Experimental Study of Material Constitutive Behavior Under Nonproportional Cyclic Loading

Sun Xunfang, Ning Jie
Southwestern Jiaotong University, Emei, PRC

INTRODUCTION

It is increasingly leading to widely pay attention to the research for the nonproportional cyclic constitutive behavior of material. With the widespread application of larger-scale computer, it profoundly affected the development of solid mechanics, and transfered its emphasis from traditional structural analysis to developing accurate and realistic material constitutive relation. In recent years, a lot of material constitutive models has been built and successfully applied to describe constitutive behavior of material under uniaxial and multiaxial proportional loadings. Unfortunately, so far there is no a successful constitutive model which can describe constitutiv behavior of material under general loadings, specially under nonproportional cyclic loadings. This is due to we have not systematically and clearly mastered some basic properties of the nonproportional cyclic constitutive behavior of material. On the other hand, many engineering structures, such as railwheel, neuclear reactor structures, pressure vessel etc. , are subjected to nonproportional cyclic loadings, therefore, it is necessary to study the nonproportional cyclic constitutive behavior of material to ensure the safety and reliability of structure.

In recent years, many researchers, such as Ohashi [1], Tanaka [2], McDowell [3-4], Benallal and Marquis [5], author [6-7] etc. , studied some basic features of nonproportional cyclic constitutive behavior of material by experiments. But, these experimental data are too insufficient to develop material constitutive models we required, it is still needed to perform systematical experiments to explicate basic features of nonproportional cyclic constitutive behavior of material.

According to previous experimental results, it showed that the nonproportional cyclic constitutive behavior of material is closely related to the deformation history, strain amplitude, deformation direction and deformation path. In fact, a general plasticity theory may be expressed in deviatoric vector space as [8]:

$$\vec{\sigma} = \int_{s-h}^{s} K\{ s, s'; k(s), k(s') \} \, d\vec{\varepsilon}(s') \qquad (1)$$

where s is the length of deformation path, h is the influence range of previous deformation, k is the shape parameter of deformation path.

Therefore, it is necessary to investigate the influence of shape and its history of the deformation path on the constitutive behavior of material to build accurate material constitutive model. In this paper, based upon a series of experiments, studied the effects of curvature and shape of deformation path on the nonproportional cyclic constitutive behavior of material.

EXPERIMENT PROCEDURE AND CONDITIONS

The material chosen for this study is TB451-63 axle steel. The chemical compositions of the material consist of C: 0.37, Mn:0.48, Si:0.15, P:0.045 S:<0.05, Cr:<0.3, Cu:<0.3, Ni:<0.025 percent. The specimen is thin-walled tubular specimen and its shape and geometrical sizes are shown in Fig.1. All experiments were conducted by a computer controlled testing system which consists of a DEC PDP 11/23 minicomputer and MTS 809 servo-controlled hydraulic testing machine. Experimental data acquisition was performed by MTS data acquisition system. The components of strain were evaluated with a set of three strain gages glued on the outer surface of the specimen. All experiments were conducted at a low strain rate 7×10^{-5} /s, and at room temperature. All experiments were conducted under total strain control condition.

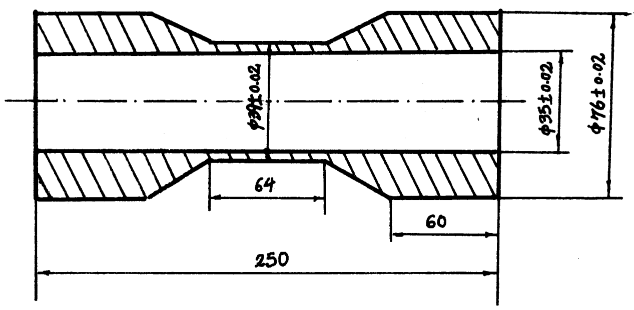

Fig.1 Geometry shape and sizes of the specimen

When a thin-walled tubular specimen is subjected to combined loadings of axial force and torque, it is convenient to discuss the material deformation response in a axial and torsional subspace which is defined as a subspace of Ilyushin's five-dimensional deviatoric vector space. In this subspace, define the stress vector as:

$$\vec{\sigma} = \sigma_1 \vec{n}_1 + \sigma_3 \vec{n}_3 \tag{2}$$

where $\sigma_1 = \sigma_z$, $\sigma_3 = \sqrt{3}\tau$, σ_z and τ are axial and shear stress, respectively, n and n are orthonormal base vectors in the stress plane.

Define total strain vector as:

$$\vec{\varepsilon} = \varepsilon_1 \vec{n}_1 + \varepsilon_3 \vec{n}_3 \tag{3}$$

where $\varepsilon_1 = \varepsilon_z$, $\varepsilon_3 = \gamma/\sqrt{3}$, ε_z and γ are axial and engineering shear strain, respectively.

The effective stress σe defined as stress aplitude:

$$\sigma e = |\vec{\sigma}| = (\sigma_1^2 + \sigma_3^2)^{\frac{1}{2}} \tag{4}$$

The effective strain εe defined as strain amplitude:

$$\varepsilon e = |\vec{\varepsilon}| = (\varepsilon_1^2 + \varepsilon_3^2)^{\frac{1}{2}} \tag{5}$$

In order to investigate the effects influences of the shape of deformation path on the nonproportional cyclic constitutive behavior of material, experiments based on the following elliptic and circular deformation path were performed.

Table 1 deformation path and strain amplitudes (%)

A	$\Delta\gamma/2$		1.2			
	$\Delta\varepsilon/2$	0.2	0.4	0.5	0.6	
B	$\Delta\gamma/2$		1.6			
	$\Delta\varepsilon/2$	0.2	0.4	0.5		
C	$\Delta\varepsilon/2 = \Delta\varepsilon/2 = 0.4$					
D	$\Delta\varepsilon/2$	0.2	0.4	0.6	0.8	
	$\Delta\varepsilon/2$	0.1	0.2	0.3	0.4	
E	$\Delta\gamma/2$	0.4	0.8	1.0	1.2	1.4
	$\Delta\varepsilon/2$	0.2	0.4	0.5	0.6	0.7

In the experiments, the components of strain satisfied the conditions :

$$\begin{aligned} \varepsilon_1 &= (\Delta\varepsilon_1/2)\sin\omega t \\ \gamma &= (\Delta\gamma/2)\sin(\omega t-\psi) \end{aligned} \tag{6}$$

RESULTS AND DISCUSSIONS

The smooth deformation path is described by strain amplitude and curvature. Therefore, the researches for the influences of curvature of deformation path on the constitutive behavior of material includes following contents, that is, the relations between deformation hardening of material and curvature of deformation path.

The variations of curvature is closely related to the variations of strain amplitude. In our experiments, the change of elliptic deformation path included two types. One type is that the $\Delta\varepsilon_1/2$ gradually increased and $\Delta\varepsilon_3/2$ kept a constant value, i.e. the elliptic path gradually getting round. Another type is that the $\Delta\varepsilon_1/\Delta\varepsilon_3$ kept a constant value, i.e. the elliptic path similarly getting larger.

When the shape of deformation path similarly getting larger, the curvatures corresponding to the maximum and the minimum strain amplitude are gradually getting small. Fig.2 described variations of the effective stress with the histories of the maximum curvature and the minimum curvature under path E. It showed that, althouth the ratio of strain amplitudes $\Delta\varepsilon_1/\Delta\varepsilon_3$ is a constant and the effective stress linearly varied with the curvature approximately, the variations of effective stress with the maximum curvature and the minimum curvature are different from each other due to their increments are different.

To eliminate the effects of the variations of strain amplitude and purely investigate the influences of curvature of the deformation path on the deformation response of the material, we studied the variations of effective stress with the curvature at the point corresponding to the maximum strain amplitude of the path A and path B. Results were shown in Fig.3. Under these paths, the maximum strain amplitudes kept constant values, therefore, the curvature at the point corresponding to the maximum strain amplitude of the path gradually descreased when the path getting round. Fig.3 showed that the variations of curvature due to the change of shape of the deformation path will lead to the change of effective stress. According to Fig.2 and Fig.3, results also indicated that the variation rate of the effective stress with the curvature is direct proportion to the variation rate of the curvature with the deformation history.

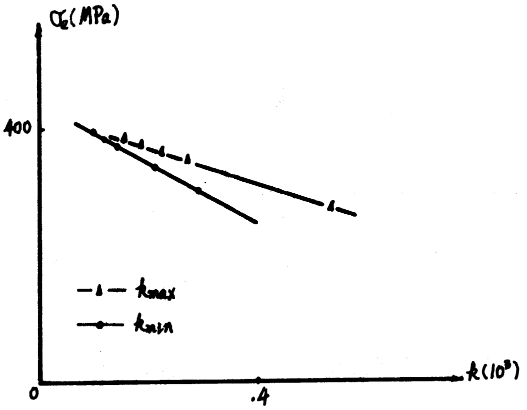

Fig.2 Variations of effective stress with the curvatures of the maximum and minimum strain amplitudes under strain path E.

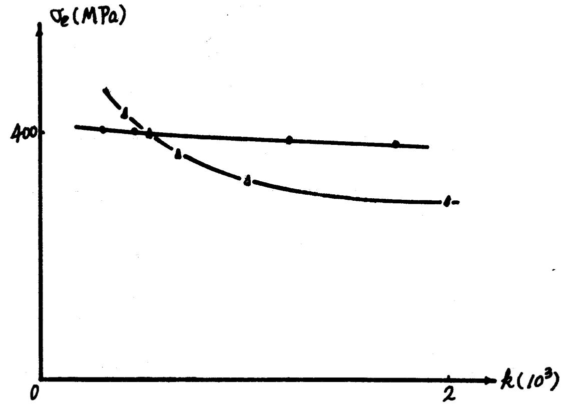

Fig.3 Variations of effective stress with the curvature of the maximum strain amplitude under strain path A and B.

Fig.4 described relations between effective stress and the curvature corresponding to the minimum strain amplitude of deformation path A and path B. Under the path A, the curvature of the minimum strain amplitude of the path is increasing with the increments of the deformation history. Under the path D, the curvature of the minimum strain amplitude is descreasing with the increments of the deformation history. From Fig.4, it was indicated that the effective stress is increasing with the increments of the curvature under path A, and decreasing with the increments of the curvature of path D. Therefore, the variation rate of effective stress with the curvature history is direct proportion to the rate of curvature with deformation history. This conclusion may be a general rule.

Fig.5 showed the variations of effective stress with the length Δs of the deformation path under the path A, E and C, where the Δs is measured from the point corresponding to the maximum strain amplitude, and the lowest point of the curve in the figure corresponding to the minimum strain amplitude of the path. It was observed that the effective stress is almost a constant under the circular deformation path C. For the elliptic deformation paths, the more oblate the path is, the stronger the variation of the effective stress is, in other words, the variation of the curvature of the path is more drastic, the variation of the effective stress is stronger. From Fig.5, results also showed that the tendency of the variations of the curvature with the length of the path is as the same as that of the effective stress under the elliptic deformation path. Therefore, the change of effective stress with the length of deformation path is direct proportion to the change of the curvature of the path.

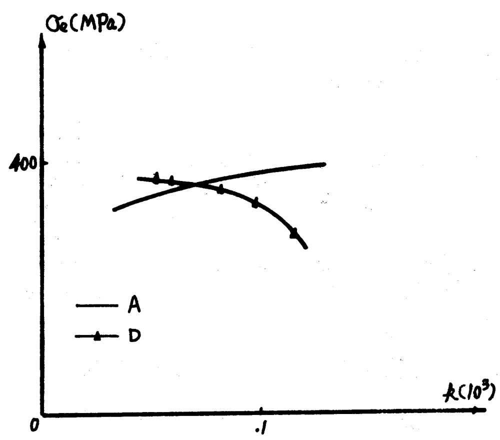

Fig.4 Relations between effective stress and the curvature of the minimum strain amplitude under deformation path A and D.

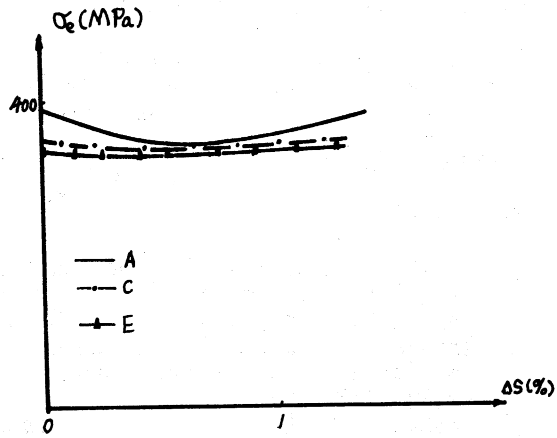

Fig.5 Influences of the shape of deformation path on the effective stress.

Fig.6 showed the variations of delay angle θ between the stress vector and the tangent to deformation path under the path B. It indicated that, with the path getting rounder, the variations of the delay angle is gradually getting smooth. Therefore, the shape of the deformation path strongly influences the plastic flow behavior of material.

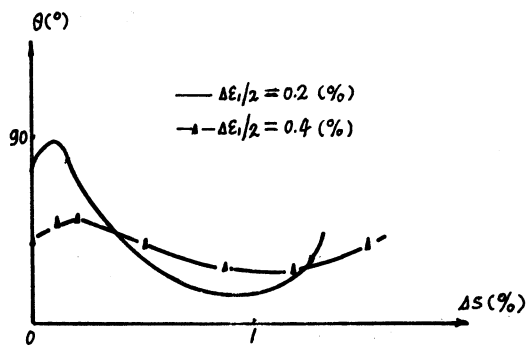

Fig.6 Influences of the shape of deformation path on the plastic flow features of material

CONCLUSIONS

From above-mentioned results, we have following conclusions:

1. The shape of deformation path strongly influences the hardening behavior and plastic flow features of material under nonproportional cyclic loadings.

2. The curvature of deformation path is a suitable parameter to reflect the influences of the shape of deformation path on the nonproportional cyclic constitutive behavior of material.

3. The change rate of effective stress is direct proportion to the rate of curvature of deformation path with the length of the path.

ACKNOWLEDGEMENT: The financial support of NSFC is very appreciate.

REFERENCES

[1] Ohashi, Y., Tanaka, E., and Ooka, M., " Plastic deformation behavior of type 316 stainless steel subject to out-of-phase strain cycles ", ASME J. Eng. Mat. Tech., Vol.107, pp.286-292, 1985.
[2] Tanaka, E., Murakami, S., and Ooka, M, " Effects of plastic strain amplitudes on non-proportional cyclic plasticity ", Acta Mech., Vol.57 pp.167-182, 1985.
[3] Mcdowell, D. L., " A two surface model for transient nonproportional cyclic plasticity ", ASME J. Appl. Mech., Vol.52, pp.298-308, 1985.
[4] Mcdowell, D. L., " An experimental study of the structure of constitutive equation for nonproportional cyclic plasticity ", ASME J. Eng. Mat. Tech., Vol.107, pp.307-315, 1985.
[5] Benalla, A., and Marquis, D., "Constitutive equations for nonproportional cyclic elasto-viscoplastic", ASME J. Mat. Eng. Tech., Vol.109, pp.326-336, 1987.
[6] Sun, X. F., Ning, J., and Chen, X., " Nonproportional cyclic plasticity: experiment and theory ", To appear in Proc. of ICCLEM, Invited lecture, 1989.
[7] Ning, J., Cai, L. X., and Sun, X. F., " Investigations for deformation hardening behavior of material under nonproportional cyclic loadings ", To appear in Proc. of ICAM, 1989.
[8] Ilyushin, A. A., " Plasticity, Foundations of General Mathematical Theory ", pp.16, Akad. Nauk SSSR, Moscow.(In Russian), 1963.