A Study on the Accuracy of Estimated Residual Stresses by the Existing Measuring Methods †

Yukio UEDA*, Keiji FUKUDA** and Setsuo ENDO***

Abstract

In order to measure three dimensional residual stresses, Sachs, and Rosenthal and Norton have been already proposed their methods which are well-known. These methods use the analytical solutions or the approximated equations as the basic relations by which residual stresses are calculated from measured data. There is a question on the basic assumptions made in the Rosenthal-Norton method and there are examples that the Sachs method is applied beyond the limiting conditions.

In this paper, validity and limits of application of these methods were investigated with the aid of the finite element method and the following information was obtained.

(1) The Resenthal-Norton method can not be applied generally in three dimensional stress state because it was assumed in the method that the relaxed stresses distribute linearly in the direction of thickness at the first step (removal of a block).

(2) The Sachs method gives the correct result if residual stresses are uniform in the axial direction and of rotational symmetry. In cases where either of two assumption is not satisfied, this method can not be applied.

(3) A general theory of measuring method of three dimensional residual stresses has not been formulated yet except by the authors.

1. Introduction

In order to estimate three dimensional residual stresses, some kinds of measuring methods have been already proposed [1]. For examples, the method of Rosenthal and Norton is to investigate those stresses existing in thick welded plates, and Sachs' boring-out method to measure stress distribution of rotational symmetry and uniform in the axial-direction.

Within the framework of the limiting conditions in each case, a relation exists between the change of stresses (or strains) measured on the surface and the amount of stresses relieved in the interior by sectioning, so that the latter can be computed from the former. The existing methods use the analytical solutions or the approximated equations with some assumptions to express that relation.

Nevertheless, these methods have been applied sometimes beyond the limits without due consideration because there has not been any way to examine the accuracy of these methods in such cases. Recently, numerical analysis have been developed remarkablly with the digital computers, especially the finite element method.

In this paper, the restrictions of applications or the accuracy of these measuring methods of residual stresses are investigated with the aid of the finite element method.

2. Rosenthal-Norton Method

2.1 Procedure

The procedure in application of this method is foundamentally composed of the following three steps.

1) At the first step, a narrow block with strain gauges attached having full thickness of the plate is cut off, as shown in Figs.1-(a) and (b).

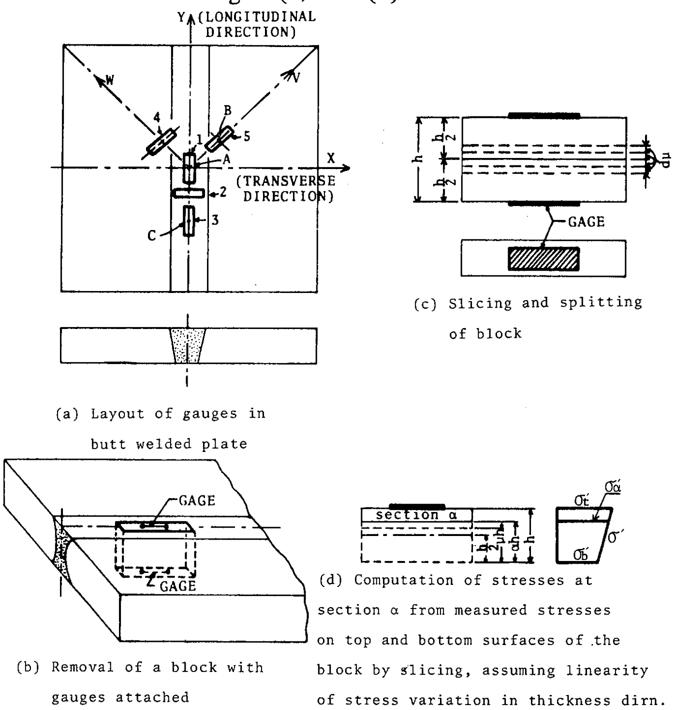

Fig. 1 Procedure of measurement of residual stresses by the Rosenthal-Norton method

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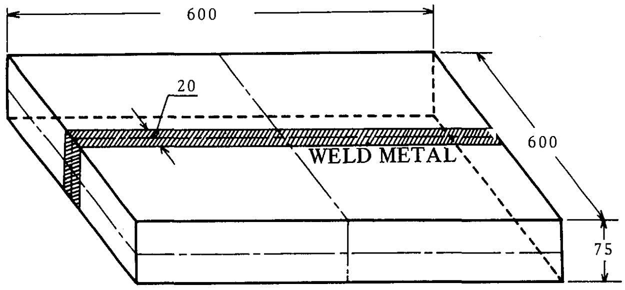
* Associate Professor
** Research Associate
*** Graduate Student, Osaka University

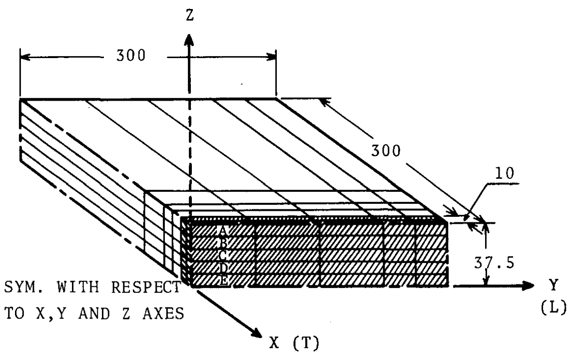
2) The block is sectioned into two with a half of thickness.
3) At the third step, the two new blocks are sliced from the sectioned surfaces to the top or the bottom surfaces.

2.2 Numerical Experiment

As the object for analysis, a butt welded plate is adopted as shown in Figs. 2-(a) and (b). Residual stresses are produced by giving constant inherent strains ($\epsilon^*_x = \epsilon^*_y = \epsilon^*_z = -3000\mu$) in the welded line, and the resulting (true) residual stresses analyzed by the finite element method (indicated by the solid lines in Fig.4-(c)).

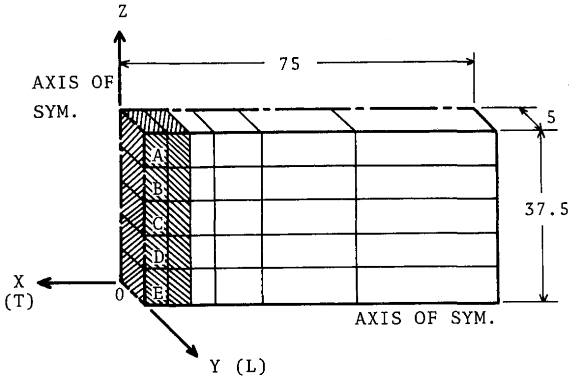


(a) Butt welded joint for numerical experiment

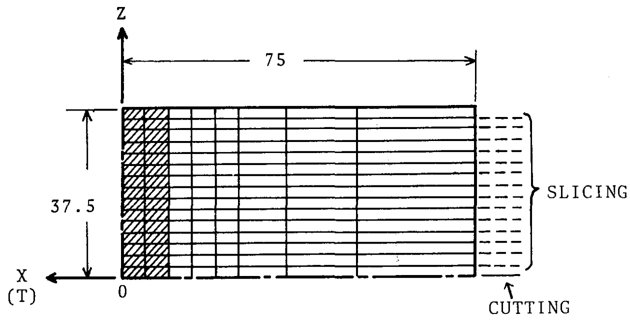


(b) Three dimensional finite element idealization

Fig. 2 Butt welded joint for numerical experiment and three dimensional finite element idealization

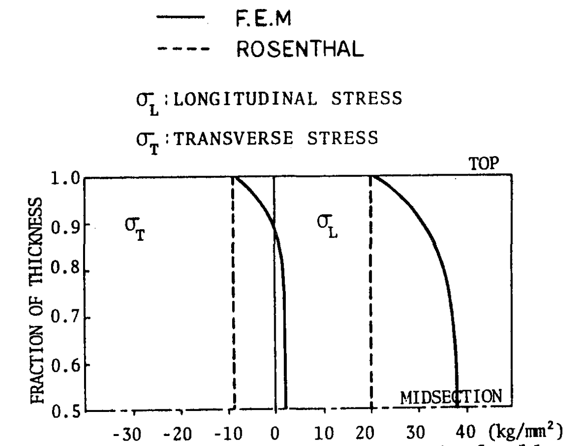


(a) Removal of a block (1st step)

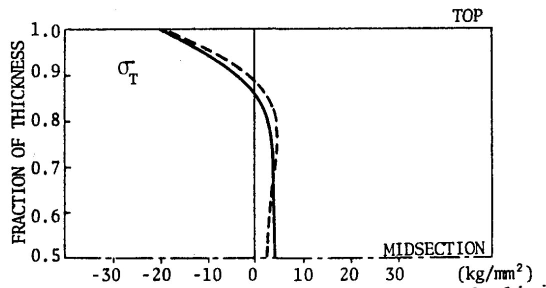


(b) Cutting (2nd step) and slicing (3rd step) of the block

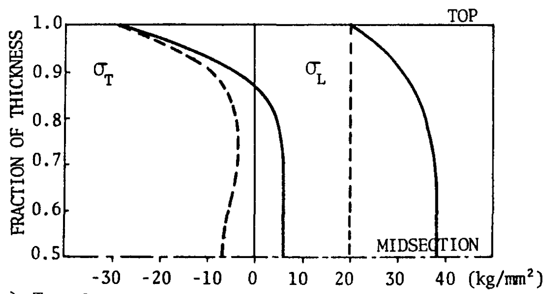
Fig. 3 Finite element idealization for each step of measurement by the Rosenthal-Norton method



(a) Relief of stresses due to removal of a block (at the first step)



(b) Relief of stresses due to cutting and slicing of the block (at the second and third steps)



(c) Total relief of stresses (residual stresses)

Fig. 4 Stress variation at each step of measurement analyzed by F.E.M. and estimated by the Rosenthal-Norton method

In the following, an analysis by the finite element method is conducted in accordance with the indication given in Sec. 2.1. As the first step, a block (Fig.3-(a)) is removed from the original plate and released stresses are calculated and represented by the solid line in Fig.4-(a). Released stresses at the second step (cutting the block to a half thickness) and the third step (slicing the new two blocks from the new surface to the top or the bottom surfaces) are calculated by the finite element method, regarding the blocks as in two dimensional stress state.

Estimated values by the Rosenthal-Norton method are shown by dotted lines in Figs.4-(a) to (c). It is seen that the estimated distribution is different from the true one. This difference is produced at the first step of the procedure.

Therefore, the assumption in this step is not suitable in such an example.

3. Sach's Boring-Out Method

3.1 Procedure of the Method

In this method, the changes of the radius and the length of the object are measured continuously when thin layers are removed by boring out from the interior to the outer surface of the object. And three dimensional stress state is estimated by these changes. The assumptions is that residual stresses are of rotational symmetry and uniform in the axial direction.

3.2 Numerical Experiment

Analyses are conducted in the following cases.

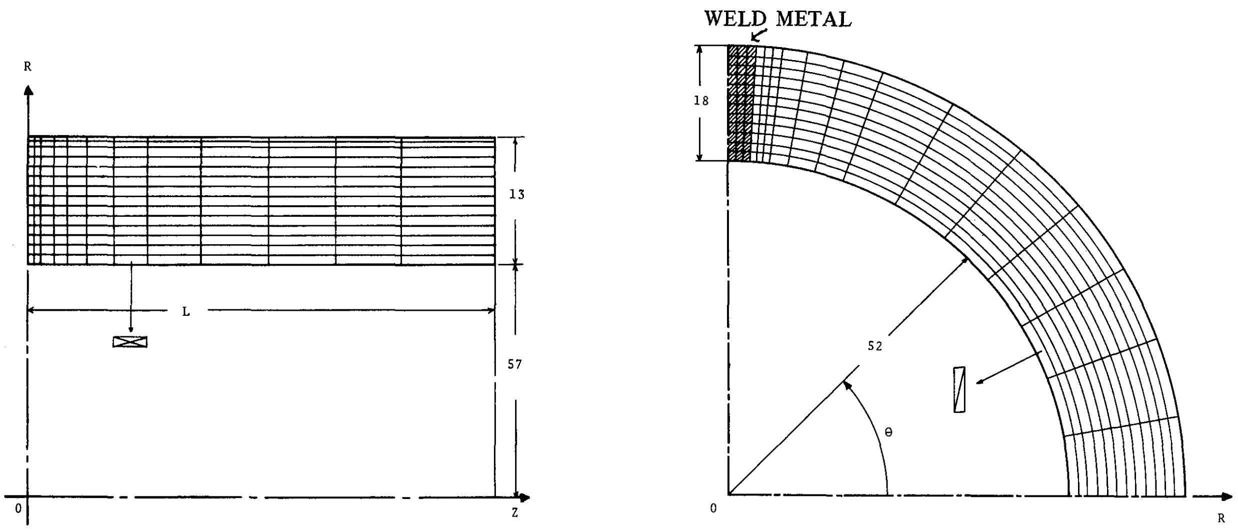
1) Residual stresses are rotationally symmetrical and uniform in the axial direction.
2) Residual stresses are rotationally symmetrical but not uniform in the axial direction.
3) The distribution is uniform in the axial direction but not rotationally symmetrical.

In the first case, a model (hollow circular cylinder) for analysis represented in Fig.5-(a) (L=140 mm) with finite element idealization. Inherent strain distribution imposed is uniform in the axial and circumferencial directions and changes in the radial direction. The true stress distribution is analyzed by the finite element method. The true stresses and the estimated ones by the Sachs method are almost coincided in Fig.6.

In the second example, a circumferencially welded joint of pipes is considered. Its mesh division is the same as in the above case of Fig.5-(a) (L=70 mm). Welded portion contains a constant inherent strain ($\epsilon^*_R = \epsilon^*_\theta = \epsilon^*_Z = -3000\mu$).

The true residual stresses by the finite element method and the estimated ones by the Sachs method are different entirely in every section (Fig.7).

In the third example, a seam welded joint of a pipe is considered (Fig.5-(b)). Inherent strains distribute uniformly in the weld metal. The result of analysis represents in Fig.8. As the stresses estimated by the Sachs method are different from the true ones by the finite element method, the application of this method is not suitable to this case.



(a) Meshes in axial direction

(b) Meshes in cross section

Fig 5 Hollow circular cylinder and its finite element idealization for numerical experiment by the Sachs method

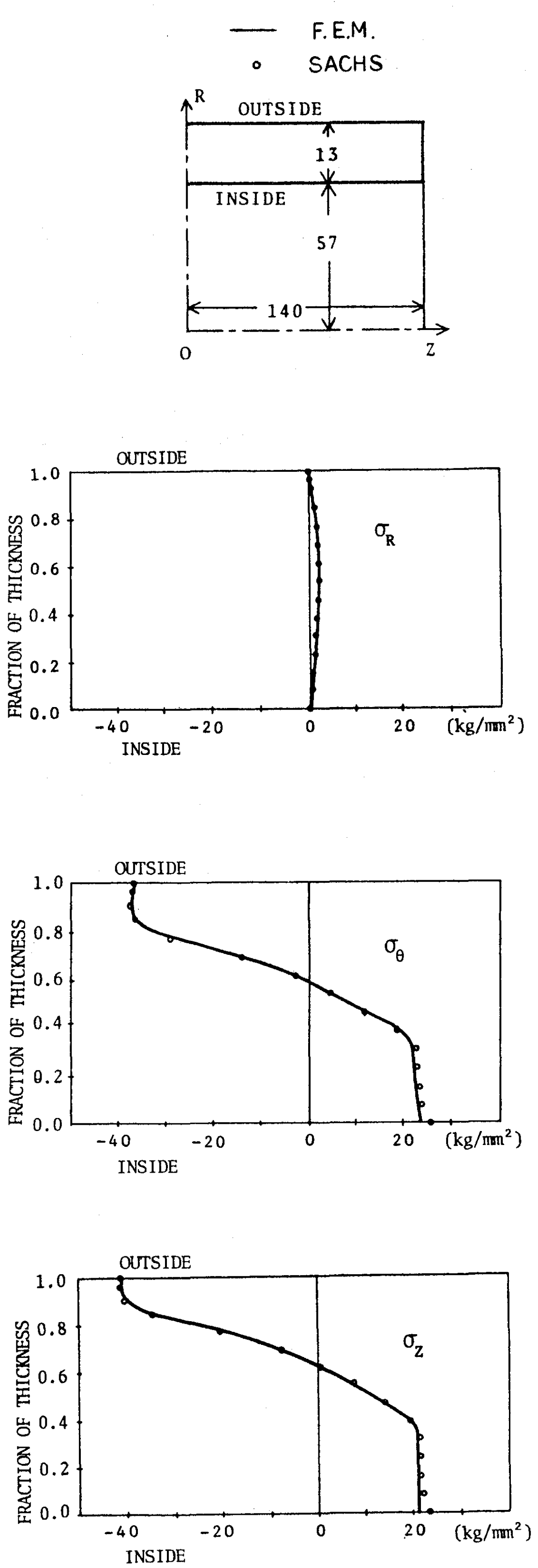


Fig. 6 Residual stresses analyzed by F.E.M. and estimated by the Sachs method for case (1) (where residual stresses are rotationally symmetrical and uniform in axial direction,

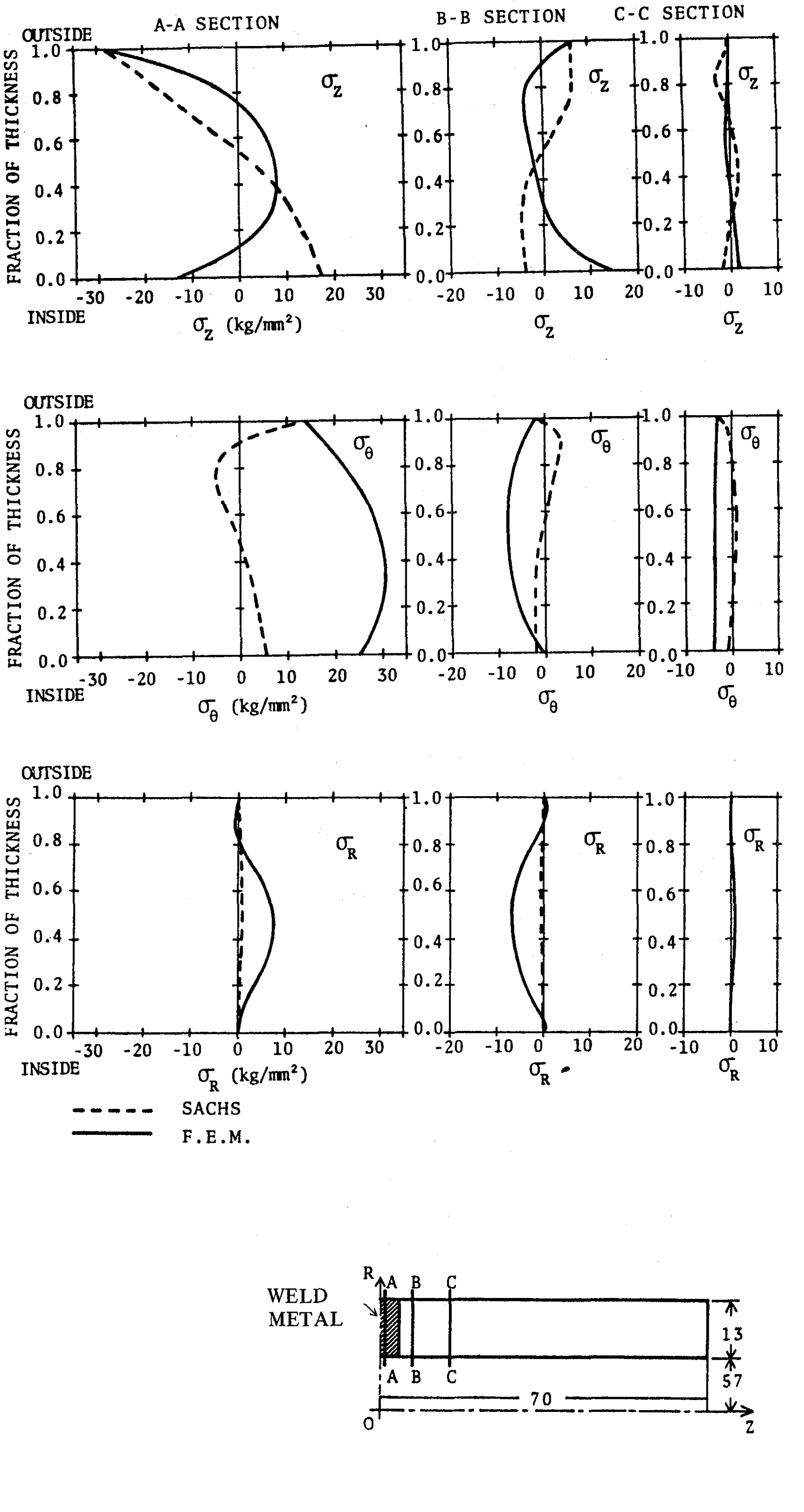


Fig. 7 Residual stresses analyzed by F.E.M. and estimated by the Sachs method for case (2) (where residual stresses are rotationally symmetrical but not uniform in axial direciton)

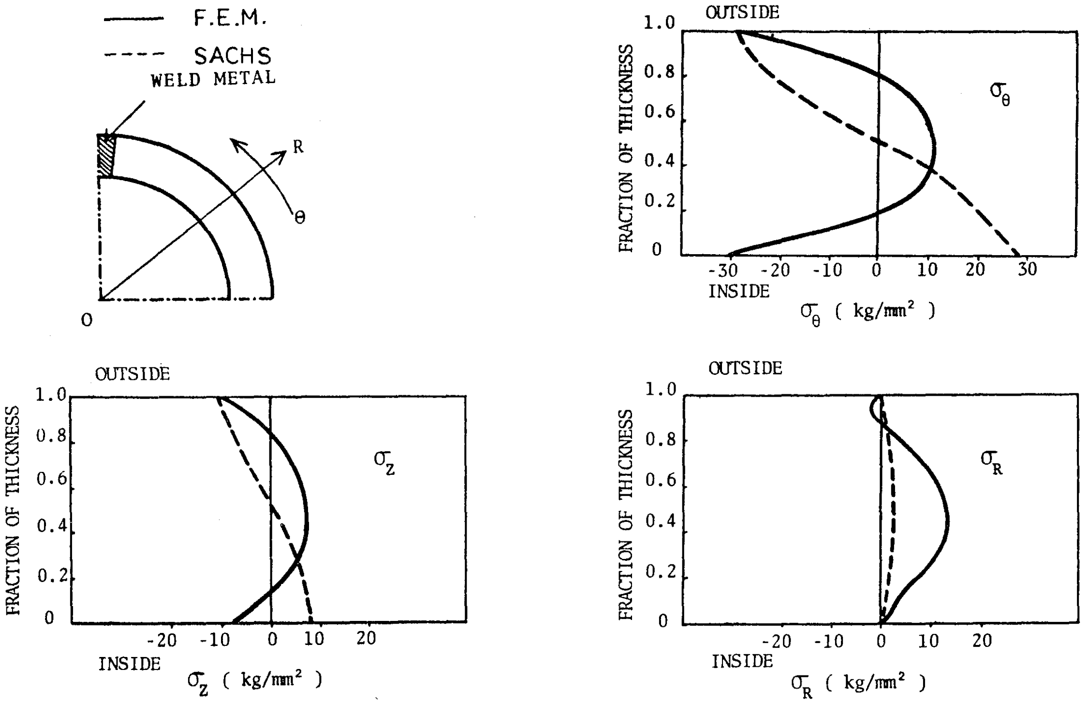


Fig. 8 Residual stresses analyzed by F.E.M. and estimated by the Sachs method for case (3) (where residual stresses are not rotationally symmetrical but uniform in axial direciton)

4. Conclusion

Some numerical experiments by the finite element method are conducted to investigate the justification of applications of the existing measuring methods to three dimensional residual stresses.

The following information is obtained.

1) The Rosenthal-Norton method can not be applied generally in three dimensional stress state because it was assumed in the method that the relaxed stresses distribute linearly in the direction of thickness at the first step (removal of a block).
2) The Sachs method gives the correct result if residual stresses are uniform in the axial direction and of rotational symmetry. In cases where either of the above two restrictions is not satisfied, this method can not be applied.
3) A general theory of measuring method of three dimensional residual stresses has not been formulated yet except by the authors[2].

Reference

1) For example, S. Watanabe and K. Satoh, "Welding Mechanics and its Application", 3rd Ed., Asakurashoten, Ltd., (1971), p332-364 (in Japanese)
2) Y. Ueda, K. Fukuda, K. Nakacho and S. Endo, "A New Measuring Method of Residual Stresses with the aid of Finite Element Method and Reliability of Estimated Values", Trans. of JWRI (Welding Research Institute of Osaka University, Japan) Vol.4 No.2 (1975) and J. of Naval Architects, Japan, Vol.138 (1975), pp525–533 (in Japanese).