrogen contents etc are summarized in Table 2.

The crack density is defined as the number of crack

Photo 2 Photograph of the test specimens

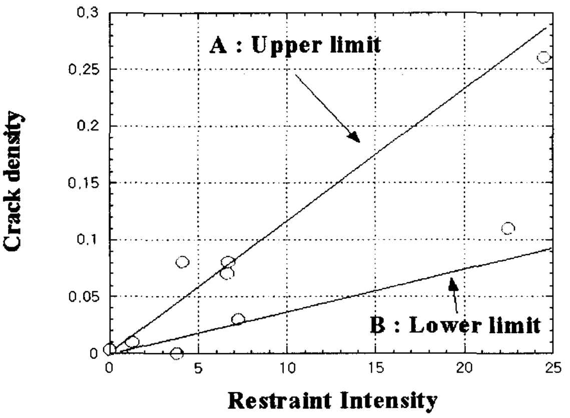

Fig. 12 Relationship between restraint intensities and crack densities for T-joint

per unit weld length. As shown in Table 2, the restraints, diffusible hydrogen, preheating temperature and crack density does not exhibit one-to-one relation. This means that cracks are due to relationships among various weld conditions, and it can be concluded that a proper combinations of weld condition is required to explain the relationship.

In general, materials become brittle when diffusible hydrogen deposit in the local area of weld metal. Moreover, since the diffusible hydrogen provide causes for the hydrogen induced or low-temperature cracks, the humidity is carefully controlled not to exceed certain level. However, due to the difficulty of maintaining precise humidity, preheating is normally exercised to prevent crack occurrences. There exists a certain relationship between diffusible hydrogen and preheating temperature since improper preheating results in more number of crack initiations.

Table 2 Details of analysis conditions and numerical solutions

	Preheating temp. (℃)		Restraint intensity		Diffusible hydrogen	Crack density	
	Measured	Normalized	Calculated	Normalized		Measured	Normalized
TRC-01	18	0.27	3.24	0.85	4.6	65	0.11
TRC-02	18	0.27	0.56	0.15	5.8	45	0.08
TRC-03	58	0.88	3.24	0.85	5.1	17	0.03
TRC-04	58	0.88	0.56	0.15	6.5	7	0.01
TRC-05	38	0.58	3.8	1.0	6	-	-
TRC-06	38	0.58	0	0.0	7.5	2	0.003
TRC-07	10	0.16	1.9	0.5	5	161	0.26
TRC-08	66	1.0	1.9	0.5	4.9	0	0.0
TRC-09	38	0.58	1.9	0.5	6.2	46	0.08
TRC-10	38	0.58	1.9	0.5	5.6	44	0.07
TRC-11	38	0.58	1.9	0.5	5.9	-	-
TRC-10	38	0.58	1.9	0.5	5.6	42	0.07

On the other hand, since the constraint is determined once the shape of structure is defined in design stage and the hydrogen content is determined once the weld condition is defined, it is required to consider the effect of hydrogen content on the top of restraints. It is desired to define restraints having cross relationship with reheating temperature and diffusible hydrogen content. In this study, it is proposed to use the constraints as follows :

$$RI_H = RI \times f(T_H) \qquad (3)$$

$$F(T_H) = T_{cr} / T_a \qquad (4)$$

where, RI is the calculated constraint as discussed in chapter 2, and $f(T_H)$ is a compensation constant in order to consider the preheating temperature. The ratio of preheat temperature based on the hydrogen content level and the actual preheat temperature is used as a compensation constant.

Preheating temperature proposed by Satoh[5)] is used as compensation constants as shown in equation (4) in this study. The measured restraints and crack density and the calculated one based on equation (3) are illustrated in Fig. 12. The line A and the line B demonstrate the maximum and the minimum limits of crack density. Thus the area between the line A and B conform to crack density based on the experiment. Therefore, crack density can be reduced based on the qualitative movement of line A and B according to different preheating temperature or diffusible hydrogen control. For example, less constraint would be an effective mean to reduce the probability of crack initiations since the constraint and the crack density are in a proportional relationship.

Or the detailed conditions can be suggested based on the movement of line A and B even for similar values calculated using qualitative (3). This could be a useful information in reducing the probability of crack occurrences. The method proposed in this research can be used as a useful tool in predicting the probability of crack occurrence as well as validating the dimension of structures and the welding conditions for the minimum crack occurrence.

4. Conclusion

The evaluation method of the possibility of crack occurrence was presented in terms of crack density. The restraint intensity was defined in a numerical way, and it was used to establish contour diagram of crack density for given T-joint weldments. The comparison between the results of the numerical estimation and the experiments shows good agreement. This demonstrates the usefulness of the proposed method as a practical tool for evaluating the welding induced crack.

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