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Simplified welding distortion analysis for fillet welding using composite shell elements

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ABSTRACT: *This paper presents the simplified welding distortion analysis method to predict the welding deformation of both plate and stiffener in fillet welds. Currently, the methods based on equivalent thermal strain like Strain as Direct Boundary (SDB) has been widely used due to effective prediction of welding deformation. Regarding the fillet welding, however, those methods cannot represent deformation of both members at once since the temperature degree of freedom is shared at the intersection nodes in both members. In this paper, we propose new approach to simulate deformation of both members. The method can simulate fillet weld deformations by employing composite shell element and using different thermal expansion coefficients according to thickness direction with fixed temperature at intersection nodes. For verification purpose, we compare of result from experiments, 3D thermo elastic plastic analysis, SDB method and proposed method. Compared of experiments results, the proposed method can effectively predict welding deformation for fillet welds.*

KEY WORDS: Prediction of welding distortion; Fillet welding; Inherent strain; Composite shell; Strain as direct boundary (SDB).

INTRODUCTION

Since welding is one of high productive joining method to assemble various parts, it is widely used in shipbuilding and offshore plants industries. Although welding affords many benefits such as flexibility of design, weight reduction and cost savings, residual stress and distortion are unavoidable (Wang et al., 2013). These distortions are caused by the heating and cooling cycle in welding process. In particular, welding distortion negatively affects the dimension accuracy, external appearance and various strengths of the structures. Avoiding these disadvantages, it requires such re-works, for example cutting, alignment and straightening, that schedule delay and additional costs are caused. However, by predicting magnitude of welding distortion in advance, we can not only efficiently construct structures maintaining same quality but also reduce reworks by means of reverse design and distortion margin. For these reasons, prediction of welding distortion became so crucial that many researches have been conducted in this field (Deng et al., 2007).

In order to predict welding distortion, some researchers introduced the 3D thermo elastic plastic finite element method to deeply look into interior phenomena as well as exterior (Teng et al., 2001; Deng et al., 2007; Perić et al., 2014). Even though thermal elastic plastic finite element method can be effectively used to predict welding residual stress and distortion for sample size structures, this method cannot be applied to large welded structures because of computation time and costs. Accordingly,

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simplified analysis methods have been frequently used for the prediction of welding distortion because those methods requires less computation time and resource compared to the 3D thermo elastic plastic analysis while maintaining reasonable prediction accuracy. Many simplified methods have used the inherent strain, which is regarded as the plastic strain equivalent to the distortion during welding process. If the inherent strain is known for each thermal process, deformation can be predicted using elastic analysis without the computationally expensive plastic stress analysis (Luo et al., 1997).

Recently, based on the long weld assumption, many researchers have proposed approaches, which use equivalent thermal strain and shell elements, to describe welding deformation (Jung and Tsai, 2004; Ha et al., 2008). It is more convenient for predicting welding distortion because of scalar parameters such as thermal expansion coefficient and artificial temperature as well as it is able to reduce modeling costs. In particular, the SDB method can describe the angular deformation of plates by introducing artificial temperatures of top and bottom surfaces in shell elements. Since temperatures at interior integration points are automatically assigned by linear interpolation of finite element methods, it can be easily depicted with a trapezoidal shapes of inherent strain region, which usually occur in butt joint. In this respects, the SDB method is the effective way to predict the welding deformation for butt joints without substantial efforts.

However, an important issue has not been considered in these methods. When it comes to fillet joints, which consist of a plate and a stiffener, it cannot predict deformation for both members. As you can see Fig. 1, since the nodes, which are located at intersections, share their degree of freedom such as a temperature, there is nothing but predicting deformation of either the plate or the stiffener.

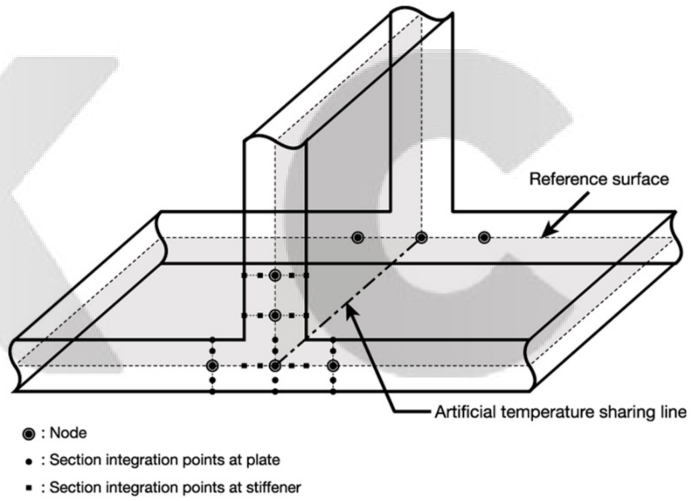


Fig. 1 Shell element in fillet welds.

For the ship production, previous methods didn’t consider the stiffener deformation because it is not the main issue to predict stiffener deformation. The former purpose of prediction of welding deformation was how much deformation occurs during fabricating hull forms, which is mostly affected by the plate deformation (Wang et al., 2013). In addition, since the plate deformation is relatively substantial than stiffener deformation, it was neglected. In the offshore structure, however, since all of the part should be under the control, the stiffener deformation must be also taken consideration in simplified analysis as well as the plate deformation.

In this paper, we suggest that new approach can predict both plate and stiffener deformation at once. In order to verify this method, we compare with results from experiments, 3D thermo elastic plastic analysis and previous simplified analysis.

BACKGROUNDS

Ueda et al. (1975) referred that the inherent strain, which is such incompatible strain produced by plastic strain, phase transformation or other means, was originally regarded to predict the residual stress. For seeking practical methods to predict the residual stress, Ueda and co-workers studied the characteristics of the inherent strain (Ueda et al., 1989; Ueda and Ma, 1994; Ma et al., 1995). They found where the inherent strain is uniform except starting and end regions of plates and inherent strain is distributed like trapezoid near weldment in butt joints while the distribution of inherent strain looks like ellipsoid in T-joints. Luo et al. (1997) suggested the models to figure out inherent strain and how to predict welding distortion based on inherent strain with elastic analysis. This paper presented that the inherent strain is not only mathematically calculated based on restraint rates and the maximum experienced temperature but also become the important factor to predict welding distortion. Jang et al. (1997) developed the equivalent load method to predict welding deformation with force and moment concept. In their method, welding distortion can be intuitionally predicted as well as modeling costs can be reduced by employing shell elements. Deng et al. (2007) investigated prediction of welding distortion for large structures by employing inherent deformation method. Furthermore, they considered influence of initial gap together. In above all methods, although each procedure is totally different, source of deformation is considered as vector components. So it is relatively difficult to apply to practical structures. Especially, in case of curvature plates, there is possibility for structures to move rigid body motion due to the remaining force.

For these reasons, the way to directly input the inherent strain as the equivalent thermal strain was developed. Luo et al. (1999) showed that welding deformation can be described using the thermal expansion coefficient and artificial temperatures. In particular, by employing two layer plate elements, it is shown that angular deformation can be depicted by difference with top and bottom strain. Jung and Tsai (2004) developed the Plasticity based Distortion Analysis (PDA) to investigate which plastic strain component is most influential in T-joint fillet angular deformation. Particularly, it is shown that how artificial temperature is obtained by the systematical procedure. However, it is so applied to solid elements that it is not considered to represent how to apply this method to shell elements. Ha et al. (2008) introduced that Strain as Direct Boundary (SDB), which is also employed shell elements, has been consistently used for welding distortion of large structures because it is systematically designed. In SDB, the inherent strain is obtained based on combination of the thermal expansion coefficient and top and bottom artificial temperature, which are calculated from the inherent strain distribution. By using top and bottom artificial temperature in shell elements, it can automatically express trapezoidal inherent strain region by linear interpolation in finite element method. Compared of previous methods, it has the benefit that there are no possibility to occur rigid body motion in the analysis. In chapter 4.1, detailed explanation is described.

However, since the SDB method mainly focuses on welding distortion on butt joints, as mentioned above, introducing the SDB method to fillet welds become a big challenge. Therefore, new approach is presented to describe welding distortion of both plates and stiffeners maintaining SDB benefits in this paper.

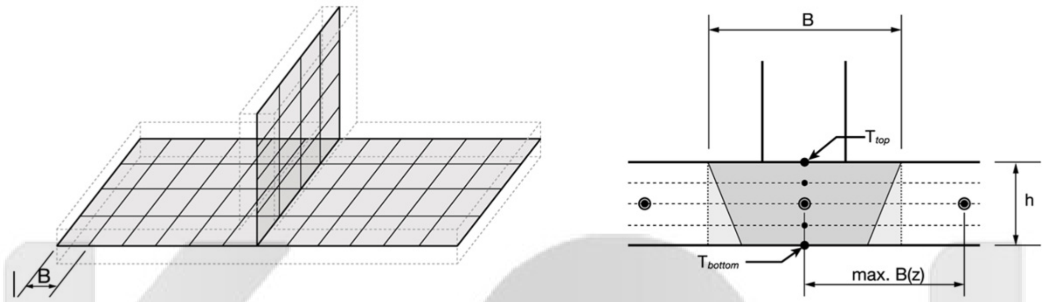
SIMPLIFIED WELDING DISTORTION ANALYSIS FOR FILLET WELDING

In simplified welding distortion analysis, several assumptions exist to simplify whole welding process. Firstly, long weld assumptions, where the inherent strain is constant except starting and end regions, are applied. It is because middle of plate is under quasi-static state in case of long welding. Secondly, it can only deal with continuous inherent strain region. Lastly, the weldment bead is considered not to influence welding distortion. In shell elements, implementing complicated shape is so difficult that weldment bead and discontinuous inherent strain region are neglected. Moreover, in case of weldment size, if bead size is increasing, more heat input is needed. Increase in bead size is closely related to magnitude of the inherent strain and area of the inherent strain region rather than the structural stiffness.

Based on this assumption, the approach suggested in this paper follows mechanism of the SDB method. It is assumed that inherent strain and the inherent strain region is already given. In simplified method, it is important how to closely describe the inherent strain and their region in the shell element. In the SDB method, the inherent strain is regarded as the thermal expansion coefficient and artificial top and bottom temperatures are calculated based on proportion of the inherent strain region so that the equivalent thermal strain is entered in accordance with trapezoidal inherent strain distribution seen in Fig. 3 by means of linear interpolation through thickness. In this respect, the SDB method is systematically designed for butt joints. However, as seen Figs.1 and 2, the SDB method do not take into consideration the stiffener deformation in fillet welds as well as cannot expect high prediction accuracy for plate deformation due to limitation of expressing ellipsoidal inherent strain region in T-joint. We suggest new approach where we can directly manipulate the thermal expansion coefficient through thickness using multi-layered shell elements in order to imitate precisely actual inherent strain region. For detailed explanation, the SDB method and new approach is sequentially dealt with in this chapter.

Strain as direct boundary

The basic idea of the SDB method is that the inherent strain can be directly entered as the equivalent thermal strain. In commercial software, there are no option to directly input a strain as an external load except for a thermal strain. Since the inherent strain is generally a compressive strain, this manipulation is similar to shrinkage of welding zone where deposited metal only experiences cooling phenomena. The SDB method has 4 parameters, which are the thermal expansion coefficient, artificial top and bottom temperatures and the mesh size at weldments, and each parameter is decided based on inherent strain and its region. As mentioned above, the inherent strain is regarded as the thermal expansion coefficient and the inherent strain region determines each artificial temperature, of which range is from 0 to 1 in general. In SDB method, shrinkage is derived from average of two temperatures, whereas angular deformation is derived from mean difference of two temperatures. The equation for artificial temperature is written in Eqs. (2) and (3). As shown in the equations, each artificial temperature is determined based on proportion of inherent strain region and boundary area with weighting factor to describe appropriate angular deformation. Mesh size in the model is determined same as maximum width of inherent strain region.



(a) Element picture for fillet welds in SDB method. (b) Schematic picture of mechanism of SDB.

Fig. 2 Schematic picture of SDB method in fillet welds.

$$\alpha = \varepsilon^* \tag{1}$$

$$T_{top} = \frac{1}{A}\int_{-\frac{h}{2}}^{\frac{h}{2}} b(z)\cdot(1-\frac{4}{h}\cdot z)dz \tag{2}$$

$$T_{bottom} = \frac{1}{A}\int_{-\frac{h}{2}}^{\frac{h}{2}} b(z)\cdot(1+\frac{4}{h}\cdot z)dz \tag{3}$$

$$A = B\cdot h \tag{4}$$

where α : Thermal expansion coefficient

ε^* : Inherent strain

T_{top} : Artificial temperature on top surface

T_{bottom} : Artificial temperature on bottom surface

$b(z)$: Mathematical function for width of inherent strain region at z

A : Area of boundary region

h : Thickness

B : Maximum width of inherent strain region

The way to implement the SDB method is that artificial temperatures are assigned at the welding zone nodes and the material property, not depended on temperature, is used. It can be applied that temperatures through thickness are linearly gradient from top to bottom surface by linear interpolation of finite element method.

$$\varepsilon_k^{\ eq} = \alpha * T_k \tag{5}$$

where $\varepsilon_k^{\ eq}$: Equivalent thermal strain at the *k*-th integration point
T_k : Artificial temperature at the *k*-th integration point

Consequently, in accordance with Eq. (5), equivalent thermal strain, which is same as inherent strain information, can be applied to the shell model by the SDB method.

The proposed method

As mentioned above, we introduce new approach to overcome the limitation of SDB method, which is not to directly manipulate the equivalent thermal strain through thickness direction and not to imitate the ellipsoidal inherent region. In order to solve this limitation, we employ the composite shell elements to use different thermal expansion coefficients through thickness. In SDB method, the artificial temperatures is responsible for making different shrinkage through thickness and the thermal expansion coefficient is responsible for the source of deformation, whereas in suggested method, the artificial temperature is devoted to the source of deformation and thermal expansion coefficients in each layer are devoted to representing their inherent region. Fig. 3 schematically illustrates the suggested method.

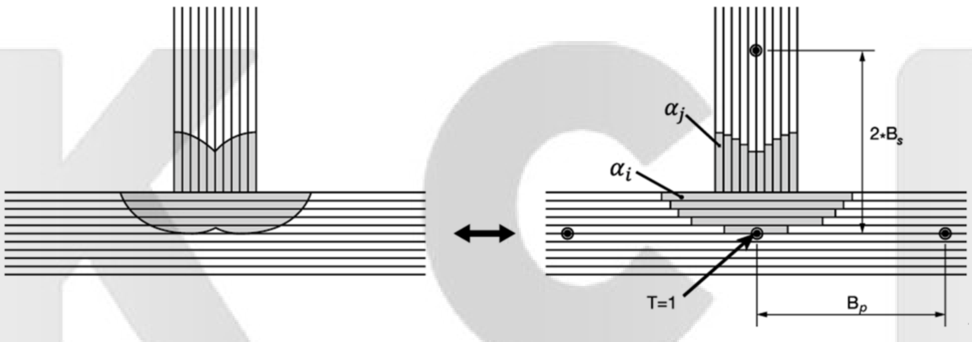


Fig. 3 Comparison of inherent region in fillet welds and distribution of thermal expansion coefficient in each layer for stiffener and plate

The procedure of suggested method is that 1 °C artificial temperature is assigned at intersection nodes and the function presented as Eqs. (6) and (7) are used to calculate thermal expansions for each layer. In this procedure, Unit length of each layer is regarded as 1 *mm*.

$$\alpha_{i,j} = \varepsilon^* \cdot L_{i,j} \tag{6}$$

$$L_{i,j} = \frac{(b_{p,s}(z) + b_{p,s}(z-1))/2}{B_{i,j}} \tag{7}$$

where p : The plate
s : The stiffener
i : The layer number in the plate
j : The layer number in the stiffener
$\alpha_{i,j}$: Thermal expansion of *i,j*-th layer in each member
$L_{i,j}$: The relative length of *i,j*-th layer
$b_{p,s}(z)$: The mathematical function for width of inherent strain region regarding each member
$B_{i,j}$: Maximum width of inherent strain region regarding each member

As mentioned, this procedure is same as the SDB mechanism. The equivalent thermal strain is equally entered to analysis models. Particularly different from the SDB method, it can assign equivalent thermal strain to the stiffener member with loss of generality, so we can describe deformation of stiffener members and plate member at once

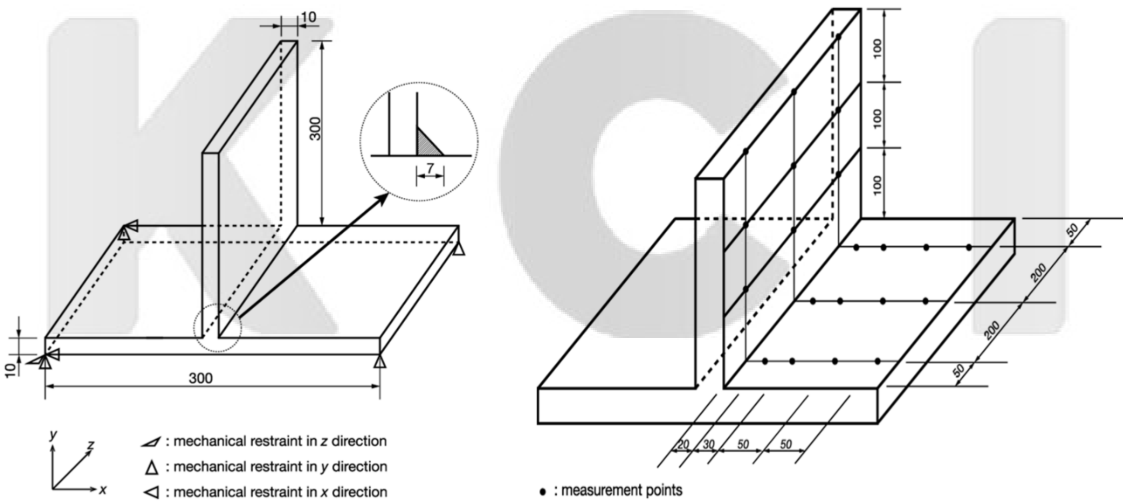
$$\varepsilon_{i,j}^{eq} = a_{i,j} * 1 \tag{8}$$

where $\varepsilon_{i,j}^{eq}$: Equivalent thermal strain at the *j*-th layer

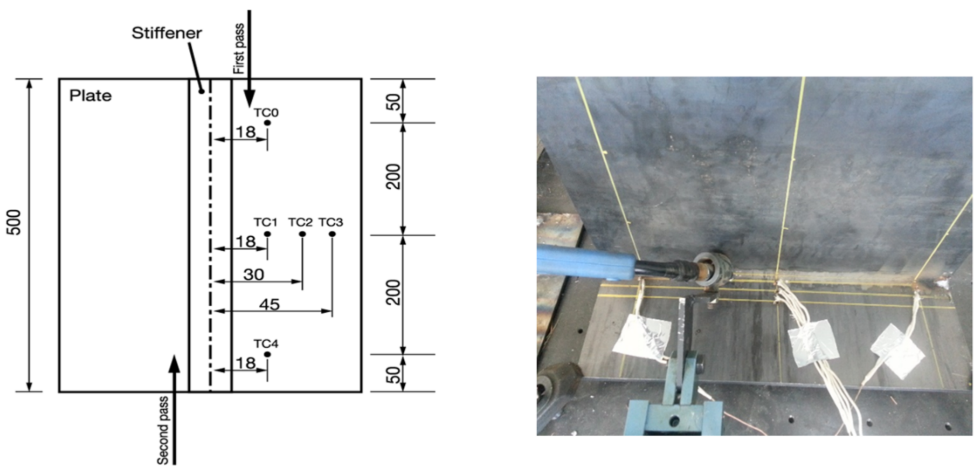
In next chapter, by comparing of experiment, 3D thermo elastic plastic analysis and the SDB method, it is verified that suggested method is very effective to describe welding deformation in fillet welds.

EXPERIMENTAL PROCEDURE

For verifying the effectiveness of the proposed method, T-joint fillet welding, which consist of a plate and a stiffener, is prepared. The objective of this experiment is to check how much displacement of a plate and a stiffener occur after each pass. Among many research regarding T-joint fillet welding, Peric et al. (2014) experiment is selected to follow since experiment procedure is well explained in his paper. In this experiment, each dimension of plate and stiffener is same as 10 *mm* thickness, 300 *mm* width and 500 *mm* length with structural steel, SS400. Detailed geometry of sample is schematically shown in Fig. 1.



(a) Mechanical boundary condition and bead size. (b) Displacement measurement points.



(c) Temperature measurement point. (d) Picture of experiment procedure.

Fig. 4 Geometry and welding experiment configuration.

In the experiment, T-joint is processed through double-sided fillet welds. The welding is precisely performed by Autonic™ Controller based stage system. Table 1 indicates the welding conditions. The welding procedure chosen for this experiments is as follow. After each pass, displacement measurement is conducted. Cooling time is given enough to generate welding deformation. Coordinate Measuring Machine (CMM) is used for displacement measurement and K-type thermocouples are used for surface temperature measurement during fillet welding. Detailed welding information such as welding direction, sequence and parameters is described in Fig. 4 and Table 1.

Table 1 Welding condition.

Voltage [*V*]	Current [*A*]	Welding speed [*mm/s*]	Efficiency
29	270	6.31	0.85

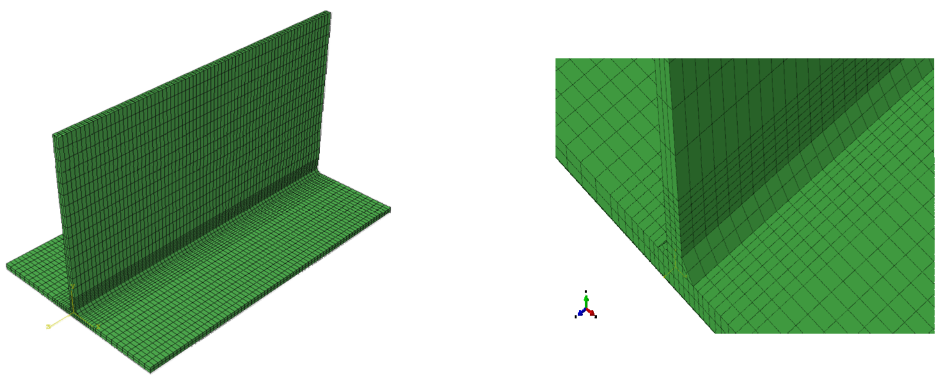
3D THERMO ELASTIC PLASTIC ANALYSIS

Sequentially coupled 3D thermo elastic plastic analysis has been also conducted for prediction of the residual stress and distortion in detail. In this paper, this analysis is introduced for comparison of other methodologies. For modeling of T-joint fillet welds, we use ABAQUS software. Three dimensional 8 node solid DC3D8 elements are used for the thermal analysis, and C3D8R elements are applied for the stress analysis. Fig. 5 presents the 3D solid mesh model in detail including the region near weldments. The thermal analysis is performed by applying a uniform heat flux to the welding beads considering convection and radiation effects. The uniform heat flux is calculated in accordance with Eq. (9).

$$Q = \frac{\eta EI}{V} \tag{9}$$

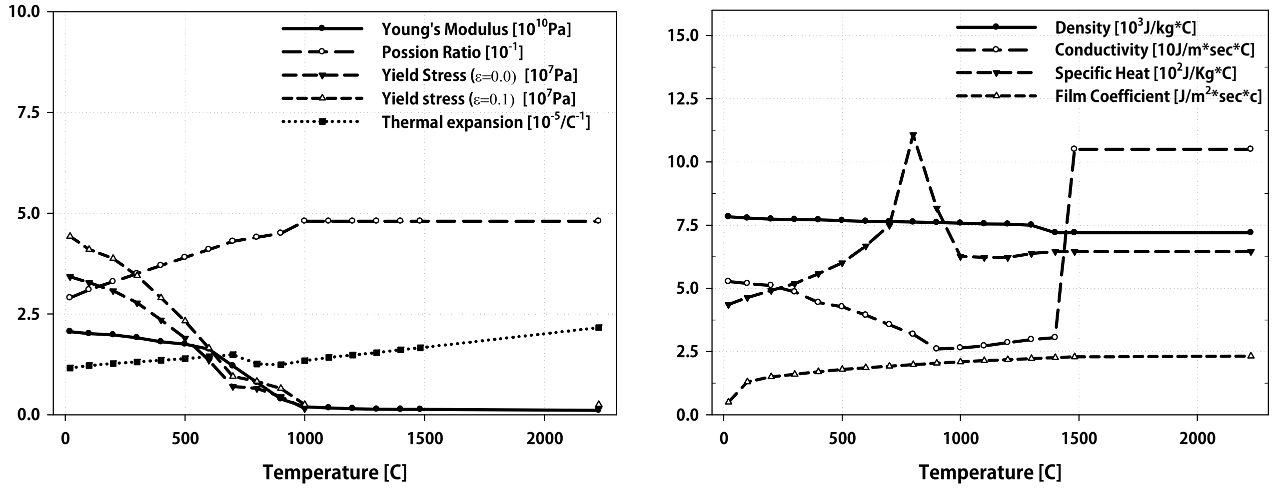
where Q : Heat input [*W/mm*^{2}]
E : Voltage [*V*]
I : Current [*A*]
η : Efficiency
V : Volume of the weldment set per unit length

The uniform body heat flux, $4.074\times10^{10} W/mm^2$, is assigned to the set of weldment bead per unit length. Latent heat, 273790W from 1427 °C to 1482 °C is also considered. Fig. 6 shows the material properties applied to this simulation. The emissivity coefficient is 0.32.



(a) Overviews. (b) The region near weldments.

Fig. 5 3D Solid models.



(a) Stress analysis. (b) Heat transfer analysis.

Fig. 6 Material properties.

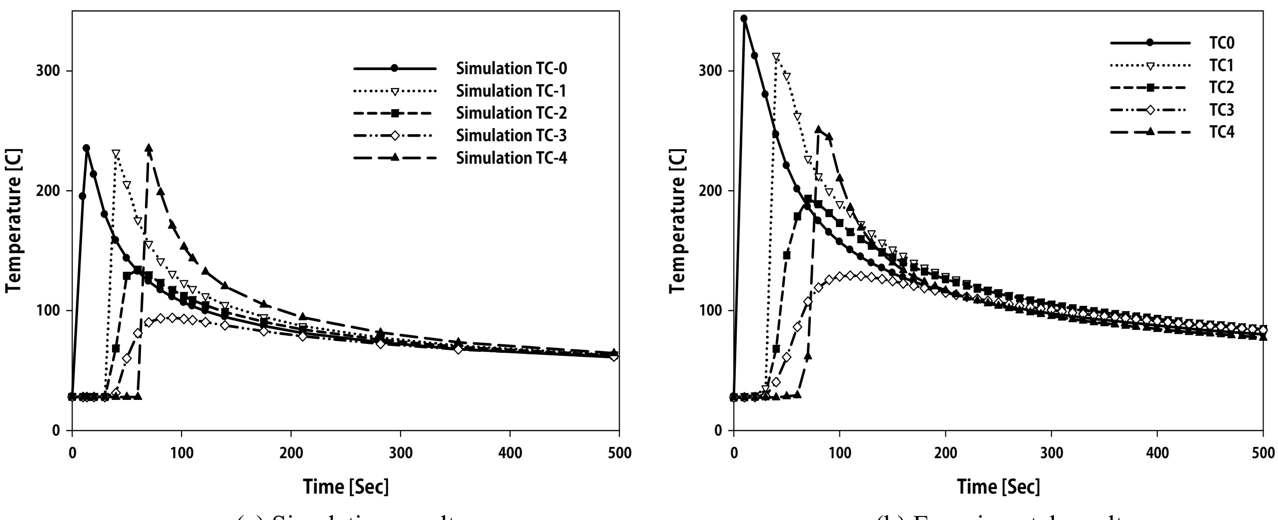
After heat transfer analysis, stress analysis is followed. Temperature history from thermal analysis is regarded as the external loads in stress analysis. For more details about analysis, refer the earlier papers.

RESULTS AND DISCUSSION

In this section, the results of experiment and simulation are illustrated. For verification, we compare of each result in term of two models: 1) Thermal analysis between experiment and 3D thermo elastic plastic analysis 2) Stress analysis between the SDB and the proposed method with previous simulation.

Thermal analysis

Fig. 6 presents comparison of results for the temperature history of each 3D simulation and experiment. It is obvious that the temperature history of 3D heat transfer simulation is somewhat lower than those obtained from experimental measurements. This difference is also mentioned in the paper written by Perić et al. (2014). They stated that it may occur since uniform body heat flux, very simple heat source, is applied. Since the purpose of this study shows simplified welding distortion analysis for fillet welds, this difference is neglected.

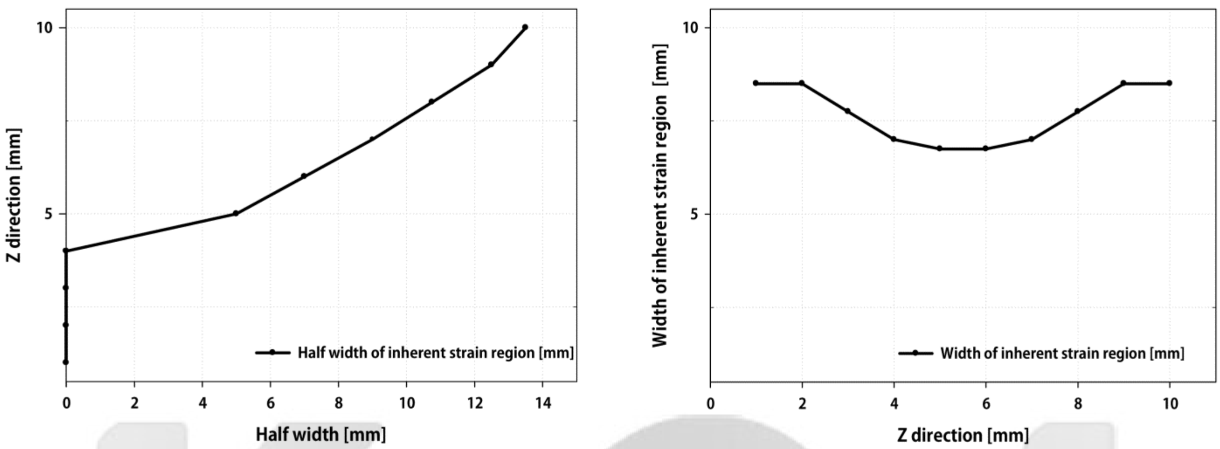


(a) Simulation result. (b) Experimental result.

Fig. 7 Comparison of result for experiments and 3D heat transfer simulation.

Stress analysis

For calculating parameter for the simplified method, we refer the plastic strain information from 3D thermo elastic plastic analysis. We assume that the inherent strain is same as the plastic strain when all members are completely cooled down. According to the definition of the inherent strain defined as incompatible strain, the plastic strain is equal to the inherent strain except weldments if all surface temperature is returned to the initial condition. Therefore, in order to calculate parameters for the simplified methods, the average plastic strain and its region is used. Fig. 6 and Tables 2, 3 indicate applied parameters for simplified methods.



(a) Plate. (b) Stiffener.

Fig. 8 Inherent strain region.

Table 2 Information of modelling for SDB and suggested method.

Inherent strain	Mesh size	
	Plate	Stiffener
-0.009845	27 *mm*	18 *mm*

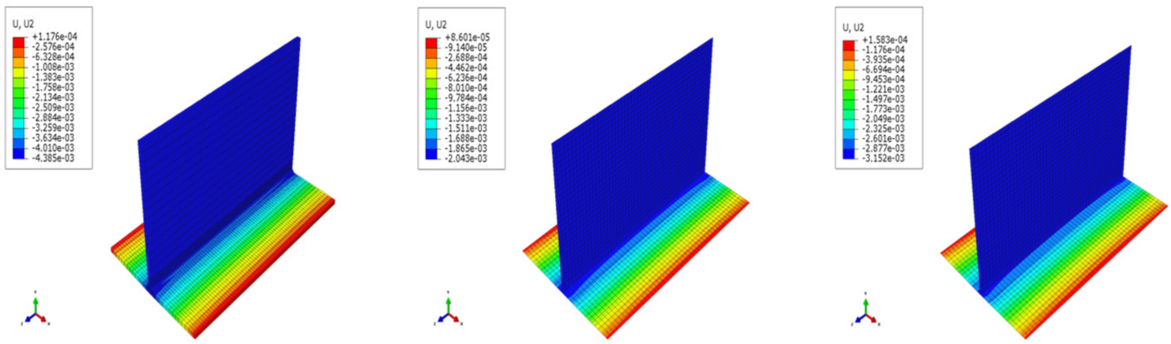
Table 3 Parameter of one and two sided fillet welds for SDB and suggested method.

Two sided welds				One sided welds			
SDB		This paper		SDB		This paper	
Temperature in plate [℃]	Temperature in stiffener [℃]	Thermal expansion in plate [$℃^{-1}$]	Thermal expansion in stiffener [$℃^{-1}$]	Temperature in plate [℃]	Temperature in stiffener [℃]	Thermal expansion in plate [$℃^{-1}$]	Thermal expansion in stiffener [$℃^{-1}$]
T_{top} = 0.86 T_{bottom} = -0.0044	-	-0.009845	-0.009845	T_{top} = 0.86 T_{bottom} = -0.0044	-	-0.009845	-0.009845
		-0.009116	-0.009845			-0.009116	-0.009845
		-0.00784	-0.008977			-0.00784	-0.008977
		-0.006563	-0.008108			-0.006563	-0.008108
		-0.005105	-0.007818			-0.005105	-0.007818
		-0.003646	-0.007818			-0.003646	0
		0	-0.008108			0	0
		0	-0.008977			0	0
		0	-0.009845			0	0
		0	-0.009845			0	0

For comparison of effectiveness of each method, the magnitude of angular deformation is compared. In double sided fillet welds, stiffener member is rarely deformed. In the contrast, stiffener member is enough deformed in one-sided fillet welds. In order to validate stiffener deformation, we deal with one sided fillet welds as well as double sided fillet welds.

Two sided fillet welds

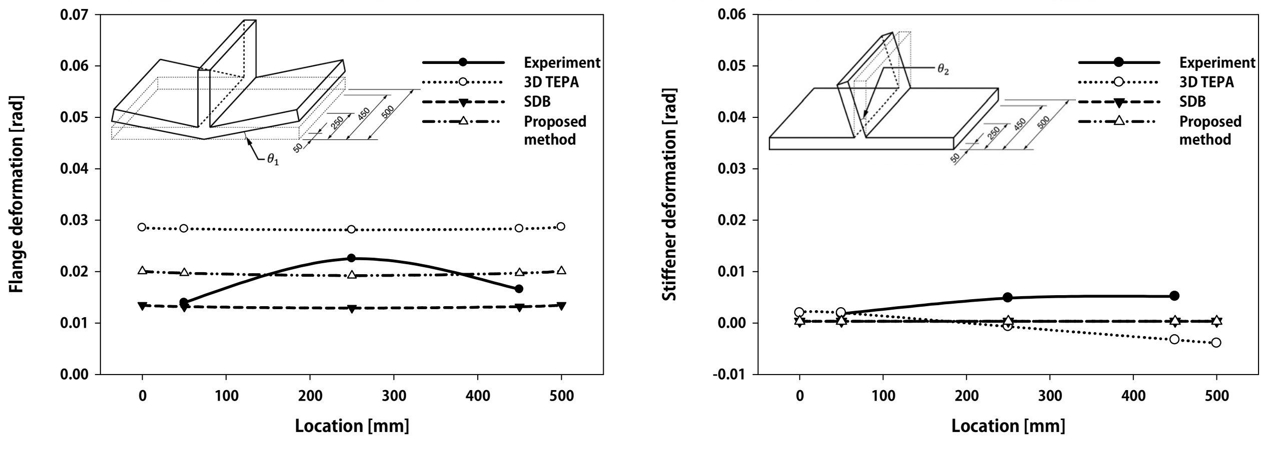
Fig. 9 indicates comparison of the plate and the stiffener deformation about two sided fillet welds from each method.



(a) 3D thermo elastic plastic analysis. (b) Strain as Direct Boundary. (c) Proposed method.

Fig. 9 Displacement of y direction in two sided fillet welds.

As seen Fig. 10(b), stiffener deformation rarely occurs but plate deformation is shown enough. 3D thermo elastic plastic analysis is overstated. In comparison of the SDB and the proposed method, suggested method is more suitable for prediction of plate deformation than the SDB method. The reason why proposed method is more effective is that the result is closest to the experimental result in middle of plate. Since these method is based on the long weld assumption, there are no meaning of comparison of start and end region. As a result, the proposed method can effectively predict plate deformation.



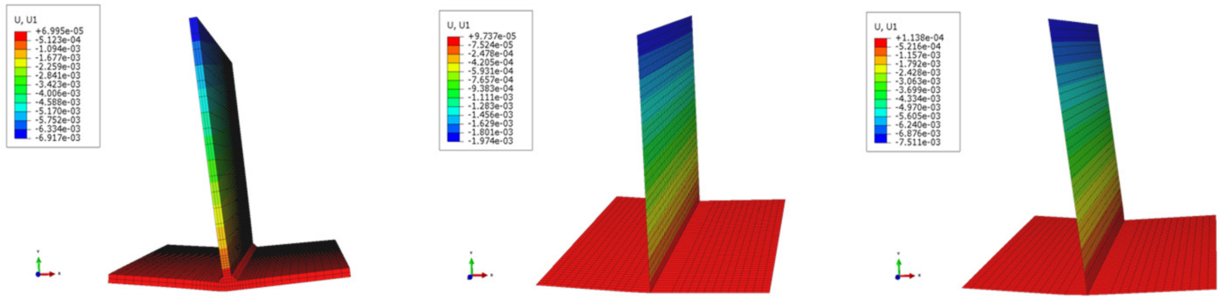
(a) Angular deformation of plate. (b) Angular deformation of stiffener.

Fig. 10 Comparison of each deformation in two sided fillet welds.

One sided fillet welds

Fig. 11 indicates comparison of the plate and the stiffener deformation about one sided fillet welds from each method.

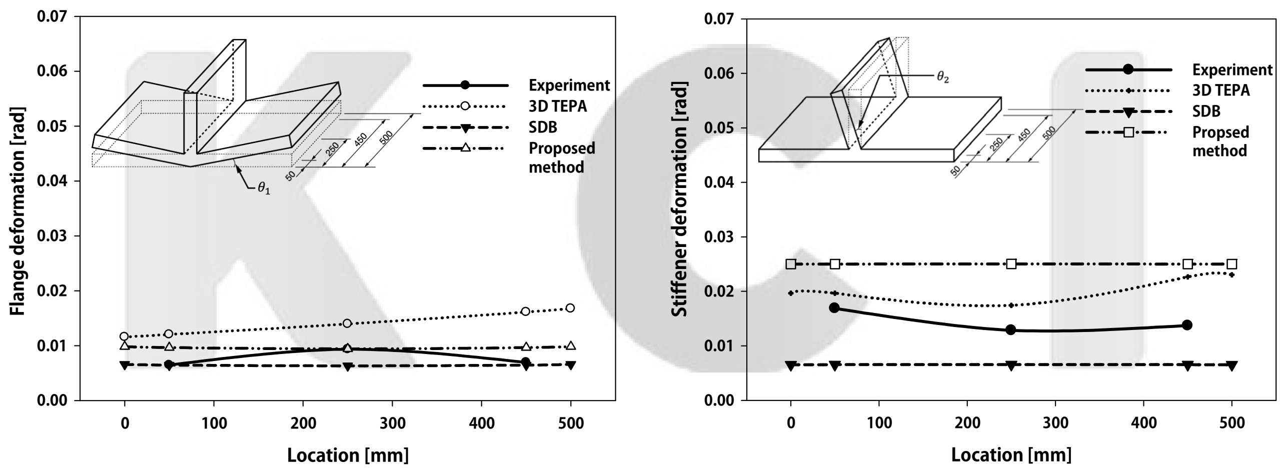
In contrast with two sided fillet welds, angular deformation of stiffener is one of major deformation in one-sided fillet welds. Fig. 12 shows comparison of results in one-sided fillet welds.



(a) 3D thermo elastic plastic analysis. (b) Strain as Direct Boundary. (c) Proposed method.

Fig. 11 Displacement of x direction in one sided fillet welds (scale factor x5).

Regarding the plate deformation, the result is very similar to those of two sided fillet welds. As seen middle of plate in Fig. 12(a), it indicates that the proposed method is very effective to predict the angular deformation for plates. In terms of stiffener deformation, the prediction tendency is different from previous one. The result of 3D thermo elastic plastic analysis is closest to experiments data. In case of the SDB, it cannot predict stiffener deformation at all due to limitation of mechanism. On the other hands, even though the result of proposed method is over estimated, but it sufficiently shows that the proposed method can reasonably predict stiffener deformation.



(a) Angular deformation of plate. (b) Angular deformation of stiffener.

Fig. 12 Comparison of each deformation in one sided fillet welds.

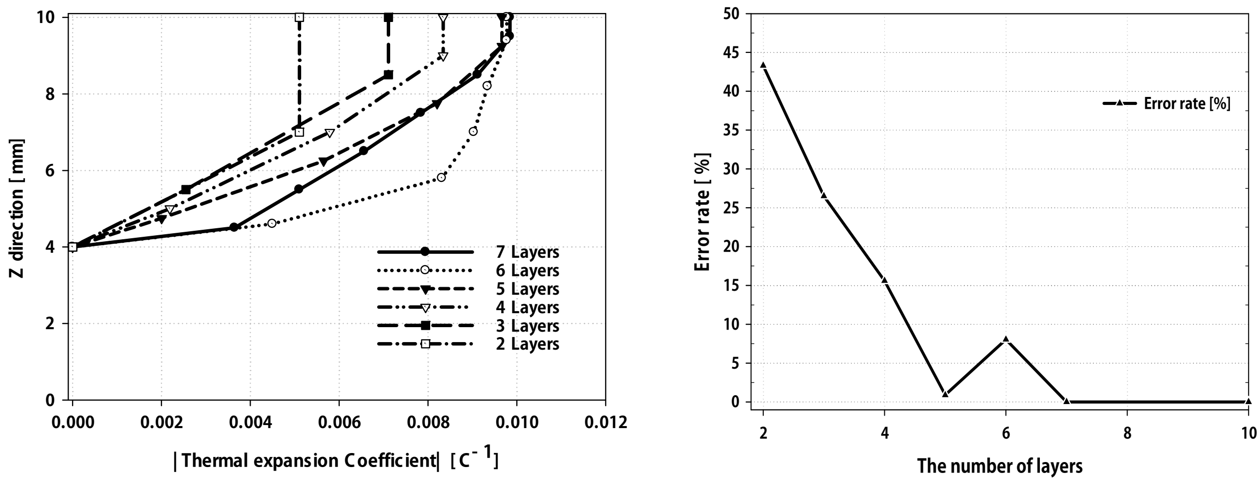
Discussion

Table 4 Summary of comparison of each method for T-joints fillet welds.

Category	3D Thermal elastic plastic analysis	SDB	The proposed method
Element [*ea*]	17936	357	357
Step [*ea*]	153	1	1
Computation time [*sec*]	Heat transfer: 90897 Mechanic: 63107	1.2	1.2
Input variables	Heat transfer: Heat input Mechanic: Temp. History	Thermal expansion coefficient and artificial temperature	Thermal expansion coefficient for each layer
Observable variable	All	Displacement	Displacement
Observable deformed member in T-joints	Both members	Plate	Both members

*3D Thermo elastic plastic analysis was only performed on high performance computing using 8 cores.

Table 4 presents the comprehensive comparison of simulations. From these results, we can aware of efficiency of simplified analysis in terms of computational costs. In addition, we realize that the proposed method affords reasonable prediction of welding deformation for T-joints fillet welds from Figs. 10 and 12.



(a) Thermal expansion coefficient for each layer models. (b) Percentage of error rates.

Fig. 13 Effect of the number of layers.

In order to find effect of the number of layers, we perform comparative study changing the number of layers in a same simulation model. In this analysis, we introduce 2, 3, 4, 5, 6, 7 layers. As you can see Fig. 8(a), there are no inherent strain region from 0 to 4 *mm*, this region is regarded as 1 layer in all layers models. For example, in 2 layers model, each layer is distinguished at 4 *mm*. 0~4 *mm* region is involved in 1 layer and 4~10 *mm* region is involved in 2 layer. Thermal expansion coefficient applied to each layers model is described in Fig. 13(a) Based on these information, we calculate displacement compared of 10 layers model which has been used in the former analysis. For quantitative comparison, we introduce the statistic, named error rate, which is derived like Eq. (10).

$$Error\ rate = \frac{|\delta_l - \delta_{10}|}{\delta_{10}} \tag{10}$$

where δ_l : Displacement from the l-th layer model [*mm*]

Fig. 13(b) indicates that increasing layers assure higher the prediction accuracy and 5 layers model is adequate policy to follow describe fillet joint considering trade-off between the number of layers and the prediction accuracy. In particular, the 6 layer model has more error rate than the 5 layer model. As you can see the thermal expansion coefficients of the 6 layers model in Fig. 13(a), those things are so over-stated that results of deformation is also over-stated than results of 7 layers model. From this result, we realize again that it is important how thermal expansion coefficients of multi layers are closely described as the actual inherent strain distribution. But, since the error rate in the 6 layer model is little, around 5%, it doesn't matter to apply 6 layer analysis to describe welding deformation.

However, there exists limitation of the proposed method. Firstly, since we do not consider the duplicated region at intersection nodes in T-joints, where thermal coefficient expansions located in between the upper region of the plate and the stiffener mutually influence, it is thought that overestimation of stiffener deformation is caused. We can improve the performance of proposed method by employing post process, but it is contrary to the purpose of simplified analysis. Since the purpose of simplified analysis is to estimate reasonable welding distortion with little efforts, those overestimation can be regarded as acceptable errors. Secondly, the inherent strain region should be continuously connected. Based on this assumption, the shell element can be employed to predict deformation. Upon mechanism of the proposed method, it is assumed that the all areas of elements with the nodes assigned artificial temperatures are considered the inherent region. From this reason, the inherent strain region should be connected in the proposed method. If it is considered that disconnected inherent strain region such as partial penetration cases, it is possible that the results will be different from actual welding situations due to distinction between the actual inherent strain region and the inherent strain region in the proposed method. However, it is rare case that thick plates will be joined in T-joints fillet welds, because most of thick plates have been joined by butt welds. Despite of these disadvantages, the proposed method offers to effectively and simply predict both main modes of welding deformation without waste time and assure reasonable magnitude of deformation.

CONCLUSIONS

In this paper, we have looked into welding deformation for T-joint fillet welds. We conducted the experiments, 3D thermal elastic plastic analysis and simplified welding distortion analysis including the proposed method. In order to predict huge structures such as offshore structures, we can show that simplified welding distortion analysis is the best solution to analyze within short time. However, the previous method, Strain as Direct Boundary, is useful for butt welds joints, but it is not appropriately performed for fillet welds. We, accordingly, propose the new approach to simulate both welding deformation at once maintaining the SDB mechanism. From several comparisons, we verified that proposed method is useful to be applied to T-joint fillet welds. In addition, since there are no conflict with the SDB method, Synergy effect will occur as SDB method is applied to butt joints and proposed method is applied to fillet joints. Although we need to define more material properties, it can be used to predict welding deformation of huge structures in accordance with those policies. In the future, the simplified method considering multi-pass should be proposed. In this paper, we show stiffener deformation from one sided fillet welds. But angular deformation of the stiffener occur much more when multi-pass fillet joint is applied. Also, since it is very sensitive to sequence of welding, it is necessary for simplified analysis considering multi-pass to be proposed.

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