Simplifying Methods for Analysis of Transient and Residual Stresses and Deformations due to Multipass Welding†

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Abstract

Information about transient and residual stresses and deformations produced in welded joints by welding is important. One of the methods to obtain such information is to perform thermal elastic-plastic analysis. This method furnishes accurate results of them but needs long computation time (CPU time), especially in the case of multipass welding. So simplifying methods for analysis of residual stresses due to multipass welding are necessary.

In this study, simplifications of thermal elastic-plastic analysis were carried out aiming to obtain the residual stress distribution of (1) the whole cross section of the welded joint, (2) the part of the cross section near the finishing bead, in short CPU time. As a result, for each purpose, the simplifying method was developed by which CPU time required for analysis can be much shortened, keeping the accuracy of analysis.

KEY WORDS: (Thermal Elastic-Plastic Analysis) (Simplifying Method) (Multipass Welding) (Welding Stress) (Welding Deformation)

1. Introduction

The demand for a large capacity in nuclear reactors and chemical plants requires the use of high quality thick plates for pressure vessels, which are the main structural components of these plants. These thick plates are usually welded by multipass welding. In the process of multipass welding, cold cracks may be produced. For this reason and others, information about residual stresses produced by welding is important. Meanwhile, the needs to conserve energy lead to the development of narrow gap arc welding. Narrow gap arc welding uses less heat input, less weld metal, less time than normal welding methods. It also affects the metallurgical and mechanical properties of the base metal less due to smaller heat input. Narrow gap arc welding is usually conducted by MIG welding (inert gas arc welding using a consumable electrode) where not only the transient and residual stresses but also the shrinkage of the groove due to welding deformation are important.

In this study, theoretical analysis (thermal elastic-plastic analysis)[1] based on the finite element method is performed to obtain the residual stresses and deformations due to multipass welding by narrow gap arc welding method. The thermal elastic-plastic analysis furnishes accurate results but needs long computation time, CPU time (Central Processing Unit time), in the case of very thick plates which are welded with many welding passes, even with large computer. That is, CPU time is one of the obstacles in that case. This investigation was carried out to develop analysis methods to shorten CPU time without loss of accuracy of analytical results for multipass welding of very thick plates.

2. Specimens and Methods of Theoretical Analysis

Theoretical analysis for multipass welding is done by thermal elastic-plastic analysis based on the finite element method[1]. In this study, when standard thermal elastic-plastic analysis is applied to the problem of multipass welding, the mesh division for weld zone is performed with elements not bigger than the weld metal of each pass. This mesh division is then used for heat conduction analysis and thermal stress analysis for every welding pass which leads to large computation time. So simplifying methods for analysis of residual stresses due to multipass welding are necessary.

In this study, simplifications of thermal elastic-plastic analysis are carried out aiming to obtain the residual stress distribution of (1) the whole cross section of the welded joint, (2) the part of the cross section near the finishing bead, in short CPU time.

2.1 Specimens for analysis

SM-50 steel plates of thickness 50 mm and width 95 mm are to be welded with groove width 10 mm by

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multipass welding as shown in **Fig. 1** (model 1). Since the welding method is narrow gap arc welding, each layer is formed by one welding pass. Models 2 and 3 in Fig. 1 have the same dimensions as model 1 except the depths of groove are different. The total numbers of passes are 20, 1 and 3 for the models 1, 2 and 3, respectively.

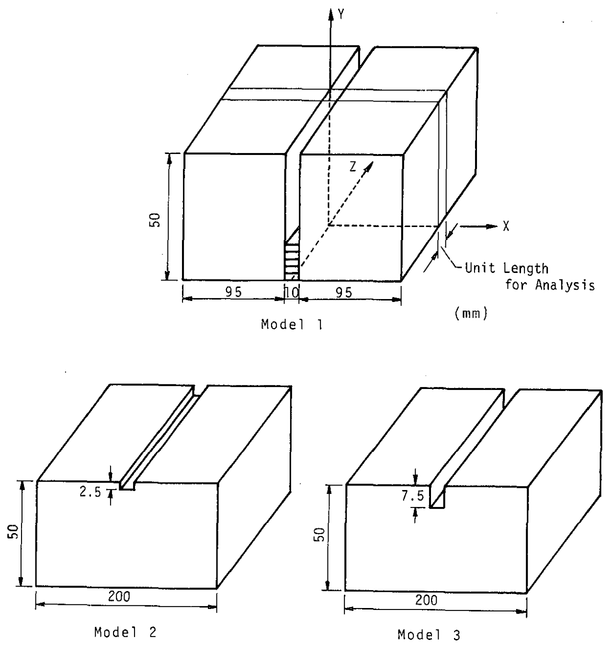

Fig. 1 Specimens for Analysis

The specimens are symmetric about the middle cross section YZ plane, so only half of each specimen is to be analyzed. Two types of mesh divisions are used in this study, "Fine mesh division" and "Rough mesh division", as shown in **Figs. 2** and **3**. These mesh divisions are used for heat conduction analysis as well as thermal elastic-plastic analysis. The physical and mechanical properties of the specimens used in analyses are shown in **Figs. 4** and **5**.

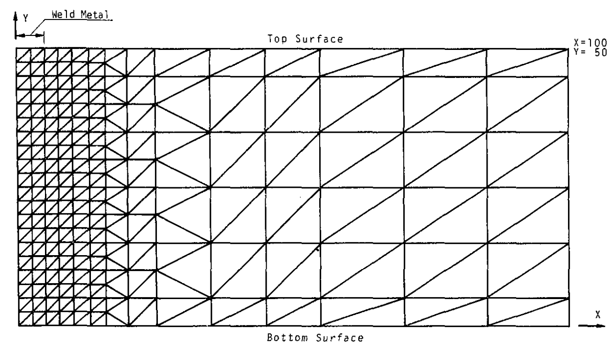

Fig. 2 Fine Mesh Division

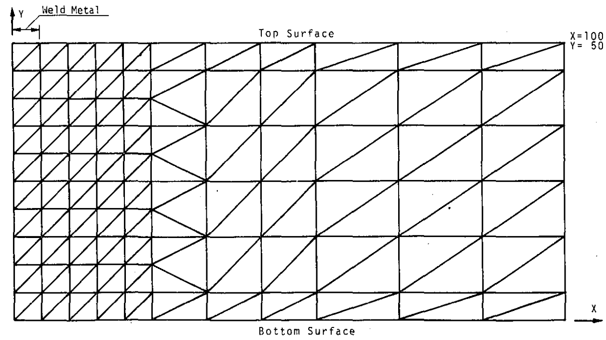

Fig. 3 Rough Mesh Division

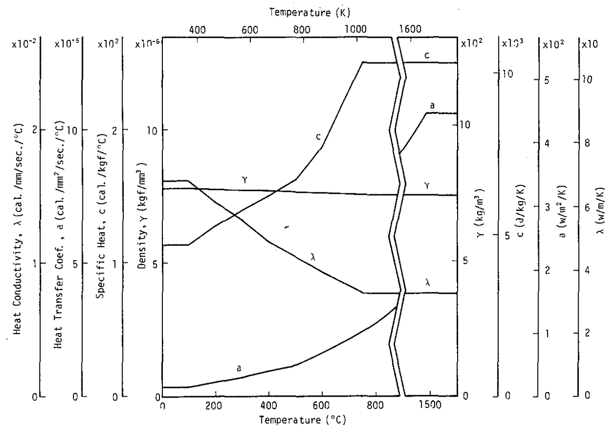

Fig. 4 Physical Properties used in Heat Conduction Analysis

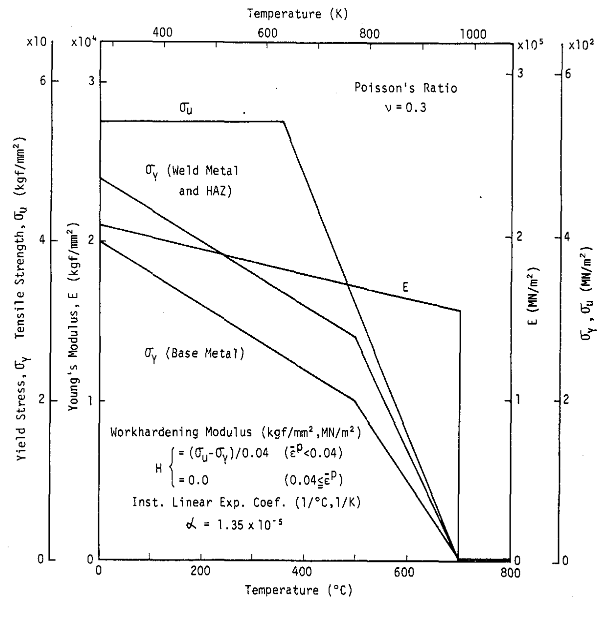

Fig. 5 Mechanical Properties used in Thermal Stress Analysis

2.2 Methods of thermal elastic-plastic analysis

2.2.1 Standard thermal elastic-plastic analysis

As the effect of coupling between temperature and stress fields for welding problem is small, theoretical analysis can be divided into two separate parts: heat conduction analysis and thermal stress analysis based on the temperature distributions calculated in the preceding heat conduction analysis.

The heat conduction analysis is performed by the finite difference method for each welding pass with instantaneous heat source. The welding conditions for all welding passes are the same, heat input is 30,000 J/cm and heat efficiency is 0.95. The interpass temperature is room temperature, 15°C.

The method of thermal stress analysis used in this study is the thermal elastic-plastic analysis based on the finite element method developed by the authors. This method can take into account the temperature-dependence and plastic history-dependence of mechanical properties (e.g., yield stress, Young's modulus, instantaneous linear expansion coefficient, etc.). The analyses are carried out under two different restraint conditions, restraint conditions A and B as shown in **Figs. 6 (a)** and **(b)**. Restraint condition A possesses

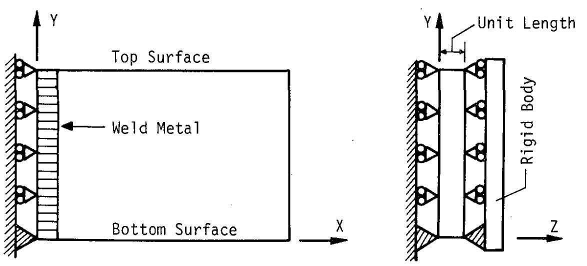

Fig. 6 (a) Restraint Condition A

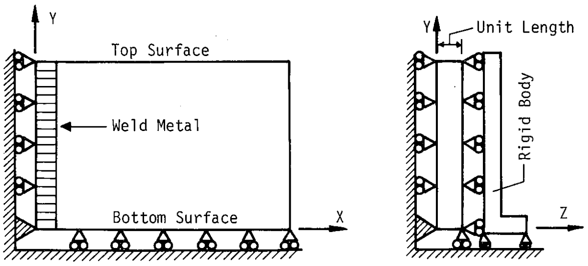

Fig. 6 (b) Restraint Condition B

no external restraint on the model. Restraint condition B restricts the rotations of the model about X-axis and Z-axis (longitudinal deformation and angular distortion). These restraint conditions are the two extreme restraint conditions for actual butt joints. If the model is sufficiently long, it might be rational to regard that the XY plane of model is allowed to move, remaining as a plane. Making this as an assumption, three dimensional stress state is realized in thermal elastic-plastic analysis.

For model 1, thermal elastic-plastic analysis for 20 passes-20 layers welding, M-1 series, are carried out under two different restraint conditions A and B with the fine mesh division (standard thermal elastic-plastic analysis). As the mesh division for M-1 series is fine enough and the calculation is done for all welding passes successively, so the analytical results of M-1 series are considered to show actual residual stresses of model 1 for 20 passes welding in this study. The conditions of analyses of M-1 series and other simplifying methods are shown in **Table 1**.

2.2.2 Simplifying Method 1 for thermal stress analysis

This simplifying method is to obtain the transient and residual stress distribution of the whole cross section of the model like standard thermal elastic-plastic analysis.

By observing the region of HAZ (heat affected zone) for each welding pass, it is known that the regions of HAZ of two consecutive welding passes are mostly overlapped and the stresses in the region are relieved at higher temperature than phase transformation temperature. So the thermal elastic-plastic analysis, M-2 series, are carried out only for the even number of welding passes of M-1 series with fine mesh division for model 1. The analysis, M-3 series, is further simplified by reducing the number of unknowns in analysis by using a rough mesh division as shown in Fig. 3. This process of simplification is shown in **Fig. 7**. In this M-3 series, the analysis is conducted for 10 passes (half number of actual passes) like M-2 series. Heat input of each pass is the same as M-1 series and M-2 series, that is, 30,000 J/cm.

Table 1 Conditions for Analysis and Comparison of CPU Time

Method of Analysis	Total Number of Welding Passes	Total Number of Passes in Analysis	Mesh Division	Restraint Condition	Comparison of CPU Time
M - 1	20	20	Fine	A , B	100
M - 2	20	10	Fine	A , B	50
M - 3	20	10	Rough	A , B	12
M - 4	1	1	Fine	A , B	5
M - 5	3	3	Fine	A , B	15

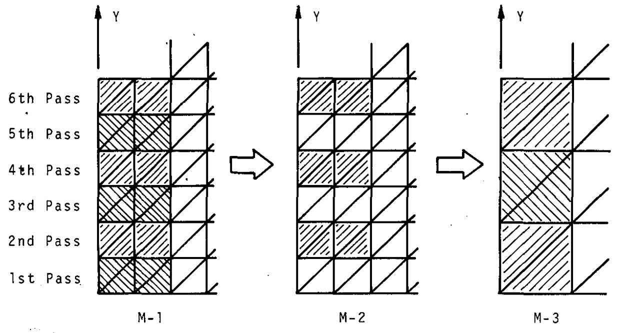

Fig. 7 Process of Simplification of Analysis

2.2.3 Simplifying Method 2 for thermal stress analysis

This method is to obtain the residual stress distribution of the part of the cross section near the finishing bead.

In previous studies[2] on residual stresses of multipass welding, it is reported that the maximum tensile residual stress which is very important appears near the finishing bead in the weld metal. As it is presumed that the residual stress near the finishing bead is induced almost only by the welding passes near it, as an extreme analysis, thermal elastic-plastic analysis, M-4 series, only for the finishing bead is performed to obtain the residual stress distribution near the finishing bead, using model 2. For the same purpose, the analysis, M-5 series, of last three welding passes are performed on model 3.

3. Analytical Results and Discussion

As cold cracks are caused by transverse welding residual stresses (σ_X) and longitudinal welding residual stresses (σ_Z), so attention is focused on these stresses at the middle cross section (at X=0) and on the top surface (at Y=50). Since narrower groove width saves more energy, the limit of groove width is restricted only by the welding machine and the welding deformation. Therefore the shrinkage of groove width at the top surface is investigated.

3.1 Results of standard thermal stress analysis (M-1 series)

Figures 8 (a) - (d) show the residual stresses of M-1 series. For transverse welding residual stresses (σ_X) at the middle cross section (Fig. 8(a)), under the restraint condition A, the maxima of tensile residual stresses appear a few layers below the finishing bead and on the bottom surface. Under the restraint condition B, the maximum tensile residual stress appears a few layers below the finishing bead but large compressive residual stress appears on the bottom surface.

For longitudinal welding residual stresses (σ_Z) at the middle cross section (Fig. 8(b)), under the restraint condition A, the maximum tensile residual stresses appear a few layers below the finishing bead and on the bottom surface like transverse stresses (σ_X). Under the restraint condition B, large tensile residual stresses are distributed from a few layers below the finishing bead to the center of thickness, but on the bottom surface, compressive residual stress appears.

In actual welding, all butt joints are welded under the restraint condition between the restraint conditions A and B, so, in many cases, the largest tensile residual stresses in transverse and longitudinal directions appear only a few layers below the finishing bead. The values are larger than the maxima on the top surface (compare them with Figs. 8(c) and (d)), that is, largest over the whole cross section.

Figure 9 shows the shrinkgage variation of groove width at the top surface. For welding up to the 6th

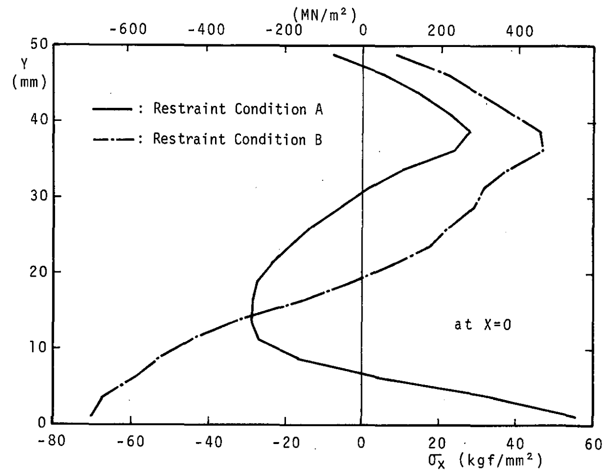

Fig. 8 (a) Transverse Welding Residual Stresses (σ_X) at the Middle Cross Section (M-1)

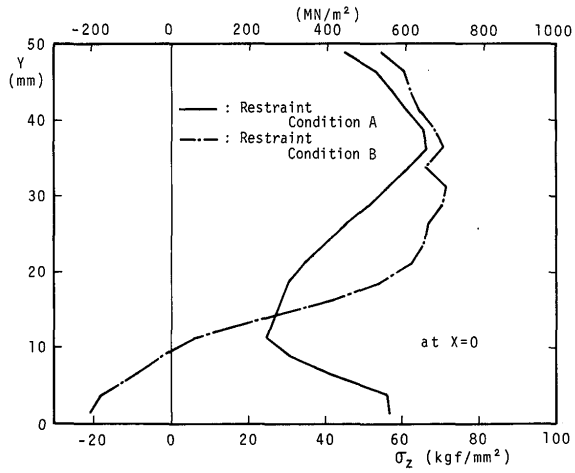

Fig. 8 (b) Longitudinal Welding Residual Stresses (σ_Z) at the Middle Cross Section (M-1)

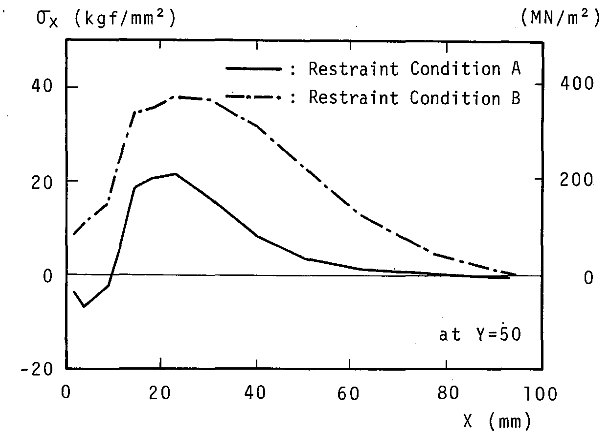

Fig. 8 (c) Transverse Welding Residual Stresses (σ_x) on the Top Surface (M-1)

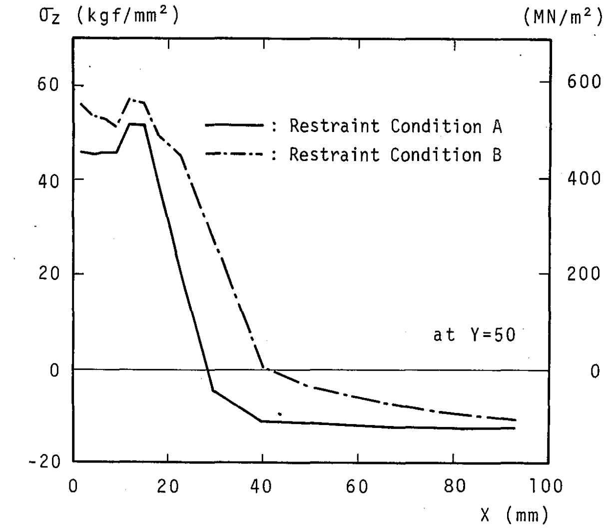

Fig. 8 (d) Longitudinal Welding Residual Stresses (σ_z) on the Top Surface (M-1)

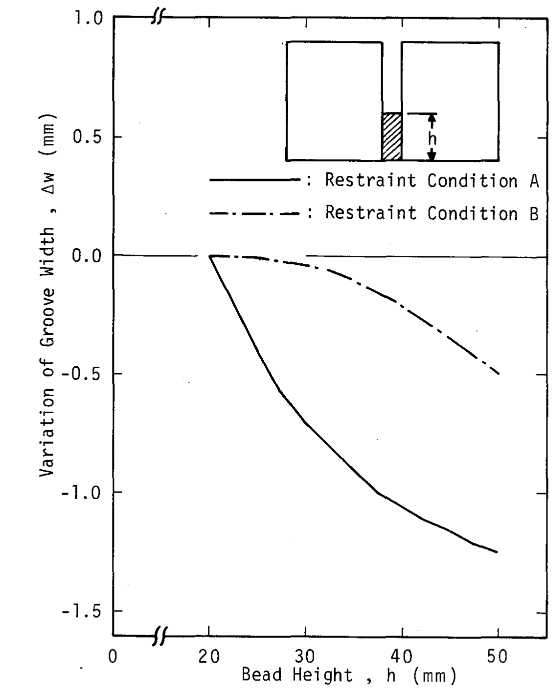

Fig. 9 Variation of Groove Width due to Welding without the Shrinkage before 7th Pass (M-1)

pass, HAZ which possesses no rigidity at high temperature, penetrates the middle cross section of model 1, so analytical results of shrinkage of groove width in this time tend to be greatly influenced by the mesh division, mechanical properties and temperature distributions used in thermal stress analysis, round-off error of computation, etc.. Although the shrinkage of groove width during the first 6 passes is large, the present analytical method is not reliable to obtain it completely, so only the shrinkage due to the welding of the passes above 20 mm from the bottom surface is shown in Fig. 9.

3.2 Results of analysis by Simplifying Method 1 (M-2 series and M-3 series)

Figure 10 and **Fig. 12** show the comparisons of residual stresses between M-1 series and M-2 series, and between M-1 series and M-3 series.

From Fig. 10, for practical purposes, the residual

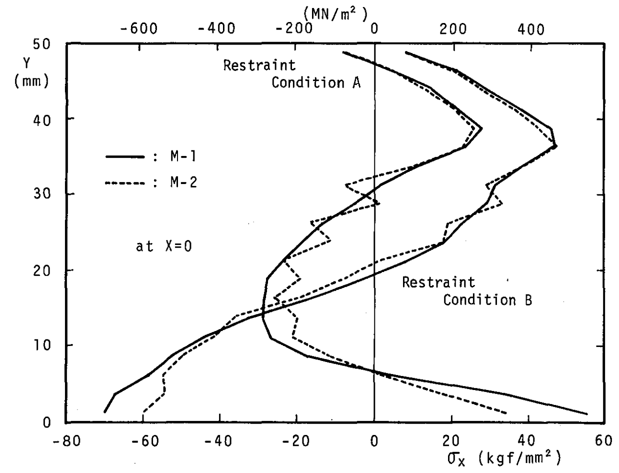

Fig. 10 (a) Comparison of Transverse Welding Residual Stresses (σ_x) at the Middle Cross Section (M-1, M-2)

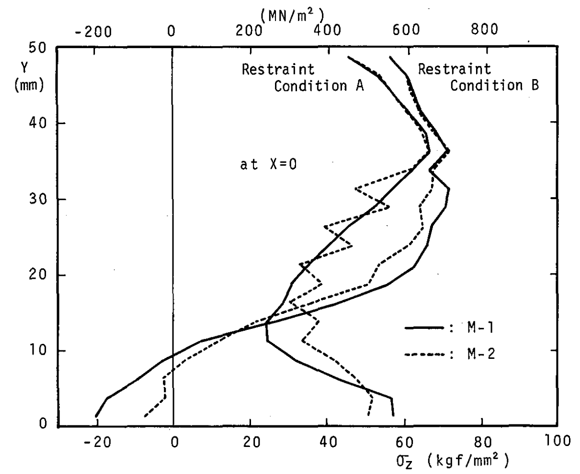

Fig. 10 (b) Comparison of Longitudinal Welding Residual Stresses (σ_z) at the Middle Cross Section (M-1, M-2)

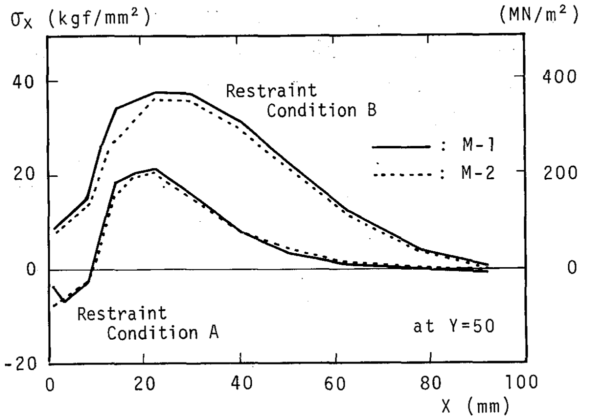

Fig. 10 (c) Comparison of Transverse Welding Residual Stresses (σ_x) on the Top Surface (M-1, M-2)

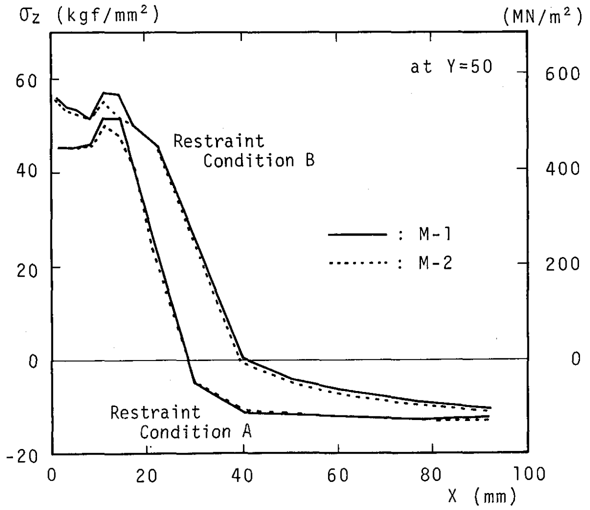

Fig. 10 (d) Comparison of Longitudinal Welding Residual Stresses (σ_z) on the Top Surface (M-1, M-2)

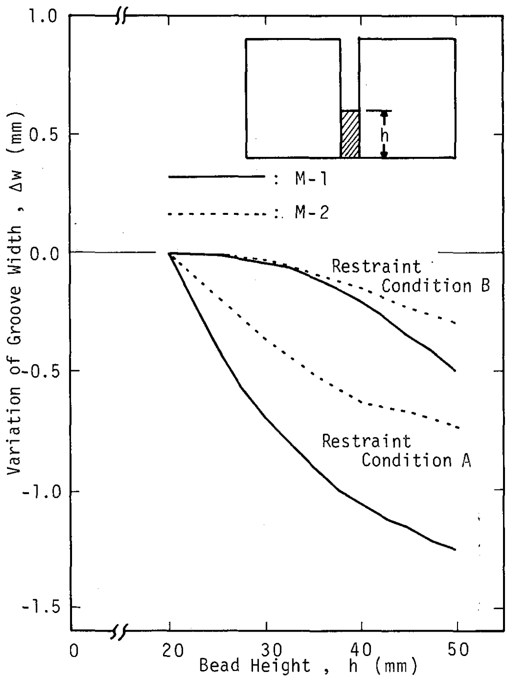

Fig. 11 Comparison of Variations of Groove Width due to Welding without the Shrinkage before 7th Pass (M-1, M-2)

stresses calculated in M-1 series and M-2 series are the same under any restraint condition. Partly because the HAZ of the finishing bead reached about 10 mm below it, the residual stress distribution near it almost coincide. The residual stresses near the bottom surface of M-2 series are somewhat smaller than those of M-1 series. Zigzags appear in the distribution at the middle section along Y-axis. The shrinkages of groove width in M-2 series shown in **Fig. 11** are smaller than the ones of M-1 series. The above three phenomena are attributed to the missing-out of the odd number of welding passes with fine mesh division in the analysis.

In Fig. 12, the residual stresses calculated in M-1 series and M-3 series show good coincidence. The somewhat smaller residual stresses near the bottom surface are due to less welding passes analyzed. The differences in residual stresses near the finishing bead are due to the roughness of mesh division. From **Fig. 13**, the shrinkage of groove width on the top surface of model calculated in M-3 series shows rather

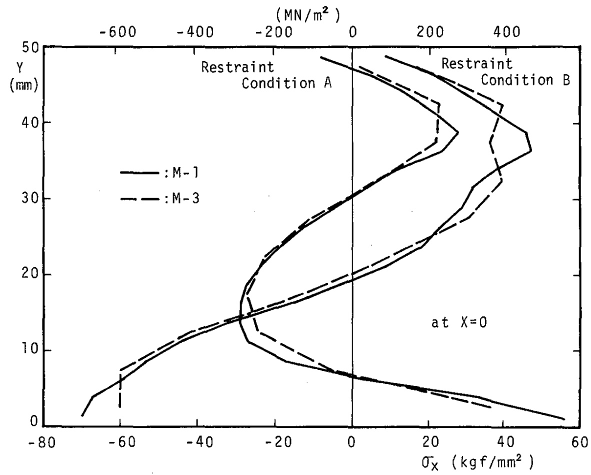

Fig. 12 (a) Comparison of Transverse Welding Residual Stresses (σ_x) at the Middle Cross Section (M-1, M-3)

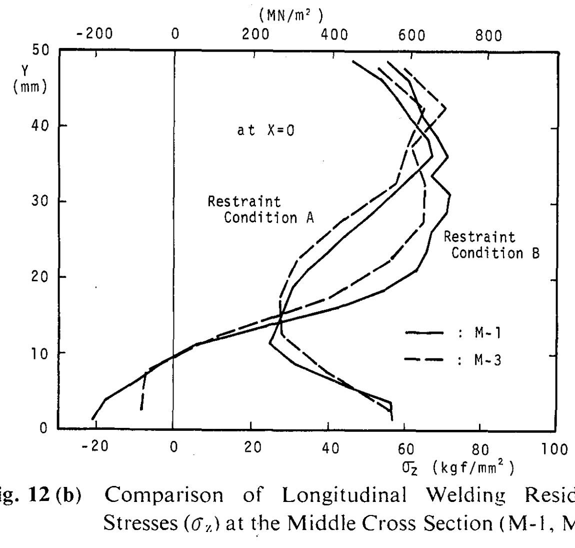

Fig. 12 (b) Comparison of Longitudinal Welding Residual Stresses (σ_z) at the Middle Cross Section (M-1, M-3)

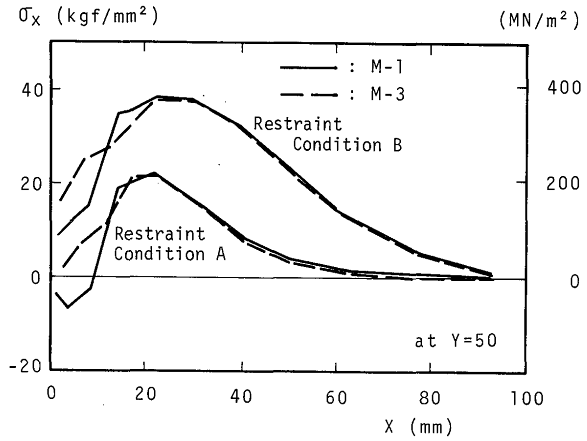

Fig. 12 (c) Comparison of Transverse Welding Residual Stresses (σ_x) on the Top Surface (M-1, M-3)

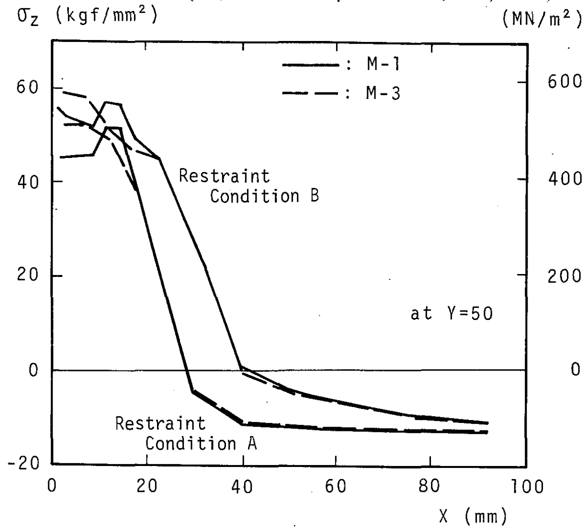

Fig. 12 (d) Comparison of Longitudinal Welding Residual Stresses (σ_z) on the Top Surface (M-1, M-3)

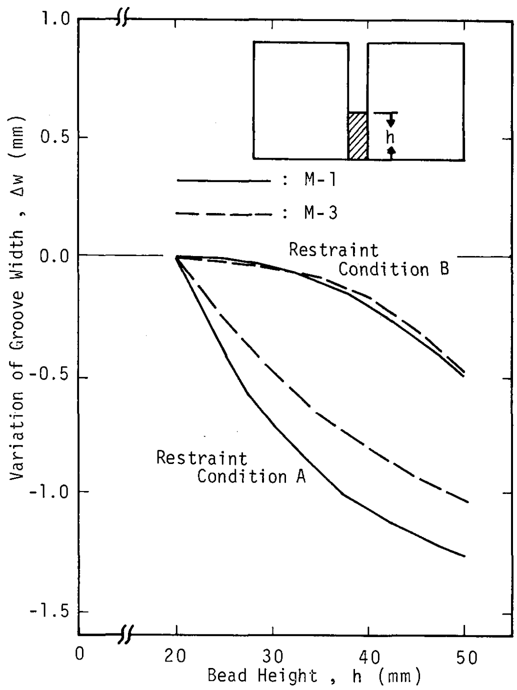

Fig. 13 Comparison of Variations of Groove Width due to Welding without the Shrinkage before 7th Pass (M-1, M-3)

good approximation of M-1 series.

Comparison of CPU time required for the calculation by each method is shown in Table 1. The comparison of CPU times among M-1 series, M-2 series and M-3 series shows that by using the method of M-3 series, with only about 1/10 of the CPU time of the standard analysis, the residual stress distributions can be obtained without much loss on the accuracy of analysis.

3.3 Results of analysis by Simplifying Method 2 (M-4 series and M-5 series)

Figure 14 and **Fig. 15** show the comparisons of residual stresses between M-1 series and M-4 series, and between M-1 series and M-5 series.

Residual stresses near the finishing bead obtained in M-4 series show the almost same stress distributions as in M-1 series, but on the other part of cross section, the stresses are much smaller than those in M-1 series. This confirms that the residual stresses near the finishing bead are mostly produced by the welding passes near it.

M-5 series which calculated the last three passes furnishes better results of the residual stresses near the finishing bead than those in M-4 series, because those stresses are produced by the last pass, being affected by the stresses near it, which have been induced before the last pass. The magnitudes and locations of the maximum tensile residual stresses of M-5 series are the same as M-1 series.

The comparison of CPU time is shown in Table 1. The residual stress distributions of M-5 series are almost the same as M-1 series until the depth of HAZ of the finishing bead, 15 mm from the top surface. So the CPU time of Simplifying Method, M-5, can be further shortened by using larger finite elements in the region away from the HAZ of the finishing bead.

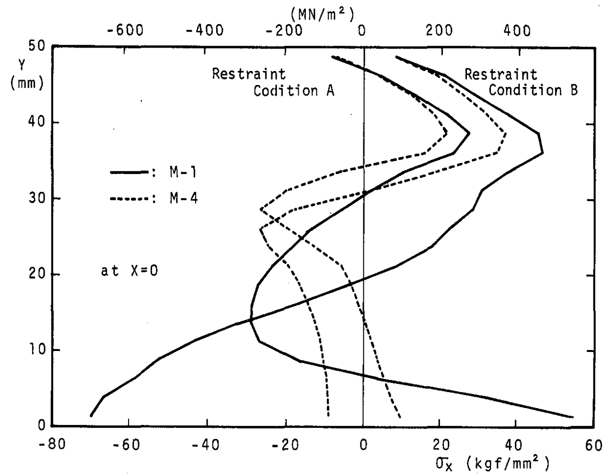

Fig. 14 (a) Comparison of Transverse Welding Residual Stresses (σ_x) at the Middle Cross Section (M-1, M-4)

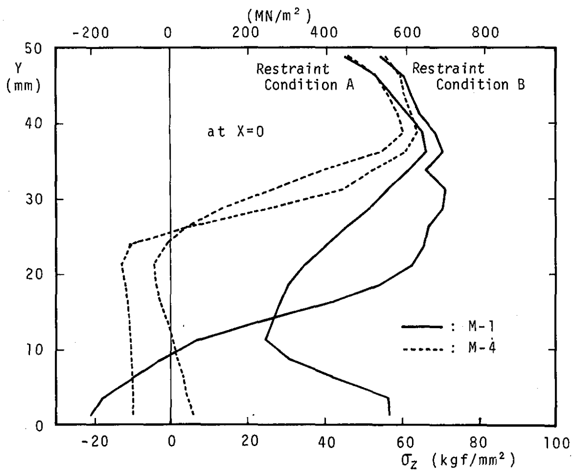

Fig. 14 (b) Comparison of Longitudinal Welding Residual Stresses (σ_z) at the Middle Cross Section (M-1, M-4)

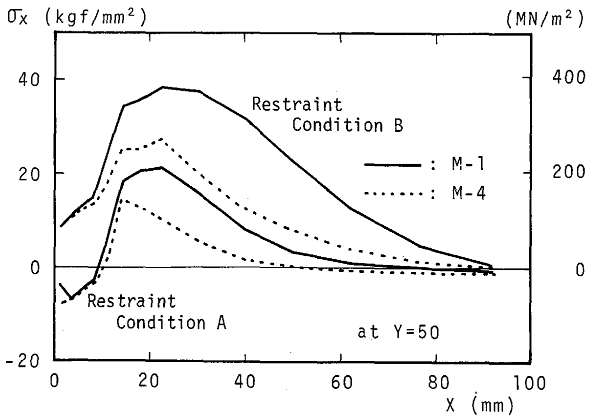

Fig. 14 (c) Comparison of Transverse Welding Residual Stresses (σ_x) on the Top Surface (M-1, M-4)

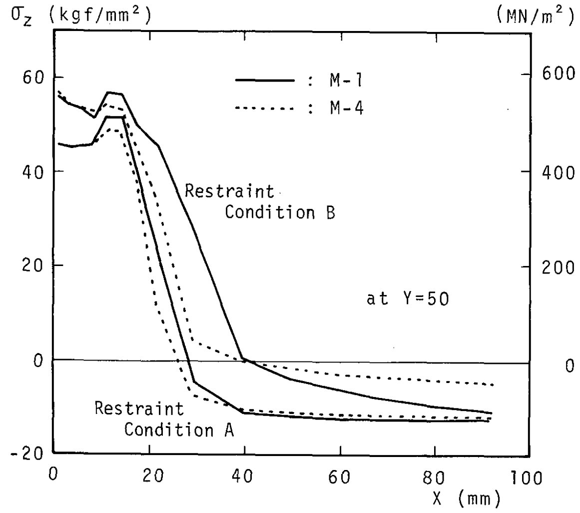

Fig. 14 (d) Comparison of Longitudinal Welding Residual Stresses (σ_z) on the Top Surface (M-1, M-4)

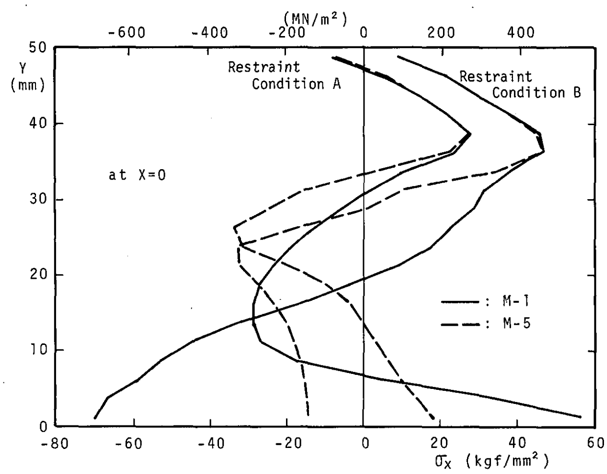

Fig. 15 (a) Comparison of Transverse Welding Residual Stresses (σ_x) at the Middle Cross Section (M-1, M-5)

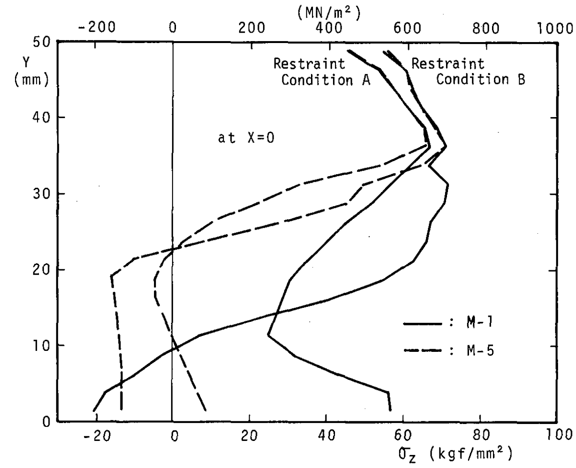

Fig. 15 (b) Comparison of Longitudinal Welding Residual Stresses (σ_z) at the Middle Cross Section (M-1, M-5)

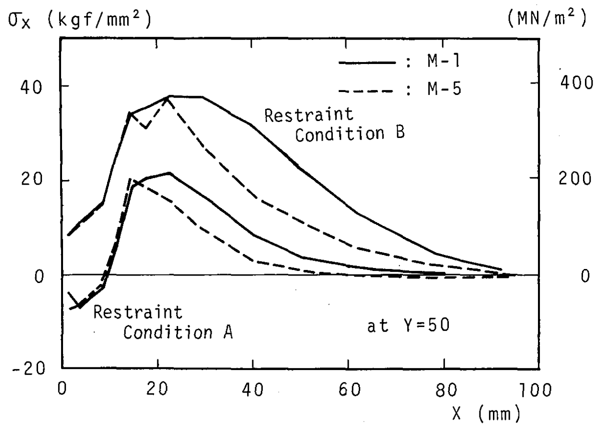

Fig. 15 (c) Comparison of Transverse Welding Residual Stresses (σ_x) on the Top Surface (M-1, M-5)

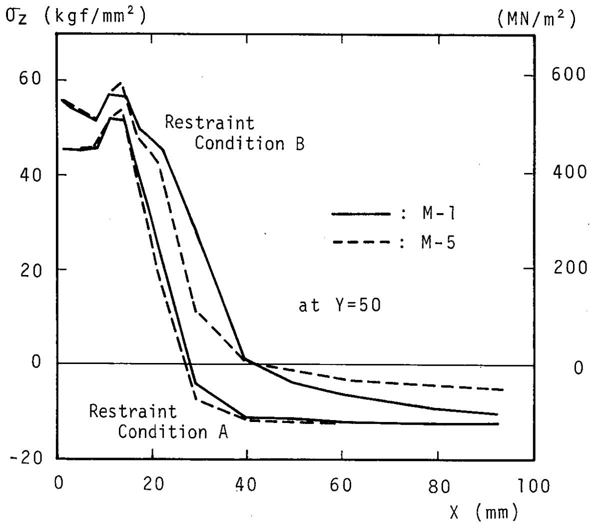

Fig. 15 (d) Comparison of Longitudinal Welding Residual Stresses (σ_z) on the Top Surface (M-1, M-5)

From the comparison of M-1 series and M-5 series, by performing theoretical analysis or experiment of the last few (for example, three as M-5 series) welding passes using the specimen like model 3, information about maximum tensile residual stresses can be obtained at high accuracy by very short CPU time and little labor.

4. Concluding Remarks

In this study, Simplifying Methods 1 and 2 for analysis of transient and residual stresses and deformations due to multipass welding were examined and the results were satisfactory, though the transient stresses are not shown because of space limitations. Although the first method had been used in a study[2] performed in 1973 and the effect of reducing the welding passes in analysis was checked, but due to the capacity of the computer at that time only rough mesh divisions were used for analysis and the effect of mesh division on the accuracy of analysis was not fully studied. In this study, fine mesh division was used to obtain analytical results with sufficient accuracy, and using the results as the basic solution for comparison, the effects of number of welding passes analyzed and mesh division used were investigated.

The following informations are obtained from this study.

(1) The number of welding passes for multilayer welding of thick plates can be halved in analysis and the mesh division can be roughed according to the passes analyzed, keeping the accuracy of analysis. As a result, CPU time required for analysis is much shortened.

(2) Very accurate magnitude and location of the maximum tensile residual stresses which appear near the finishing bead and may cause cold cracks, may be found out by conducting the theoretical analysis or experiment only for the last few welding passes under the same condition as adopted in this study, such as the interpass temperature being room temperature. Even when the interpass temperature becomes higher, the results are presumed also accurate. This method can make CPU time in analysis very short and can make labor in analysis or experiment very little.

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