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HYSTERETIC BEHAVIOR OF STRUCTURAL STEELS UNDER BIAXIAL NONPROPORTIONAL COMPRESSION AND TORSION

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Abstract: This paper deals with the hysteretic behavior of structural steels under biaxial nonproportional compression and torsion. The experimentally observed biaxial cyclic behavior of steels subjected to combined nonproportional compression and torsion is examined and discussed. Some important cyclic behavior of steels within the yield plateau and strain-hardening region, such as reduction of the elastic range, the decrease of the yield plateau, cyclic strain hardening, fading and nonfading memory under biaxial nonproportional loading are presented. The rate of nonproportionality of loading on cyclic behavior is evaluated.

1 Introduction

Steel structures are subjected to variable severe stress levels under extreme loading conditions, such as, severe earthquakes and winds. Therefore, it becomes important to accurately model the cyclic elastoplastic behavior of structural steel because it is one of the key factors influencing the precision of the inelastic structural analysis [1]. An extensive review of the literature on experimental and theoretical studies on cyclic plasticity of metallic materials can be found in works by Mamaghani [1] and Ohno [2]. Experimental study of the cyclic behavior of structural steel under multiaxial loading has attracted limited attention. Some of the cyclic behavior of annealed steel grade A36 under biaxial nonproportional loading was reported by Chang and Lee [3]. Mamaghani et al. [4] carried out a, series of experiments on steel grade SS400 (equivalent to A36) under proportional and nonproportional biaxial cyclic loading. Some of the important cyclic behavior of steel SS400 under nonproportional loading within the yield plateau, which is one of the important features of structural steels, and strain hardening range were pointed out and evaluated. The main purpose of this paper is to further investigate the cyclic behavior of structural steels under biaxial loading, through the conducted experiments [1]. In what follows, the experimentally observed biaxial cyclic behavior of the steel grade SS400 subjected to combined compression and torsion under nonproportional loading is presented and discussed.

2 Experiments

The outline of the testing system is shown in Figure 1. The specimen was subjected to torsional moment produced by the vertical force from the testing machine (MTS810) and axial compression force is applied by the hydraulic jack, see Figure 1. The tested specimens were annealed thin-walled square tubes of size b = 50mm, thickness t = 4.5mm and useful length 257mm, as shown in Figure 2. The material properties obtained from tensile tests for annealed SS400 are summarized in Table 1, where E, σ_y, $\varepsilon_{y,,}$ ε^{p}_{st}, E_{st} , σ_u and u stands for the modulus of elasticity, yield stress, yield strain, length of yield plateau, initial hardening modulus, ultimate stress and Poisson's ratio, respectively.

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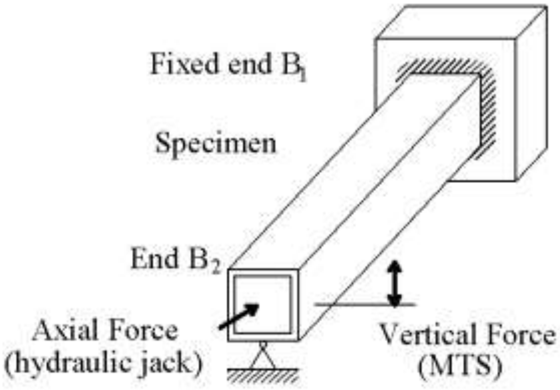
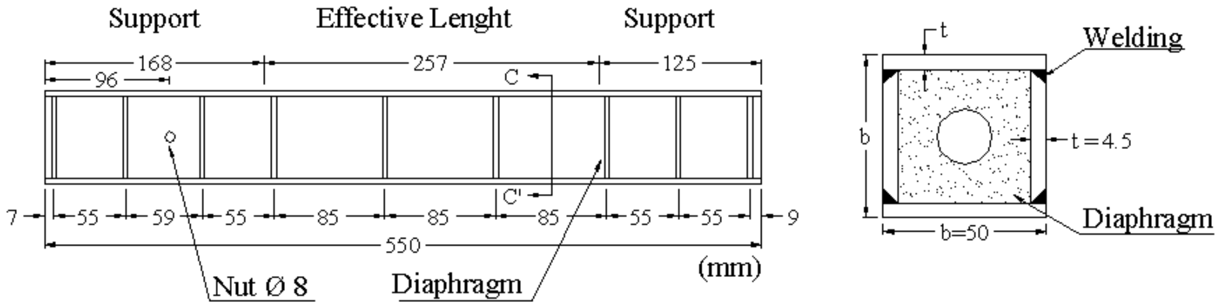


Figure 1: Outline of testing system



(a) Longitudinal view

(b) C-C' section

Figure 2: Outline of testing system

The nonproportional loading were idealized into three selected patterns of rectangular, diagonal and zigzag paths in the axial force P-torsional moment T space, examples of the diagonal and zigzag paths are shown in Figures 3a and 4a. The experiments are carried out in multiple steps for the twisting angle rates φ_i = (40,80,120,160,200) ×10^{-4} rad/cm and varying axial load with the prescribed limit of $P_{max} = 0.55P_y$ (P_y = squash load), where i stands for the step number. The details of experiments and loading procedures are given in work by Mamaghani [1]. In what follows, the biaxial cyclic behavior of steel grade SS400 will be discussed through the selected two typical experiments.

Table 1: Material constants for SS400

Parameter	E (GPa)	E^P_{st} (GPa)	σ_y (MPa)	σ_u (MPa)	ε_y	ε^P_{st}	ν
Value	204	3.88	260	434	1.3×10^{-3}	1.7×10^{-2}	0.27

3 Biaxial Cyclic Behavior

The response for the two typical experiments with the diagonal and zigzag loading paths, respectively, corresponding to the torsional moment T, twisting angle rate φ, averaged axial stress σ and axial strain ε are given in Figures 3 and 4. In the following, with reference to Figures 3 and 4, some of the observed general biaxial cyclic characteristics of the steel grade SS400 are briefly discussed.

1. In the virgin state of the material, when the combined compression force and torsional moment reaches a critical value (loading point A, in Figures 3 and 4), yielding occurs and both the twisting angle rate (see T-φ and φ-ε curves in Figures 3 and 4) and axial strain (see σ-ε and φ-ε curves in Figures 3 and 4) increase along the yield plateau. It is observed that the yield plateau decreases and disappears depending on the amplitude of plastic strain and plastic work due to cycling within the yield plateau.

2. The elastic range of stress in the T- φ hysteresis curves for the first and second steps decreases rapidly (cyclic softening of the yield surface) and later it doesn't change noticeably. This effect is apparent in all the experimental results, i.e., see the T -φ hysteresis curves in Figures 3 and 4.

3. In the experiments, cycling is carried out under constant torsional moment $T(\varphi_i)$ for the corresponding step i. Therefore, the amount by which the T- φ loops become thinner indicates the cyclic strain hardening of the material, as shown in Figures 3b and 4b. The T- φ and φ-ε curves of the experiment results show that the stabilized hysteresis curves are achieved after a few cycles without further noticeable cyclic hardening.

4. In the case of the rectangular and zigzag loading paths, the thinning out of the T- φ hysteresis loops is more than that of the diagonal loading path for the corresponding steps, as can be noticed by comparing the T- φ curves in Figures 3 and 4. This may be due to the degree of severe nonproportionality in the rectangular and zigzag loading paths, when there is an abrupt change in the direction of loading. That is, the material experiences more cyclic hardening as the degree of nonproportionality of loading history increases.

5. As shown in Figure 3b, after the stabilized state is achieved for the fourth step with a large effective stress, the fifth step is described by repeating the loading path for the second step with a smaller effective stress (loading path A_5 B_5 A_5 is the same as A_2 B_2 A_2). Figure 3b shows that the T- φ hysteresis loops for the fifth and second steps are nearly identical, with the exception that it is translated in the positive direction of the φ-axis. That is, if a loading path with a small effective stress is repeated after a path with a large effective stress, it washes out the influence of the preceding path with a large effective stress (fading memory of the material for the preceding step) and has a unique hysteresis loop which characterizes that loading path (nonfading memory of the material for the repeated step).

6. As shown in Figures 3c and 4c, the overall axial strain increases in compression side during cycling. The increase in axial strain is small for the first and second steps and gradually becomes more for the further steps. The rate of increase in the axial strain decreases significantly after the first cycle

(cyclic hardening) and is almost stabilized for the other cycles. The axial strain increases more in experiment with zigzag loading path, in which during one cycle the axial load is reversed two times as compared with the other experiments.

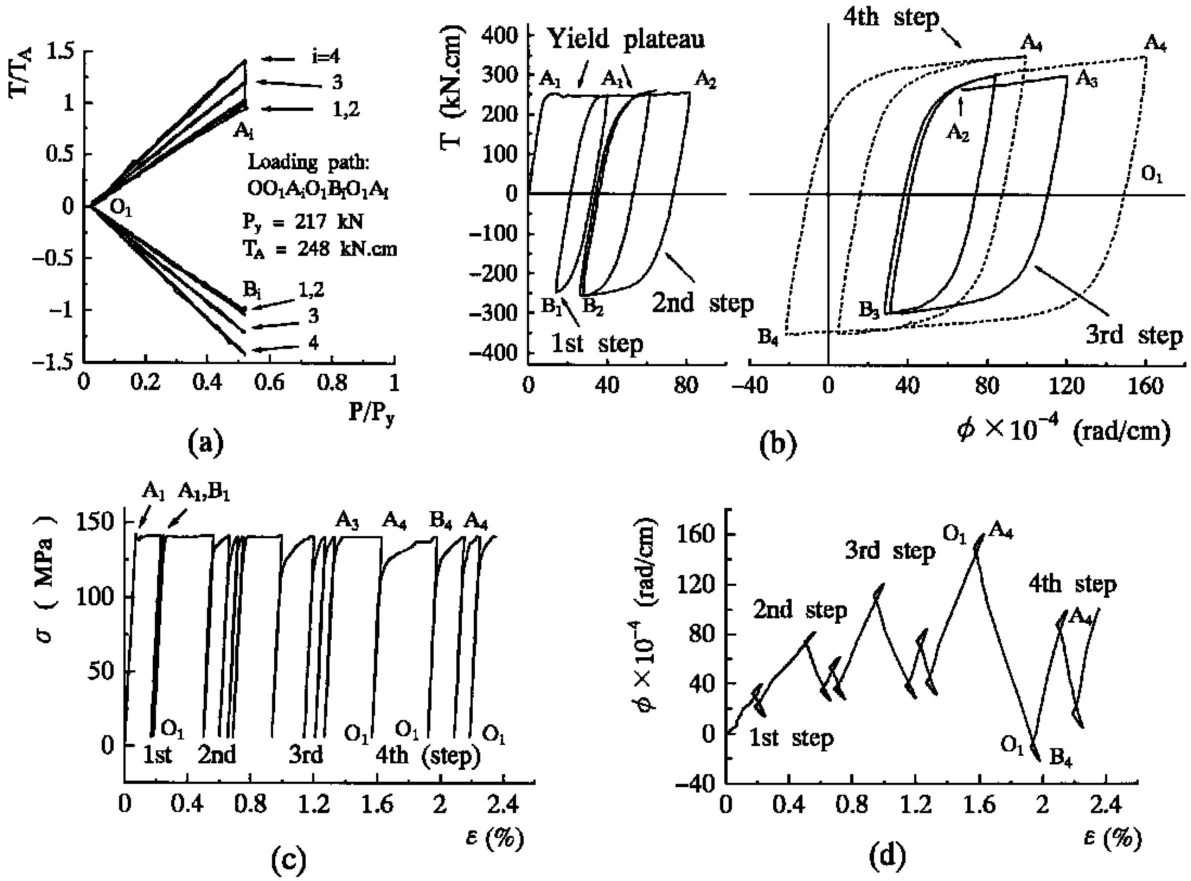


Figure 4: Experiment 3; (a) normalized exact loading path; (b) torsional moment T-twisting angle rate φ ; (c) averaged axial stress σ -axial strain ε ; (d) twisting angle rate φ -averaged axial strain ε

4 Conclusions

This paper dealt with the biaxial hysteretic behavior of structural steels. The results of combined compression and torsion tests on structural steel with special emphasis on hysteretic behavior under nonproportional loading within the yield plateau were discussed. The biaxial test results revealed that: (1) the yield plateau decreases and disappears depending on the plastic work; (2) the elastic range of stress is reduced very rapidly and gradually becomes stable due to cycling; (3) the material experiences more cyclic hardening as the degree of nonproportionality of the loading history increases; (4) structural steels have both fading and nonfading memories; and (5) under biaxial loading, when the state of stress is in the plastic state, the increase of load in one direction causes the increase of plastic strain in the other direction. The test results indicated that stress cycling affects significantly all the important elements in the time- and rate-independent plasticity theory of structural steel, such as, the yield plateau, flow rule that relates the increments of stress and plastic strain, and hardening rules. Therefore, an accurate constitutive law should account for the above-discussed hysteretic behavior of structural steels.

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