Journal of Constructional Steel Research 104 (2015) 64–73

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Dependence of the cyclic response of structural steel on loading history under large inelastic strains

Feng Zhou, Yiyi Chen *, Qi Wu

State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, China
Department of Building Engineering, School of Civil Engineering, Tongji University, Shanghai 200092, China

A R T I C L E I N F O

Article history:
Received 16 June 2014
Accepted 27 September 2014
Available online 18 October 2014

Keywords:
Cyclic loading
Damage evolution
Large inelastic strain
Plastic energy dissipating capacity
Strain hardening
Stress–strain response
Structural steel

A B S T R A C T

This paper presents a series of cyclic loading tests on structural steel materials under cyclic tension–compression at large inelastic strains with amplitude up to 20% (±10%). A total of six different cyclic loading protocols were considered in this study. The effects of the loading history on the cyclic response of structural steels including strain hardening, stress–strain response, damage evolution and plastic energy dissipating capacity have been investigated. The test results show that structural grade steels of Q345B and Q420D have the same trend in cyclic hardening or softening behavior and the loading history has quite obvious effect on the behavior of cyclic hardening or cyclic softening. The effect of loading history on cyclic stress–strain response is obvious especially at low amplitude. The effect of pre-cyclic strain loading is more obvious than those of pre-single strain loading. The steel Young's modulus *E* generally decreases with the number of cycle increases and the degradation rate becomes faster and faster with the increment of strain amplitude level. The energy dissipating capacity is nearly the same for all loading protocols. The cumulative dissipated hysteretic energy is only related to the total experienced strains but irrelevant to the loading paths for structural steels under fully reversed cyclic tension–compression at large inelastic strains with amplitude up to 20% (±10%).

1. Introduction

Structural steel members will experience very large displacement cycles under extreme seismic conditions, which is classified as low-cycle fatigue. Low-cycle fatigue is characterized by repeated inelastic strains leading to material failure that occurs within a low number of cycles. The response of structural steel members to this form of loading is controlled by their geometry and also by the hysteretic behavior of the constituent structural steel material [1]. The cyclic behavior of structural steel material under large inelastic strains including the Bauschinger effect, cyclic softening or hardening and damage accumulation is much different to the monotonically static response of the structural steel material [2]. Better understanding of structural steel inelastic cyclic behavior is very important for determining the suitability of the material for high strain applications and for determining its seismic performance. Chen et al. [3] conducted a total of seven tensile coupon tests and a total of twenty one cyclic material tests on hot-rolled structural steels with four kinds of strength grades. Three different cyclic loading protocols of cyclic ascend, cyclic alternate and cyclic tensile were considered with strain amplitudes varying from ±0.5% to ±2%. The effects of loading protocols on the hysteresis material behavior had been studied. The results concluded that the loading protocols affected the hysteresis behavior but are insignificant for seismic applications within the range of the strain in the tests. However, there is a need to determine the validity of the conclusion under large range of inelastic strains.

The hysteretic behavior of the structural steel material can be studied through low-cycle fatigue testing at large inelastic strain amplitudes. Although a lot of experimental data have been reported for cyclic plasticity of structural steels, quite limited numbers of papers on cyclic deformation have been published for structural steels at large strain range due to test setup limitations and specimen buckling issues. Yoshida et al. [4] investigate the elastic–plastic behavior of steel sheets under in-plane cyclic tension–compression at large strains. Two types of steel sheets, i.e. an aluminum-killed mild steel sheet and a dual-phase high strength steel sheet were tested using adhesively bonded specimens with an anti-buckling device. Stress–strain responses during cyclic straining of the strain ranges of 4% and 10% for the mild steel and the high strength steel were reported. It should be noted that the experiments were not conducted subjected to fully reversed cyclic strains, but with large tension mean strain. Saeki et al. [5] tested the cyclic mechanical properties of low yield strength steels for potential use in energy dissipation mechanism in seismic isolation and buckling restrained brace. A total of 44 coupons were tested at constant strain amplitudes ranging from 0.15% to 1.5%. Kaufmann et al. [6] performed axial coupon tests at strain amplitudes of 1%, 3% and 4% strain on four rolled wide flange steel beams, two made from ASTM A572 steel and one each of

* Corresponding author. Tel.: +86 21 6598 2926; fax: +86 21 6598 4976.
E-mail address: yiyichen@tongji.edu.cn (Y. Chen).

http://dx.doi.org/10.1016/j.jcsr.2014.09.019

Table 1
Mechanical properties of tested steel grades.

Designations of steel	Yield stress	Tensile strength		Elongation
		f_u (MPa)		
	f_y (MPa)	Nominal stress σ_{nom}	True stress σ_{true}	ε_f (%)
Q345B	351	510	617	32
Q420D	511	592	677	28

A992 and A36 steels. Dusickaa et al. [2] reported the cyclic response of plate steels under large inelastic strains. Axial coupons were tested for five types of plate steel, including conventional and high performance A709 steel as well as specialty low yield point steels, to investigate the material response under repeated inelastic demands of constant amplitude up to $\pm 7\%$ strain.

To explore the low cycle fatigue behavior of structural steel sustaining further large strain than the available test data, this paper reports an experimental investigation on the stress–strain characteristics of structural steels subjected to large repeated cyclic plastic deformations. The aim of the experimental program was to examine the hysteresis material behavior difference between under large inelastic strains and under small strains. In addition, the difference of the loading history effects on the cyclic response of structural steel between under large inelastic strains and under small strains has also been studied. The limit between large inelastic strains and small strains can be defined as 5%, beyond which the true stress is quite different from the nominal value. Two structural grade steels, i.e. Q345B and Q420D which are commonly used for fabrication and construction of steel structures in China including specific areas of expected plastic deformations imposed by earthquake loading, are considered in this study. A series of cyclic loading tests were performed under cyclic tension–compression at large strains with amplitude up to 20% ($\pm 10\%$). To investigate the effects of pre-cyclic strain loading and pre-large single tension strain loading, a total of six different cyclic loading protocols were imposed to study the effects of the loading history on the cyclic response of structural steels, such as strain hardening, stress–strain response, damage evolution and plastic energy dissipating capacity.

2. Experimental investigation

2.1. Specimen details

The studied structural grade steels are Q345B and Q420D with the nominal yield stress of 345 MPa and 420 MPa respectively, which are commonly used in China. The measured monotonic mechanical properties are summarized in Table 1. The test specimens were cut in the rolled direction. In order to prevent the buckling at the large compressive strain of −10% desired for this study, the test specimens were machined from steel plates into round coupons with reduced section effective length according to the test method for axial loading constant-amplitude low-cycle fatigue of metallic materials [7], as shown in Fig. 1a. The section diameter was maintained at 15 mm with a reduced length of 17 mm, resulting in a reduced section length-to-diameter ratio of 1.13. The reduced section and transition zone were machined using numerically-controlled equipment such that no undercut would result. For consistency among all of the tests, the surface finish was carefully polished using sand paper.

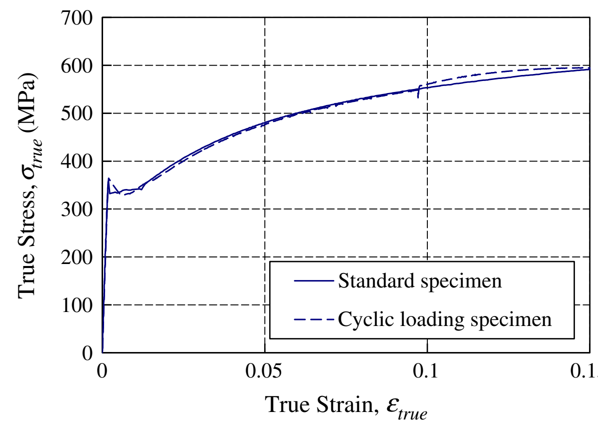

Fig. 2. Comparison of stress–strain curves obtained from uniaxial tension tests.

It should be noted that standard tensile only test procedures, such as American Society for Testing and Materials Standard [8] and Chinese Tensile Testing Standard [9], recommend section length-to-diameter ratio of 5 or greater, as shown in Fig. 1b, since compression buckling is not of concern. To verify the cyclic tension–compression test results, the stress–strain curve obtained from a uniaxial tension test using the cyclic specimen (Fig. 1a) was compared with the one using a standard specimen (Fig. 1b), as shown in Fig. 2. Since the analysis involves large in-elastic strains, the nominal (engineering) static stress–strain curve obtained from the test was converted to a true stress–true strain curve by using the following Eqs. (1) and (2).

$$\sigma_{\text{true}} = \sigma_{\text{nominal}}(1 + \varepsilon_{\text{nominal}}) \tag{1}$$

$$\varepsilon_{\text{true}} = \ln(1 + \varepsilon_{\text{nominal}}) \tag{2}$$

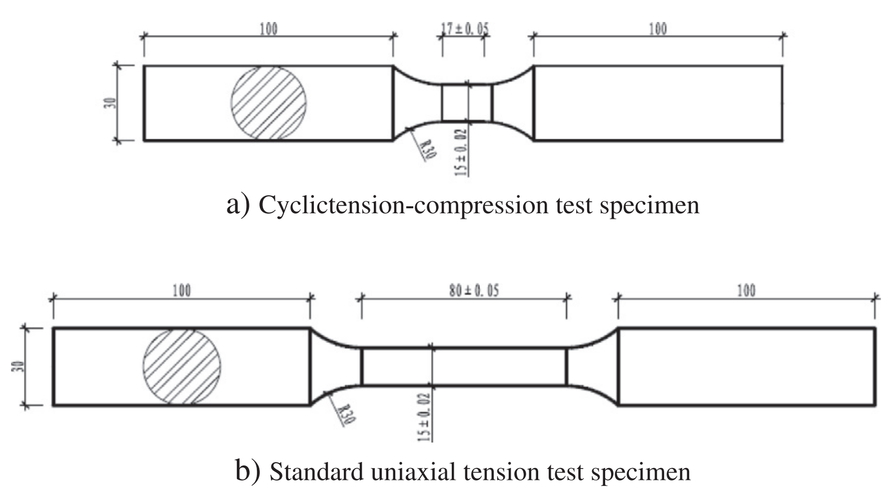

Fig. 1. Shapes of test specimens.