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An experimental investigation of mechanical properties of structural cast iron at elevated temperatures and after cooling down

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ABSTRACT

This paper presents the results of an extensive experimental investigation of the mechanical properties of structural cast iron at elevated temperatures and after cooling down to room temperature. A total of 135 tests were carried out. The specimens were subjected to tension (83 tests), compression (48 tests) or were heated for measurement of the thermal expansion (4 tests). The tests in tension include 35 steady-state tests up to 900 °C, 32 transient tests (5 °C/min and 20 °C/min heating rates, applied stress from 20% to 80% of 0.2% proof stress) and 16 tests after cooling down (heated up to 800 °C and cooled down with two different methods: quenching and air flow cooling). 32 steady-state tests (up to 900 °C) and 16 transient tests (5 °C/min and 20 °C/min heating rates, applied stress from 50% to 120% of 0.2% proof stress) were carried out for specimens in compression. The paper evaluates and proposes elevated temperatures material models.

1. Introduction

From the middle of the 18th until the beginning of the 20th century [1], cast iron elements were commonly encountered in the structural framing of buildings in Great Britain, United States and Central and Northern Europe [2–9]. However, since cast iron is no longer a mainstream construction material, there is a lack of extensive research on this type of construction. Furthermore, of the research investigations conducted on cast iron structures, most have been focused on their ambient temperature behavior [10–14]. Although there have been some efforts of evaluating the behavior of cast iron structural members in fire conditions, such studies have either been based on early fire tests or largely qualitative observations of their response in fire incidents [15–23]. There was a general lack of rigor when evaluating fire performance of cast iron structures even when dealing with rehabilitation of the fire exposed cast iron construction [22,23]. A main reason for the limited treatment of this subject is the lack of reliable data regarding the mechanical behavior of cast iron at elevated temperatures and after cooling down. The detailed survey of literature by the present authors [24] has revealed that there is a good number of historical sources of data on various aspects of mechanical properties of cast iron at elevated temperatures [25–28]. However, there is a large scatter in results from these different sources. Also, these earlier references often lack detailed information on the experimental methodology as well as composition of the cast iron investigated. To enable accurate assessment of the fire resistance of cast iron structures and their residual structural performance after cooling down, it is clearly important that reliable mechanical property data is available. The follow-on sensitivity study by the present authors [29] has shown that the fire resistance of cast-iron structural members is particularly sensitive to the following mechanical properties: strength, thermal expansion and modulus of elasticity. Providing detailed experimental information on elevated temperature and residual mechanical properties of cast iron is the focus of this paper.

This paper presents the results of an extensive experimental program involving a total of 135 cast iron specimens subjected to elevated temperature effects. Both steady-state and transient heating conditions were applied. Since cast iron has different tensile and compressive properties, the specimens were tested in tension and compression. Furthermore, a total of 16 specimens were tested to measure their residual strengths after cooling down from high temperatures. Two different cooling methods were used, one natural cooling and one quenching with cold water. Based on the test results, mathematical expressions have been proposed for the mechanical property–temperature relationships.

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2. Testing arrangement

2.1. Test specimens

The test specimens were made from two cast iron columns with a circular hollow cross-section. These columns came from the Orangery at Tatton Park in Cheshire in the UK. 65 specimens with dimensions shown in Fig. 1a were made from the first column (material 1, Table 1) and were prepared for tensile testing according to EN ISO 6892-1: 2009 [30]. The grip part of the specimens tested at room temperature was made into three specimens for thermal expansion testing. From the other column (material 2, Table 1), 17 specimens (with dimensions shown in Fig. 1b) were prepared for tensile testing according to the same standard [30] and 49 specimens (with dimensions shown in Fig. 1c and d) were prepared for compression testing according to the ASTM E9-09 [31] and ASTM E209-00 [32] standards. The chemical compositions of the materials are presented in Table 1. Fig. 2 shows the typical microstructure of the test specimens, which clearly differs from that of a homogeneous material.

2.2. Testing device

The testing devices include a type 8802 INSTRON Universal Testing Machine of 250 kN maximum capacity, a type SC1706 short electric furnace with a maximum heating capability of 1400 °C, a spring-loaded type thermo-couple (placed on the specimen to measure the specimen temperature) and an Epsilon CP8830C (25 mm/±20%) high temperature extensometer. Fig. 3 shows the experimental arrangement.

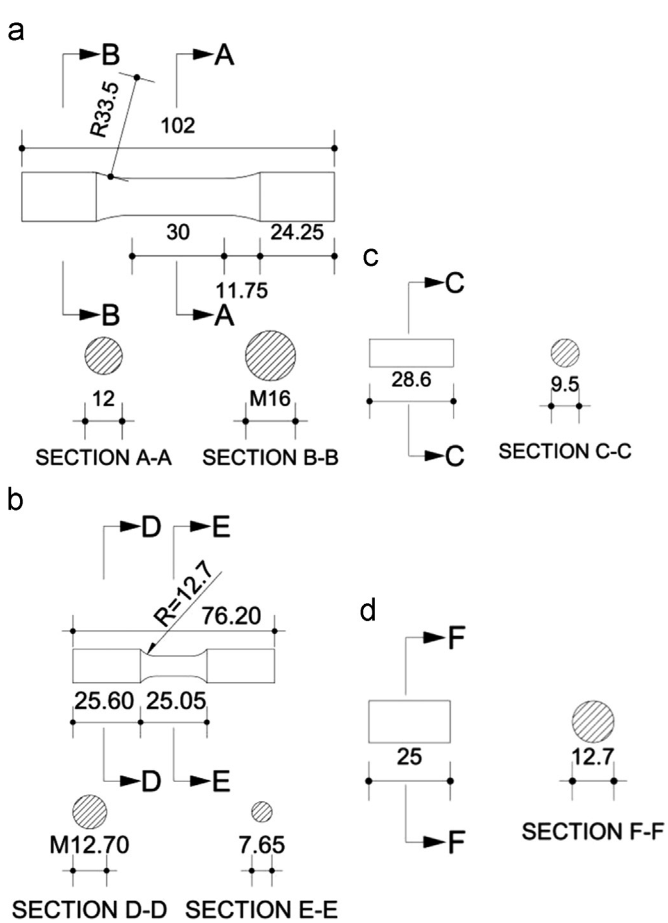

Fig. 1. Cast iron specimens for tensile and compressive tests (units in mm): (a) tensile specimen (material 1), (b) tensile specimen (material 2), (c) compressive specimen (material 2) and (d) thick compressive specimen (material 1).

2.3. Test procedure

The tests were categorized in eight groups (A–H) according to the heating method, the type of stress applied (tensile or compressive) and the testing condition (during heating or after cooling down). Table 2 provides details of the experimental program.

3. Tensile mechanical properties of cast iron at elevated temperatures

3.1. General

It is known [33] that cast iron does not exhibit a distinct yield stress point and that its stiffness in tension changes as the various flaws in its microstructure open [28,34]. For this reason, a clear definition of the mechanical properties (i.e. yield stress, fracture stress etc.) presented in this paper is given below. These are generally in accordance with Refs. [25,28,33] pertaining to the experimental investigation of the mechanical properties of cast iron.

In Fig. 4, a typical stress–strain diagram of cast iron in tension is presented. From this it can be observed that the initial tangent modulus, which is typically (in other materials) assumed to be equal to Young's modulus of elasticity, does not follow the stress–strain diagram, except for the region in which the strain has small values. For this reason, the tensile elastic modulus in this paper is assumed to be equal to the secant modulus of elasticity at 0.2% proof stress. The yield strength is defined, conventionally, as the 0.2% proof stress based on using the initial tangent modulus. The proportional limit does not have to be defined, because, practically, there is no linear region in the stress–strain diagram. The ultimate tensile strength f_u is defined as the maximum stress in the diagram and the fracture stress σ_f is the stress at the failure (breaking) point of the specimen. In general, $f_u/\sigma_f=1$, but for temperatures higher than 500 °C this ratio reduces below unity ($f_u/\sigma_f<1$).

The observed failure mode in all specimens was brittle, intergranular, without necking around the failure region (Fig. 5a). At temperatures exceeding 700 °C, the fracture surface was less flat (Fig. 5b), which is an indication of a moderately brittle fracture. Some of the specimens tested at 700 °C and 800 °C failed through multiple surfaces (Fig. 5c), which suggests that the increased elongation of the specimens in the high temperature region may have led to a different failure mechanism, most possibly as a result of opening of the flaws. Because necking of the specimens is not observed, i.e. the cross-section is not altered, the engineering stress is identical with the true stress. During these tests, the behavior of the material when near failure in tension was unstable, with the results from the duplicate specimens at the same temperature showing some inconsistence. The duplicate specimens were made from the opposite sides of the same cast iron column. A chemical analysis of these specimens showed a 0.05% difference in the carbon content, which may have contributed to the difference in results.

The specimens from Group E, which were intended for testing at 1000 °C, failed at 950–965 °C under a small prestress load of approximately 5 N (applied to stabilize the extensometer). The corresponding specimens in Group B displayed stable behavior at 1000 °C when the applied load was low. A possible explanation for this is the small diameter of the specimens in Group E.