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Prediction of temperature and prestraining effects on fracture toughness of high-strength structural steel by the local approach

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ABSTRACT

To investigate the tensile properties and facture toughness of high-strength structural steel of Q420 under different conditions, tensile tests and crack tip opening displacement (CTOD) tests were conducted. The test results revealed that temperature significantly influenced the fracture toughness of structural steel and that fracture toughness was significantly reduced with the decrease in temperature, resulting in brittle fractures. Prestraining increased the yield stress and tensile strength of the structural steel. However, it significantly reduced the plasticity and fracture toughness, and further increased the probability of brittle fractures. As determined by FE-analysis, temperature and prestraining facilitated brittle fractures due to the activation of the resulting near crack tip stress fields. Based on the Weibull stress fracture criterion, the temperature and prestraining effects on the fracture toughness were predicted from fracture toughness results of the virgin material at room temperature by the local approach. The prediction was in good agreement with the experimental results. It certified that the critical Weibull stress obeys the two-parameter Weibull distribution in the local approach and the fracture behavior of the prestrained material at different temperatures can be characterized by the local approach.

1. Introduction

Due to their outstanding mechanical properties, economic properties and service performance, steel structures have been widely applied in the fields of industry workshop, bridge, large industry equipment and high-rise buildings, etc. Structural steels such as Q235, Q345 and Q420 are widely used in power towers in China. However, the plasticity and fracture toughness of structural steels decrease at lower temperatures, and the fracture mode also changes from ductile fracture to brittle fracture. Even under low stress, brittle fracture might occur at lower temperatures. Brittle fractures occur suddenly, instantaneously and without any symptoms. This leaves no time to take remedial measures, greatly increasing the damage danger of steel structures. Furthermore, the power towers may suffer from large plastic deformation under strong winds or heavy loads caused by broken wires. Steel structures have produced plastic prestrain which may reach more than 2%. Prestrain due to plastic deformation directly affects the deformability and fracture resistance of steel structures, as well as causes a decrease in fracture toughness, even resulting in the brittle fracture [1,2]. Hence, clarifying the temperature and prestrain effects on the deformation and fracture toughness is necessary in evaluating the structural integrity of steel structures.

Many accidents involving steel structures at home and abroad have caused serious economic losses and casualties. The damage of steel structures is often the combined result of many factors, rather than a single factor. Previous studies [1–7] have mainly investigated the relationship between prestrain and fracture toughness (crack tip opening displacement (CTOD) and J-integral) of line pipe steels. The prestrain causes a reduction in critical CTOD and critical J-integral. In addition, the compressive prestrain has greater effects on their reduction than tensile prestrain. Furthermore, studies by Cosham [8] and Minami and Arimochi [9] predicted prestraining effect on crack initiation fracture toughness using the local approach [10–13].

Based on the Weibull stress fracture criterion, the local approach has a strong theoretical foundation and a wide range of applications to describe the brittle fracture. The Weibull stress σ_W is used as the fracture driving force in the local approach and obeys the Weibull distribution with two parameters at the brittle fracture initiation. Its advantage is that the critical Weibull stress $\sigma_{W,cr}$ at the brittle crack initiation is independent of specimen geometry, loading pattern (static and dynamic loading) and strength mismatching [14–18]. Furthermore, it also considers the effect of plastic damage on fracture behavior [17,18]. According to the local approach, the

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Table 1
Chemical composition of Q420 steel used (wt. %).

Steel	C	Mn	Si	P	S	V	Nb	Ti	Cr
Q420	0.15	1.52	0.32	0.033	0.028	0.048	0.02	0.12	0.18

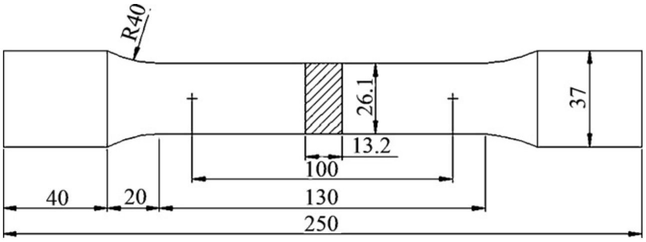

Fig. 1. Geometry of specimen for prestraining.

Weibull stress fracture criterion can also eliminate the temperature and prestrain effects on fracture behavior. Therefore, predicting and evaluating the fracture toughness of the structure with prestrain is possible, even at different temperatures.

In this paper, the temperature and prestrain effects on the mechanical properties of typical high-strength structural steel Q420 were analyzed. CTOD tests were also conducted on virgin and prestrained materials. Finally, based on the finite element (FE)-analysis on the distribution of stress/strain fields near the crack tip, the fracture behavior of the prestrained material at different temperatures was predicted from the toughness results of the virgin material at room temperature by the local approach.

2. Experiments

Typical high-strength structural steel of Q420 rolled angle with 16 mm thickness and 200 mm width was employed. Table 1 shows the chemical composition of the steel used in this study.

2.1. Prestraining

From the Q420 rolled angle, plate tensile specimens were extracted along the longitudinal direction and the geometry of the specimen is shown in Fig. 1. A clip gauge was mounted onto the center of the parallel portion of each specimen to measure the residual engineering prestrain *e*. Then, using a 300 kN universal testing machine, a uniaxial tensile load was applied to each specimen at room temperature. The crosshead speed of the testing machine was 0.1 mm/min. Each specimen was loaded until a predetermined *e* could be obtained. Then the residual prestrain ε_{pre} was calculated using Eq. (1) [1].

$$\varepsilon_{pre} = \ln(1+e) \tag{1}$$

2.2. Tensile tests

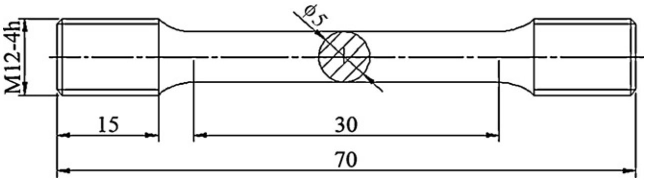

Fig. 2. Geometry of round-bar tension specimen.

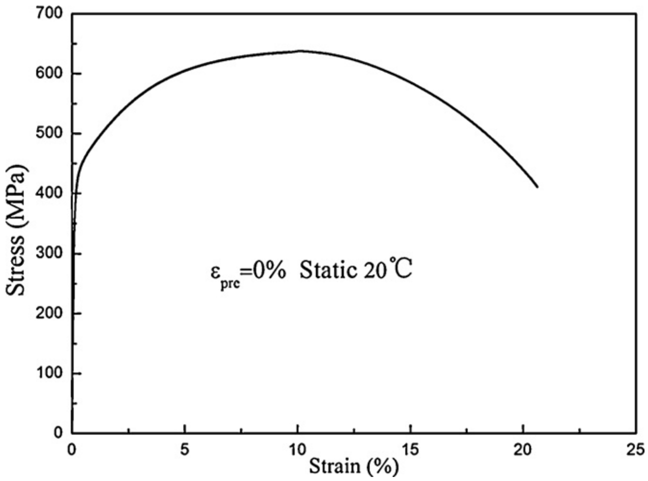

Fig. 3. Nominal stress-strain curve of Q420 steel.

Round-bar tension specimens without prestrain were directly extracted longitudinally from the virgin steel, as shown in Fig. 2. Using a 100 kN universal testing machine, tensile tests were performed on the specimens without prestrain at different temperatures. Fig. 3 shows the nominal stress-strain curve of the virgin material at room temperature. The true stress-strain curve after warm-prestraining almost follows the original stress-strain curve of the material. Hence, the yield stress σ_Y and tensile strength σ_T after prestraining can be given by the following formulae [9].

$$\sigma_Y(\varepsilon_{pre}) = \text{true stress of virgin material at true strain } \varepsilon_{pre} \tag{2}$$

$$\sigma_T(\varepsilon_{pre}) = \frac{1+\varepsilon_T}{1+\varepsilon_T-\varepsilon_{pre}}\,\sigma_T\,(\text{virgin material}) \tag{3}$$

$$\varepsilon_T(\varepsilon_{pre}) = \varepsilon_T\,(\text{virgin material}) - \varepsilon_{pre} \tag{4}$$

where ε_{pre} and ε_T are the applied plastic prestrain and the uniform elongation (nominal strain at the maximum load) of the virgin material, respectively. Meanwhile, the uniform elongation ε_T decreased with the increase in the amount of prestrain. According to practical application of structural steel Q420 in the power towers in China, a plastic prestrain of 2% was investigated. Table 2 summarizes the tensile properties of the virgin and prestrained materials along the longitudinal direction at different temperatures. It shows that the temperature and prestrain increase the yield stress and tensile strength, but deteriorate the plastic property. In addition, the prestrain has a larger effect on yield stress than tensile strength. Ouchi et al. [19] and Song et al. [20] reported that a high density of dislocations induced by prestrain was the main reason why the ductility decreased.

2.3. CTOD Tests

Three-point bending specimens with prestrain were cut from the center of the parallel portion of the prestrained plate tensile specimens (Fig. 1) and were machined to the dimension shown in Fig. 4. Test specimens without prestrain ($\varepsilon_{pr} = 0$), that is, virgin steel specimens, were directly extracted longitudinally from

Table 2
Tensile properties of Q420 steel.

Q420	Temperature (°C)	Yield stress (MPa)	Tensile strength (MPa)	Elongation (%)
$\varepsilon_{pre} = 0$	20	440	638	21.2
	0	450	661	20.7
	−20	460	677	20.0
$\varepsilon_{pre} = 2\%$	20	531	650	19.53
	0	542	671	19.02
	−20	554	690	18.3