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Comparative study on mechanical behavior of low temperature application materials for ships and offshore structures: Part II – Constitutive model

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ABSTRACT

Austenitic stainless steel (ASS), aluminum alloy, and nickel steel alloy are strong temperature- and strain-rate-dependent materials. They exhibit very complicated nonlinear behaviors during plastic deformation. While the typical characteristics of their nonlinear behaviors, including second hardening and strain-rate sensitivity, can be easily identified through experimental investigation, a useful numerical model is not available. The unavailability of such a model is because of the wide variance in the nonlinearities of the materials. In the present study, a unified constitutive model is proposed for representing the temperature- and strain-rate-dependent material nonlinearities in ASS and aluminum and nickel steel alloys. Based on the Bodner model, a strain-hardening function was developed for expressing second hardening as well as strain-rate sensitivity. To provide unified material parameters for the hardening exponent and strain-rate control, a new type of material parameter identification method is proposed. Based on the proposed constitutive model, in conjunction with both a damage model and the material parameters, a verification study is conducted. The experimental results of both Park et al. [1] and Tomita and Iwamoto [2], which are valid within a temperature range of 80–345 K and a strain-rate range of 0.0005–500/s, are compared with the numerical results of this study.

1. Introduction

It is well known that austenitic stainless steel (ASS), aluminum alloy, and nickel alloys are highly functional materials and are candidates for use in cryogenic applications [3]. They are materials with a face-centered cubic (FCC) lattice, and they exhibit superior material performances at low temperatures [4,5]. Because of these advantages, the number of applications of these materials is increasing in several industrial fields.

In previous studies, experiments were performed to investigate the characteristics of AISI 300 series ASS, aluminum alloy, and nickel steel alloy for application in ships and offshore structures [1]. This research was the part of an effort to establish a robust design scheme for structures used for storing and shipping liquefied natural gas (LNG). While the essential mechanical characteristics have been clearly identified through a comprehensive study, an applicable numerical model for describing their nonlinear material behavior has not yet been developed. A proper numerical model is of crucial importance for evaluating the design schemes of these metals, because almost all such evaluations will be carried out using finite element analysis (FEA). It is also clearly recognized that reliable calculation results can be guaranteed by using a proper constitutive model for the expected material nonlinearities. In this regard, there has been a significant amount of effort in recent decades to develop constitutive models. Based on this effort, various useful constitutive models are now available as material model libraries in several commercial FEA codes [5].

In this study, we developed a unified constitutive model to describe the material nonlinearities of AISI 300 series ASS, aluminum alloy, and nickel steel alloy at low temperatures. To the best of our knowledge, no unified practical model has yet been developed. This is owing to the difficulties involved in the numerical description of nonlinear characteristics such as strain hardening and strain-rate sensitivity. To develop a constitutive model for certain phenomena, typical steps should generally be followed: (1) identification of the particular phenomena, (2) selection of possible constitutive relationships, (3) identification of material parameters for the selected model, and (4) verification. Of these, steps (1) and (3) may be the most difficult to achieve. Even if the phenomena in question are well identified through comprehensive experimental investigations, material parameter identification is not an easy task when the materials exhibit inconsistent behavior in different environments.

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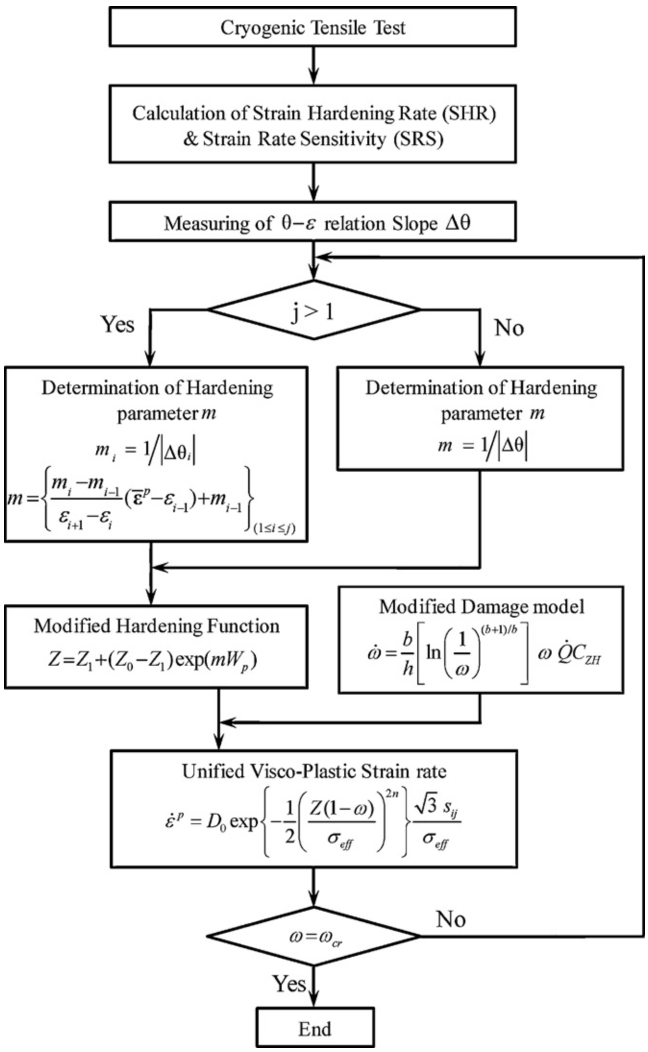

Fig. 1. Overall procedure used in the present study.

As a prior motivation for this study, a novel method was introduced for representing material nonlinearities using well-defined mechanical variables, i.e., hardening rate and strain-rate sensitivity [1]. This study is a continuation of our previous work; it was conducted to understand the mechanical behavior of low-temperature application materials.

In this study, by adopting the mechanical variables of the previously proposed constitutive model, a simple and unified numerical model is proposed. More specifically, the usefulness of the direct application of experimental observation is verified.

To develop a new numerical model, a comparative study was carried out using a series of consecutive tasks (see Fig. 1). First, modifications were made to the current constitutive model in order to consider temperature and strain-rate dependency. Second, a new method to identify the material parameters was proposed to overcome the existing difficulties or uncertainties. We propose a direct method for using experimental insight and a damage model to account for the strain-rate dependencies. Finally, as a relevant numerical technique for a performance-based design, an FEA using the proposed constitutive equations was developed and applied to cryogenic tensile test results for verification purposes.

2. Constitutive model

The target phenomena, which will be described using the new constitutive model developed in this study, are nonlinear second hardening, hardening rate, and strain-rate sensitivity. As previously mentioned, AISI 300 series ASS, aluminum alloy, and nickel steel alloy exhibit the above material nonlinearities; however, their absolute magnitudes and tendencies differ because they are fcc lattice structure materials. In this regard, a unified constitutive model is required to establish a consistent numerical algorithm.

Regarding the second hardening of fcc-lattice-structure ASS, phase-transformation-induced plasticity (TRIP) is the most well-known phenomenon [4–7]. Because the amount of phase transformation affects the plastic deformation characteristics, a great deal of research has focused on measuring the phase transformation. Once a phase-transformation equation becomes available, we will be able to analyze the TRIP phenomena numerically by incorporating the phase-transformation equation into the constitutive model. This method, known as direct formulation, is the most preferable method for describing TRIP. In view of this advantage, various studies have been conducted [2,5–7]. However, considering the numerous material types, which vary according to their chemical components, a direct formulation is not always possible. In other words, a direct phase-transformation measurement should be carried out under every possible condition.

Moreover, additional information should also be incorporated because TRIP is strongly dependent on temperature and strain rate. This is the main obstacle in the development of a unified constitutive model for TRIP phenomena.

In the present study, a unified constitutive equation is proposed for simulating the nonlinear material behavior of AISI 300 series ASS, aluminum alloy, and nickel steel alloys. The proposed mechanical variables, i.e., strain hardening rate θ and strain-rate sensitivity M, are directly and consistently used as the material parameters.

In addition to the constitutive model, a damage variable is also adopted on the basis of the continuum damage mechanics approach. By calculating the damage variable, a material fracture can be precisely evaluated. The required material parameters for creating a damage evolution equation are also identified for each selected material.

2.1. Viscoplastic constitutive model

Bodner and Partom proposed a unified viscoplastic constitutive model (BP model) to represent inelastic creep behavior [8]. This model is based on isotropic hardening and can be used to describe the range of tertiary creep strain. The most important advantages of this model can be summarized as follows: (1) it postulates no yielding function, (2) it has a wide range of applications in terms of the viscoplastic problem, and (3) it is a sufficient database for material parameters. In addition, because it was developed as a time-dependent constitutive model, the BP model is applicable to a wide range of time-dependent problems. In the present study, a viscoplastic constitutive model was developed from the BP model.

According to the BP model, the total strain rate $\dot{\varepsilon}_{ij}$ can be expressed as the sum of elastic strain rate $\dot{\varepsilon}^{e}_{ij}$ and inelastic strain rate $\dot{\varepsilon}^{p}_{ij}$, as shown in Eq. (1):

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}^{e}_{ij} + \dot{\varepsilon}^{p}_{ij}. \quad (1)$$

$$\dot{\varepsilon}^{p}_{ij} = D_0 \ \exp\left[-\frac{1}{2}\left(\frac{Z}{\sigma_{eff}}\right)^{2n}\right] \frac{\sqrt{3}\, s_{ij}}{\sigma_{eff}}, \quad (2)$$