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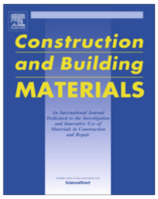

Characterization of strain rate effects on the plastic properties of structural steel using nanoindentation

Ngoc-Vinh Nguyen [a], Thai-Hoan Pham [b], Seung-Eock Kim [c,*]

[a] Dept. of Civil and Environmental Engineering, Sejong University, Seoul, South Korea
[b] Dept. of Concrete Structures, National University of Civil Engineering, 55 Giai Phong, Hanoi, Viet Nam
[c] Dept. of Civil and Environmental Engineering, Sejong University, 98 Gunja-dong, Gwangjin-gu, Seoul 05006, South Korea

HIGHLIGHTS

- Strain rate sensitivity was obtained using indentation and dynamic tensile tests.
- Strain rate effects on plastic properties were investigated using nanoindentation.
- A modified method was proposed to estimate plastic properties at high strain rates.
- Dynamic tensile tests were performed to demonstrate the accuracy of modified method.
- Relationship between the indentation and uniaxial strain rates was discovered as $\dot{\varepsilon} = 0.15\dot{\varepsilon}_I$.

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ABSTRACT

SM490, a structural steel, has been widely used in the construction of buildings, bridges, and tunnels due to excellent machinability and weldability. Since the mechanical properties of structural steel are important material input data in engineering design as well as in both static and dynamic analyses of structure, the important task is to deeply understand the mechanical properties of structural steel and the effecting factors on these properties, in which the strain rate effect is most important. In this study, the indentation strain rate effects on the mechanical properties of SM490 steel, including hardness, yield strength, the strain hardening exponent and shear stress were investigated using the nondestructive indenting technique. The dynamic tensile tests were performed at different strain rates to demonstrate that the strain rate effects on the hardness and yield strength investigated by using indentation are reliable. The strain rate sensitivity value of SM490 steel obtained using the nondestructive indentation experiment was reported. The linear relation between the indentation strain rate $(\dot{\varepsilon}_I)$ and uniaxial strain rate $(\dot{\epsilon})$ was discovered, and the coefficient C_2 of 0.15 relating to both strain rates was well estimated. A modified method was also proposed to determine the values of plastic properties considering uncertain contact stiffness at high indentation strain rates. The results were used to assess and understand the variation of mechanical properties of SM490 as the indentation strain rate changes.

1. Introduction

The depth sensing instrumented indentation experiment is most commonly used to estimate the mechanical properties of materials at the micro- and nano-scale [1–3]. It can be normally used to investigate the microstructure as well as to determine the mechanical properties of hardness and elastic modulus. The sharp indentation experiment is more advantageous than traditional experiments including the tension and compression experiments. For instance, the indentation specimen can be used many times; therefore, it can save time and cost for the preparation of a specimen, and the short testing time also is another advantage of the sharp indentation experiment. Therefore, the nondestructive indentation experiment is a good choice to replace the traditional tests, such as the time-consuming compressive or tensile experiments, for determining the mechanical properties of material.

Normally, the instrumented indentation test can be carried out by controlling the constant loading rate (CLR) and constant loading strain rate (CSR) [4–8]. Many researchers have investigated the indentation strain rate effects on the hardness or indentation stress [9–12]. According to the indentation technique, the strain rate

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[*] Corresponding author.
E-mail address: sekim@sejong.ac.kr (S.-E. Kim).

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effect on hardness is often considered using the strain rate sensitivity concept which is defined as the change in the indentation hardness (H) divided by the change in the indentation strain rate at a constant temperature [9].

The influence of the indentation strain rate on the plastic properties, such as yield strength, has been studied by using the loading tensile test [11,12]. Although this approach provides an acceptable result, performing the traditional tensile tests at various uniaxial strain rates is a rather time-consuming task and is uneconomical because of the high cost involved. Another approach that uses the instrumented indentation technique has been used to investigate the strain rate effect on the yield strength based on the ratio of hardness and yield strength [13]. This ratio was assumed that the yield strength is one-third of the hardness value, in which the hardness is firstly obtained by using the nano-hardness test at various indentation strain rates, and the corresponded yield strength is then determined as $\sigma_y = H/3$. However, Cahoon et al. [14] indicated that this assumption was valid for several cold worked materials, and this ratio of several other materials changed in the range from 3.4 for alloys with a low strain hardening coefficient to 6.0 for alloys with a high strain hardening coefficient. To investigate the strain rate effect on the yield strength using the sharp indenter experiment, the tension and nondestructive indentation experiments have to be simultaneously carried out. Thus, this approach is a rather time-consuming task.

The aim of this study is to investigate the indentation strain rate effects on the mechanical properties of SM490 steel using the nondestructive indentation experiment. Based on the indentation parameters extracted from the load-displacement curves at different indentation strain rates, the corresponding material properties can be estimated; therefore, the strain rate effects on these material properties can be directly investigated using solely the sharp indenter test results. For this purpose, the sharp indenter-constant loading rate (CLR) experiments are performed at room temperature at various indentation strain rates. The indentation creep (IC) experiments are also performed to estimate the strain rate sensitivity value. The indentation strain rate effects on the hardness, yield strength, strain hardening exponent (n) and indentation shear stress ($\tau_{Indentation}$) are investigated and discussed. The dynamic tensile tests were performed at different strain rates to demonstrate that the strain rate effects on the hardness and yield strength investigated by using indentation are reliable. The correlation between the indentation strain rate and uniaxial strain rate is discovered. An efficient method was also proposed to estimate the yield strength considering the uncertain contact stiffness at high indentation strain rates.

2. Methods

2.1. Conventional method for determining mechanical properties

Fig. 1 exhibits the indentation load-displacement curve of elastoplastic material including the loading and unloading regimes. According to the loading regime, the power-law function, $P = Ch^k$, where k is in the range of 1.5–1.9, is normally used to describe the loading stage, where C and h are the loading curvature and indentation penetration depth [15–17]. However, the second-order function ($k = 2$), which was used in the previous method for determination of yield strength and strain hardening exponent [18], was demonstrated to approximately describe the relationship of applied load and displacement at loading stage in case of the sharp indentation [19–22]. The unloading regime is described by using a power-law function as $P = B(h - h_f)^m$, where B is constant and h_f is the final displacement of unloading regime.

The hardness can be extracted as the following equation [2].

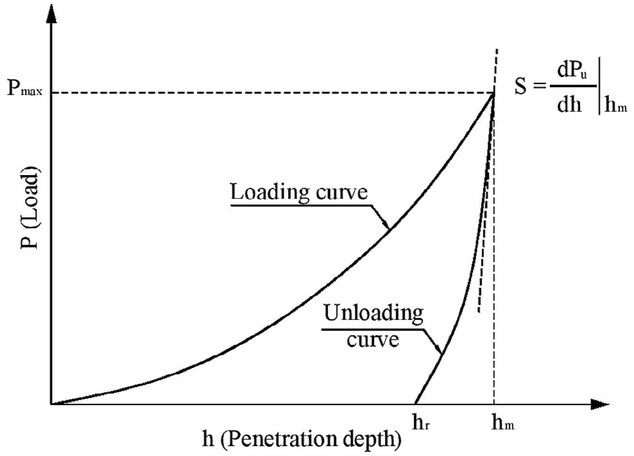

Fig. 1. A typical load-displacement curve (P-h) of elastoplastic material obtained using a nondestructive indentation experiment.

$$H = \frac{P_m}{A_c} \tag{1}$$

where P_m is a maximum load, A_c is the contact area that depends on the geometry of the indenter tip and is therefore defined as $A_c = 24.5h_c^2$ for the Berkovich indenter tip, in which h_c is the contact depth. Elastic modulus (E) is also determined based on the relationship between the material properties of the indenter tip and the reduced modulus (E_r), and expressed as [2]

$$\frac{1}{E_r} = \frac{1-\vartheta^2}{E} + \frac{1-\vartheta_i^2}{E_i} \tag{2}$$

where E_i, ϑ_i are the elastic modulus and Poisson's ratio of industry diamond.

According to the determination of yield strength of structural steel from the indentation load-displacement curve, a method was well established [18]. This method includes a reverse algorithm that uses the reduced modulus, maximum load, loading curvature, and contact stiffness as the input data. The reverse algorithm consists of two dimensionless functions, which are expressed as follows:

$$\frac{E_r^*}{\sigma_y} = \Pi_1 = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3}\left[a_{ijk}n^{j-i}\alpha^{k-1}\left(\frac{E_r}{C}\right)^{i-1}\right] \tag{3}$$

$$\frac{S}{E_r^* h_m} = \Pi_2 = \sum_{i=1}^{4}\sum_{j=1}^{4}\sum_{k=1}^{3}\left[b_{ijk}n^{j-i}\alpha^{k-1}ln\left(\frac{E_r}{\sigma_y}\right)^{i-1}\right] \tag{4}$$

where a_{ijk} and b_{ijk} are coefficients, C is the loading curvature, and α represents the plastic plateau in stress-strain curves of structural steel [4,7,18].

2.2. Determination of strain rate sensitivity

Strain rate sensitivity (SRS) is an indication of the effects of strain rate on material properties such as hardness. In earlier works, SRS for the tensile test was defined as the change in the yield stress or tensile strength divided by the change in the uniaxial strain rate ($\dot{\epsilon}$) at a constant temperature using the following equation [23,24]

$$m = \frac{\partial \log_e\left(\frac{\sigma}{\sigma_0}\right)}{\partial \log_e \frac{\dot{\epsilon}}{\dot{\epsilon}_0}} \tag{5}$$