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Development of analytical method for welding mechanics using idealized explicit FEM†

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1. Introduction

Dynamic explicit FEM has been used to analyze dynamic problems such as impact problems. This method is discretized for each node and does not need a global stiffness matrix. It does not use much computer memory because it solves only scalar equations. Therefore, unlike implicit FEM, dynamic explicit FEM can analyze large-scale structural problems. However, in dynamic explicit FEM, the time increment at a single time step is determined by the Courant condition, which means the time increment depends on the stress propagation velocity and the smallest element size of the model. Therefore, the Courant condition requires a tremendous number of time steps and much computing time for long-time phenomena such as welding.

In this study, a new dynamic explicit FEM based analytical method is proposed. This method permits large time increments for solving welding problems. The proposed method neglects the mass and damping effects and treats the welding phenomena as quasi-static. This means that the static equilibrium condition of the model is satisfied at each load step in the proposed method.

The proposed Idealized Explicit FEM is presented in this paper. It is compared with static implicit FEM by analyses of bead-on-plate welding. The results show the proposed method has almost the same accuracy as that with static implicit FEM. The computing time and memory utilization of the proposed method are also discussed.

2. Development of Idealized Explicit FEM

As described in the previous section "Dynamic Explicit FEM", Eq. (2) is solved to calculate displacement. However, in long-time phenomenon problems such as welding, the computational steps become enormous because of the limitation of the very short time increment. This limitation is due to the Courant condition, which is related to the stress wave propagation velocity and time increment. The Courant condition requires the distance traveled by stress wave in a time increment to be less than the minimum element size . In this study, the authors propose a method to overcome this limitation.

In this research, the temperature increment is automatically divided into tens of time steps which depend on temperature load rate. After loading the temperature increment, Eq. (2) is solved to compute the displacement until the whole system reaches the static equilibrium state. In this method, the dynamic effect becomes quite small. This means that plastic strain is not largely influenced by the dynamic effect and the residual displacement and stress for each step have almost the same accuracy as the static implicit FEM.

$$[M]\{\ddot{u}\}_t + [C]\{\dot{u}\}_t + \int [B]^T\{\sigma\}dV = \{F\}_t \tag{1}$$

$$\left(\frac{1}{\Delta t^2}[M] + \frac{1}{2\Delta t}[C]\right)\{u\}_{t+\Delta t} = \{F\}_t - \int [B]^T\{\sigma\}dV + \frac{2}{\Delta t^2}[M]\{u\}_t - \left(\frac{1}{\Delta t^2}[M] - \frac{1}{2\Delta t}[C]\right)\{u\}_{t-\Delta t} \tag{2}$$

3. Verification of Proposed Method

The time history of stress σ_y for points a, b, and c is shown in **Fig. 1**. In Fig. 1, symbols ◇, △ and □ show

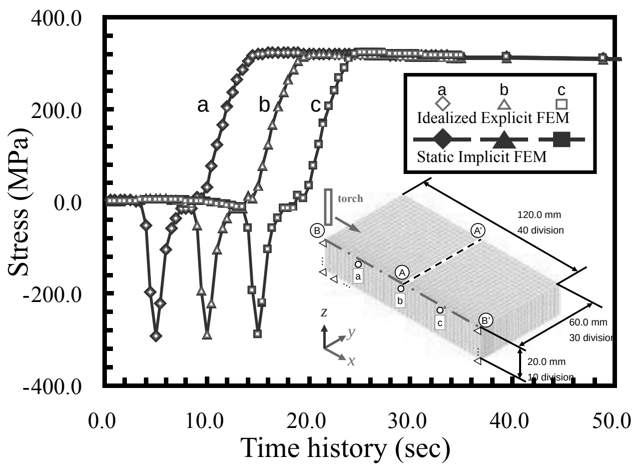

Fig. 1 Time history of stress σ_x

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the transient stress computed by the Idealized Explicit FEM and symbols ◆, ▲ and ■ show that computed by the static implicit FEM. Compressive stress is presented before the welding torch is passed. After that, the stress becomes zero due to melting. Finally, tensile residual stress develops after cooling. It is verified that the transient stress σ_y computed by the Idealized Explicit FEM and that by the static implicit FEM are almost the same.

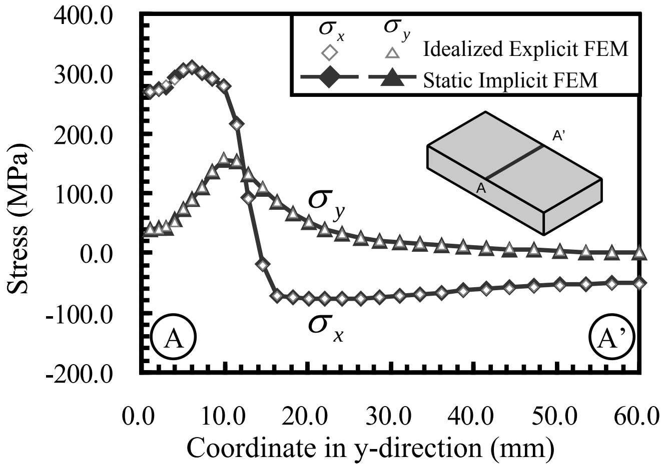

Fig. 2 Comparison of residual stress between Idealized Explicit FEM and static implicit FEM on top of transverse cross section

Figure 2 shows the distribution of residual stress in x-direction σ_x on the A-A' cross section. From Fig. 2, it is verified that the residual stress distribution of the Idealized Explicit FEM quantitatively agrees well with that of the static implicit FEM.

Angular distortion is shown in **Fig. 3**. From the figure, it is verified that the results of the Idealized Explicit FEM and the static implicit FEM show almost the same accuracy.

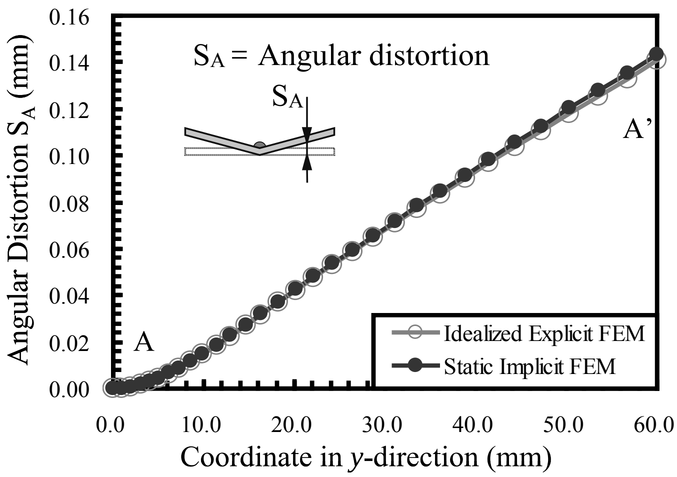

Fig. 3 Comparison of angular distortion between Idealized Explicit FEM and static implicit FEM

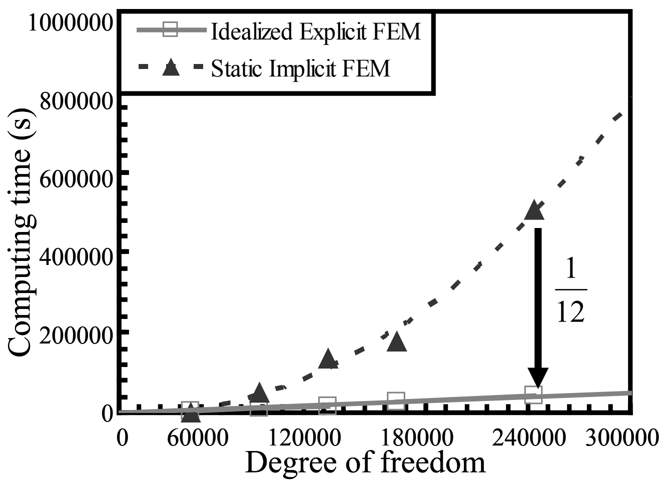

Fig. 4 Comparison of computing time between Idealized Explicit FEM and static implicit FEM

4. Computing time

Comparisons of the computing time and memory consumption between the Idealized Explicit FEM and the static implicit FEM are discussed here by using different models. The static implicit FEM requires a very long time for computing. Then, the computing time is measured for only 0.5-second phenomena after the welding starts to evaluate welding-specific local plasticity and melting. The number of nodes of the analysis models is 13981, 27511, 41041, 54351 or 81081. The degree of freedom of the model is 41,943, 82533, 123123, 163053 or 243243. The welding condition and boundary condition are the same as those in the previous section. Specifications of the computer used in this comparison are as follows: CPU is Xeon 2.53 GHz, memory size is 32 GB, operating system is Windows XP Professional x64 edition. The static implicit FEM uses a skyline solver.

Figure 4 shows the relation between the computing time and the number of nodes. The solid triangles shows the computing time of the static implicit FEM and the open rectangles shows that of the Idealized Explicit FEM. From the figure, the computing time of the static implicit FEM increases proportional to the square of the number of nodes. In contrast, the computing time of the Idealized Explicit FEM increases linearly. Especially, in the 243243-dof model, the computing of the Idealized Explicit FEM is almost 12 times faster than that of the static implicit FEM.

5. Conclusions

In this research, the authors developed a new numerical method for welding analysis, named Idealized Explicit FEM, which is based on the dynamic explicit FEM. The proposed method is compared to the static implicit FEM in the application of bead-on-plate welding. The following results are obtained:

(1) It is demonstrated that Idealized Explicit FEM is capable of analyzing the long duration problem such as cooling process of welding that Dynamic Explicit FEM has difficulty in analyzing.

(2) Using the model of bead-on-plate welding, the Idealized the same accuracy for transient stress, residual stress and residual deformation.
(3) By comparing the computing time, it is verified that the Idealized Explicit FEM is 12 times faster than the static

Explicit FEM and the static implicit FEM show almost implicit FEM in the analysis of large-scale welding problem whose dof is 243243.

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