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# Mechanical properties of heat-treated high tensile structural steel at elevated temperatures

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ABSTRACT

This paper investigates experimentally the mechanical properties of heat-treated high tensile strength low alloy structural steel RQT 701 with proof strength of 740 MPa at elevated temperatures. Standard axial tensile tests at elevated temperatures were carried out by using both steady-state and transient-state methods. The test results were compared with those from mild steels of grades up to S460. The comparisons indicate that the RQT 701 steel has smaller relative thermal elongation, and higher reductions of effective yield strength and elastic modulus at elevated temperatures. The test results on proportional limit, effective yield strength and elastic modulus were fitted into Eurocode stress–strain models for numerical analysis and fire resistant design.

## 1. Introduction

Nowadays, the production of high tensile steel with yield strength up to 800 MPa becomes possible with the development of metallurgical technology and availability of variety of alloy elements. High tensile steel is mostly used in cars, cranes, bridges, trucks, roller coaster structure, marine and offshore constructions which are designed to resist abrasion and maintain a high strength to weight ratio. High tensile steel is less commonly used in building constructions because of issues concerning post-yield ductility and their unknown behavior at elevated temperatures. The main advantages of using high tensile steel are lower self-weight and thinner plate components and therefore less weld consumables are required to fabricate thinner high strength plated sections.

Design guidelines for structural members made of hot-finished mild steels with grades up to S460 at ambient temperature can be found in modern structural steel codes such as EN 1993-1-1 [1]. Accordingly, their mechanical properties at elevated temperatures are given in EN 1993-1-2 [2]. Although EN 1993-1-12 [3] gives supplementary rules for the applications of steels with strength up to 700MPa, their mechanical properties at elevated temperatures are not available. Given their mechanical properties at artic temperature (down to −80 °C) have been studied by Yan et al. [4], further investigations on their properties at elevated temperatures are essential to extend their applications to building and offshore industries.

Kirby and Preston [5], Lie and Chabot [6], Outinen et al. [7], Poh [8], Schneider [9] and Qiang et al. [10,11] investigated the mechanical properties of hot rolled steel plates with grades not greater than S460 at elevated temperatures. Cold-formed steels were studied by Outinen et al. [7], Chen and Young [12], and fire resistant steel by Kelly and Sha [13]. Kirby [14] and Li et al. [15] tested high strength bolts at elevated temperatures to gain further knowledge on bolted joints in fire. Hu et al. [16] and Sadeghian et al. [17] studied the microstructures of high tensile steels at elevated temperatures. Chen and Young [18], Qiang et al. [19] and Chiew et al. [20] carried out some tests on high tensile steels at elevated temperatures. Regarding the tests by Chen and Young and Qiang et al., the high tensile steels were manufactured in different heat-treatment processes, and in the study by Chiew et al. [20], the high tensile RQT-S690 steel was tested by using the steady-state method and the transient-state tests were not carried out. The present study is to supplement their researches, considering the effects of different heat-treatment process and the transient-state method.

In present study, RQT 701 steel manufactured by Corus Long Products was used. It is a quenched and tempered structural steel, and have a specified nominal yield strength of 690 N/mm$^2$. The RQT 701 steel plates comply with the EN 10025-6 Grade S690 specifications. The chemical compositions of the RQT 701 steel are shown in Table 1. It can be found that the carbon content of the RQT 701 steel is similar to those of mild steels. Both the steady-state and transient-state tests were conducted to investigate the mechanical properties of the RQT 701 steel heated up to 800 °C. The investigated mechanical properties included the relative thermal elongation, elastic modulus, effective yield strengths corresponding to various strain levels, and the stress–strain

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**Table 1**
Chemical compositions of RQT 701 steel (%).

| | C | Si | Mn | S | P | Cr | Mo | Nb |
|---|---|---|---|---|---|---|---|---|
| Typ. | 0.14 | 0.44 | 1.44 | 0.003 | 0.011 | 0.022 | 0.003 | 0.032 |
| Max. | 0.2 | 0. 5 | 1.6 | 0.01 | 0.025 | 0.25 | 0.2 | 0.06 |
| | **V** | **Ni** | **Ti** | **N** | **Cu** | **Al** | **B** | |
| Typ. | 0.059 | 0.023 | 0.029 | 0.003 | 0.018 | 0.038 | 0.002 | |
| Max. | 0.08 | 0.7 | 0.04 | - | 0.2 | 0.06 | 0.004 | |

curves. The test results were compared with those of mild steels as given in Eurocode and American code, and with high tensile steels tested by Chen and Young [18], Qiang et al. [19] and Chiew et al. [20]. The aims of the present research are to extend the application of high tensile steel for building construction and to study the structural behavior of high tensile steel members subject to fire.

## 2. Microstructure of RQT 701 at elevated temperatures

It is well known that the nonheat-treated mild steels with carbon content about 0.2% by weight is morphologically characterized by α-ferrite and θ-cementite below a critical temperature of 727 °C at which the specific heat value approaches infinity [21]. Beyond this critical temperature, α-ferrite and θ-cementite transform into γ-austenite. Heat-treated high tensile steel is generally processed by heating the mild steel to a temperature higher than 727 °C where it is characterized by the austenite. Then it is annealed or quenched under various cooling rates to achieve required strength and ductility. Cooling rate affects phase transformations [22]. In general, a microstructure with lamellar mixture of ferrite and cementite is obtained if the cooling rate is slow. Moderate cooling rate results in microstructure mainly characterized by bainite. A hard martensite microstructure with the retained austenite can be observed under rapid cooling.

The RQT 701 high tensile steel is heat-treated from mild steel plate. It is quenched by water at 880–900 °C where the microstructure is fully characterized by the austenite. During quenching, large volumes of high pressure water are sprayed across the full width of the plate and to both top and bottom surfaces to ensure that the plate is uniformly cooled down [23]. The cooling rate is high. Therefore the microstructure of RQT 701 steel is mainly characterized by the martensite structure rather than the α-ferrite and θ-cementite after it is quenched. The martensite structure is hard and brittle, leading to distortion and cracking. Hence, it is generally necessary to modify the mechanical properties by tempering [24].

The RQT 701 steel is tempered at temperature between 560 °C and 640 °C. Tempering relieves tight crystals and leads to improved ductility but reduced strength [25]. The transformation of microstructure during tempering depends on the tempering temperature. As a rule of thumb, coagulation and spheroidization of cementite and recrystallization of ferrite will be finally achieved as the tempering temperature increases [24,26]. The transformation implies that the microstructure of the RQT 701 steel, with increasing temperature, gradually approaches the mixture of cementite and ferrite which characterizes the microstructure of mild steels at room temperature. Thus, the RQT 701 steel is expected to have similar mechanical properties as mild steels at elevated temperatures and heating RQT 701 steel in excess of 560 °C (tempering temperature) in practice is generally not recommended as it may result in deteriorations in mechanical properties [23]. At high temperatures, most martensite in RQT 701 steel would have transformed into the mixture of ferrite and cementite, leading to lower strength.

## 3. Experimental investigations

### 3.1. Test coupons

Steel coupons were prepared in accordance with ASTM standards [27,28]. The dimensions of the test coupons are shown in Fig. 1. High pressure water jet cutting machine was used to cut the coupon shape to avoid unnecessary heat built-up which may affect the mechanical properties. The test coupons were generally longer than those tested at room temperature since the shoulder ends were elongated so that they could be pin-connected to the testing machine outside the heating furnace [28]. The thickness of coupons was 12 mm. Before the tests were carried out, the reduced sections of the coupons had been grinded to make the surfaces flat. Then the dimensions of the reduced section and gauge length were measured. The test coupons were attached to the testing machine and lightly tensioned to about 1 kN to ensure full contact between the pins and pin holes. The test setup is shown in Fig. 2.

### 3.2. Test equipment and instrumentation

The standard axial tensile tests were conducted on a servo-hydraulic testing machine, with a maximum stroke displacement of 75 mm and a capacity of 500 kN. The heat apparatus was a split-tube furnace with three-zone configuration and a side entry extensometer port. A type K thermocouple was mounted at center of each zone to measure the heating temperatures. For tests at ambient temperature, both the extensometer and strain gauges were used to measure the strains. The strain gauge readings were used to calibrate the extensometer. For tests at elevated temperatures, only the extensometer was used. The arms of the

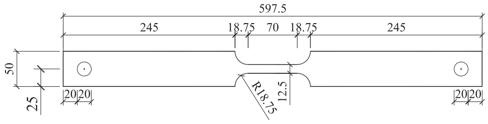

**Fig. 1.** Dimensions of test coupon (units in mm).

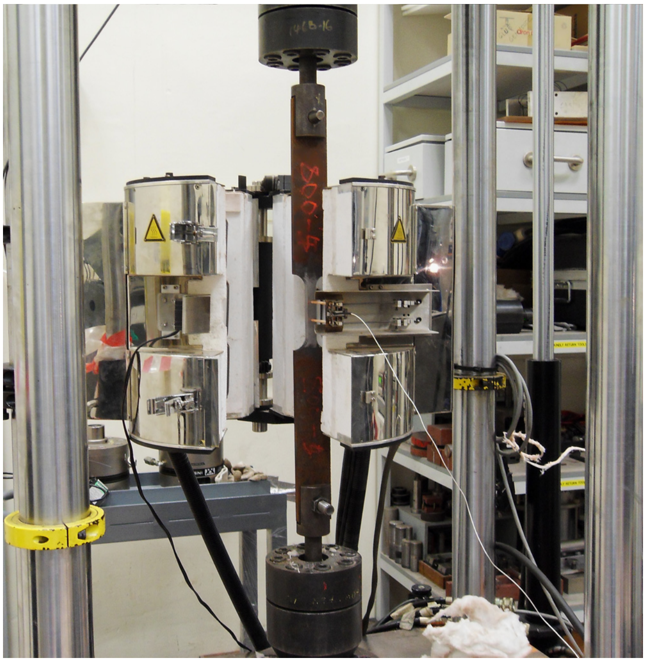

**Fig. 2.** Test setup.