Construction and Building Materials 162 (2018) 596–607

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Constitutive model for full-range cyclic behavior of high strength steels without yield plateau

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HIGHLIGHTS

- Q550 and Q690 high strength steels were tested under monotonic and cyclic loadings.
- They exhibited good ductility under monotonic tension without yield plateau.
- They developed isotropic softening at small strains after initial yielding.
- They developed isotropic and kinematic hardening at moderate and large strains.
- Constitutive model for their cyclic behavior and calibration method were proposed.

ARTICLE INFO

Article history:
Received 13 June 2017
Received in revised form 17 November 2017
Accepted 24 November 2017

Keywords:
Constitutive model
Cyclic behavior
High strength steel
Experiment
Plasticity

ABSTRACT

In order to characterize static and cyclic behavior of high strength structural steels, coupons made of two typical kinds of such steels in China, i.e. Q550 and Q690 steels with nominal yield strength of 550 MPa and 690 MPa respectively, were designed and tested under monotonic tension and a variety of cyclic loading protocols. Uniaxial stress-strain curves from the test show that for both steels no obvious yield plateau was observed, and short-range isotropic softening occurred right after initial yielding, while the subsequent strain hardening was contributed by both kinematic hardening and long-range isotropic hardening. Based on these phenomena, a constitutive model was developed specifically for those high strength steels and implemented in numerical analysis through user-defined subroutines. Calibration method for material parameters in this constitutive model was also established that mainly depends on tension coupon test result. After that, simulation was conducted by using the developed model with its stress-strain curves compared with those from cyclic loading test. Good agreement was obtained. Therefore, the constitutive model and its calibration method can be used for further seismic or dynamic nonlinear analysis of high strength steel structures and will help to develop reasonable and reliable ductile design method of those structures.

1. Introduction

1.1. Background and motivation

Thanks to the rapid development in production technique of structural steels, innovative high strength steels have been applied in many engineering structures to take full advantage of their architectural, structural and economical benefits [1–5]. Generally, high strength steels refer to those structural steels with nominal yield strength (f_y) not less than 460 MPa and excellent toughness, weldability as well as processability [6]. However, a problem that cannot be ignored on high strength steels is associated with their deformation capacity, or rather, ductility, which quantifies only the capacity in plastic deformation before rupture. So far, a number of experimental studies have shown that in general, the yield-to-tensile strength ratio (Y/T) of high strength steels is higher than that of ordinary strength steels, while both the ultimate strain which corresponds to the ultimate tensile strength and the elongation after rupture of high strength steels are smaller [6]. The yield plateau which is commonly observed in tensile stress-strain curves

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https://doi.org/10.1016/j.conbuildmat.2017.11.128
0950-0618/

for conventional mild steels may disappear for high strength steels with nominal yield strength higher than 460 MPa [7]. These differences in fundamental material properties will certainly change their behavior, especially their cyclic and seismic performance in structural systems.

As a pioneer study, Huang et al. [8] investigated in 1995 the inelastic mechanical properties of two kinds of class WT590 and class WT780 high strength steels made in Japan whose nominal yield strength is 590 MPa and 780 MPa, respectively. A series of cyclic loading experiments were carried out under four kinds of different gradient stresses generated by narrowing the center width while keeping the same end width of test coupons. This experimental investigation was more focused on validating their deformation capacity up to a total strain of 1% without crack under cyclic loading, and illustrating the detrimental effects of the gradient stress on deformation capacity, rather than proposing a general mechanical model to characterize the inelastic behavior of those high strength steels for further application. Dusicka et al. [9] tested a variety of structural steels, including conventional steels, two kinds of low yield point steels and class A709M HPS 485 W high performance steel (f_y = 485 MPa) made in the US by repeated loading with constant amplitudes of 1% and 7% strains. Ramberg-Osgood model was used to define their cyclic backbone curves and parameters were calibrated that varied among the steel types. Coffin-Manson model, then, was employed and calibrated to approximate their low-cycle fatigue behavior. However, a model to describe the complete cyclic hysteretic stress-strain relation still remains unknown. After that, several researchers such as Shi et al. [10,11], Wang et al. [12], Sun [13] and Lu et al. [14] have conducted lots of coupon tests to investigate the cyclic behavior of high strength steels made in China, including class Q460 (f_y = 460 MPa) and class Q690 (f_y = 690 MPa) steels. On the positive side, substantial test data on cyclic stress-strain relation under different loading histories have been collected that can be analyzed to discover innovative properties of high strength steels. The data can also be used for validation of proposals of various constitutive models. Nonetheless, none of those existing studies have contributed significantly to reasonable modeling of cyclic or hysteretic behavior. Either the classical isotropic/kinematic hardening model was used for simulation without any modification or improvement [10,11], or a trilinear kinematic hardening model was proposed which depends heavily on the empirical equations for stress boundary and elastic limits [12]. It is also questionable whether both aforementioned models can be generalized to cover other loading histories since they may be unable to accurately capture the Bauschinger effect under certain strain amplitudes. Therefore, the necessity of developing and calibrating a constitutive model for high strength steels is highlighted, which should be capable of describing cyclic responses under different strain ranges.

1.2. Scope

As a first step, the authors have developed an innovative constitutive model for conventional mild steels and some high strength steels with yield plateau, such as class Q460 steels in China, in a previous study [15,16]. Following that, this paper is concerned with the development of a constitutive model to describe cyclic behavior of high strength steels without yield plateau under various strain ranges. First, monotonic tension and a number of tension-compression tests on coupons made of two kinds of class Q550 (f_y = 550 MPa) and Q690 high strength steels in China are conducted under different loading histories to discover their unique phenomena and consistent rules in cyclic behavior of high strength steels. Then, based on the observations and some assumptions, a constitutive model in the framework of classical theory of plasticity is explored. This model uses a yield surface and isotropic and kinematic hardening to describe the nonlinear behavior. Isotropic softening is introduced to account for the contraction of yield surface or elastic limit after initial yielding; then, cyclic hardening of both isotropic and kinematic components takes effect, and a memory surface is used to correctly represent the hardening stabilization. It will be shown that such a model can be quite conveniently calibrated depending on the monotonic tensile stress-strain relation from a coupon test. Finally, the proposed constitutive model is implemented and validated with the above experimental results.

2. Experimental investigation

2.1. Experimental program

Since a total of 14 loading histories were designed, 16 coupons were fabricated, respectively, with class Q550 and Q690 steels produced in China, each corresponding to a loading history. The additional two coupons were prepared for case of unexpected failure or accident in test. In order to prevent those specimens from buckling under compression, the dimensions of coupons made of both high strength steels were designed to fit the test machine with reference to ASTM E466-15 [17] and ASTM E606/E606M-12 [18], as shown in Fig. 1. All the coupons were extracted from a steel plate with a thickness of 48 mm. The reduced section in the coupon has a length-to-width ratio of 1.5 (i.e. 15 mm/10 mm), which can effectively minimize compression buckling as shown in the following experimental results.

The reduced section and the transition zone were machined using numerical-controlled equipment such that no undercut would result. The surface finish was polished for consistency among all of the tests. The experiments were conducted using a universal fatigue test machine Instron Model 8801, as shown in Fig. 2. Hydraulic grips were used to mount the coupon such that both tension as well as compression loads could be applied. Each coupon was carefully installed for vertical alignment along the central axis to minimize the eccentricity which may easily result in significant buckling under compression. An extensometer with a gauge length of 12.5 mm was utilized for measuring the axial deformation within the effective length of the coupon.

All of the tests were displacement-controlled using the extensometer to eliminate the effect of possible grip slippage or deformation outside of the effective length. The loading histories adopted in this paper are shown in Fig. 3, where the ordinate is the nominal strain calculated as the measured displacement divided by the gauge length. Coupons CP550-1 and CP690-1 were loaded under monotonic tension till fracture, while the other coupons were subjected to various cyclic loading histories. Coupons from CP550-2 (CP690-2) to CP550-6 (CP690-6) were all tested under six-constant-cycle and then loaded in tension to fracture, among which the strain amplitude ranges from ±0.5% to ±4%, while CP550-7 (CP690-7) and CP550-8 (CP690-8) were tested under increasing and decreasing strain amplitudes, respectively, from ±0.5% to ±3% or the vice versa, and then loaded in tension to fracture. CP550-9 and CP690-9 were tested similarly to CP550-7 and CP690-7 but now with a positive mean strain of 2%, while CP550-10 and CP690-10 were subjected to increasing strain amplitudes only in tension and always zero strain amplitudes in compression. CP550-11 and CP690-11 were tested under six-constant-cycle after necking of the coupons and then loaded in tension to fracture. CP550-12 (CP690-12) and CP550-13 (CP690-13) were loaded with increasing positive mean strains, and with small and large strain reversals, respectively, and then loaded in tension to fracture. The last CP550-14 and CP690-14 were subjected to a random strain history and finally loaded in tension to fracture. It