Full Paper Transactions, SMiRT 28
Toronto, Canada, August 10-15, 2025

# STUDY ON ADVANCED CONSTRUCTION METHOD APPLICATION TO NPPS: CONSTRUCTABILITY TEST FOR SC STRUCTURES USING ADVANCED CONSTRUCTION METHODS

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## ABSTRACT

For the walls ("SC walls") in a steel plate reinforced concrete structure ("SC structure"), welded joints are used as the basic method in this study because of their low impact on interference with the metal fittings embedded in walls and from a cost perspective. Since welding work takes up a large part of the process in the nuclear power plants to which SC structures are applied, it is essential to save labour in welding work. Therefore, the introduction of automated welding robots ("welding robots") to replace the conventional on-site welding is considered to be effective. This paper presents the results of the full-scale constructability tests conducted to check the design, constructability and weldability of SC walls, the deformations caused by welding, the quality of welds and other check items through tests on a full-scale SC wall (basic dimensions of members: 2,000 mm by 4,000 mm, and wall thickness 2,000 mm).

The conclusion of this study can be summarized as follows. It was confirmed that there was no problem with the design (specifications) of the full-scale SC wall, or the constructability and workability of the welding robots (vertical and horizontal position welding). The maximum out-of-plane deformation of the steel plates after welding was approximately 8 mm, which was larger than the deformations in the analytical results. However, their deformation tendencies have turned out to be almost close to each other. We have also confirmed through tests, such as ultrasonic testing, that the quality of the welds produced by welding robots is ensured, except for the linear misalignments that occurred at some grooves for horizontal position welding.

## INTRODUCTION

Application of steel plate reinforced concrete structures ("SC structures") which are advantageous in terms of construction period is considered in the construction of next-generation nuclear power plants ("NPPs"). For the walls in SC structures ("SC walls"), welded joints are used as the basic method. When an SC structure is applied to the assumed nuclear reactor building, the total length of welds in the entire building is several kilometres, and welding takes up a large part of the process. Due to the recent serious labour shortage in the construction industry, it is essential to save labour in welding work. Therefore, the introduction of automated welding robots ("welding robots") to replace the conventional human welding is considered to be effective. Furthermore, unitization of the members into the largest possible units that can be lifted in the temporary work yard can reduce the on-site welding work as much as possible. Figure 1 shows an image diagram of the temporary yard work and on-site welding work.

We simulated the construction of an SC wall on a full scale. This paper reports the results of our study on the constructability (assemblability of steel plates, applicability of welding robots and effects of deformation caused by welding heat).

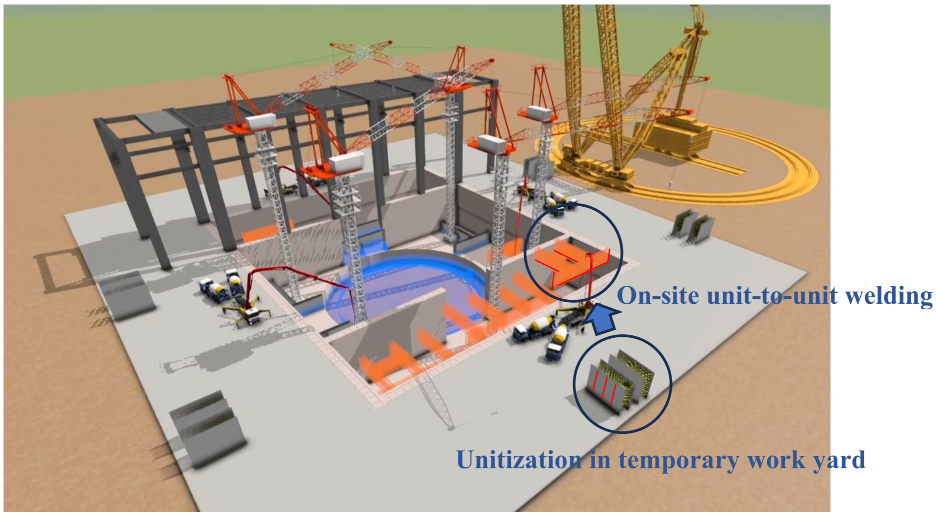
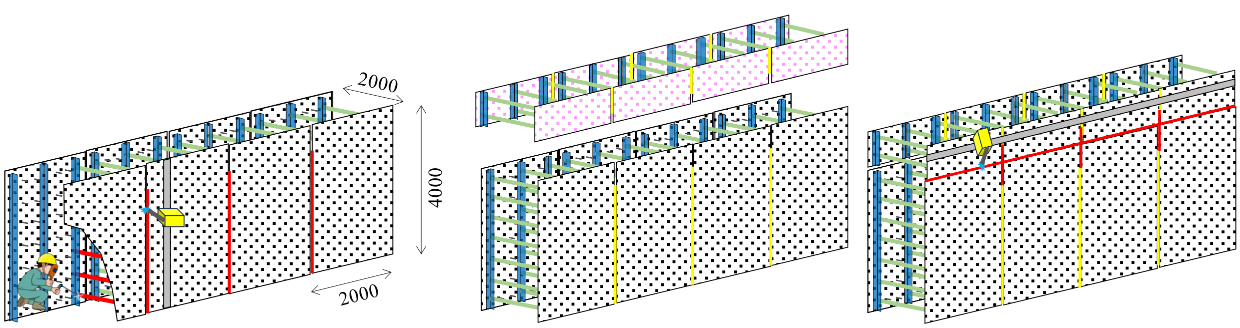



Figure 1. Image diagram of yard work and on-site welding work

## DESIGN OF TEST SPECIMEN

Figure 2 illustrates the procedure for full-scale constructability testing. A two-meter-thick SC wall was simulated. A wall with a length of 2,000 mm, a height of 4,000 mm and a thickness of 2,000 mm (the steel plates on two sides are 19 mm thick each) was taken as one unit. It was decided to integrate four units in the temporary work yard, transport them to the site and install them there. Though four more units for the second section are to be installed on the top of them at the site, the unit height for the second section was set to one meter in this test. The upper four units should be installed after concrete is cast into the lower four units at the site. However, concrete casting was not performed in this test. Figures 3 and 4 show the components of the test specimen (elevational and sectional views), and Figure 5 shows an enlarged view of a steel plate connection (erection piece).




(a) Welding of first-section units (b) Erection of second-section units (c) Welding of first and second section units

Figure 2. Procedure for full-scale constructability testing

The design concept is as follows:

(1) Arrange studs with a spacing of approximately 400 mm to prevent steel plates from shear buckling in an earthquake. Besides, install vertical reinforcing angles with a spacing of approximately 750 mm.

(2) Assuming that SC steel plates may be fabricated and temporarily placed, laid on their side, install two diagonal angles per unit so that the specimen may stand alone. (Ensure sufficient safety through buckling analysis).

(3) Provide the vertical reinforcing angles with tie bars, spaced approximately 400 mm apart, for connecting SC steel plates together to prevent SC steel plates from bulging due to lateral pressure during concrete casting. (Check through structural analysis that neither the deformations of the steel plates nor the axial forces generated at the tie bars exceed the allowable values.)

(4) Install a backing metal (9 mm thick and 25 mm wide) on the back of the groove.

(5) Install erection pieces with a spacing of approximately 400 mm for fixing the steel plates to prevent angular distortion at the welds during vertical position welding. The erection pieces should be mounted on the inside of the SC wall to prevent interference with the running rail of a welding robot. (Set the optimal mounting spacing of the erection pieces by analysis).

(6) Install angles and support the four units of the second section as shown by Figure 5 in order to secure the horizontal root gaps and ensure installation accuracy during the erection of the second section.

(7) Fix the upper and lower units during the erection of the second section. Install four erection pieces per steel plate to prevent angular distortion during horizontal position welding.

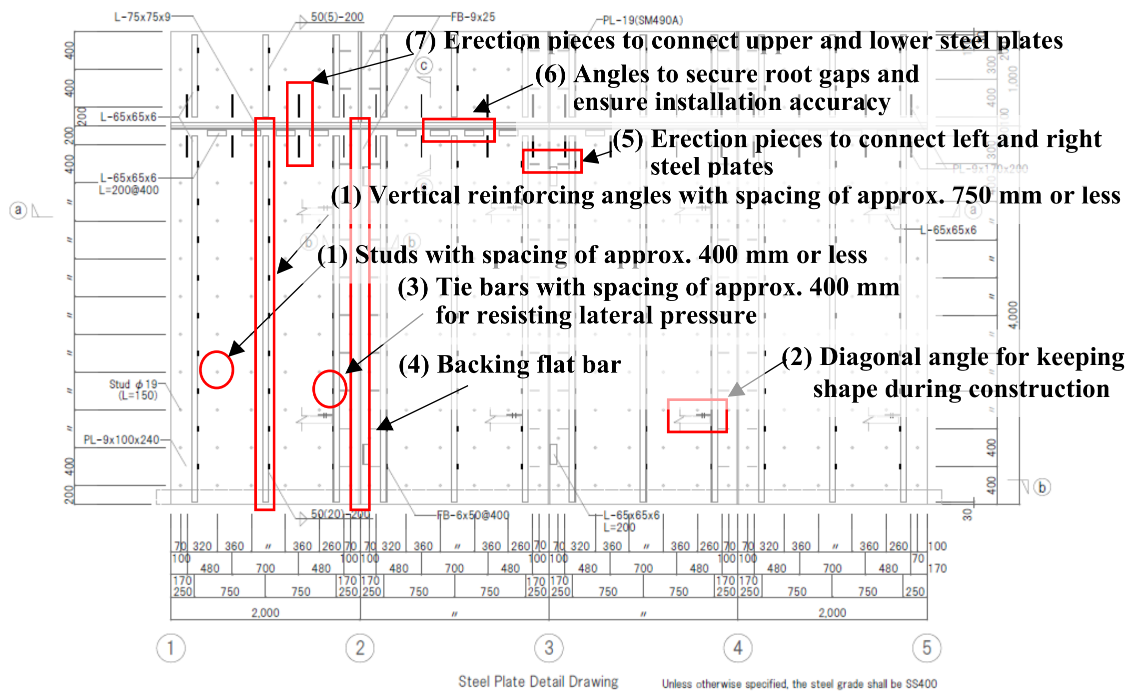



Figure 3. Components of test specimen (elevational view)

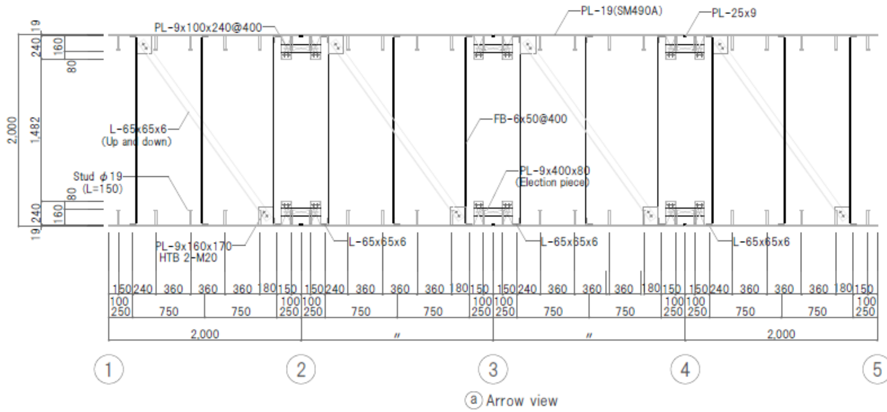



Figure 4. Components of test specimen (sectional view)

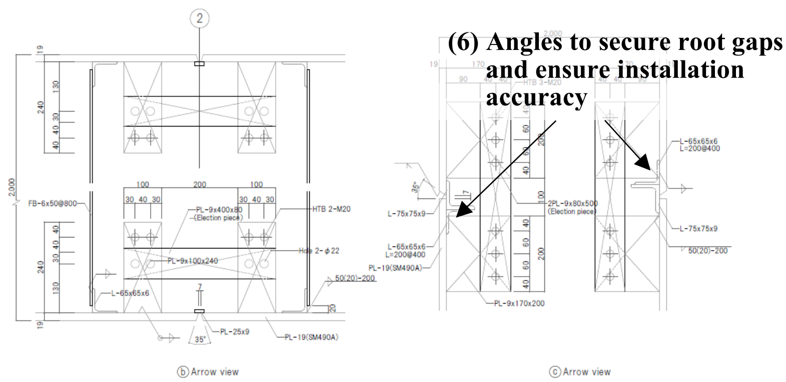



Figure 5. Enlarged view of erection piece

## TESTING

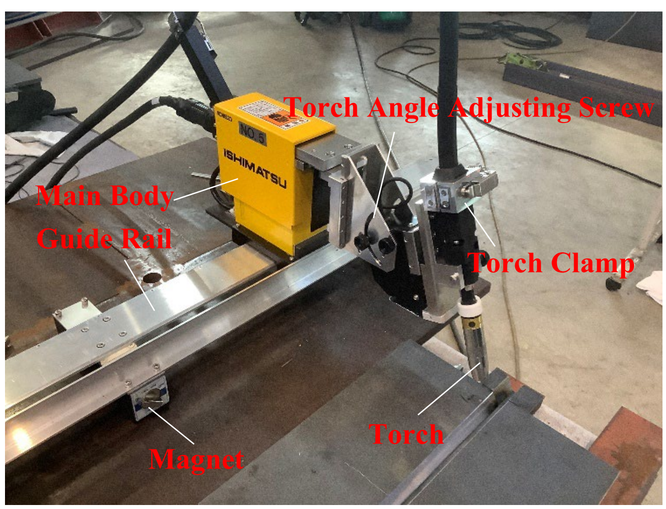
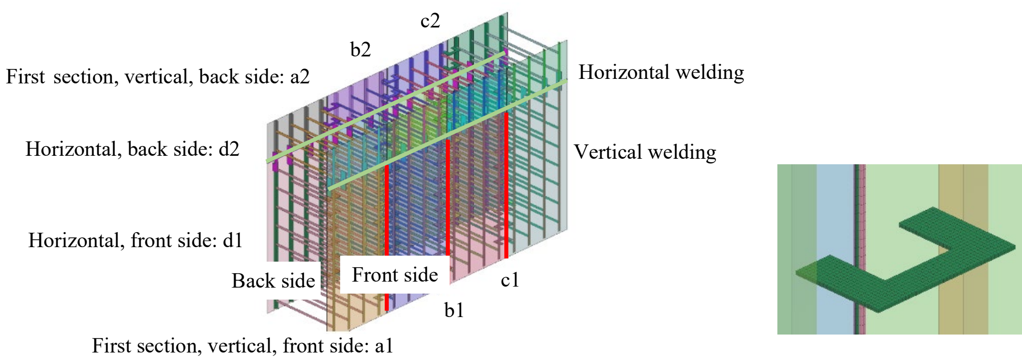



Figure 6. Details of welding robot components

In this test, we used general-purpose portable welding robots with an abundant track record of use in steel fabrication factories and other workshops (Mori, M. et al. (2019)) (Otsuka, H., Shirai, Y., Asai, H. and Suzui, Y. (2020)). Figure 6 shows the details of the welding robot components. This type of robot was used for the test because it is i) easy to transport and install on site owing to its lightweight and compactness; ii) usable in vertical and horizontal welding positions and iii) capable of automating the setting of the welding conditions that match the groove shape. The welding robot system consists of the main robot body, running rail, operation box and robot controller (computer) in addition to the welding power source and wire feeding device.

***Deformation Quantity Simulation Analysis***

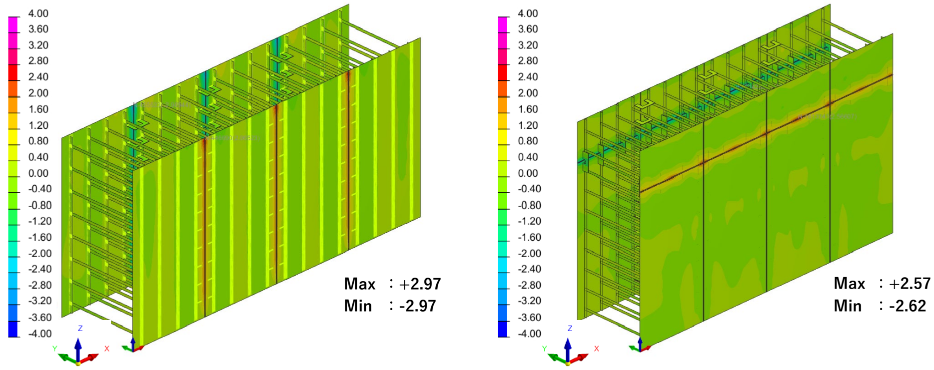
Since the deformation caused by welding heat during the welding of SC steel plates is a concern in a constructability test, we analysed the thermal deformations of SC steel plates and explored a welding procedure that minimizes the thermal deformations. Because expansion and contraction occur continuously as the weld zone moves, sequential calculations require an enormous amount of calculation time. Therefore, we conducted the analysis using a thermal contraction method (Shrinkage Method) to calculate thermal deformations in a simplified manner. The analysis conditions for the welds were set, such as the shapes and yield stress of beads, in the separately performed element test. Figure 7 shows the analysis model. The steel plates, vertical reinforcing angles, tie bars and erection pieces were modelled, and the mesh size of the elements was set to approximately 20 mm. The analysis was conducted by taking the procedure of simultaneously welding the two sides of the SC wall (a1/a2 -> b1/b2 -> c1/c2 -> d1/d2 in Figure 7), using two welding robots.




(a) Entire model (b) Model of erection piece

Figure 7. Analysis model and conditions

The analytical results indicated that welding caused angular distortion of the SC steel plates. The out-of-plane deformations occurred up to approximately 3.0 mm after the end of the vertical position welding of the first section, and up to approximately 2.6 mm after the end of the horizontal position welding. Figure 8 and Table 1 respectively show the out-of-plane deformation diagrams and the out-of-plane deformation quantities.




(a) After the end of first-section vertical welding (b) After the end of horizontal welding

Figure 8. Y-directional deformation diagrams

Table 1: Maximum out-of-plane deformation quantities

| Parameter (welding procedure) | After the end of first-section vertical position welding | | After the end of first-to-second-section horizontal position welding | |
|---|---|---|---|---|
| | Max. displacement (mm) | Min. displacement (mm) | Max. displacement (mm) | Min. displacement (mm) |
| (1) Simultaneously on front and back sides | 2.97 | -2.97 | 2.57 | -2.62 |

***Overview and Results of Constructability Test***

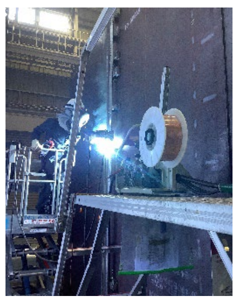
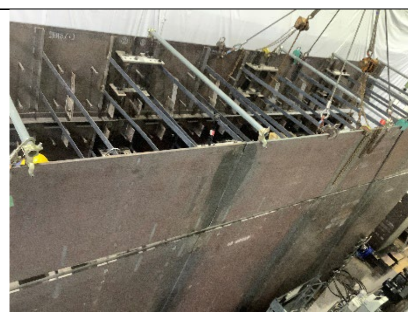
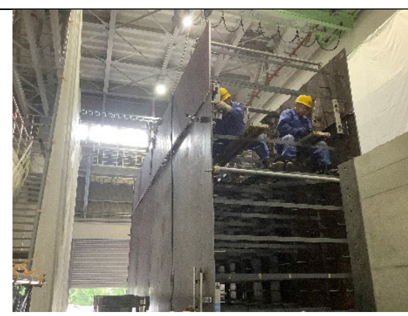
Table 2 shows the statuses of the full-scale constructability test.

Step 1: Studs, vertical reinforcing angles and other components were welded to the steel plates. Then tie bars and diagonal angles were welded with the steel plates upright, and the steel plates were bolt-connected, using erection pieces. We were able to perform the welding of tie bars and bolt connections of erection pieces in the SC wall without any problems. The groove root gaps during the vertical position welding met the tolerance of 7 mm (-2 mm, +∞) specified in the standard specification (Japanese Architectural Standard Specification), and the linear misalignments also almost met the limit tolerance, which is 1.9 mm or less.

Step 2: A welding robot running rail was installed on the steel plates with magnets, and then vertical position welding between steel plates was performed. We checked the welding status on an electric mobile elevating work platform during welding. By installing the wire feeding device in a central position at a height of two meters, the need for rearrangement of the welding robot was eliminated even for as long vertical position welding as four metres. The time required for the four-metre-long vertical position welding was approximately 4.7 hours, including the preparations. The ultrasonic and mechanics test results indicated that the quality of the welds was sufficient.

Step 3: The four units of the second section were installed on the top, and the upper and lower four units were joined together, using erection pieces. The upper four units were supported by angles to ensure installation accuracy as shown in Figure 5, which enabled the root gaps to be kept within the tolerance. However, it was not possible to install sufficient tools for correcting the plumbing accuracy, such as a wire rope and a chain block, due to the tightness of the work area. Consequently, the steel plates were inclined inwards during the first-section erection because the vertical accuracy of the steel plates was not fully maintained, which caused a difference in the wall thickness between the first and second section units. Although the wall thickness was corrected, misalignments exceeding the allowable values occurred at some welding grooves. Thus, the issue in actual construction is how to ensure the plumbing accuracy.

Table 2: Statuses of constructability test

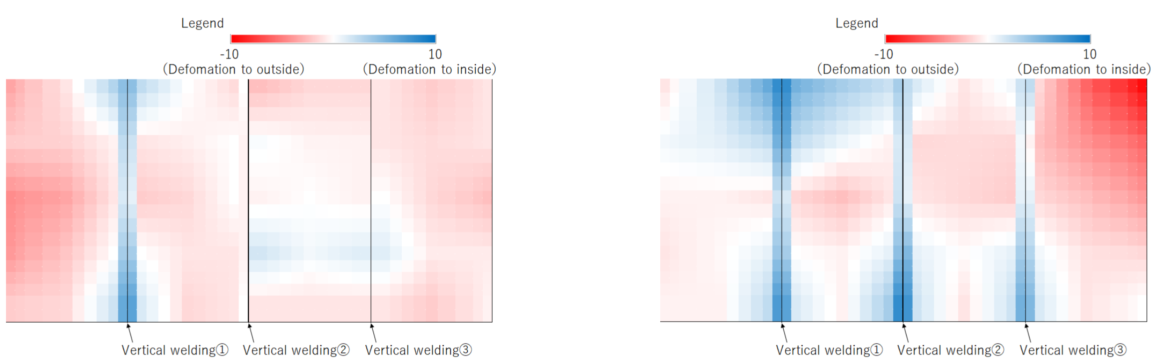
| Procedure | Construction status |
|---|---|
| [Step 1] Fabrication of first-section four units<br>1-1. Installation of studs, reinforcing angles and erection pieces<br>1-2. Installation of tie bars and buckling prevention angles with steel plates upright |  Stud welding  Erection of units  Installation of tie bars |
| [Step 2]<br>Vertical position welding<br>2-1. Vertical position welding<br>2-2. Ultrasonic testing |  Vertical position welding  Welding completed  Ultrasonic testing |
| [Step 3]<br>Installation of second-section four units<br>3-1. Erection of second-section units<br>3-2. Correction of misalignments and root gaps<br>3-3. Installation of erection pieces |  Second-section steel erection  Misalignment correction |
| [Step 4] Connection of upper and lower four units<br>4-1. Horizontal position welding for connection of the first and second sections<br>4-2. Welding of intersections of the first and second sections<br>4-3. Ultrasonic testing |  Horizontal position welding  Preparations for intersection welding  Completed |

Step 4: We performed the horizontal position welding to connect the upper and lower four units and the welding of the intersections between the vertical and horizontal directions. With the welding robots, the horizontal position welding was performed without any problems. However, there was an insufficient penetration of the first layer in some horizontal position welds due to the effect of the linear misalignments. The ultrasonic and mechanics test results indicated that the quality of the welds was sufficient, except for the insufficient penetration of the first layer. It is considered that the insufficient penetration of the first layer can be corrected by correcting the vertical accuracy of the steel plates to reduce the linear misalignments to within the tolerance. The time required for the eight-metre-long horizontal position welding was approximately 6.7 hours, including the preparations.

***Results of Deformation Quantity Simulation and Verification of Constructability Test Results***

In the constructability test, we measured the quantities of the out-of-plane deformation of the SC steel plates before and after welding, compared them with the results of the Deformation Quantity Simulation Analysis discussed earlier and verified the validity of the analysis. To find the deformation quantity, a laser marker was installed in a reference position parallel to an SC steel plate, and the distance between the steel plate and the marker was measured by placing a metal ruler on the steel plate. The initial values were measured after the erection of the first-section units, and the out-of-plane deformations were measured every time the vertical position welding of the front and back surfaces was completed. Then the differences from the initial values were taken as the quantities of the out-of-plane deformation of the SC steel plates after welding.

Figure 9 shows the quantities of the out-of-plane deformation after the end of the vertical position welding (1) and (3) as typical values. The charts in this figure indicate that the welding caused inward angular distortions up to approximately 8 mm in the area around the vertical-position welding line, and that the deformations are larger at the unit ends than in the unit centres. Furthermore, the analytical results in Figure 8 show their tendency of inward angular distortion along the welding line like the test measurement results. However, the maximum deformation in the analytical results was 2.97 mm, which was generally smaller than the measurement results.

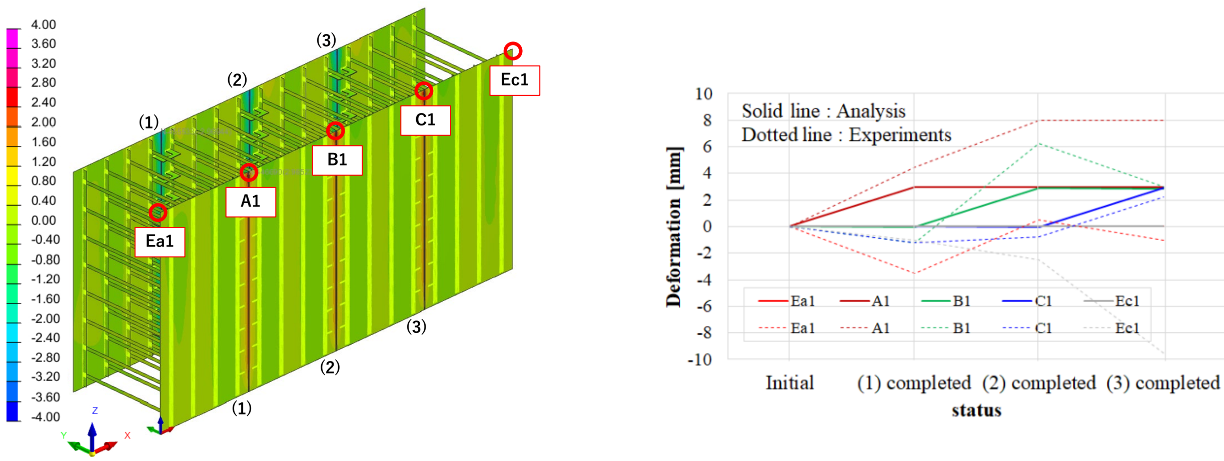



(a) Differences between deformations after vertical welding (1) and initial values

(b) Differences between deformations after vertical welding (3) and initial values

Figure 9. Deformation measurement results

Figure 10 shows the comparison in the deformations at different positions on the SC wall top at the time of the vertical-position welding completion between the analytical and measurement results. Although the measured deformations at the top are generally larger again, their tendency that the angular distortion at the top of the welding position progresses as welding progresses is found to be similar to the analytical results. The reason why the measured deformations were larger than the analytical results is considered that it was affected by the difference in the restraint conditions because while the lower ends of the steel plates were not forcibly restrained in the test, the lower ends were restrained in the Y and Z translational directions in the analysis. Therefore, it is considered that more accurate deformation quantity analysis can be performed by adjusting the analysis conditions for the welds, such as the shapes and yield stress of beads, in the analysis and applying the same restraint conditions.




(a) Deformation quantity output positions (b) Deformations at top of SC steel plate

Figure 10. Results of deformation quantity simulation analysis and measurement results

Moreover, while the specimen end (Ec1) was not deformed in the analysis, the measurement results indicate that the out-of-plane deformation progressed as the welding progressed, which reveals that the deviation between them has increased. The reason for the deviation is considered to be that the plumbing accuracy of the steel plates could not be maintained, which caused the specimen to be slightly inclined during the testing period. The whole specimen shrunk even in the in-plane direction. The shrinkage after the end of the vertical position welding (3) turned out to be 3.8 to 4.5 mm in the analysis and 1 to 8 mm in the measurements. Since the deformation caused by welding heat affects the constructability and construction accuracy, it is important in actual construction to explore a welding procedure that minimizes the deformations and design the members, considering the welding distortions, by accurately predicting the deformations through prior analysis.

## CONCLUSION

For the SC structures which are under consideration for application in next-generation NPPs, we performed a full-scale constructability test applying the design of an SC wall and using welding robots on the assumption of the construction procedures for setting the basic dimensions of the SC wall members to 2000 mm by 4000 mm and the wall thickness to 2000 mm, unitizing the members into four units in the yard, erecting them on site and installing the second section on their top. The summary of the test results is as follows.

The spacings and quantities of the studs, vertical reinforcing ribs, diagonal angles, tie bars and erection pieces were determined on the basis of the analytical study results. The erection pieces were designed to be installed on the inside of the SC walls so as not to be interfered with the welding robot running rail.

We have analytically grasped the quantity of thermal deformation caused by welding and performed vertical position welding of the two sides of the SC wall simultaneously, using two welding robots.

During the specimen erection, while the groove root gaps met the allowable values, some of the horizontal grooves were misaligned.

We performed horizontal position welding and intersection welding, following the vertical position welding, using welding robots, and checked the welding labour productivity. In the ultrasonic testing, only the horizontally misaligned areas were rejected due to the insufficient penetration of the first layer. However, the other areas were accepted, which proved the quality of the welds.

The maximum out-of-plane deformation of the steel plates after welding was approximately 8 mm in the area around the welding line. Thus, the measured deformations were generally larger than the analytical results. However, their deformation tendencies have turned out to be almost similar to each other.

## ACKNOWLEDGEMENTS

This study  was carried out by The Kansai Electric Power Co., Inc., Hokkaido Electric Power Co., Inc., Shikoku Electric Power Co., Inc., Kyushu Electric Power Co., Inc., The Japan Atomic Power Co., The Institute of Applied Energy, Mitsubishi Heavy Industries, Ltd., Obayashi Corp., Taisei Corp. and Takenaka Corp. with the Ministry of Economy, Trade and Industry (METI) subsidy.

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