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Evaluation on steel cyclic response to strength reducing heat treatment for seismic design application

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HIGHLIGHTS

- Effect of an ultra-high temperature heating slow cooling heat treating process were studied on four steel grades.
- The strength reduction extent from heat treatment ranked decreasingly as Q345, Q390, AG235 and Q235.
- The heated Q235 and AG235 presented considerate strain hardening and cyclic hardening effect.
- The strength reduction effect of heated Q345 and Q390 steel can be maintained under cyclic loading.
- Chaboche model parameters were calibrated for all tested specimens.

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ABSTRACT

Using fundamental material cycling loading tests, this paper examined the application potential of a new strength reducing heat treatment on seismic design. This heat treatment method aims to reduce mechanical strength from commonly used structural steel grades, and create locally weakened regions that can participate into energy dissipation. Focusing on stiffness, strain/cyclic hardening, and energy dissipation abilities, heat treatment influence on monotonic behavior, cyclic characteristics, and residual loading performances were all studied. Results showed that this slow-cooling heat treatment can effectively reduce yield and ultimate strength, with the strength reduction extents ranked decreasingly as Q345, Q390, AG235, and Q235. Heated Q235 and AG235 specimens showed considerate strain hardening and cyclic hardening effects. On the other hand, heated Q345 and Q390 steel specimens exhibited apparent reduction on both yield and ultimate strengths, and this reduction effect was retained during different cyclic loading protocols. Hardening characteristics, material elastic stiffness, and energy dissipation ratio were all related to loading histories. Finally, to explore the application of this heat-treatment method on seismic design, Chaboche's cyclic constitutive model parameters were calibrated for future analyses on the structural level.

1. Introduction

Structures are subjected to huge amounts of energy during earthquakes. In modern seismic designs, energy dissipation regions, members, or dampers are often incorporated into structures for energy dissipation. The main goal of this design is to protect main structural components from severe damage; therefore special designs are needed to induce inelastic deformation or energy dissipation onto desired unimportant locations or components [1]. This goal is generally attained through creating the locally weakened regions that can enter plastic state first before large deformation happens at key structural components. And this artificial weakening process is often ensured through section-reduction measures like dog bone connections or perforated designs [2–4]. With development of steel-making techniques in recent decades, low yield strength steels have been widely used in seismic design for energy dissipation because of their significant mechanical properties, including, low yield stress, high ductility, and excellent energy dissipation capacity [5]. These steels have been widely applied in earthquake resistant, passive control devices, such as, shear dampers, buckling restrained braces (BRBs), and steel plate shear walls (SPSWs) [6,7].

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In recent years, a novel heat treating process has been proposed to modify the mechanical strengths from existing steel, which can also achieve the locally weakened effect for energy dissipation [8]. The strength reducing heat treatment mainly includes two steps: Heating the steel to extremely high temperature (600 °C–1200 °C), and then cooling it within a controlled and low rate. With a series of austenite crystal transformations, overall steel strengths could be reduced, creating a regional soft area that can act as ductile fuses without section reduction and corresponding stiffness variations. The strength reduction effect of the heating method has been validated through a series of material tests on low alloy A992 steel under American standards [9], and on generally used Q235B, Q345B, Q390B, and Q235 angle steel types under Chinese standards [10,11].

Previous material studies on heat-treated steels were mainly through uniaxial material tension tests. However, for most polycrystalline metals, kinematic hardening and isotropic hardening are generally observed under cyclic loading. Many experiments have been performed on cyclic response of different structural steel types under different inelastic strain ranges [12–14]. And results displayed quite different cyclic strength developing patterns when compared with monotonic behavior. Especially for low yield point steel [5,15,16], cyclic strain hardening is dramatic and plays a critical role in mechanical response. Given that the heating technique is applied to produce energy dissipation regions or dampers, during an earthquake, treated steel parts need to absorb energy through elasto-plastic deformation, especially under cyclic loading. In order to accurately evaluate the effectiveness and application potential of the heating process for seismic energy dissipation design, thoroughly understanding the developing rule of stress-strain relations for heat treated steels under both monotonic and cyclic loads is critical.

An experimental study on Q235B, Q345B, Q390B, and Q235 angle steel types was initiated to comprehensively investigate the influencing pattern of strength reducing heat treatment on mechanical property variations, and cyclic strength developing characteristics of structural steels. Both monotonic and cyclic tests were performed and the obtained results were studied and compared with focus on the hardening responses, cumulative damage degradation properties, loading history differences, steel types, and heating process Based on strength reduction extent and hardening performance, primary evaluation on the application potential of this heat treatment into seismic design can be worked out. Evaluation result can be used as reference for future applications.

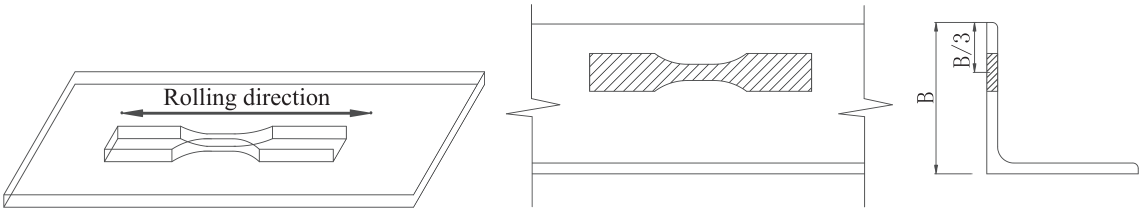
2. Experimental program

2.1. Specimen details

The primary objective of the experimental program is to investigate the effect of this strength reducing heat treatment and loading protocols on structure steels' uniaxial and hysteresis behavior. Studied steel grades were hot rolled Q235, Q345, Q390, and angle steel Q235 under Chinese standards, with nominal yield stress of 235, 345, 390, and 235 MPa, respectively. As steel plates are widely used in engineering structures, specimens adopted plate type rather than cylindrical one. These plates were cut in rolling direction from the hot rolled plates and along the longitudinal direction of finished angles. Detailed information on tested coupons is given in Fig. 1. Considering generally used thickness selections and specimen identifiability during testing, different coupon thickness d were adopted for each steel type: $d(Q235) = 16$ mm,$d(Q345) = 12$ mm, $d(Q390) = 14$ mm, $d(AG235) = 10$ mm. Due to manufacturing, real dimensions might slightly vary from the designed value. Therefore, before tensile tests, the real dimensions were measured as the average value of three measurements within gauge length.

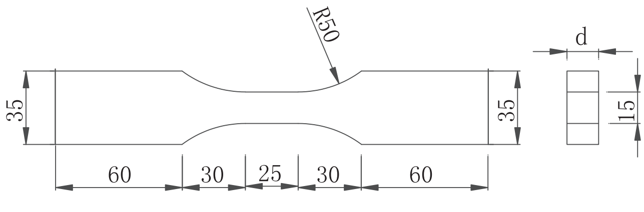
2.2. Heating strategies

The strength reducing heating process involves locally heating the existing steel to a high temperature (≥800 °C) followed by slowly cooling (cooling speed was less than 1.5 °C/min) to enable formulations of coarse grain and low strength pearlite-ferrite microstructure [8]. The heating process is given in Fig. 2(a). A serial of material tension tests have been performed on the influence of different heating parameters with the detailed data and comparisons given in Ref. [11]. Then, based on the results of previous study, the heating process with ultimate temperature 1000 °C, 20 min holding time, and 0.5 °C/min cooling speed to 500 °C, can lead to a satisfying strength reduction effect (the reduction extents for yield strength and ultimate strength were 27.7% versus 12.3% for Q235 steel, 37.5% versus 17.8% for AG235 steel, 40.2% versus 30.2% for Q345 steel, and 35.6% versus 20.8% for Q390 steel). Furthermore, strength reduction is mainly related to the ultimate



(a) coupon cutting from the plate

(b) coupon cutting from the finished angle steel



(c) Dimensions (in mm)

Fig. 1. Location and details of the cyclic test specimens.