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Fast three-dimensional multipass welding simulation using an iterative substructure method

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ABSTRACT

An iterative substructure method has been proposed as a technique to calculate thermal elastic–plastic problems quickly and efficiently. Based on the iterative substructure method, an analysis code for the multipass welding was developed so as to realize accurate residual stress computation using a 3D precise model within a practical time. In the present study, the fast computation performance of the iterative substructure method was considered as a means to improve the original code. Then analysis accuracy and speed of the improved code were investigated. The proper analysis accuracy of the improved code was demonstrated by comparing with residual stress measurements of a multipass butt-welded pipe joint. The analysis speed of the improved code was clarified to be faster than a well-known commercial code in comparison between their computation times.

1. Introduction

Residual stress especially is known to be an important factor that affects the strength of brittle fracture and the propagation of fatigue cracking and stress corrosion cracking. Lidbury (1984) described the significance of residual stress to the structural integrity. Dong and Brust (2000) reviewed the influence of residual stress in the viewpoint of fracture mechanics. James (2011) introduced the failure modes associated with residual stress. Webster and Ezeilo (2001) and Ghosh et al. (2011) examined the relationship of residual stress with fatigue cracking and stress corrosion cracking, respectively. Hence, the accurate evaluation of the magnitudes and distribution of residual stress achieves reliable integrity evaluation of the welding parts.

The weld residual stress is generally evaluated by three classified methods. The first one is measurement of actual structures and mock-ups using destructive methods, semi-destructive methods and non-destructive methods. For instance, for the destructive methods, Maekawa et al. (2010a) measured the detailed 3D distribution of weld residual stress in stainless steel pipe joints using inherent strain method. For the semi-destructive methods, deep hole drilling technique developed by Mahmoudi et al. (2009) was frequently used for measuring weld residual stress in large structures. For the non-destructive methods, Maekawa et al. (2010b) and Haigh et al. (2013) measured weld residual stress of stainless steel pipe joints using angle dispersive technique and time-of-fight technique of neutron diffraction, respectively. The second is simple evaluation formulas, in which one of them was proposed by Umemoto and Furuya (1989). The third is numerical simulation. Recently numerical simulation is more commonly used for various weld structures because of improvement of computer performances and advancement of simulation techniques. Repair welding (Dong et al., 2005) and dissimilar multipass welding (Lee et al., 2013) were simulated at present though only 2D welding simulation for plates (Free and Porter Goff, 1989) and pipes (Teng and Chang, 1997) were done in the past. Welding simulation is a methodology to model mechanical phenomena of welding as thermal elastic–plastic problems and to solve the problems using techniques such as finite element analysis. Welding simulation techniques were proposed in 1970s by Ueda and Yamakawa (1971) and Rybicki et al. (1978). Advancements in simulation techniques have been researched for a long time. Ueda et al. (1995) mentioned the developing history of welding simulation. Lindgren (2001) made a commentary on the model and simulation for welding. Boitout and Bergheau (2003) described the state-of-the-art and the trends in the welding simulation. However, because welding phenomena are transient problems with strong nonlinearity and this nonlinearity needs enormous calculation time to be simulated

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faithfully according to the phenomena, two-dimensional analysis and simplification of modeling and analysis conditions are generally used. From these viewpoints, lumping techniques have been proposed by Rybicki and Stonesifer (1979) and Shim et al. (1992) researched the appropriate modeling approaches. Methods to use composite elements have been proposed by Zhang et al. (1997) and the applicability was examined by Dong (2001). The lumping techniques solve the welding problems by grouping a few weld passes. The composite element method can reduce calculation time based on simplification of the weld part using the composite elements which deal with multi weld passes as one pass. However, in these simplification techniques, there is some possibility of decreasing the analysis accuracy. For the point at issue, the suitability of the simplifications has been examined in comparison with measurements (Deng et al., 2008) and precise 3D analysis results (Jiang et al., 2005).

On the other hand, many researchers have studied how to speed-up the welding simulation of precise 3D models to improve the analysis accuracy. For instance, the adaptive mesh technique (Lindgren et al., 1997), composite mesh technique (Goldak et al., 2000), dynamic substructuring technique (Brown and Song, 1993), and multiscale approaches (Faure et al., 2005) were all proposed. In the adaptive mesh technique, the whole structure is modeled using large meshes roughly and the weld heat source and its vicinity are modeled using a fine mesh repeatedly while the source moves (Runnemalm and Hyun, 2000). Qingyu et al. (2002) and Duranton et al. (2004) demonstrated that this approach allows accurate welding simulation using a small number of elements in a short time. In the composite mesh technique, the simulation time is reduced by embedding a special mesh to simulate around the weld heat source for the whole structure. In the dynamic substructuring technique, the area around the weld heat source is re-distinguished from the whole structure model as it moves and its area is re-meshed finely. In the multiscale approaches, the whole structure is modeled using shell elements and the solid elements are embedded in the area around the weld heat source. These techniques divide the whole structure into coarse meshes and the area around the weld heat source, where the stress gradient is larger, into fine meshes. Accordingly, they can realize an accurate simulation efficiently. However, for fast computation the process to mesh the model again as the weld heat source moves has to be added.

Murakawa et al. (2005) and Murakawa (2010) proposed the iterative substructure method (ISM) to speed-up welding simulation focusing on specific mechanical phenomena of welding, in which only the area around the weld heat source expresses nonlinear behavior. The ISM solves welding problems by combining the whole region which is a large scale problem with constant stiffness with the area around the weld heat source which is a small scale problem with strong nonlinearity. The validation examples of the ISM for dissimilar metal welds of surge nozzle (Maekawa et al., 2012, 2013a) and large-diameter pipe joints (Maekawa et al., 2013b, 2013c) have been compared with experiments though further examinations for the practical use should be done. Furthermore, it was reported that the ISM could reduce the calculation time to one tenth or one twentieth (Nishikawa et al., 2004). The realization of fast and accurate welding simulation can evaluate weld residual stress accurately and can improve reliable integrity of weld structures.

The authors (Maekawa et al., 2009, 2011) previously developed a multipass welding analysis code using the ISM to simulate the multipass welding process quickly and accurately. In this paper, the speed improvement of this code is introduced and the analysis accuracy of the ISM and the computational performance regarding speed and efficiency are evaluated using the improved code. First, the analysis speed was improved by adding parallel computation and refinement of convergent condition. Next, the analysis accuracy was validated using comparison of the analysis results with measurements using a welded pipe joint with five layers and five passes. Finally, the weld residual stress for the same analysis model was computed using the improved code and a commercial finite element analysis code and then the computational speeds were compared.

2. Iterative substructure method (ISM)

Welding phenomena are a transient problem with very strong nonlinearity and require a large computation time to be solved using the finite element analysis. It takes a few weeks to solve the multipass welding problem of pipes commonly installed in nuclear plants using general analysis codes. To predict welding distortion and residual stress in the actual plants, more efficient analysis methods are desirable. One of the candidates is the ISM.

Welding problems have two distinguishing characteristics. One is to express mechanical nonlinearity in a tiny region around the welding torch, that is, the weld heat source, and to express behavior as linear in most of the remaining region. The other is to move the nonlinear region as the torch moves.

General analysis methods solve welding problems iteratively according to time histories assuming the whole consists of large scale nonlinear problems even if only a part actually has nonlinear behavior. On the other hand, the calculating method to separate the problems to be solved into a linear region and a nonlinear region has been proposed. The ISM enhances the analysis speed on the basis of this idea. The ISM differs from the dynamic substructuring technique proposed by Brown and Song (1993) in the definition of the linear region during constitution of the stiffness matrix though both ideas are similar. The ISM is another idea used when separating the problems to be solved into a linear region and a nonlinear region.

The solution approach for static mechanical problems by the finite element analysis comes down to the following equation: $[A]\{u\}=\{F\}$ in which $[A]$ is the stiffness matrix, $\{u\}$ represents displacements at the nodes, and $\{F\}$ represents forces at the nodes. First, the equation is solved with regard to displacements at the nodes after constituting the stiffness matrix. Fig. 1(a) shows the definition of linear and nonlinear regions of the stiffness matrix. For the stiffness matrix, $A+B$ of the whole region is defined as the linear region and B is defined as the nonlinear region. In the next step, the linear region is also $A'+B'$ of the whole region ($=A+B$) and the nonlinear region is B'. Because this region division results in the same linear region for the two steps, the constituting process of the stiffness matrix in the linear region can be omitted by using the same matrix as the past. The constitution process of the stiffness matrix in the nonlinear region, that is, the tiny region B and B′ whose stiffness changes as the weld heat source moves, only has to be done. This approach can reduce the computation time extremely. On the other hand, Fig. 1(b) shows the definition of the linear and nonlinear regions to calculate stresses. The stress calculation is conducted assuming the displacement on the boundary Γ or Γ' as the boundary condition between the linear region ($A+B$ or $A'+B'$) and the nonlinear region (B or B') and using the stiffness matrix obtained in Fig. 1(a). The continuity and balance of stress on the boundary Γ and Γ' are achieved by the iterative calculation because the equilibrium condition of stress in the region A or A' and region B or B' are satisfied due to their independence. As shown in the calculation flowchart of Fig. 2, the ISM assumes welding as problems to update only the stiffness of the local area though the conventional methods assume it as thermal elastic–plastic problems of the whole area. The characteristics of welding problems are the nonlinear region having a small ratio to the whole and the nonlinear region movement. The ISM solves the welding problems making good use of their characteristics.