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Rotational capacity of steel I-beams under fire conditions
Part I: Experimental study

Ronny Budi Dharma, Kang-Hai Tan*

School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

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Abstract

An extensive experimental programme has been conducted to investigate the rotational capacity of steel I-beams under fire conditions. Two main objectives are to study the effects of temperature on the rotational capacity and to identify key parameters which affect the rotational capacity. Parameters including temperature, flange slenderness, web slenderness and effective length were varied in the test programme. The test set-up was designed to represent the internal joint of a continuous beam. The segments between the plastic hinge and adjacent point of inflection where hogging moment occurs were represented by each half of a simply supported beam subjected to a mid-span point load. The specimens were heated to the desired temperature before they were subjected to an increasing point load up to failure (isothermal test). The results showed considerable reduction in the rotational capacity at elevated temperatures. In addition, the effects of flange and web slenderness, together with effective length, on the rotational capacity were clearly observed. These tests probably represent the first of its kind in the world in the experimental investigation of ductility of beams under fire conditions. Moreover, these test results were very useful to investigate the feasibility of applying finite element method to study the moment–rotation relationship of steel I-beams at elevated temperature, as described in the companion paper.

Keywords: Steel beams; Rotational capacity; Fire resistance; Moment–rotation; Local buckling; Experimental study

1. Introduction

The ability to redistribute moment among members under fire conditions is one reason that beams which form part of an integral frame structure give much better performance than isolated members in real fires. In order to avoid premature failure and to allow sufficient redistribution of moment, members should be designed to have sufficient rotational capacity or ductility in fire. In addition, the ability to redistribute moment results in a more efficient usage of steel beams because it allows the transfer of hogging moment over the support, which from elastic analysis is usually higher than sagging moment, to the mid-span region. It is therefore important that the beam section over the supports possess certain level of inelastic rotation to allow some degree of moment redistribution. Thus, the available rotational capacity of a beam should be greater than the required rotational capacity to allow moment redistribution in the event of distress. One of the most important factors affecting the beam rotational capacity is local buckling. Briefly, local buckling is due to considerable distortion of a cross-section that is confined locally in the highest moment region. Another factor that can limit rotational capacity is lateral torsional buckling (LTB), which occurs after the attainment of plastic moment capacity. Interaction between local buckling and lateral torsional buckling has often been observed during fire incidents as well.

Although many research works have been conducted on quantifying the rotational capacity of steel beams at ambient temperature over the past few decades, there is no research on this subject under fire conditions. As a result, the design codes have not addressed this aspect adequately. BS5950:8 [1] does not even provide any cross-sectional classification at elevated temperature. EC3:1.2 [2] classifies the cross-section as for normal temperature design, although the effective yield strength at elevated temperature is only reached at a large, non-reversible strain of 2%. The only modification for fire conditions is the

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* Corresponding author.
E-mail address: CKHTAN@ntu.edu.sg (K.-H. Tan).

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Nomenclature

b	flange width
c	half flange width
d	depth of web
E	elastic modulus
$f_{p,T}$	limit of proportionality at elevated temperature
f_{ult}	ultimate strength
f_y	yield strength
$f_{y,T}$	yield strength at elevated temperature
I	moment of inertia
L_E	effective length
L_i	half-span length
M	moment
M_{cx}	in-plane bending moment capacity
M_E	elastic buckling moment capacity
M_m	maximum moment
M_p	plastic moment capacity
$M_{p,T}$	plastic moment capacity at elevated temperature
r_a	available rotational capacity
T	temperature
t_f	flange thickness
t_w	web thickness
λ_{LT}	lateral torsional buckling slenderness ratio
θ	rotation
θ_a	inelastic rotation
θ_e	elastic rotation
θ_p	plastic rotation
ε	strength equivalent factor

introduction of a reduction factor 0.85 to the strength equivalent factor ε such that

$$\varepsilon = 0.85\sqrt{\frac{235}{f_y}} \tag{1}$$

in which $f_y =$ yield strength.

Thus, current treatment of local buckling and section classification at elevated temperature in the BS and EC design codes is brief and sketchy. Besides, these two codes are still using the concept of cross-section behavioural classes, which is derived from plate buckling theory and neglects the interaction between the flange and the web elements. Another shortcoming of current design codes is that they are solely based on material and cross-section factors, while the very important member characteristics are ignored. A more rational way of quantifying the ductility of beams should be based on the member behavioural classes, where ductility is quantified by measuring the available inelastic rotation θ_a, as shown in Fig. 1, over which applied moment M at a section exceeds its design plastic moment resistance M_p. A term called available rotational capacity r_a is widely used to describe the non-dimensional form of inelastic rotation and defined as:

$$r_a = \theta_a/\theta_p \tag{2}$$

in which $\theta_p =$ plastic rotation.

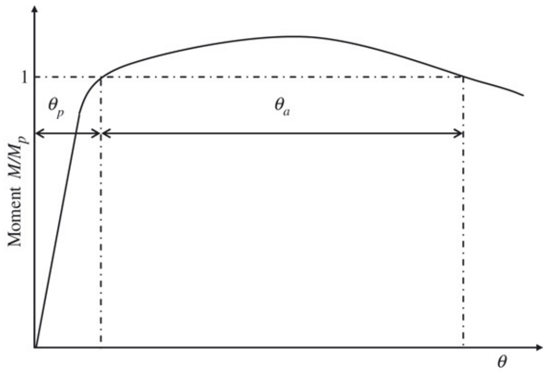

Fig. 1. Standard moment–rotation curve of plastic/compact beams.

Subsequently, this available rotational capacity needs to be compared with the required rotational capacity from plastic analysis of the structure to withstand a given design temperature.

This paper first describes the experimental programme, including the design of specimens, instrumentation, geometrical imperfection measurements, material testing and test set-up, together with the test procedure. Subsequently, the results of a fairly extensive experimental programme of steel I-beams subjected to hogging bending moment are presented. The thermal restraint is not considered in this study; hence, the experiments may represent fire situations which occur at the outer span of a continuous steel beam. The behaviour of the joints, however, is not part of this study since it focuses on the inelastic behaviour of the member. Therefore, this study is applicable to a relatively rigid type of connection system such as “fully welded”, “top and bottom seat angle” and “extended end plate”. For these types of connection, the joint stiffness is greater than the member stiffness, hence the rotation near the support is largely provided by the member and the ductility is also governed by the member. EC3:1.1 [3] considers these types of connections as “continuous joint” in which the joint behaviour may be assumed to have no effect on structural analysis. In addition, this study may also be applicable to continuous beams with semi-rigid joints, such as “flush end plate” and “flange and web angles”, under fire conditions. The reason is that, in the event of fire, the temperatures of the joints are often lower than that of the member due to the shielding effect; hence the relative stiffness of the connections compared to the member itself is increased. Consequently, the rotation near the support is largely provided by the member. This is analogous to a beam with rigid joints and the member, instead of the connection, often fails by local flange and web buckling. Thus, in the event of fire, the semi-rigid joints in effect behave like rigid joints since the steel section is relatively weaker due to relatively higher temperatures compared to the partially shielded joint regions.

A total of nine beams were tested with four varied parameters, namely, temperature, flange slenderness, web slenderness and effective length. The objectives were to study the temperature effects and to identify key parameters which affect the rotational capacity. The results reported herein provide test data and hopefully, to shed light in this important