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Behavior of cold-formed stainless steel single shear bolted connections at elevated temperatures

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ABSTRACT

The current design rules on bolted connections of cold-formed stainless steel structures are allowed for room (ambient) temperature condition only. Research on structural behavior of single shear bolted connections at elevated temperatures is limited. In this study, 100 single shear bolted connection specimens and 22 coupon specimens involving three different grades of stainless steel were conducted by using steady state test method in the temperature ranged from 200 to 950 °C. The three different grades of stainless steel are austenitic stainless steel EN 1.4301 (AISI 304) and EN 1.4571 (AISI 316Ti having small amount of titanium) as well as lean duplex stainless steel EN 1.4162 (AISI S32101). Furthermore, different bolts arrangement was also considered in the investigation. Two main failure modes were observed in the single shear bolted connection tests, namely the net section tension and bearing failures. The test results were compared with the predicted strengths calculated from the American Specification, Australian/New Zealand Standard and European Codes for cold-formed stainless steel structures. In calculating the nominal strengths of the connections, the reduced material properties of stainless steel obtained at elevated temperatures were used. It is shown that the strengths of the single shear bolted connections predicted by the specifications are generally conservative at elevated temperatures. A similar tendency of reduction was found when compared the reduction factor of material properties with that of the deterioration of the bolted connection test strengths with the corresponding type of cold-formed stainless steel at elevated temperatures. The austenitic stainless steel type EN 1.4571 (AISI 316Ti) generally performed better than the other two stainless steel types at elevated temperatures.

1. Introduction

In recent years, significant progress has been made in developing design rules for stainless steel structures at room temperature, but the performance of fire resistance has received less attention [1]. Bolted connections are one of the common connection types in cold-formed steel structures construction. The design rules of cold-formed stainless steel bolted connections are available in current specifications, i.e., the American Society of Civil Engineers Specification (ASCE) [2], Australian/New Zealand Standard (AS/NZS) [3] and European Code 3 Part 1.4 (EC3-1.4) [4]. Tests of carbon steel bolted connections have been conducted by Zadanfarrokh [5] and Rogers and Hancock [6–8], whereas tests of stainless steel bolted connections have been conducted by Bouchaïr et al. [9] and Cai and Young [10]. It should be noted that these tests were carried out at room (ambient) temperature. However, investigation on structural behavior of bolted connections of cold-formed stainless steels at elevated temperatures is limited.

Tests of stainless steel material properties at elevated temperatures have been conducted [1,11–13]. Baddoo and Burgan [14] proposed a methodology for predicting the structural performance of austenitic stainless steel EN 1.4301 beams and columns at elevated temperatures. Ng and Gardner [15] analyzed the behavior of stainless steel columns and laterally restrained beams under elevated temperatures. However, investigation of stainless steel bolted connections at elevated temperatures is limited. Yan and Young [16,17] recently studied the structural behavior of single shear bolted connections of thin sheet carbon steels at elevated temperatures by steady state and transient state test methods. Previous research has shown that the strength and stiffness retention of austenitic stainless steel at elevated temperatures is superior to those of carbon steel [18]. It should be noted that the bolted connection design rules in the current specifications [2–4] are applicable at room temperature condition only.

In this study, the material properties of three different types of stainless steels, namely the austenitic stainless steel EN 1.4301 (AISI 304) and EN 1.4571 (AISI 316Ti having small amount of

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Nomenclature

d	nominal diameter of stainless steel bolt
d_0	nominal diameter of bolt hole
E_N	the elastic modulus at room (ambient) temperature
E_T	the elastic modulus at elevated temperatures
$f_{0.01}$	longitudinal 0.01% tensile proof stress
$f_{0.2}$	longitudinal 0.2% tensile proof stress
$f_{0.2,N}$	longitudinal 0.2% tensile proof stress at room temperature
$f_{0.2,T}$	longitudinal 0.2% tensile proof stress at elevated temperatures
f_u	longitudinal tensile strength
$f_{u,N}$	longitudinal tensile strength at room temperature
$f_{u,T}$	longitudinal tensile strength at elevated temperatures
$\varepsilon_{u,N}$	ultimate strain at room temperature
$\varepsilon_{u,T}$	ultimate strain at elevated temperatures
$\varepsilon_{f,N}$	elongation (longitudinal tensile strain) at fracture at room temperature
n	exponent in the Ramberg–Osgood expression
$P_{u,N}$	ultimate load of bolted connection test at room temperature
$P_{u,T}$	ultimate load of bolted connection test at elevated temperatures
$P_{u,\mathrm{EC}}$	predicted strength of bolted connection based on Eurocodes
$P_{u,\mathrm{ASCE}}$	predicted strength of bolted connection based on ASCE Specification
$P_{u,\mathrm{AS/NZS}}$	predicted strength of bolted connection based on AS/NZS Standard

titanium) as well as lean duplex stainless steel EN 1.4162 (AISI S32101) were firstly determined by tensile coupon tests using the steady state test method for the temperature ranged from 200 to 950 °C. The coupon test results obtained from this study showed a similar trend of deterioration of the material properties at elevated temperatures when compared with those obtained by Chen and Young [13] and the EC3-1.2 [19]. Based on the coupon test results at elevated temperatures obtained from this study, six critical high temperature levels were selected for the single shear bolted connection tests. The structural behavior of the bolted connection tests was investigated by varying different grades of stainless steels, different bolt diameters, number of bolts and arrangement of the bolts in 15 series of specimens. The failure modes observed from the tests include the bearing, net section tension and bolt shear. The ultimate strength of single shear bolted connections of different stainless steel types at elevated temperatures were compared, and it was shown that the type EN 1.4571 (AISI 316Ti) stainless steel generally performed better than the other two types of stainless steels at elevated temperatures. A similar tendency of reduction was found when compared the deterioration of the connection strengths with that of the corresponding material properties at elevated temperatures.

The objectives of this study are to present a test program on cold-formed stainless steel single shear bolted connections at elevated temperatures using steady state test method, and the test results compare with the nominal strengths predicted by the ASCE Specification [2], AS/NZS Standard [3] and EC3-1.4 [4] for stainless steel structures. In addition, the load–deformation curves and the failure modes obtained from the tests are useful for numerical analysis of stainless steel bolted connections at elevated temperatures.

2. Coupon tests

2.1. Test device

The tensile coupon tests at elevated temperatures were conducted using an MTS 810 Universal testing machine. The MTS model 653.04 high temperature furnace was used to heat up the specimen to the specified temperature as shown in Fig. 1. The heating device contains three independent-controlled heating chambers with a maximum temperature up to 1400 °C. Inside each heating chamber, an internal thermal couple was used to measure the air temperature in the furnace. Due to the distance between the internal thermal couples and the coupon specimen, the temperature obtained from the internal thermal couples could be slightly different from the temperature of the coupon specimen. Hence, an external thermal couple was used to measure the actual temperature of the coupon specimen. The external thermal couple was inserted inside the furnace and contacted on the surface of the coupon specimen at mid-length. The temperature obtained from the external thermal couple was recorded as the specimen temperature in this study. The heating rate of the furnace for the coupon tests was approximately 40–60 °C/min, depending on the specified temperature level. Higher heating rate was used as the temperature increases. The MTS model 632.54F-11 high temperature axial extensometer was used to measure the strain of the middle section of the coupon specimen. The extensometer has a gauge length of 25 mm having a limitation of ±2.5 mm movement. Therefore, the extensometer was reset once it approaches the range limit during testing such that the complete stress–strain curve of the coupon specimen was obtained.

2.2. Test specimens

The coupon test specimens were designed according to the Australian Standard AS-2291 [20]. A total of 22 specimens were

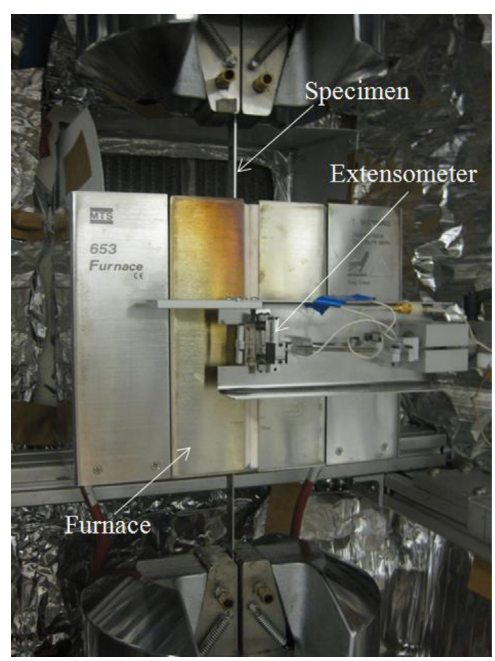

Fig. 1. Testing device of coupon test at elevated temperatures.