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Determination of equi-biaxial residual stress and plastic properties in structural steel using instrumented indentation

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A R T I C L E I N F O

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A B S T R A C T

This study describes a method that allows estimation of the equi-biaxial residual stress (σ_R), yield strength (σ_y), the strain hardening exponent (n), and the ratio (α) between strain at starting-point of strain hardening (ε_{st}) and yield strain (ε_y) of structural steel from the load-depth curve of one sharp indentation test. In this method, the relationships between the structural steel properties, residual stress, and the characteristics of the indentation loading-unloading curves were established in the form of dimensionless functions via extensive finite element (FE) analyses. Based on the FE analysis results of the indentation process with a large number of different material properties combinations, the effects of residual stress and plastic parameters on the indentation response were investigated, and a reverse algorithm for estimating four unknown quantities (σ_R, σ_y, n, and α) of steel from an indentation test was proposed. A stress-applying apparatus that allows the introduction of a compressive or tensile stress to the sample by applying a compressive or tensile force and maintaining the stress after releasing the force was also developed in this study. Indentation and tensile tests of structural steels (SS400 and SM490) were carried out and the proposed algorithm was validated through both numerical analyses and experimental results.

1. Introduction

Residual stresses can exist in many engineering parts and structures made of various materials, especially structural steel, due to the thermal mismatch or thermal and mechanical processing during welding, joining, and manufacturing [1]. Since it has significant effects on the mechanical performance of materials, such as fracture, fatigue, wear, corrosion, and fraction, measurement of residual stress in materials has become important in engineering design. There are several methodologies for measuring the residual stress, including mechanical methods such as hole-drilling, saw-cutting, and layer-removing techniques [1,2], physical methods such as analysis of ultrasonic wave, X-ray and neutron diffraction, and the newly developed indentation technique [3,4]. The indentation technique has shown advantages over the others in terms of simplicity, non-destruction, applicability, and convenience at various scales [5,6].

The effect of residual stress on the load-depth (P-h) curve of indentation was first investigated by Tsui et al. [7] using experiments and by Bolshakov et al. [8] using finite element analysis. A bilinear relation between residual stress and indentation hardness was established from these investigations [7,8]. Various characteristics of the indentation load–depth curve, including contact stiffness (S), maximum indentation depth (h_m), loading curvature (C), and indentation work (W), have also been found to be in nonlinear relationships with residual stresses [9–12]. Based on the correlation between residual stress and indentation parameters from both experiments and analysis, numerous methods for the determination and measurement of residual stress from the characteristics of indentation have been proposed. For example, Suresh and Giannakopouls [9] utilized the difference in the indentation contact area between free-stress and stressed indented materials at the same indentation depth to characterize the equi-biaxial residual stress. Carlsson and Larsson [10,11] also reported the effects of residual stress on the indentation contact area, from which the residual stress can be estimated. Lee and Kwon [12] developed a new procedure to determine the residual stress based on the difference between indentation load at the same penetration depth of indented materials with and without residual stresses. One of the drawbacks of these aforementioned methods is that the indentation contact area needs to be measured accurately. Subsequently, many other methods for direct determination of residual stresses from the load-penetration depth curves of indentation without measurement of contact area have been suggested through extensive dimensional and finite element (FE) analyses [13–18]. However, these methods are only valid for either elastic, perfectly plastic materials [13,14] or materials exhibiting a

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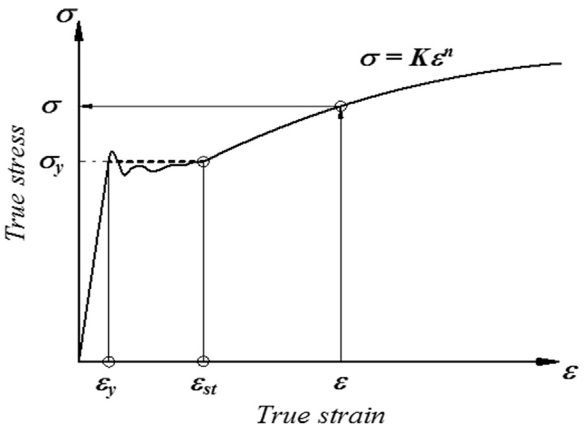

Fig. 1. Model for stress-strain behavior of structural steel (the plastic plateau is assumed perfectly plastic presented by the dotted line).

power law description in stress-strain behavior [15–17], or else need extra tests on free stress specimens for reference [18].

To our knowledge, no method has yet been established for estimating residual stress of structural steels, which exhibit a plastic plateau initiated from ε_y and ended at ε_{st} in their stress-strain curve from indentation. This study proposes a method that allows estimation of the equi-biaxial residual stress σ_R, together with yield strength σ_y, the strain hardening exponent n, and the ratio α of structural steels from the load- depth curve of indentation test. The material model for structural steels used in the previous works [19–21], which is illustrated in Fig. 1 and can be expressed as Eq. (1), was applied. The mechanical model of material with equi-biaxial residual stress indented by a sharp indenter (Berkovich or Vickers) can be considered an axisymmetric sample indented by a conical indenter with 70° of half apex angle [18], as illustrated in Fig. 2. The relationships between the structural steel properties, residual stress, and the characteristics of indentation loading-unloading curves were established in the form of dimensionless functions via extensive finite element (FE) analyses. The proposed method was validated through the results from indentation and tensile tests of structural steels (SS400 and SM490) subjected to residual stress and free stress as well.

$$\sigma = \begin{cases} E\varepsilon & (\varepsilon \le \varepsilon_y) \\ \sigma_y & (\varepsilon_y < \varepsilon < \varepsilon_{st}) \\ \sigma_y[1 + E(\varepsilon - \varepsilon_{st})/(\alpha\sigma_y)]^n & (\varepsilon \ge \varepsilon_{st}) \end{cases} \tag{1}$$

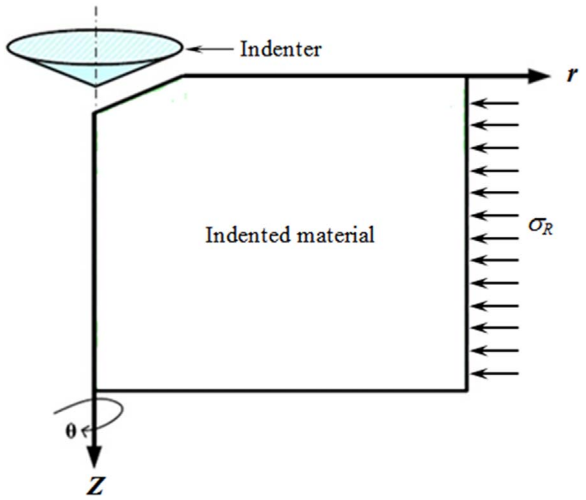

Fig. 2. Indentation model of a sample with equi-biaxial residual stress.

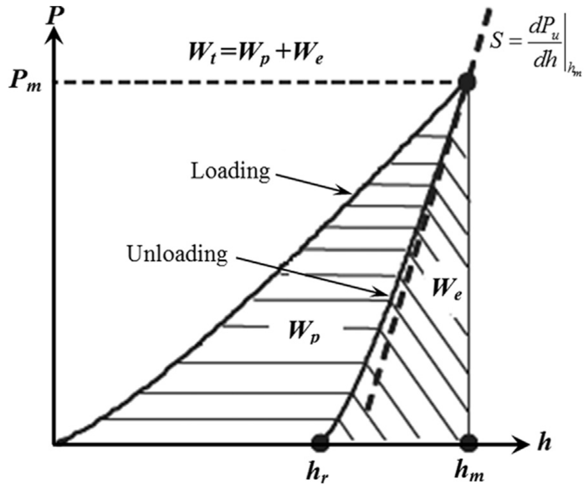

Fig. 3. Typical load-penetration depth curve.

2. Dimensional analysis and finite element simulation

2.1. Dimensional analysis

Fig. 3 illustrates a typical load-penetration depth curve of an unstressed specimen from a sharp indentation. The applied load P during loading can be depicted as a function of the indenter and material properties, as follows:

$$P = P(h, E, \nu, E_i, \nu_i, \sigma_y, n, \alpha) \tag{2}$$

where h is the penetration depth; E, υ, E_i, and υ_i are the elastic modulus and Poisson's ration of the indented material and indenter, respectively.

Using the reduced modulus E_r, which is defined as $E_r = [(1 - \nu^2)/E + (1 - \nu_i{}^2)/E_i]^{-1}$ [22,23], Eq. (2) can be written as

$$P = P(h, E_r, \sigma_y, n, \alpha) \tag{3}$$

For indentation of a specimen subjected to an equi-biaxial residual stress (σ_R), the applied load during loading can be expressed as

$$P = P(h, E_r, \sigma_y, n, \alpha, \sigma_R) \tag{4}$$

The $\prod$ theorem [24] is applied in dimensional analysis to form Eq. (4) as

$$P = \sigma_y h^2 \Pi_1^0\left(\frac{E_r}{\sigma_y}, n, \alpha, \frac{\sigma_R}{\sigma_y}\right) \tag{5}$$

The total indentation work of the indentation W_t, which is defined as the area under the loading curve from 0 to the maximum depth h_m (Fig. 3), can be determined as

$$W_t = \int_0^{h_m} P dh \tag{6}$$

From Eqs. (5) and (6), with a given indentation maximum depth h_m, the total indentation work (loading work) of indentation can be written in the following form:

$$W_t = \sigma_y h_m^3 \Pi_1^1\left(\frac{E_r}{\sigma_y}, n, \alpha, \frac{\sigma_R}{\sigma_y}\right) \tag{7}$$

Since σ_y and E_r have the same dimensional unit, Eq. (7) then can be written in an alternative form as

$$\frac{E_r h_m^3}{W_t} = \Pi_1\left(\frac{E_r}{\sigma_y}, n, \alpha, \frac{\sigma_R}{\sigma_y}\right) \tag{8}$$

Similarly, the unloading curve of an indentation into a specimen subjected to an equi-biaxial residual stress must be a function of the