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STRAIN RATE AND ITS HISTORY EFFECT ON THE INELASTIC MATERIAL BEHAVIOR OF STRUCTURAL STEEL UNDER MULTIAXIAL STRESS CONDITION

K. SUGIURA[1], K.C. CHANG[2] and G.C. LEE[3]

[1]Department of Civil Engineering
State University of New York at Buffalo
Buffalo, New York, U.S.A.

[2]Same as above

[3]Same as above

SUMMARY

An experimental study concerning the strain rate and strain rate history effect on the inelastic material behavior of structural steel under biaxial non-proportional loading is reported. A plasticity based formulatin including the effects of nonproportional loading and strain rate is present.

INTRODUCTION

It is generally accepted philosophy that structures should be designed to allow large inelastic deformation without collapse under the most credible earthquake ground motion. The ability of a steel structure to undergo large deformation without collapse depends on the development of ductile inelastic deformation at the critical sections. Because of the randomness of the ground motions, the stresses induced by the earthquake are generally dynamic and non-proportional in nature.

The effect of strain rate and its history dependence on the inelastic behavior of structural metals have been studied quite extensively in the last few decades. It has been well understood from experimental observations that certain material properties of metals such as the yield stress, are different under different loading rates. Most of the past experimental studies on loading rate have been devoted to the effect of high strain rate on the inelastic properties of metals under impact type monotonic loading. Very little information is available about the rate sensitivity of structural steel subjected to earthquake-type cyclic loading conditions in which the strain rate is generally within 10^{-1}/sec. The strain rate effect and its history dependence on the inelastic behavior of structural steel under dynamic multiaxial nonproportional loading, however, has not been studied yet.

In addition to experimental observations,various material constitutive equations for metals have been developed. Among those efforts the "Overstress Model" proposed by Malvern (Ref. 1) and Perzyna (Ref. 2) received much attention because of its simplicity. In a recent paper the authors applied the "Overstress" concept in the endochronic theory to describe the strain rate effect on the inelastic behavior of structural steel under cyclic loading condition (Ref. 3).

In this paper experimental study of the strain rate effect and its history dependence on the inelastic behavior of structural steel under biaxial non-proportional loading conditions at room temperature is reported. An analytical formulation, using a modified endochronic theory to include both effects of strain rate and nonproportional loading, is obtained between the test results and the numerical predictions.

TEST SETUP AND EXPERIMENTAL PROCEDURE

All the test results reported in this paper were conducted by using an MTS axial-torsional testing system which consists of two major components: (1) a closed-looped servo-controlled axial-torsional machine with maximum speed of 1 in/sec and (2) a PDP-11 computer system which performs function generation, test control, data acquisition and data analysis. More detailed description of this testing system can be found in Ref. 4.

Test specimens were machined from commercially available A-36 structural steel with 1-3/8 in. outside diameter (OD) and 7/8 in. inside diameter (ID). Following precision machining the specimens were annealed in a furnace for 1/2 hour and then furnace cooled.

Strain control was used throughout the test by using an MTS axial-torsional extensometer with gage length of 1 in. mounted at the mid-length of the specimen surface where strain rate of Von Mises type was controlled. The strain rates tested were between 10^{-5}/sec and 10^{-2}/sec. In general, all the specimens were first loaded in either axial or torsional direction followed by cyclic and non-proportional loading paths. Both constant and variable strain rates were used throughout the test.

TEST RESULTS

Strain Rate Effect Figure 1 represents typical results of strain rate effect on the inelastic behavior of structural steel under proportional loading and 90 degree out-of-phase nonproportional loading repsectively. Figure 2 is a summary of the strain rate effect of structural steel under various loading conditions with different effective strain ranges. The peak stresses are normalized with respect to the static yield stress which is determined by conventional methods (Ref. 4). Some important phenomena can be observed from Figure 2:

(1) The strain rate effect is very significant under monotonic loading condition in the plastic plateau range. The upper and the lower yield levels have increased 56.5% and 35.6% respectively when the strain rate is increased from 10^{-5}/sec to 10^{-2}/sec.

(2) The strain rate effect is less prominent under cyclic loading conditions because the material is usually strained in the strain hardening range. For proportional loading the increase in peak stress when the strain rate is increased from 10^{-5}/sec to 10^{-2}/sec lies between 12% and 16% depending on the cyclic strain range. Larger cyclic strain range has slightly larger strain rate effect. Strain rate effect under nonproportional loading is more sensitive than under proportional loading (about 19% increase within the above-mentioned strian rate range).

(3) Strain hardening effect plays a more important role in the increase of the peak stress response than the strain rate effect. At strain rate of 10^{-5}/sec, the increase in peak stress due to strain hardening with 1% effective strain is 49% for 90 degree out-of-phase nonproportional strain cycling and about 30% for proportional strain cycling.

Strain Rate History Effect Previous studies have shown that the strain rate history effect may be negligible for structural steel under axially applied monotonic and cyclic loading conditions with moderate strain rate changes (Ref.4).

Similar observations are also made in this study for structural steel under proportionally applied biaxial loading conditions. Figure 3 shows the stress-strain curves under 1% effective strain biaxial proportional loading with strain rates changes between 10^{-2}/sec and 10^{-5}/sec. It appears from Figure 3 that there is little strain rate history effect since the stress-strain curves converge to a unique state very fast before and after the strain rate changes.

Figure 4 shows an axial stress-shear stress curve with strain rate changes from 10^{-2}/sec to 10^{-5}/sec and then changes back to 10^{-2}/sec under 90 degree out-of-phase cyclic loading with 1% effective strain. Furthermore, when the strain rate changes from 10^{-2}/sec to 10^{-5}/sec, the stress point does not immediately return to the stress path unique to 10^{-5}/sec immediately. In other words, there is strain rate history effect on nonproportional loading when strain rate changes from high to low. This phenomenon suggests that the process of stress reduction is slower than stress increase. Similar phenomena for strain hardening and strain softening have also been observed. Therefore, the stress-strain curve can not return to a stabilized state with limited relaxation time. On the other hand, if the specimen is subjected to continued nonproportional cycling at the low strain rate (10^{-5}/sec), a stabilized state which is unique to that strain rate will be obtained.

CONSTITUTIVE EQUATIONS AND EXAMPLES

In order to describe the inelastic behavior of structural steel under dynamic nonproportional loading, the authors have introduced a nonproportionality function (Ref. 5) similar to the rate sensitive function used by Wu et al (Ref. 6) in conjunction with the concept of overstress model into endochronic theory of plasticity (Ref. 3). The constitutive equations are given by

$$\frac{d\epsilon_{ij}^{p}}{dt} = g_0 F^n \frac{(s_{ij} - \alpha_{ij})}{s_y^0 f/\kappa} \qquad (1a)$$

in which,

$$F = \sqrt{\frac{(s_{ij} - \alpha_{ij})(s_{ij} - \alpha_{ij})}{(s_y^0 f/\kappa)^2} - 1} \qquad (1b)$$

where s_{ij}, α_{ij}, ϵ_{ij}^{p}, s_y^0 and g_0 are deviatric stress tensor, the back stress tensor, the plastic strain tensor, the static yield stress in deviatoric stress space and the material constant representing the viscosity for rate effect, respectively. Furthermore, functions f and κ are considered as scalers of isotropic hardening/softening due to plastic strain accumulation and nonproportionality in straining. This type of formulation is based on the overstress concept which has been developed by Malvern (Ref. 2) and Perzyna (Ref. 3) and often used in the past because of its simplicity. F is a plastic potential which defined the material response from elastic to fully elastic-plastic behavior.

The function κ in Eq. (1-a) was introduced by the authors to evaluate additional hardening due to nonproportional straining for the rate-independent case. It was incorporated into the rate-dependent formulation as shown in Eq.(1-a). A simple form of this function is given by

$$\frac{d\kappa}{d\epsilon_{eff}^{p}} = (P(L) - \kappa)Q \qquad (2)$$

where ϵ^p_{eff} , $P(L)$ and Q are the effective plastic strain defined by $\int \sqrt{\frac{3}{2} d\epsilon^p_{ij} d\epsilon^p_{ij}}$, value of κ under 90 degree out-of-phase strain cycle and the stabilization rate coefficient, respectively. Also, the distance, L, is measured as the perpendicular distance from origin to the tangent of plastic strain path (Ref. 5).

The example given in Figure 5 is for 90 degree out-of-phase straining with its effective strain amplifued of 1%. The characteristics of the stress response are well predicted.

ACKNOWLEDGMENTS

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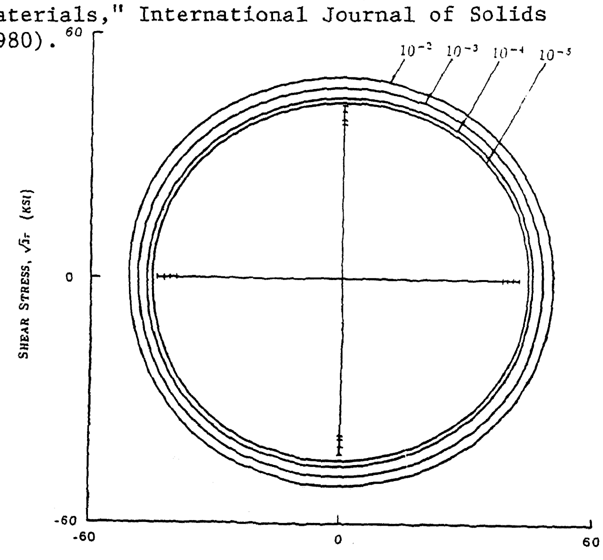

Fig. 1 Typical Results of Strain Rate Effect on Structural Steel

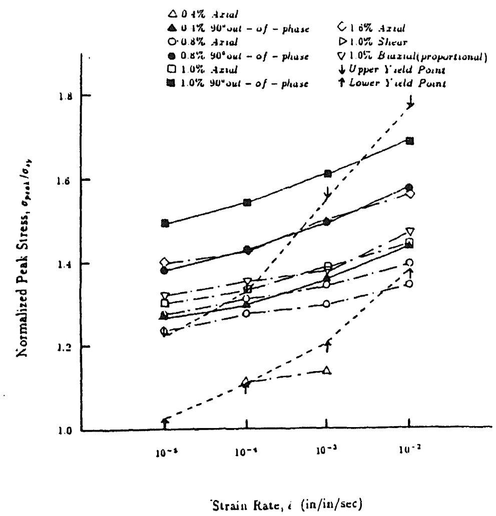

Fig. 2 Summary of Strain Rate Effects on Structural Steel

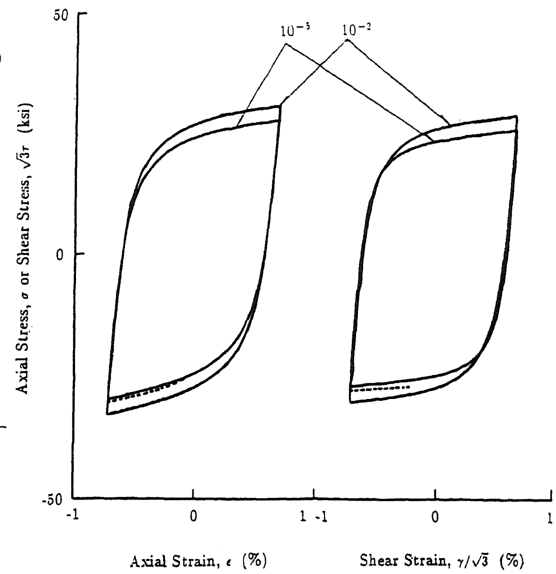

Fig. 3 Strain Rate History Effect on Structural Under Biaxial Proportional Loading

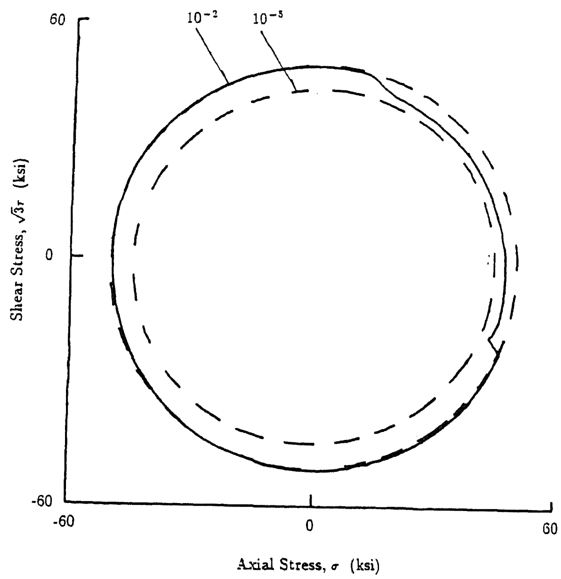

Fig. 4 Strain Rate History Effect on Structural Steel Under Phase Nonproportional Loading

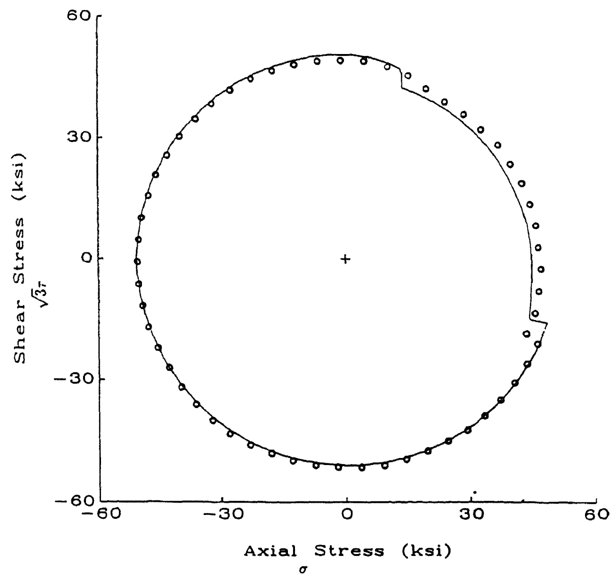

Fig. 5 Numerical Example