Thin-Walled Structures 98 (2016) 94–102

Contents lists available at ScienceDirect

Thin-Walled Structures

journal homepage: www.elsevier.com/locate/tws

The continuous strength method for steel cross-section design at elevated temperatures

M. Theofanous [a], T. Propsert [b], M. Knobloch [c], L. Gardner [b,*]

[a] University of Birmingham, UK
[b] Imperial College London, UK
[c] University of Bochum, Germany

ARTICLE INFO

Article history:
Received 21 January 2015
Received in revised form
14 May 2015
Accepted 24 June 2015

Keywords:
Continuous strength method
Structural fire design
Elevated temperatures
Steel structures
Stub column
Cross-section resistance

ABSTRACT

When subjected to elevated temperatures, steel displays a reduction in both strength and stiffness, its yield plateau vanishes and its response becomes increasingly nonlinear with pronounced strain hardening. For steel sections subjected to compressive stresses, the extent to which strain hardening can be exploited (i.e. the strain at which failure occurs) depends on the susceptibility to local buckling. This is reflected in the European guidance for structural fire design EN1993-1-2 [1], which specifies different effective yield strengths for different cross-section classes. Given the continuous rounded nature of the stress–strain curve of structural steel at elevated temperatures, this approach seems overly simplistic and improved accuracy can be obtained if strain-based approaches are employed [2]. Similar observations have been previously made for structural stainless steel design at ambient temperatures and the continuous strength method (CSM) was developed as a rational means to exploit strain hardening at room temperature. This paper extends the CSM to the structural fire design of steel cross-sections. The accuracy of the method is verified by comparing the ultimate capacity predictions with test results extracted from the literature. It is shown that the CSM offers more accurate ultimate capacity predictions than current design methods throughout the full temperature range that steel structures are likely to be exposed to during a fire. Moreover due to its strain-based nature, the proposed methodology can readily account for the effect of restrained thermal expansion on the structural response at cross-sectional level.

© 2015 Elsevier Ltd. All rights reserved.

1. Introduction

The behaviour and design of steel structures subjected to fire poses a great challenge for both practising engineers and researchers due to its complexity and the severe safety and economic implications. At high temperatures, steel structures experience a substantial deterioration of their material characteristics and the development of thermal strains, which are, in most cases, non-uniform both along the member length and through the cross-section, whilst creep also becomes increasingly significant. These features, coupled with the inherent uncertainty associated with fire loading, have prompted widespread research, focusing on various aspects of structural fire design.

The resistance of steel structures under fire conditions can be considered on four levels [3]: the material behaviour at elevated temperatures (Level 1); the cross-sectional behaviour considering local stability effects (Level 2); the member behaviour considering global stability effects (Level 3); and the global structural behaviour considering effects based on large deformations, change of structural systems and alternative load paths (Level 4). Experimental research on the behaviour of steel structures under fire is mainly restricted to the study of the material (Level 1) and structural response of isolated members (Levels 2 and 3), due to the high cost and complexity associated with testing of full-scale structures under fire. Nonetheless some fire tests on frame sub-assemblies [4], plane frames [5] and complete structures [6] (Level 4) have been reported. Numerous isothermal tests on isolated long columns [7–9], stub columns [10] and beams [11,12] have been conducted to investigate the effect of high temperature on the structural response of members failing by local buckling or overall buckling without the added complexity of the effects of heating rate. Tests on isolated members [13,14] subjected to standardized fire curves [15], which allow a more realistic representation of the structural response of members in fire, have also been performed and are utilized to obtain critical temperatures as a function of parameters such as the load level and the member slenderness [16].

Key to the structural response of either an isolated member or a complete structure subjected to elevated temperatures is the

---

[*] Corresponding author.

http://dx.doi.org/10.1016/j.tws.2015.06.016
0263-8231/© 2015 Elsevier Ltd. All rights reserved.

material response. Therefore, in addition to tests on structural members, numerous experimental studies have been conducted to study the effect of temperature on the material response of structural steel of various grades [17–19], cold-formed steel [20] and stainless steel [21,22]. At elevated temperatures, the stress–strain curve of structural steel has been shown to deviate significantly from the elastic-perfectly plastic one traditionally assumed for steel design at ambient temperature [23] and becomes increasingly rounded with a pronounced loss of stiffness and strength and significant strain hardening occurring at low strains. The influence of strain rate [24] and heating rate on material response, depending on whether the experimental procedure followed is isothermal or transient, has also been studied [25]. Based on experimental results, suitable reduction factors for stiffness (i.e. Young's modulus) and strength (i.e. ultimate tensile stress, effective yield stress and various proof stresses) have been proposed for the various material grades investigated. Moreover, material models reflecting the rounded nature of the stress–strain response of steel at elevated temperatures have been developed. The model proposed by Rubert and Schaumann [26], which assumes an elliptical transition from the end of the elastic range up to the effective yield strength corresponding to 2% strain has been adopted in EN 1993-1-2 [1] and implicitly accounts for the effect of creep. Other material models, usually variants of the Ramberg–Osgood model [27,28] and originally developed for stainless steel at ambient temperature [29–32], have also been proposed [17–22].

This paper focuses on the structural response of steel members failing by local buckling at elevated temperatures. The continuous strength method (CSM), which was originally developed as a deformation-based approach to rationally incorporate strain hardening into the design of stainless steel [32–34] and structural steel [35,36] cross-sections at room temperature, is extended herein to cover the design of steel sections at elevated temperatures. Existing experimental data are first reviewed in Section 2 and subsequently used for the development and validation of the CSM in Sections 3 and 4, respectively.

2. Review of existing experimental studies

Key to the development of the CSM for steel sections at elevated temperatures is the collation of relevant test data against which the method can be validated. Given the high scatter typically encountered in the results of structural fire tests and the numerous factors affecting structural response at elevated temperatures, only isothermal test results on isolated steel stub columns and beams with unrestrained thermal expansion are utilized herein for the development and assessment of the method. Tests extracted from the literature are summarized in Section 2.1, recent experiments reported by the third author and his co-workers [37] are described in Section 2.2, where the aspects of these tests relevant to the deformation-based design approach developed herein are expanded upon.

2.1. *Test data extracted from the literature*

The primary focus of the CSM is deformation-based design and the exploitation of strain hardening. Experimental data are therefore sought on non-slender cross-sections which exhibit material nonlinearity prior to failure. Slender (i.e. Class 4) cross-sections are not currently covered by the CSM and can be designed using the traditional effective width method [1,38]. Hence experimental studies on slender steel sections at elevated temperatures have not been considered herein.

A total of 42 isothermal test results on concentrically loaded non-slender stub columns have been gathered and are summarized in Table 1. The tested sections include SHS and I-sections of various slendernesses, while the material grades covered include hot-rolled structural steel [7,9] and fire resistant steel [10]. Excluding the tests performed at room temperature and those where insufficient information was provided for the elevated temperature material properties, left 26 test results from the literature suitable for the development of the CSM. These test data were augmented with the results of a series of tests recently performed at ETH Zurich [37], for which the material properties are reported in detail in [24]; these tests are summarized in Section 2.2. All collated experimental results are utilized in Section 3 to develop and assess the CSM for steel sections at elevated temperatures.

2.2. *Additional recent test data from ETH Zurich*

The experimental data collected from the literature are supplemented with the results of additional tests recently performed at ETH Zurich [37], which are outlined herein, with the key aspects relevant to the development of the CSM expanded upon. The testing programme comprised a total of 106 structural tests at elevated temperatures (stub and slender column tests loaded concentrically and eccentrically) as well as corresponding material coupon tests at various temperatures and strain rates. SHS and RHS (square and rectangular hollow sections), as well as HEA sections, were examined. Given the high sensitivity of the material response to strain rate at elevated temperatures [24], only specimens for which the material response was obtained at a strain rate matching the strain rate of the stub column tests have been included in the subsequent analysis.

Steady state tensile material coupon tests were carried out to determine the elevated temperature material behaviour of the steel sections used for the stub column tests. An electric furnace with three vertically distributed heating zones was used for the elevated temperature tests. In addition to the overall stress–strain relationship, the mechanical parameters, including the modulus of elasticity, the proportional limit, the 0.2% proof stress and effective yield strengths at different levels of total strain, were obtained from the test results. Fig. 1 shows the stress–strain relationships at different temperatures obtained from tensile coupons taken from the stub column specimens and tested at a strain rate of 0.10%/min as an example. Details of the test setup and results are given in [24].

A series of steady state stub column tests at ambient and elevated temperatures under uniform axial compression was

Table 1
Collated isothermal stub column tests.

Source	Section type	Material grade	Temperatures considered	No. of stub column tests reported	Class at RT
Yang et al. [7]	Welded I-sections	ASTM A572 Gr. 50	RT, 300 °C, 400 °C, 450 °C, 500 °C, 550 °C, 600 °C	7	3
Yang and Hsu [9]	Welded I-sections	JIS SN490	RT, 500 °C, 550 °C, 600 °C	12	1–3
Yang et al. [10]	Welded I-sections and SHS	Fire resistant steel	RT, 400 °C, 500 °C, 600 °C	23	1–3

RT = room temperature.

Download English Version:

https://daneshyari.com/en/article/308576

Download Persian Version:

https://daneshyari.com/article/308576

Daneshyari.com