Title	Three Dimensional Cold Bending and Welding Residual Stresses in Penstock of 80kgf/mm² Class High Strength Steel Plate(Welding Mechanics, Strength & Design)
Author(s)	Ueda, Yukio; Fukuda, Keiji; Nishimura, Iwao et al.
Citation	Transactions of JWRI. 1983, 12(2), p. 277-286
Version Type	VoR
URL	https://doi.org/10.18910/5627
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Three Dimensional Cold Bending and Welding Residual Stresses in Penstock of 80 kgf/mm^2 Class High Strength Steel Plate†

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Abstract

In the process of fabrication of large size penstock, cold bending and welding are applied to thick plate. The resulting residual stresses should exhibit complex three dimensional distribution. These residual stresses should influence brittle fracture and fatigue strength. Therefore, it is worthwhile to measure these residual stresses as accurate as possible.

The authors presented the new measuring principle based on the theory of inherent strains and developed several measuring methods for three dimensional residual stresses, which were very accurate judging from the theory of elasticity, although some approximate methods such as Rosenthal-Norton Method have been used so far.

In this paper, the authors develop a new measuring method of residual stresses due to cold bending. For actual measurement, a large size model of penstock of 80 kgf/mm^2 class high tensile strength steel plate is fabricated. Residual stresses due to cold bending are measured in the shell plate. Welding residual stresses at the longitudinal and circumferential weld joints are measured by L_y method which the authors presented before. It is observed that the maximum residual stress is about 50 kgf/mm^2 to 60 kgf/mm^2 which is less than the yield stress of the material.

KEY WORDS: (Residual Stress) (Cold Bending) (Welding) (Penstock) (Cylindrical Shell) ($L_{\theta z}$ Method)

1. Introduction

In recent years, large-size penstocks are demanded. This requires the use of thick plates of high tensile strength steel. In the process of fabrication of these large-size structures of high tensile strength steel plates, cold bending and welding are applied. The resulting residual stresses distribute complicatedly in three dimensions and there have been few examples[1] of measured residual stresses in such structures as penstocks which are welded after bending process. The residual stresses influence variously on cold weld cracking, brittle fracture strength, fatigue strength, etc. In order to evaluate these influences rationally it is indispensable to predict three dimensional residual stresses produced in the process of fabrication with high accuracy.

For three dimensional residual stresses, approximate measuring methods including Rosenthal-Norton Method were used since there is no accurate method to apply to these subjects. The authors have proposed a new measuring principle for measurement of three dimensional residual stresses in which inherent strains are dealt as parameters. Based on this principle, they have also proposed accurate measuring methods[2-8] than ever for uniformly distributed residual stresses along the weld line.

In this study[7], a large-size penstock model of 80 kgf/mm^2 class high tensile strength steel plate is fabricated so as to measure three dimensional residual stresses produced in the fabrication process by (1) cold bending of the shell plate, (2) welding of the longitudinal joint and (3) welding of the circumferential joint.

Although welded residual stresses can be measured by L_y method which has been proposed by the authors, residual stresses due to cold bending cannot be measured by any of the existing measuring methods. Therefore, based on the above mentioned measuring principle, a new measuring method is developed.

2. Measuring Theory of Residual Stresses

2.1 Assumptions of the theory

In the measuring theory of three dimensional residual stresses[2-5] to be applied in this study, inherent strains,

† Received on October 31, 1983

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Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

which are the source of residual stresses distributed in the measuring object are dealt as parameters. The measuring method adopted here is simplified based on the assumption that residual stresses distribute uniformly in one direction. For measurement of residual stresses, test specimens from the object are cut out so as to fulfil the following conditions.

(1) Cutting is accompanied only with elastic change of strain. No further inherent strain is produced.
(2) Remaining stresses in each thinly sliced specimen is in the plane stress state (the specimen should be so thin that the inherent strain in the plate thickness direction does not produce any stress).

2.2 Measuring method of three dimensional residual stresses due to cold bending of shell plate

If cold bending is applied to steel plates, residual stresses are induced. It is presumed that if a steel plate is bent into a cylindrical shape like the shell plate of a penstock, the theory of plate bending can be applied to the deformation of the plate except the very narrow portions along the edges. This means that the straight line perpendicular to the neutral surface of a plane plate before deformation sustains its straightness after deformation. Therefore, most portion of the processed shell plate is presumed to be subjected to uniform bending in one direction having the following features.

(1) The longitudinal cross sectional surface of a plate including the bending axis sustains to be plane after deformation.
(2) The transverse cross sectional surface with respect to the bending axis keeps to be plane after deformation.

Consequently, a part of the self-equilibriating shell plate shown with the system of coordinates in **Fig. 1** is considered to be in the state of plane deformation in θ and z directions. In other words, the edge sections of $dL \times d\theta$ as indicated in Fig. 1(a) are to be in the plane deformation. σ_θ, σ_z, ϵ_θ^* and ϵ_z^* denote circumferential and axial components of residual stresses and inherent strains which are uniform in both θ and z directions except in small portions along the edges. The residual stresses are in the two dimensional stress state, since normal stresses in the plate thickness direction and shear stresses are not produced. While, when the curvature of the cylindrical plate is small ($R/t > 10$, R: radius of the shell, t: plate thickness), the theory of bending of plane plate is considered to be applicable as it is. The shell plate to be measured here has such a small curvature as to be dealt as a plane plate.

In the following, taking into account of the features of deformation of the shell plate, a new measuring theory is developed for measurement of residual stresses induced by cold bending. The new measuring method will be named $L_{\theta z}$ method.

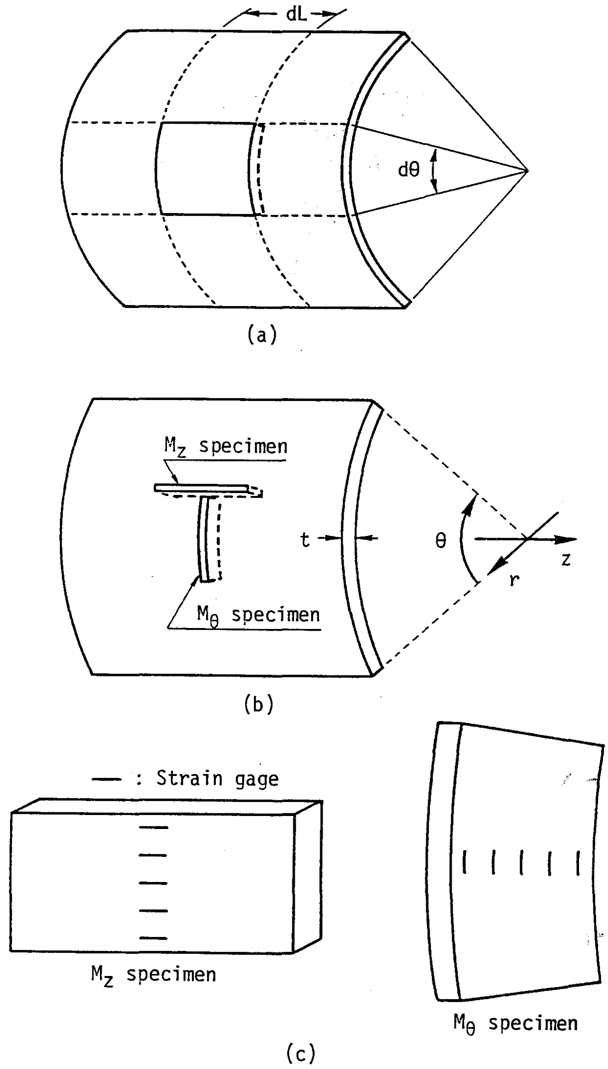


Fig. 1 Shell plate, M_z and M_θ specimens

As illustrated in Fig. 1(b), M_θ and M_z specimens are to be cut out from the central portion of the shell plate. In this case, inherent strains are still uniform in θ and z directions because the cutting is accompanied without any additional inherent strain. This means that inherent strain in M_θ and M_z specimens are same as those in the original shell plate. On the other hand, M_θ and M_z specimens are so thin that the inherent strain components perpendicular to respective plate surfaces are not considered to contribute to stresses remain in the plates. Therefore, stresses remain in M_θ specimen are induced by inherent strain in θ direction, ϵ_θ^*, alone and those in M_z specimen are by inherent strain in z direction, ϵ_z^*. As a result, two components of inherent strains (ϵ_θ^*, ϵ_z^*) can be divided into ϵ_θ^* in M_θ specimen and ϵ_z^* in M_z specimen.

At this stage, each specimen contains only an inherent strain in the respective longitudinal, θ or z, direction. Then, each specimen corresponds to L specimen in the previous developed methods. This is the reason why the measuring method is named $L_{\theta z}$ method.

If the length of each specimen (M_θ and M_z specimens), ℓ, is two times longer than the original plate thickness t, the central portion of each specimen is distant from both ends by more than the plate thickness in the longitudinal direction. According to the Saint-Venant principle, residual stresses in the central portion are little influenced by the free boundaries[4]. It is considered, therefore, that a uni-axial stress state is produced respectively by ϵ_θ^* and ϵ_z^* in the central portions of M_θ and M_z specimens.

Uni-axial strain gages are attached longitudinally to the central portion of each specimen along the plate thickness direction as illustrated in Fig. 1(c). These specimens are then cut into pieces so that the longitudinal relaxed strains can be directly observed as $-\epsilon_\theta$ and $-\epsilon_z$, respectively. Assuming that the plane stresses are σ_θ^{AO} and σ_z^{BO} in M_θ and M_z specimens, the following equations are derived.

$$\sigma_\theta^{AO} = E\epsilon_\theta,\ \sigma_z^{BO} = E\epsilon_z \qquad (1)$$

where, E: Young's modulus.

In the next place, stresses $\{\sigma^A\} = [\sigma_\theta^A,\ \sigma_z^A]^T$ produced only by the inherent strains in θ direction, ϵ_θ^*, are considered. As is already shown in Ref. 2), when inherent strain ϵ_θ^* which is considered to be uniform in z direction is given to the original specimen, plane strain state is maintained in the z direction except portions near the plate ends and the stresses σ_θ^A and σ_z^A are produced, which may be expressed by $\{\sigma^A\}$. From the relation between plane stress and plane strain, each component of $\{\sigma^A\}$ can be calculated by the following equations.

$$\sigma_\theta^A = \sigma_\theta^{AO}/(1-\nu^2),\ \sigma_z^A = \nu\sigma_\theta^{AO}/(1-\nu^2) \qquad (2)$$

where, ν: Poisson's ratio.

In the same manner as in the case of $\{\sigma^A\}$, stresses $\{\sigma^B\} = [\sigma_\theta^B,\ \sigma_z^B]^T$ produced only by z directional inherent strains, ϵ_z^*, in the original shell plate. ϵ_z^* produces the state of plane strain since it is considered to be uniform in θ direction. Each component of $\{\sigma^B\}$, $\{\sigma_z^B\}$ and $\{\sigma_\theta^B\}$ can be expressed by the following equations.

$$\sigma_z^B = \sigma_z^{BO}/(1-\nu^2),\ \sigma_\theta^B = \nu\sigma_z^{BO}/(1-\nu^2) \qquad (3)$$

Residual stresses (σ_θ^M, σ_z^M, σ_r^M) produced in the original model can be given as the sum of stresses $\{\sigma^A\}$ by ϵ_θ^* and $\{\sigma^B\}$ by ϵ_z^*.

$$\left.\begin{aligned}\sigma_\theta^M &= \sigma_\theta^A + \sigma_\theta^B = E(\epsilon_\theta + \nu\epsilon_z)/(1-\nu^2)\\ \sigma_z^M &= \sigma_z^A + \sigma_z^B = E(\epsilon_z + \nu\epsilon_\theta)/(1-\nu^2)\\ \sigma_r^M &= 0\end{aligned}\right\} \qquad (4)$$

2.3 Measuring theory of three dimensional welding residual stresses

In this research, welding residual stresses near longitudinal and circumferential welded joints shall be measured, which are produced in a large-size model of penstock shown in **Fig. 2**. As in Fig. 2, measuring locations are to be set on such a portion as is under no influence of inherent strains in other joints. RL specimen (including the longitudinal joint) and RC specimen (including the circumferential joint) are cut out from such portions as respectively shown by **Fig. 3**(a) and (b). As the whole model contains self-equilibriating residual stresses, the residual stresses are partially relaxed in the process of furnishing RL and RC specimens. In these specimens, relaxed stresses at the portions distant from the ends by more than the plate thickness are denoted by $\{\sigma^C\}$. Both specimens have small curvatures in comparison with the plate thickness, so that they are dealt as plane plates and $\{\sigma^C\}$ is considered to change linearly in the plate thickness direction. In each specimen, the respective system of rectangular coordinates shown in Fig. 3 is set for con-

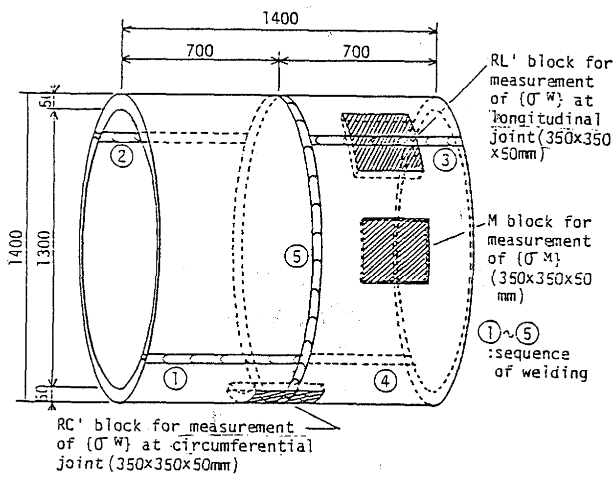


Fig. 2 Model of penstock

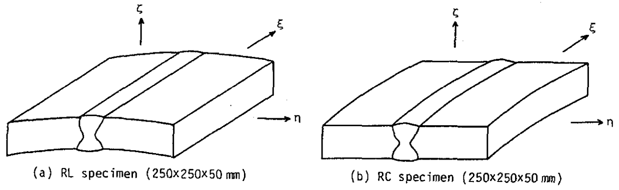


Fig. 3 RL and RC specimens

venience. Therefore, $\{\sigma^C\}$ can be concretely calculated by the following equation.

$$\left.\begin{aligned} \sigma_\xi^C &= \sigma_{\xi o}^C + (\sigma_{\xi o}^C - \sigma_{\xi i}^C)\cdot(\zeta/t) \\ \sigma_\eta^C &= \sigma_{\eta o}^C + (\sigma_{\eta o}^C - \sigma_{\eta i}^C)\cdot(\zeta/t) \\ \sigma_\zeta^C &= \tau_{\eta\zeta}^C = \tau_{\zeta\xi}^C = \tau_{\xi\eta}^C = 0 \end{aligned}\right\} \quad (5)$$

where, $\sigma_{\xi o}^C, \sigma_{\eta o}^C$: Relaxed stresses in ξ and η directions directry observed on outer surfaces of *RL* and *RC* specimens

$\sigma_{\xi i}^C, \sigma_{\eta i}^C$: Relaxed stresses in ξ and η directions directly observed on inner surfaces of *RL* and *RC* specimens

t: plate thickness.

L_y method[6] which was proposed by the authors is applied to measurement of three dimensional residual stresses remained in *RL* and *RC* specimens.

In order to explain the outline of the measuring method common to both longitudinal and circumferential joints, ξ axis is taken along the weld line, η is in the plate breadth direction and ζ in the plate thickness direction (**Fig.** 4(a)). By L_y method, the test model *R* specimen (Fig. 4(a)) is sliced so as to prepare *T* specimen of which

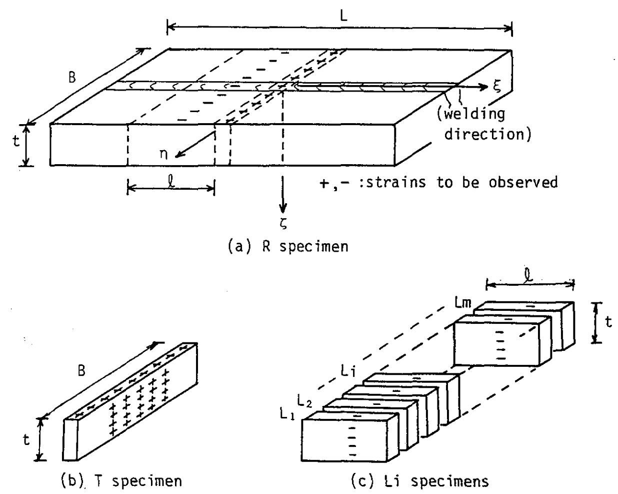


Fig. 4 Test model and slicing procedure of T and L_i specimens (L_y method)

sectioned surfaces are perpendicular to the weld line (Fig. 4(b)) and L_i specimens parallel to it (Fig. 4(c)). Nextly, effective inherent strains are estimated for each specimens. These effective inherent strains are given to the nonstressed *R* specimen so as to perform elastic stress analyses in order to obtain stresses. Inherent strains in such a longitudinal joint as treated here are uniform along the weld line (ξ axis), so that they are composed of only ϵ_ξ^*, ϵ_η^*, ϵ_ζ^*, and $\gamma_{\eta\zeta}^*$ which are considered to be the functions of η and ζ. In the thinly sliced *T*-specimen (Fig. 4(b)), only ϵ_η^*, ϵ_ζ^*, and $\gamma_{\eta\zeta}^*$ have effects as effective inherent strains (the source of residual stresses). *T* specimen is further cut into small pieces surrounding each strain gage. Then residual stresses are measured in each piece and three dimensional residual stresses $\{\sigma^A\}$ by ϵ_η^*, ϵ_ζ^*, and $\gamma_{\eta\zeta}^*$ can be estimated.

As was described in the references to L_y method, welding residual stresses of *T* specimen in the plane stress state can be obtained from the released strains by cutting *T* specimen into small pieces. Denoting this stress by $\{\sigma^{AO}\}$, $\{\sigma^{AO}\}$ can be transfer to $\{\sigma^A\}$ from the relation between plane stresses and plane strains as illustrated in Eq. (2).

In the next, the slicing procedure of L_i specimens will be mentioned. A block with length ℓ (Fig. 4(a)). is cut out from *R* specimen first of all. Then the block is thinly sliced parallel to the weld line as illustrated in Fig. 4(c). In this way, L_i specimens are sliced. As is the only effective strain in L_i specimens, ϵ_ξ^*, this is estimated in each piece of subdivided L_i specimen. Giving these estimated ϵ_ξ^* to the original *R* specimen, three dimensional elastic analysis is performed so that three dimensional stresses $\{\sigma^B\}$ produced by ϵ_ξ^* is obtained. As a result, three dimensional residual stresses of *R* specimen can be given as the sum of $\{\sigma^A\}$ and $\{\sigma^B\}$. The above is the outline of L_y method.

Three dimensional residual stresses $\{\sigma^W\}$ produced in and near welded joints of the penstock model can be given as the sum of residual stresses $\{\sigma^A\}$ + $\{\sigma^B\}$, of *RC* and *RL* specimens, obtained by L_y method and the relaxed stresses $\{\sigma^C\}$ produced by cutting of *RC* and *RL* specimens. That is,

$$\{\sigma^W\} = \{\sigma^A\} + \{\sigma^B\} + \{\sigma^C\} \qquad (6)$$

3. Experiment

3.1 A large-size model of penstock

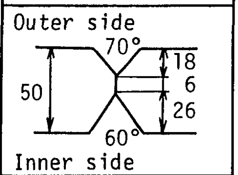
The chemical compositions and mechanical properties of 80 kgf/mm^2 class high tensile steel plate used for fabrication of the large-size model of penstock are shown in **Table 1**.

In the process of fabrication, a bending roller is used for cold bending of the plate. The longitudinal and circumferential joints are welded by submerged arc welding with the welding conditions indicated in **Table 2** by the built-up sequence method shown in **Fig. 5**. **Figure 6** shows the view of the completed model of penstock.

Table 1 Chemical compositions and mechanical properties

Material	Thick-ness (mm)	Chemical composition (wt %)												Y.P.	T.S.
		C	Si	Mn	P	S	Cu	Cr	Ni	Mo	V	B	Ceq	(kgf/mm²)	(kgf/mm²)
HT80	50	0.10	0.30	0.80	0.010	0.004	0.18	0.51	1.08	0.47	0.03	0.0015	0.49	79.6	85.1

Table 2 Welding condition

Welding process	Welding wire (mmΦ)	Preheat-ing temp. (°C)	Interpass temp. (°C)	Welding current (A)	Welding voltage (V)	Welding speed (cm/min)	Heat Input (kJ/cm)	Shape of groove
Submerged arc	4	100	100 ∿230	600 ∿650	32 ∿34	27 ∿30	38.4 ∿49.1	

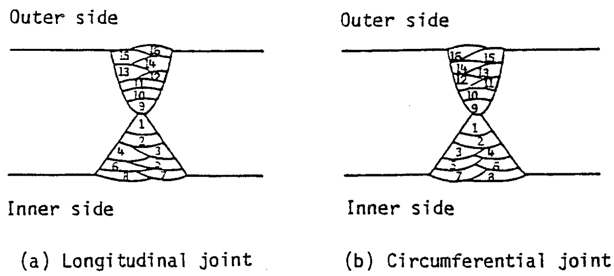


Fig. 5 Build-up sequence

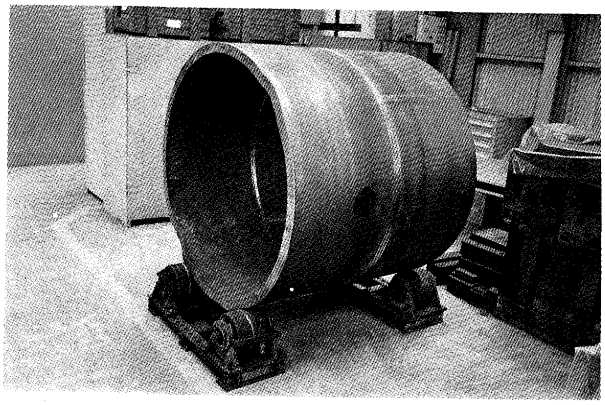


Fig. 6 View of model of penstock

3.2 Measurement of three dimensional residual stresses

In order to measure residual stresses produced in the model by (1) cold bending, (2) welding of longitudinal joint, and (3) welding of circumferential joint, three types of block specimens (Fig. 2) are cut out from the model to meet the requirements of respective cases. These block specimens, having the same size of 350 mm x 350 mm x 50 mm, are called M, RL', and RC' specimens. They are cut out by gas cutting as the first step of manufacturing. Biaxial strain gages are attached on the top and bottom surfaces at the central portion of each block so as to measure stresses released by cutting. The heat to conduct in the specimen is absorbed by the endothermic attached along the cutting line prior to the cutting. By this, the temperature around the strain gages is kept below 50°C and the thermal influence on the gages can be excluded.

At the second step of manufacturing, saw cutting is applied and the effect of plastic deformation by gas cutting is eliminated. As illustrated in Figs. 2 and 7, several thin plates, M_θ and M_z specimens, are cut out from M specimen making their length 135 mm which is twice as longer as the plate thickness of M specimen. Out of RL' and RC' specimens, reproduced are the smaller block specimens of 250 mm x 250 mm x 50 mm, which is named RL and RC specimen. For measurement of residual stresses due to cold bending, strain gages are attached to M_θ and M_z specimens shown in **Fig. 7**, and the specimens are further cut into small pieces around each strain gage. From the released strains observed after the final stage of cutting, the residual stresses are calculated accordingly.

For the welding residual stresses, released surface stresses on RL and RC specimens by cutting from the model are observed. Substituting these values into Eq. (5), stress $\{\sigma^C\}$ are obtained. The location of strain gages for the further measurement are shown in **Fig. 8**. In the same figure, the locations of T and L_i specimens are indicated. Observed on L_i specimens are the strains released by the cutting of this process. In addition, both specimens attached with strain gages as shown in **Fig. 9** are subdivided so as to observe released strains which enable us to calculate residual stresses in T specimen and effective inherent strains in L_i specimen.

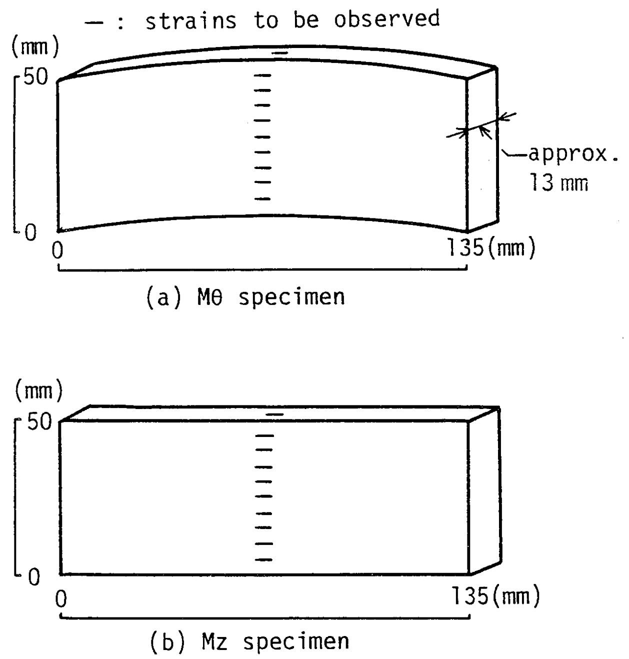


Fig. 7 Locations of measurement of strains in M_θ and M_z specimens

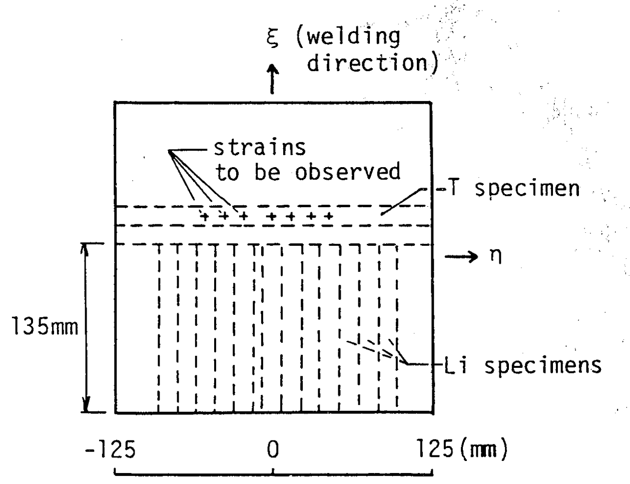


Fig. 8 T and L_i specimens in RL or RC specimens, and location of strain gages for measurement of $\{\sigma^C\}$

From the data, residual stresses $\{\sigma^A\}$ from T specimen and $\{\sigma^B\}$ from L_i specimens are evaluated according to the procedure of L_y method.

Using all these data, three dimensional residual stress distributions in each welded joint are evaluated as the sum of $\{\sigma^A\}$, $\{\sigma^B\}$, and $\{\sigma^C\}$ as expressed by Eq. (6).

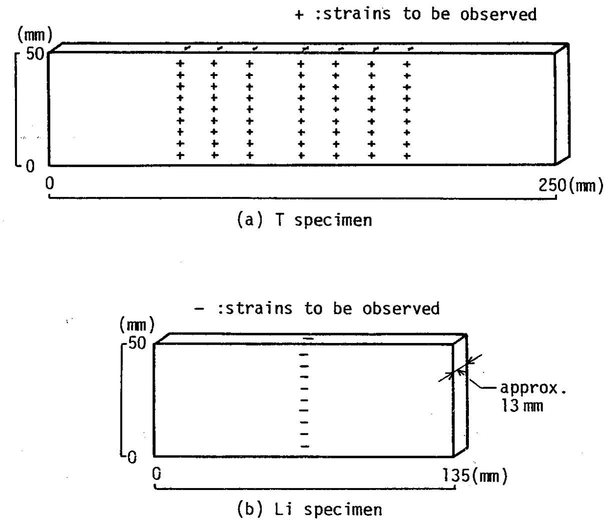


Fig. 9 Locations of measurement of strains in T and L_i specimens

4. Results of Measurement and Remarks

4.1 Three dimensional residual stress distributions in shell plate due to cold bending

Residual stresses measured on two sets of M_θ and M_z specimens are indicated in **Fig. 10**. The two sets of circumferential stresses σ_θ and axial stresses σ_z well cor-

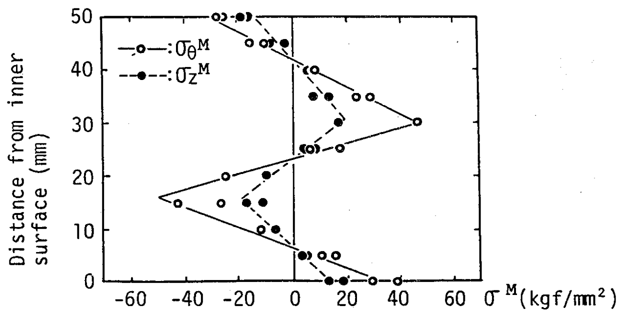


Fig. 10 Residual stresses due to cold bending in shell plate

relate each other respectively. The ratio of $\sigma_\theta^M/\sigma_z^M$ is approximately 10/3. These residual stresses distribute almost in a form of a point symmetric with respect to the center of the plate thickness, which is typical of those due to cold bending. The maximum residual stress is approximately 50 kgf/mm^2 which is smaller than the yield stress (approximately 80 kgf/mm^2) of the material. It is well known that if the load corresponding to the full-plastic moment is applied in the bending process, the maximum of stresses remaining in the plate after removal of the load is equal to the yield stress. Referring to this fact, it is evident that the load applied to the model is smaller than the above mentioned one.

4.2 Three dimensional residual stress distributions due to welding

The measuring object is the residual stresses produced in and near the longitudinal and circumferential joints of the shell plate. Actually, the combination of the residual stresses due to welding and those due to cold bending is to be measured simultaneously.

At the longitudinal joint, residual stresses in the direction of the weld line, σ_ξ^W, and stresses perpendicular to the weld line, σ_η^W, distributed on the outer and inner surfaces are shown along the η axis which is perpendicular to the weld line in **Fig. 11**. Those at the circumferential joint are in **Fig. 12**. In the figures, "○" and "●" indicate residual stresses directly observed by the gages attached on the surfaces of the joints. Residual stresses measured by L_y method, without using these directly observed values, are indicated by solid and broken lines. As is

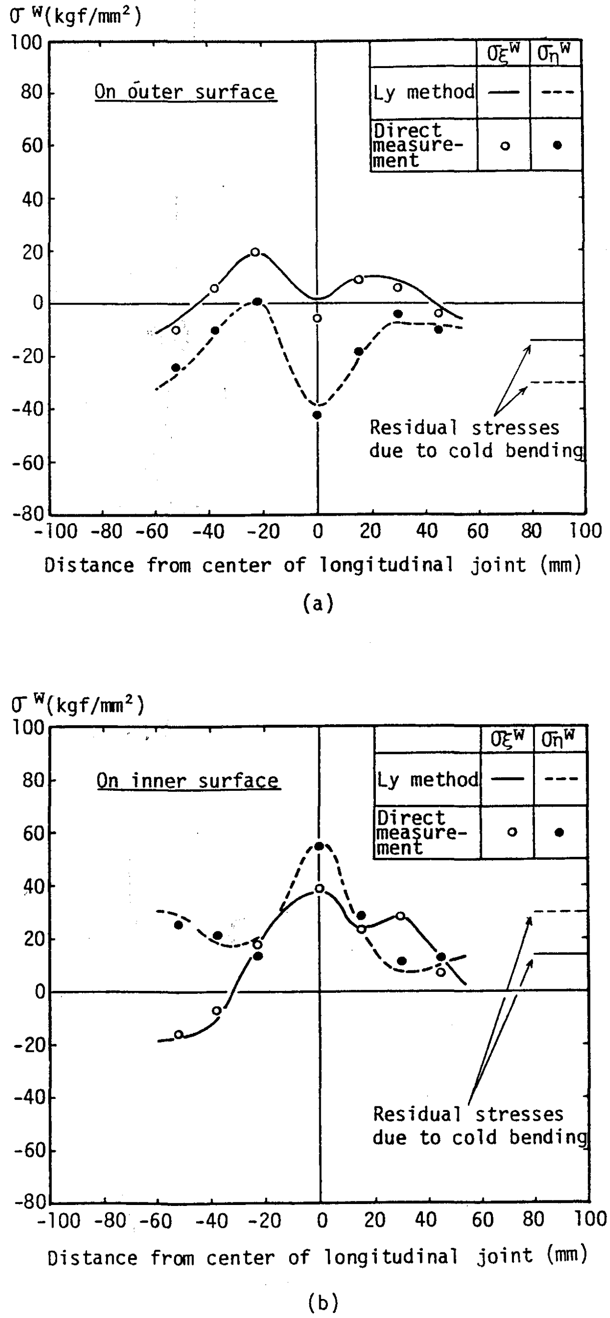


Fig. 11 Welding residual stresses at longitudinal joint

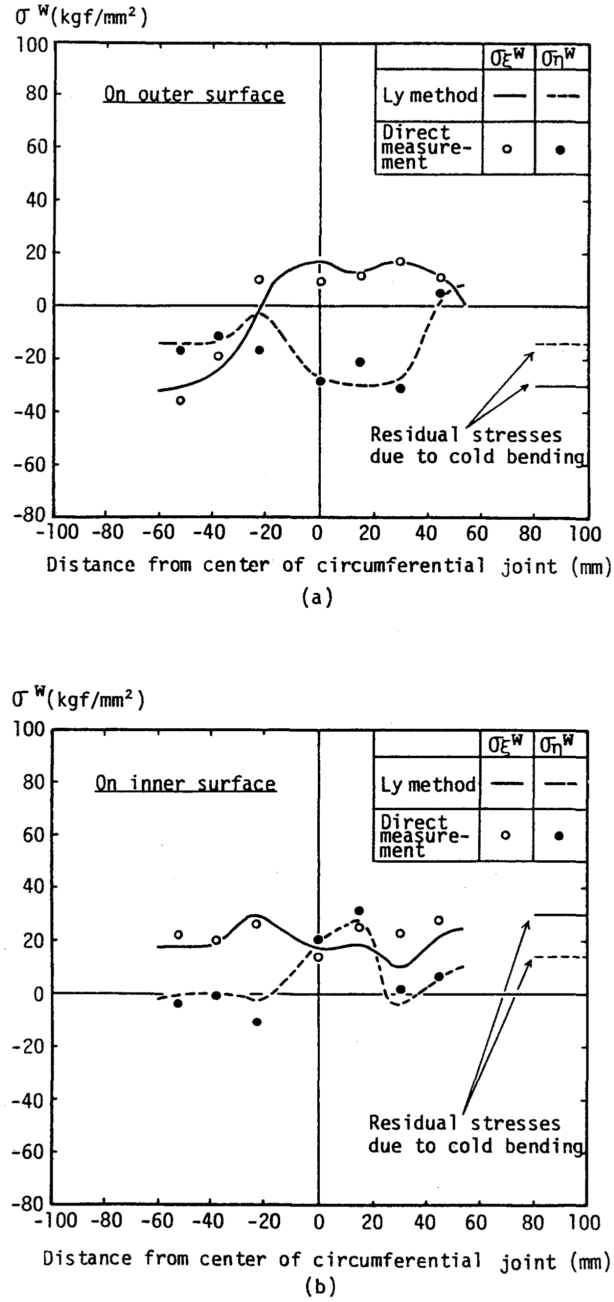


Fig. 12 Welding residual stresses at circumferential joint

evident from the figures, the stresses of both cases show a good coincidence. It can be further expected that the estimated stresses of the inside are highly reliable as well as those on surfaces. Figures 11 and 12 also indicate the values of residual stresses due to cold bending mentioned in 4.1. The total of residual stresses are considered to approach to these values due to cold bending as the location is apart from the weld line.

Distributions of the residual stresses, σ_ξ^W in the direction of the weld line, σ_η^W perpendicular to the weld line, and σ_ζ^W in the thickness direction are shown along the thickness for the longitudinal joint in **Fig. 13** and for the circumferential joint in **Fig. 14**, respectively. These figures depict not only stresses in the central portion of the weld line but those deviated from the center by ±30 mm. Cross sectional macrophotographs of the weldments in the longitudinal and circumferential joints are shown in **Fig. 15**.

In the following, the characteristics of the measured residual stress distributions will be remarked.

In the longitudinal joint, σ_ξ^W and σ_η^W are large in tension on the inner surface, while they are small on the outer surface. Bending restraint against rotation perpendicular to the weld line is relatively small in the longi-

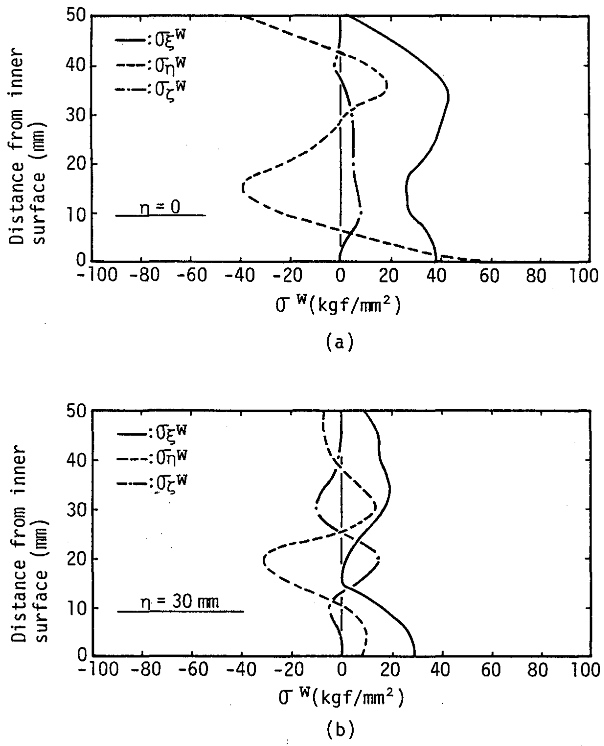


Fig. 13 Welding residual stresses at longitudinal joint

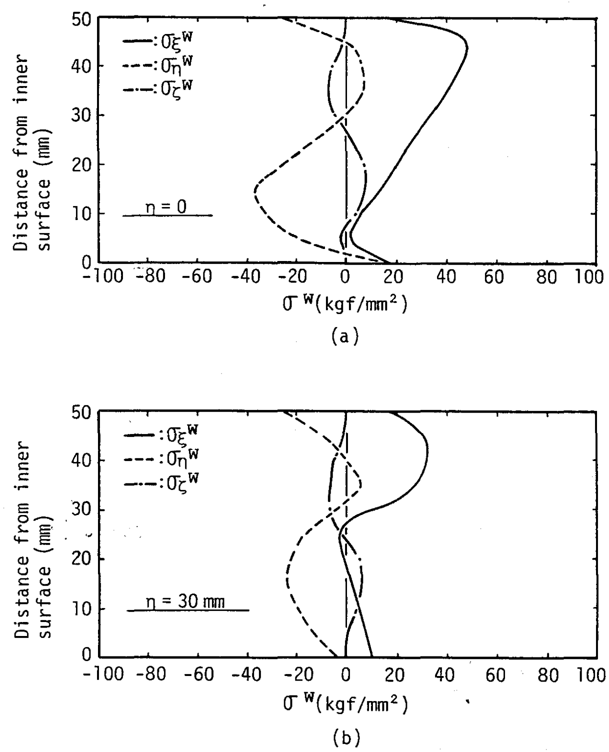
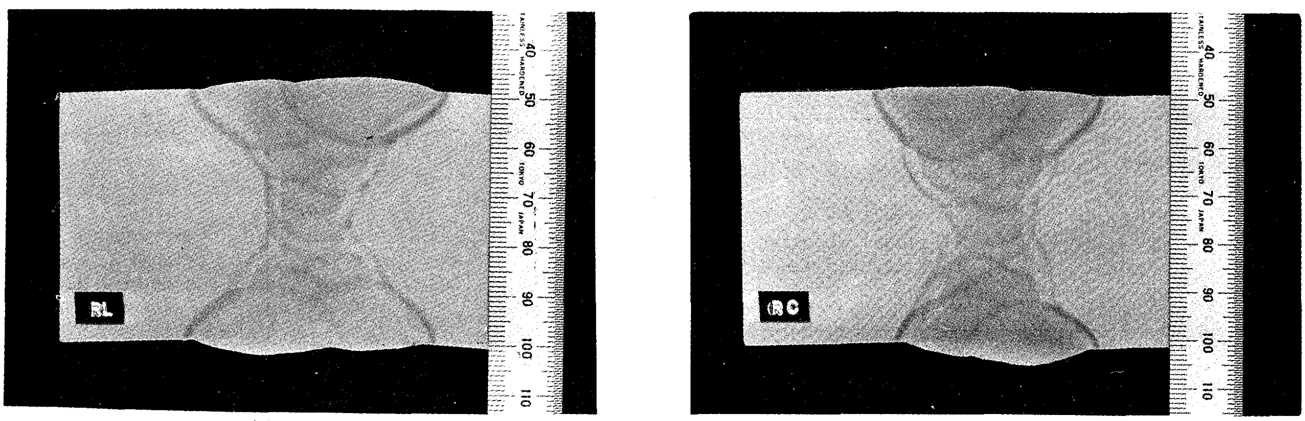


Fig. 14 Welding residual stresses at circumferential joint



(a) Longitudinal joint (b) Circumferential joint

Fig. 15 Macrophotographs of weldments tudinal joint as compared with the circumferential joint. In such a joint, an angular distortion is caused by multi-layer welding in the weldment, which increases tensile stresses on the inner surface. Among stresses distributed in the plate thickness direction, stress perpendicular to the weld line, σ_η^W, is the largest tensile stress of approximately 60 kgf/mm^2 on the inner surface (Fig. 13(a)), which is similar to the result[2)] already obtained by the authors from measurement of a multi-layer welded plate. While, the residual stress in the thickness direction σ_ζ^W is about 15 kg/mm^2 at largest. On the other hand, in the portion 30 mm distant from the weld line (Fig. 13(b)), every stress components show complicated distributions, yet their values are small.

In the circumferential joint, the residual stresses are relatively small on both inner and outer surfaces (Fig. 12). In this joint, contrary to the longitudinal joint, bending restraint against rotation perpendicular to the weld line is severe, In this case, stresses perpendicular to the weld line are considered to be small especially on the inner surface. While, among the stress components which distribute in the plate thickness direction, one in the direction of the weld line σ_ξ^W shows a high value of 50 kgf/mm^2 just beneath the outer surface. This is considered to be one of the main causes of transverse cracking.

In both joints, the maximum value of residual stresses is smaller than the yield stress of the material. This is due to the fact that restraint stresses are relaxed by the expansion of multensite transformation which occurs in the cooling process after welding.

5. Conclusion

In this research, based on the measuring principle of three dimensional residual stresses in which inherent strains are dealt as parameters, residual stresses of a large-size model of penstock of 80 kgf/mm^2 class high tensile steel plate were measured. They are due to cold bending of the shell plate and three dimensional residual stresses in and near the longitudinal and circumferential welded joints. Thus, the characteristics of their distributions were clarified. The main results are as follows.

(1) Based on the measuring principle in which inherent strains are dealt as parameters, another measuring method is devised and applied to measurement of residual stresses due to cold bending of the shell plate. This measuring method is an extremely simplified one in consideration of characteristics of both cold bending and the distributions of the resulting residual stresses.

(2) Among the residual stress components caused by one dimensional cold bending of the shell plate, the circumferential stress σ_θ^M is dominant and the longitudinal stress σ_z^M is small. The proportion between these stresses at a point, $\sigma_z^M/\sigma_\theta^M$, is between 1/2 and 1/3. Distributions of these residual stresses in the plate thickness direction are approximately point symmetric with respect to the center of the plate thickness, showing the compressive and tensile maximum values of approximately 50 kgf/mm^2 in this experiment.

(3) The maximum value of residual stresses in the welded joints is 50 to 60 kgf/mm^2 and less than the yield stress of the material (approximately 80 kgf/mm^2) which is well informed of the case of high tensile steel plates. In the longitudinal joint, the maximum residual stress perpendicular to the weld line is about 60 kgf/mm^2 in tension on the inner surface, which is relatively larger than that of 20 kgf/mm^2 in the circumferential joint. This is due to the fact that the bending restraint in the longitudinal joint is smaller than that in the circumferential one. This large stress produced in the inner side (preceding weld side) may possibly be one of the causes of toe cracking. As for the residual stresses along the weld line, the maximum tensile stress in the circumferential joint is 50 kgf/mm^2 which is little larger than that of 40 kgf/mm^2 in the longitudinal joint. Especially, the former is produced just beneath the outer surface (under the final bead) and considered to be one of the main causes of transverse cracking.

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