Welding Simulation Technologies for Highly Efficient Production of High-quality Social Infrastructure Products

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OVERVIEW: Welding makes up a large proportion of the processes involved in the manufacture of social infrastructure products, and greater use of global procurement and production practices is making weld quality assurance and welding efficiency improvements more important. Hitachi has developed technology for simulating the welding of large structures to improve their reliability and to shorten production times by predicting the behavior of the welding process. Hitachi is using this technology to establish appropriate designs and placements for welding jigs, as well as welding procedures and other operational requirements.

INTRODUCTION

LARGE welded structures are used extensively in power plants, industrial machinery, construction machinery, rolling stock, and other types of products, and welding accounts for a large proportion of the overall manufacturing process. In most cases, welds are made at a number of different locations. Typically, practices such as welding procedures and the design and placement of the welding jigs used to minimize the distortion that occurs during welding are determined based on experience, and a considerable amount of time is spent on subsequent remedial work. Greater diversity in materials procurement and production sites is also raising other concerns, such as variations in weld quality caused by differences in material properties and defects caused by inexperienced welders. To overcome these problems, Hitachi is working on the development of a support system that uses simulation to predict weld quality (execution of weld) and that can determine appropriate material selections and other operational requirements.

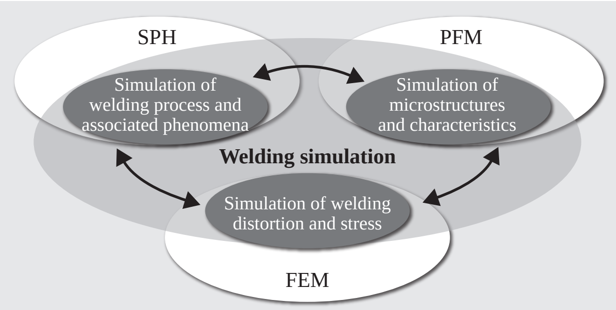
This article describes welding simulation technologies for the highly efficient production of high-quality social infrastructure products.

DEVELOPMENTS IN WELDING SIMULATION TECHNOLOGY

As welding is an extremely complex process that resists systematization as a topic of study, it is not possible to predict all welding phenomena and other outcomes from a single simulation. Accordingly, a range of different simulation methods are used to suit different objectives.

Overview of Progress in Welding Simulation

Fig. 1 shows the main research topics and analysis techniques associated with welding simulation. In broad terms, the commonly used methods can be divided into simulations of welding distortion and stress that use techniques such as the finite element method (FEM)[1], simulations of the welding process and associated phenomena that use techniques such as smoothed particle hydrodynamics (SPH)[2], and simulations of the microstructure of weld metal and its properties that use techniques such as the phase field method (PFM)[3]. Essentially, the FEM and SPH methods are discrete numerical techniques for solving equations that describe a continuous body in terms of its dynamics. PFM on the other hand is a thermodynamics-based technique for simulating



SPH: smoothed particle hydrodynamics PFM: phase field method
FEM: finite element method

Fig. 1—Research Topics and Analysis Techniques for Welding Simulation.
A range of different simulation techniques are used to suit different objectives, including analyses of welding distortion and stress, the welding process and its associated phenomena, and weld microstructures and characteristics.

phenomena such as the segregation of elements and the evolution of the microstructure in the material. The calculation accuracy and computational speed of techniques for simulating distortion and stress that were first used in the 1970s have been improved markedly, and these are now used in a wide range of fields. Attention in recent years has been directed toward areas such as research into the use of SPH for welding process simulations that include the flow of material, and the use of PFM to simulate the various different microstructural changes that occur in the material.

Current Status of Welding Simulation Research at Hitachi

Hitachi has developed techniques for improving analysis speed and accuracy, and also a database of properties material that takes account of factors such as material, structure, and environment based on past FEM analyses of heat transfer and structure. Hitachi has also worked on estimating weld life and on predicting welding distortion in actual products as well as residual stress and crack propagation in welds[(4), (5)]. Recently, Hitachi has also been actively working on SPH and PFM techniques for simulating the welding process as well as weld microstructures and properties, and is developing integrated simulation techniques that also incorporate FEM.

The following sections describe the development of a technique for simulating welding distortion in large structures, and examples of its application.

DEVELOPMENT OF WELDING DISTORTION SIMULATION TECHNIQUE

Basic Methodology of Welding Distortion Simulation

Use of FEM for welding distortion simulation can be broadly divided into the thermo elastic plastic (TEP) method and the inherent strain method of elastic analysis. TEP analysis starts with an analysis of transient heat conduction to obtain the thermal history of the welds in the welded structure being analyzed. Then, TEP analysis is used to calculate the strain and stress history. Because it divides the period from the start to the end of the welding process into small time intervals, this method allows highly accurate simulations to be performed that closely model the thermal and deformation history of actual welds. In the case of large-scale welding structures, however, the long calculation time required to combine an analysis of a moving heat source with a TEP analysis makes this impractical in many cases.

The inherent strain method uses elastic analysis to calculate the welding distortion from the response of the welded structure to the inherent strains generated in the weld and surrounding areas. The inherent strain resulting from a weld is the elastic strain subtracted from the apparent strain, which by solid mechanics is equal to the residual plastic strain. The inherent strain is obtained either from strain measurements in welding experiments or from the plastic strain calculated by TEP analysis using a model of a specific region. Because it allows the deformation of a structure to be obtained by using only elastic analysis, the inherent strain method significantly shortens the calculation time. On the other hand, its inability to track the time evolution of an actual weld means its application in high-precision simulation is limited.

More Advanced Simulation of Distortion in Large-scale Welding Structures

For simulating the distortion of large structures, Hitachi has been developing a technique suitable for use on actual products. Past activities have involved selecting suitable techniques based on the requirements of the product concerned and the purpose of the simulation, and developing techniques for optimizing the analysis model together with experimental and measurement technology. Hitachi has also been working on joint research with universities aimed at developing distortion simulation techniques that combine higher accuracy with faster calculation speed.

While use of the TEP method is desirable when simulating the deformation of large structures with small numbers of welds that require appropriate welding conditions, one problem with this is the calculation time that is needed. Accordingly, Hitachi is working to reduce the calculation time by combining an elastic analysis of the entire structure with a TEP analysis of the weld and adjacent areas based on elastic analysis using the inherent strain method. When constructing analysis models that take account of the characteristics of the actual structure, Hitachi uses a three-dimensional solid model in regions where a TEP analysis is required and a two-dimensional shell model in regions where elastic analysis is required. Meanwhile, to improve the analysis accuracy, Hitachi has also conducted experimental testing to measure inherent strain and other material characteristics, and utilized this information in the analysis models to fine-tune the analysis conditions.

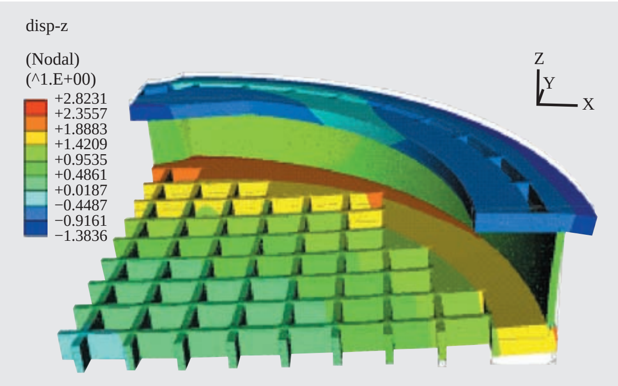


Fig. 2—Example Simulation of Deformation in Large-scale Welding Structure.
The structure has a radius of about 3 m and a height of about 1.2 m.

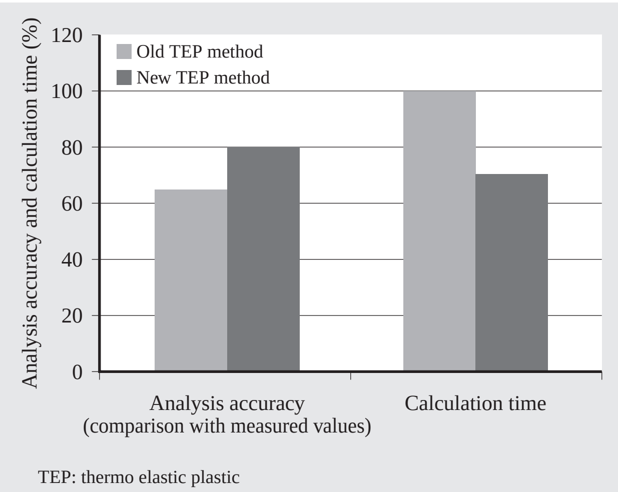


Fig. 3—Comparison of New and Old Methods.
The newly developed method achieved an improvement in accuracy of more than 10% while reducing calculation time by about 30%.

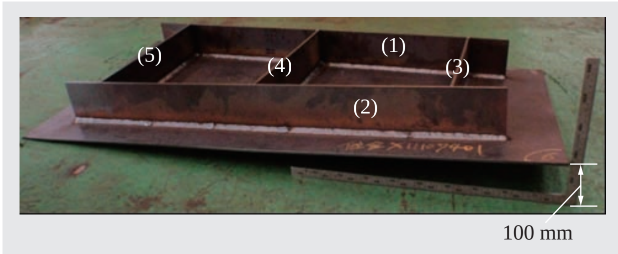


Fig. 4—Welding Structure Used for Experimental Testing.
This structure with a length of 1,200 mm and width of 600 mm was fabricated by welding sheet with a thickness of 6 mm [parts (1) to (5) in the photograph]. Welding resulted in a large deformation of approximately 100 mm.

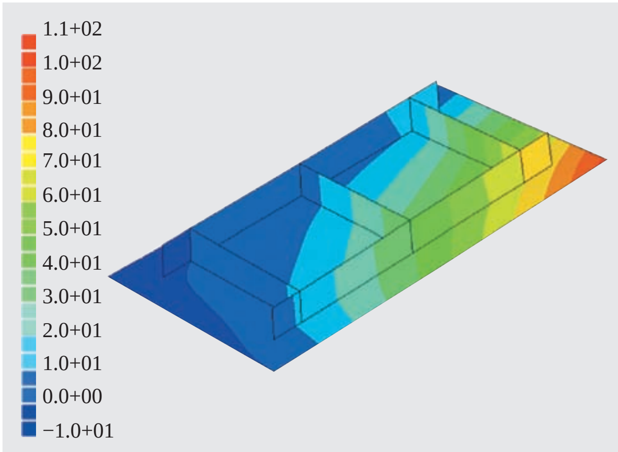


Fig. 5—Results of Analysis Using Inherent Strain Method.
By using a nonlinear version of the inherent strain method that took account of the large deformation, the simulation was able to reproduce with high accuracy the large deformation observed in the experimental test.

By combining a number of different methods in this way, it is possible to simulate the deformation in large-scale welding structures with high accuracy and speed. Fig. 2 shows example calculation results (distribution of deformation) of a welding distortion simulation of a large structure, and Fig. 3 shows a comparison of the previous and newly developed TEP analysis methods.

When simulating deformation in welded structures with a large number of welds with the same joint shape and welding conditions, emphasis is placed on using the inherent strain method and improving accuracy. The factors that influence the simulation accuracy are the inherent strain distribution that results from performing the weld and the specific dynamic characteristics of the structure. To obtain accurate estimates of inherent strain, the TEP method is used in conjunction with experimental testing to calculate the strain distribution. In the case of the specific dynamic characteristics of the structure, a separate method is used to assess the potential for a large deformation to occur, and then either a linear or nonlinear version of the inherent strain method is used, depending on the result.

Fig. 4 and Fig. 5 show an example of the inherent strain method for the case when a large deformation occurs. A test structure with a length of 1,200 mm and width of 600 mm was fabricated by welding sheet with a thickness of 6 mm [see (1) to (5) in Fig. 4]. This welding left behind a large deformation of approximately 100 mm. As running a TEP calculation for such a structure would be very time consuming, the inherent strain method was used instead. However, the version of the inherent strain method used in the past was a linear one that was unable to reproduce the large deformation, resulting in an error of up to 90% between the actual and predicted results.

On the other hand, when the results of analyzing the specific dynamic characteristics of the structure were incorporated, and a nonlinear version of the inherent strain method was adopted that took account of the large deformation, the simulation was able to reproduce with high accuracy this large deformation observed in the experimental test. Fig. 5 shows the analysis result taking account of the large deformation. This shows that the results of analysis and experiment agree, both in terms of the tendency for distortion to occur and the maximum size of the deformation[(6)].

USE OF WELDING DISTORTION SIMULATION TO ENHANCE PRODUCTION PROCESS

This section describes examples of applying welding distortion simulation to large structures.

Elimination of Welding Jig for Large Structures

A method used to minimize welding distortion in large reactor core internal structures (stainless steel) for nuclear power plants is to enclose them in a restraining ring. Using the welding simulation techniques described above, Hitachi has conducted a study into the influence that the type of restraint used has on welding distortion. The results were then used to fine-tune the use of welding jigs during the production of welded structures (to simplify the jig or eliminate it entirely), and to rationalize the production process by reducing the volume of work required for fabrication (see Fig. 6).

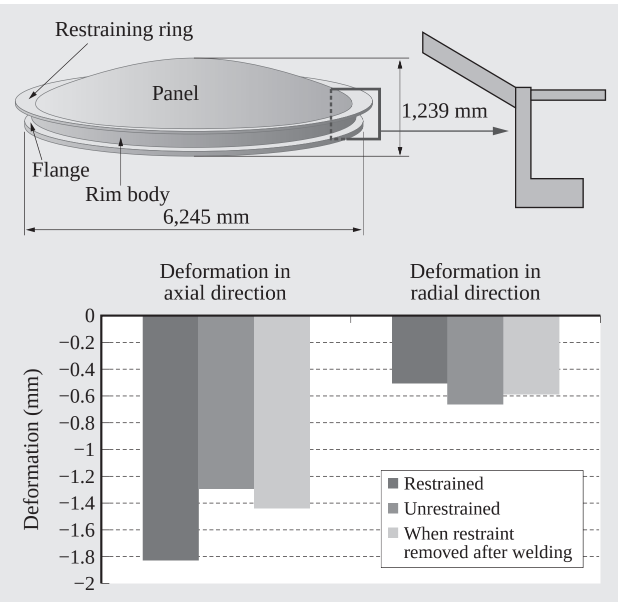


Fig. 6—Example of Welding Distortion in Large Structure.
It is possible to reduce the work associated with attaching the large welding jig used to reduce welding distortion.

Minimizing Welding Distortion

This section describes the use of welding simulation to study the effect that welding methods and the sequence of welding steps have on welding distortion with the aim of reducing work volume (time spent of remediation of welding distortion) and improving weld quality (in terms of welding distortion).

A study of the vertical welding of thick plate, aimed at predicting welding distortion and rationalizing the deformed areas, used a TEP analysis of a moving heat source to investigate the effect that the sequence and direction of weld passes had on welding distortion. The results showed good agreement between the actual and predicted deformation when welding was performed using the method that produced the minimum amount of welding distortion (see Fig. 7).

The effectiveness of the welding distortion simulation technique was also demonstrated in the development of a laser welding technique for reactor core internal structures. This involved a study of the factors that influence the amount of deformation (such as the sequence of laser welding passes) and a comparison with the distortion in arc welding.

CONCLUSIONS

This article has described welding simulation technologies for the highly efficient production of high-quality social infrastructure products.

Welding is a dynamic process made up of a complex combination of different phenomena, making it difficult to simulate in its entirety. As the progress

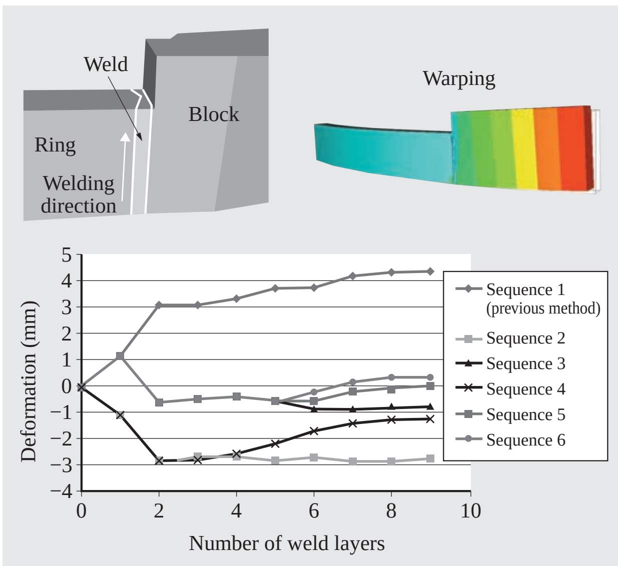


Fig. 7—Example of Reduction in Welding Distortion.
This work aims to use the sequence of successive weld layers to minimize welding distortion.

of technology in recent years has made it possible to analyze the stresses and deformations that result from welding with a level of accuracy and calculation time suitable for practical industrial applications, it is anticipated that its use as a tool for design and production will become more widespread in the future. Although still at the research and development stage, also required will be ways of fine tuning weld designs, operating practices, and similar by using simulation to predict in advance the occurrence of defects caused by the welding process.

In the future, Hitachi intends to continue working on the implementation of computer aided engineering (CAE) systems for welding that support more advanced analysis-driven welding design and process development.

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