Fire Safety Journal 92 (2017) 23–41

Contents lists available at ScienceDirect

Fire Safety Journal

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

Experimental bending tests of partially encased beams at elevated temperatures

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ARTICLE INFO

Keywords:
Partially encased beams
Composite steel and concrete
Bending resistance
Elevated temperature
Experimental tests
Lateral torsional buckling

ABSTRACT

This paper presents the result of an experimental research about the lateral torsional buckling instability during bending tests of Partially Encased Beams (PEB) at elevated temperature. A set of twenty seven four-point bending tests, grouped in ten series, were carried out to analyse the influence of relative slenderness, beam temperature and the shear bond conditions between concrete and steel in bending. In addition, this study compares the behaviour of PEB and bare steel beam under bending at room temperature.

PEB specimens are based on IPE100 steel profiles, with two different lengths 2.4 m (medium series) and 3.9 m (large series), tested in bending using simple supporting conditions and exposed to different temperatures levels of 200 °C, 400 °C, and 600 °C.

Two different shear bond conditions, between steel profile and lateral concrete, were analysed at 400 °C: one series with connectors formed by welded stirrups to the web and another series with natural adherence between steel and concrete, not welded stirrups.

PEB attained lateral torsional buckling as deformed failure mode at the ultimate limit state, except for the case of PEB tested at 600 °C that results in a plastic hinge failure. The bending resistance was determined for the maximum load event (F_u) and for the displacement limit corresponding to L/30 ($F_{L/30}$) and compared with the results of the Eurocode 3 part 1–2 simple calculation method, considering an adaptation of its formulae to PEB. The expected reduction in bending resistance at elevated temperature is in good agreement with the experimental reduction factor, when the deformation criterion is used.

1. Introduction

Partially Encased Beams (PEB) are composite steel and concrete elements in which the web of the steel section is encased by reinforced concrete. PEB have been used in different types of building structures, such as commercial centres, hospitals and hotels. This solution increases the bending and torsional stiffness, and therefore bearing capacity, and improves the fire resistance of steel beams without increasing the overall dimension of the bare steel cross section. The concreting of the beams is done prior to the hoisting and placement, without the need of formwork. The exposed steel surfaces facilitate the joints between them. This solution also improves the seismic behaviour of the bare steel beam, by increasing the stiffness, keeping their ductile behaviour. PEB is an interesting solution for long spans 12–15 m without additional protection measures, in which reinforced concrete is not viable, and where prestressing may suffer from explosive spalling.

The bending resistance requires full shear connection between the structural steel section and the encased concrete, according to Eurocode 4 part 1-1. The design solution of stirrups welded (W) to the web of the steel profile provides shear connection between the reinforced concrete and the steel profile, and increases concrete confinement. The improvement of the fire resistance of PEB is based on the reduction of the exposed steel surface area to elevated temperatures and the introduction of a low thermal conductivity material (concrete), as verified by the authors [1]. Piloto et al. [1] tested a set of PEB under fire conditions (small series) using three-point bending test, demonstrating the dependence of fire resistance on load level, giving particular emphasis to the critical temperature of this section.

Until this research, only a small number of experiments under fire conditions were reported. In 1987, J. B. Schleich [2] was the project leader of an experimental and numerical campaign developed to test and analyse the behaviour of Partially Encased Columns (PEC) and PEB with

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http://dx.doi.org/10.1016/j.firesaf.2017.05.014
Received 16 November 2015; Received in revised form 19 March 2017; Accepted 22 May 2017

Notation and symbols

Latin lower case letters

a	Distance between load and support
b	Width of the profile cross section
b_1	Width of the encased concrete in the half profile
$\overline{b}$	Average width of the profile specimen
e_{pl}	Neutral axis depth at room temperature
$e_{pl,\theta}$	Neutral axis depth at elevated temperature
e_r	Vertical position of reinforcement
f	Modification factor
f_{ck}	Characteristic compressive cylinder strength of concrete at 28 days
f_{yk}	Characteristic value of the yield strength of steel
f_{sk}	Characteristic value of the yield strength of reinforcement
h_1	depth of the of the encased concrete
$\overline{h}$	Average depth of the profile specimen
k_c	Correction factor for moment distribution
$k_{c,\theta}$	Reduction factor of the compressive strength of concrete at elevated temperature
$k_{s,\theta}$	Reduction factor of the reinforcement at elevated temperature
$k_{E,\theta}$	Reduction factor of the elastic modulus at the steel temperature
$k_{y,\theta}$	Reduction factor for the yield strength of steel at the steel temperature
t_f	flange thickness
$\overline{t}_f$	Average flange thickness of the profile specimen
t_w	web thickness
$\overline{t}_w$	Average web thickness of the profile specimen
y_r	Horizontal position of reinforcement

Latin upper case scalars

A_r, A_s	Cross sectional area of reinforcement
A_t	Percentage total extension at fracture - total extension at the moment of fracture, during material testing
$E_{a,\theta}$, $E_{s,\theta}$	Elastic modulus of steel at elevated temperature
E_s, E_a	Elastic modulus of steel
E_c	Elastic modulus of concrete
$E_{c,\theta}$	Elastic modulus of concrete at elevated temperature
$E_{s,\theta}$	Elastic modulus of the reinforcement at elevated temperature
$F_{L/30}$	Force corresponding to a vertical displacement of L/30 at mid span
F_{Mpl}	Force corresponding to the plastic moment of the cross section
F_p	Force corresponding to proportional limit of the specimen
F_u	Maximum force applied to the specimen during test
F_y	Force corresponding to yielding of the specimen
G_s, G_a	Shear modulus of the steel
$G_{a,\theta}$	Shear modulus of steel at elevated temperature
G_c	Shear modulus of concrete
$G_{c,\theta}$	Shear modulus of concrete at elevated temperature
I_t	Torsion constant of PEB section
$I_{t,c}$	Torsion constant of concrete
$I_{t,s}$	Torsion constant of the steel profile
I_w	Warping constant of the homogenised section
$I_{w,a}$	Warping constant of the steel section
I_y, I_z	Second moment of area of the homogenised section with respect to both axes
I_{za}	I_{zs} Second moment of area of the steel profile with respect to z axis
I_{zc}	Second moment of area of concrete with respect to z axis
L, L_t	Beam length of the specimen
L_f	Beam length exposed to elevated temperature
L_l	Length between loading points
L_s	Length between supports
$M_{b,fi,t,Rd}$	Design buckling resistance moment at time t, under fire conditions
$M_{b,Rd}$	Design buckling resistance moment
$M_{b,Rk}$	Characteristic buckling resistance moment to lateral-torsional buckling
M_{cr}	Elastic critical moment for lateral-torsional buckling
$M_{cr,\theta}$	Elastic critical moment for lateral-torsional buckling at elevated temperature
$M_{b,fi,t,Rk}$	Characteristic buckling resistance moment under fire at time t
$M_{b,fi,t,Rd}$	Design buckling resistance moment under fire at time t
$M_{pl,Rk}$	Characteristic value of resistance to bending moment about y-y axis at room temperature
$M_{pl,\theta,Rk}$	Characteristic value of resistance to bending moment about y-y axis at elevated temperature
R_{eH}	Upper yield strength - Maximum value of stress prior to the first decrease in force during material test, usually consider the yield stress
R_{eL}	Lower yield strength - lowest value of stress during plastic yielding, ignoring any initial transient effects
R_m	Tensile strength - stress corresponding to the maximum force during material testing
$R_{p.0.2\%}$	Strength of steel corresponding to 0.2% strain during material test
Ts_i	Average temperature of the section Si weighted to the area
$W_{pl,y}$	Plastic section modulus of steel profile about y-y axis
$\overline{X}_{F_i}$	Average value of the force type i
Y_G	Lateral displacement of the centre of gravity of the PEB section
Z_G	Vertical displacement of the centre of gravity of the PEB section

Scalar lower case letter using Greek symbols

α	Imperfection factor under fire conditions
α_{LT}	The imperfection factor
β	Value to determine the reduction factor for lateral-torsional buckling
ε	Axial strain measurement
ε_y	Axial strain corresponding to yielding of the steel profile
$\overline{\lambda}_{LT}$	Non dimensional slenderness for lateral-torsional buckling
$\overline{\lambda}_{LT,0}$	Plateau length of the lateral-torsional buckling curves for rolled sections
$\overline{\lambda}_{LT,\theta,com}$	Non dimensional slenderness for lateral-torsional buckling at the temperature of the compressed fibre
Φ_{LT}	Value to determine the reduction factor for lateral-torsional buckling
$\Phi_{LT,\theta,com}$	Value to determine the reduction factor for lateral-torsional buckling at the temperature of the compressed fibre
χ_{LT}	Reduction factor for lateral-torsional buckling
$\chi_{LT,fi}$	Reduction factor for lateral-torsional buckling in the fire design situation
$\chi_{LT,\mathrm{mod}}$	Modified reduction factor for lateral-torsional buckling
$\chi_{LT,fi,\ \mathrm{mod}}$	Modified reduction factor for lateral-torsional buckling at elevated temperature