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Variation simulation model for pre-stress effect on welding distortion in multi-stage assemblies

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ABSTRACT

In the shipbuilding industry, steel plates are assembled and joined to construct a block, and dozens of blocks are erected to build a ship. The major joining process used to assemble the steel plates is welding. Because the welding process causes strong non-uniform heating of the parts being joined, the local heating and subsequent cooling of welded pieces induce volumetric changes, producing transient and residual stresses as well as plastic deformation. This welding distortion is the main factor causing geometrical imperfections in the steel plate assembly process. These non-nominally shaped parts need to be clamped before the following joining process, which in turn causes pre-stress in the parts being joined. The pre-stresses due to welding and clamping significantly affect the subsequent welding processes. This paper proposes a variation simulation model of compliant assemblies to analyze the propagation of geometrical variations through multiple assembly stages, including the welding distortion under the effect of the pre-stress state. This research extends the mechanical variation simulation model to include the effects of clamping stresses by expressing the pre-stress terms in the form of an additional stiffness matrix. The result helps in confirming the effect of the pre-stress state on the subsequent welding distortion in the multi-stage assembly process. The proposed model can be used to predict the propagation of assembly variation in steel plate assemblies considering the pre-stress effect and welding distortion.

1. Introduction

In the shipbuilding industry, ships and offshore structures are built through multi-stage assemblies [1]. They are constructed by assembling millions of intermediate products. The fundamental joining process used during the assembly process is the heat-flux welding. The welding process causes strong non-uniform heating of the parts being joined. The local heating and subsequent cooling induce volumetric changes in the materials, thereby producing transient and residual stresses and even plastic deformation [2]. Welding distortion is one of the main causes of geometrical imperfections in the steel plate assembly process. Therefore, studies on controlling the welding distortion and its propagation to the subsequent assembly process are very important.

Thermal deformation due to local heating is the main cause of deformation during welding. Welding distortions due to thermal deformation are induced largely because of factors such as the ambient environmental conditions, temperature in the periphery of the welding area, and initial clamping conditions [3–8]. In other words, the pre-stress state significantly affects the welding distortion, which can be controlled through clamping or using an inverse transform function. The strategies used to reduce the welding distortion are based on these phenomena [9–13].

During the construction of a ship or an offshore structure, small pieces of the steel plates are assembled and joined to make a sub-assembly. Multiple sub-assemblies are then joined together to form an assembly. Through these multiple steps of assemblies and welding, larger blocks are constructed, which are erected to build a ship or an offshore structure. Because of these characteristics, the constraints on the previous welding distortion affect the welding process at the n^{th} stage in the procedure. In other words, before assembling the steel plates using the welding process, a clamping process is required to locate the welded area with respect to the nominal position of the plates. During this operation, an in-plane stress is applied to the parts, which has implications on future welding distortion. Some of the techniques of reducing the welding distortions and residual stresses, such as pre-tensioning and thermal tensioning, involve changing the initial stress and strain values and reducing the temperature difference between the welded and adjacent areas [9,13–16].

The proposed variation simulation model can incorporate the pre-stressed state in welding distortion to a variation simulation.

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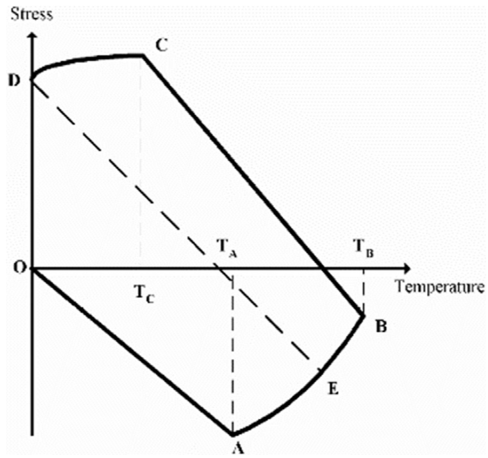

Fig. 1. Thermal histories of stress in the there-bar model.

Conventional variation simulation research mostly neglects the deformation generated during the joining process. Among a few, some researches consider the welding distortion for a variation simulation, but they have difficult to consider the pre-stresses state in parts before welding, thus they cannot simulate the difference welding sequence can generate different welding distortion in a variation simulation of compliant assemblies. Using the proposed model, the assembly process of a common and simple subassembly with non-nominal parts including initial stress state and welding distortion is simulated. In addition, this paper used FEM as a tool for variation simulation and applied the simplified prediction method developed in variation simulation to consider welding distortion and residual stresses.

2. Modeling of pre-stress state

Welding distortion occurs because of the welding residual stress due to the local heating and cooling. The Welding distortion and residual stresses are easily explained by a three-bar model [2,17]. Fig. 1 shows the stress-strain curve that can be obtained through an analysis of a general three-bar model. The middle bar only undergoes a temperature increase and decrease, which causes residual plastic strain throughout the structure. According to Fig. 1, the entire process can be divided into four steps, i.e., the elastic state during heating ($\overline{OA}$), the plastic state during heating ($\overline{AB}$), the elastic state during cooling ($\overline{BC}$), and the plastic state during cooling ($\overline{CD}$).

At this time, the stress due to the external force acts compressive stress caused by the changes in the welding residual stress. This outcome confirms that the internal stress state is changed by external forces.

For applications to welded structures and for assessing the effect of the pre-stress state on the welding distortion, a thermo-elastic-plastic analysis is required. This analysis method is the most general method used for predicting the welding distortion and the effects of the stress state on the small and medium welded structures [7,18–27]. Considering that the variation simulation sometimes requires multiple computer simulations for the same welded structure, it is inappropriate for practical use because the thermo-elastic-plastic analysis is computationally very expensive. Thus, previous studies suggested a simple variation-simulation analysis model considering the welding distortion using the mechanical variation simulation model [30].

Only a single-step assembly process was considered in previous studies, whereas the welding distortion effects were neglected in the studies on multi-step assembly processes [28,29] (Fig. 2).

The part variation (V_u) affects the final residual strain (U_w) and stress by changing the initial strain and stress of the part due to the clamping of the part into its nominal position. In a single-step assembly process, the pre-stress effect, which is the effect of the clamping of the part variation in the welding distortion, is relatively small. However, in multi-step assembly processes, because the deformation of a welded structure affects the degree of part variation at the nth step of the assembly process, the pre-stress effect on the welding distortions is more important than that in a single-step assembly process.

Using a mechanical variation simulation model, the assembly process considering the pre-stress state and welding terms could be explained with the help of additional terms describing the effects of the welding distortions.

First, this study expresses the welding distortion term as a function

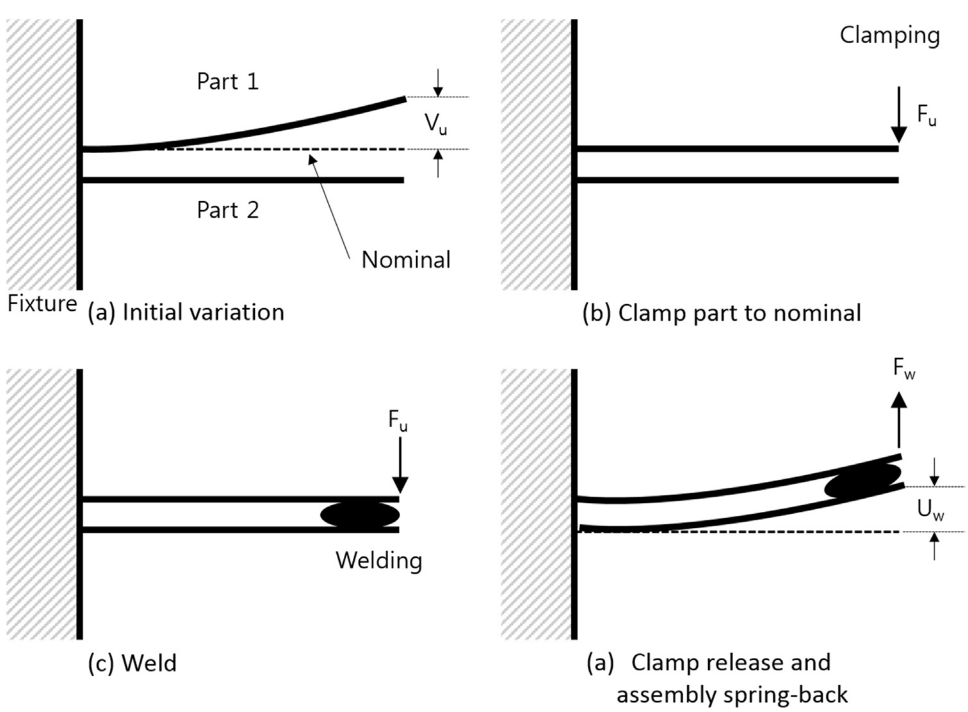

Fig. 2. Sequence of method of influence coefficients [28,29].