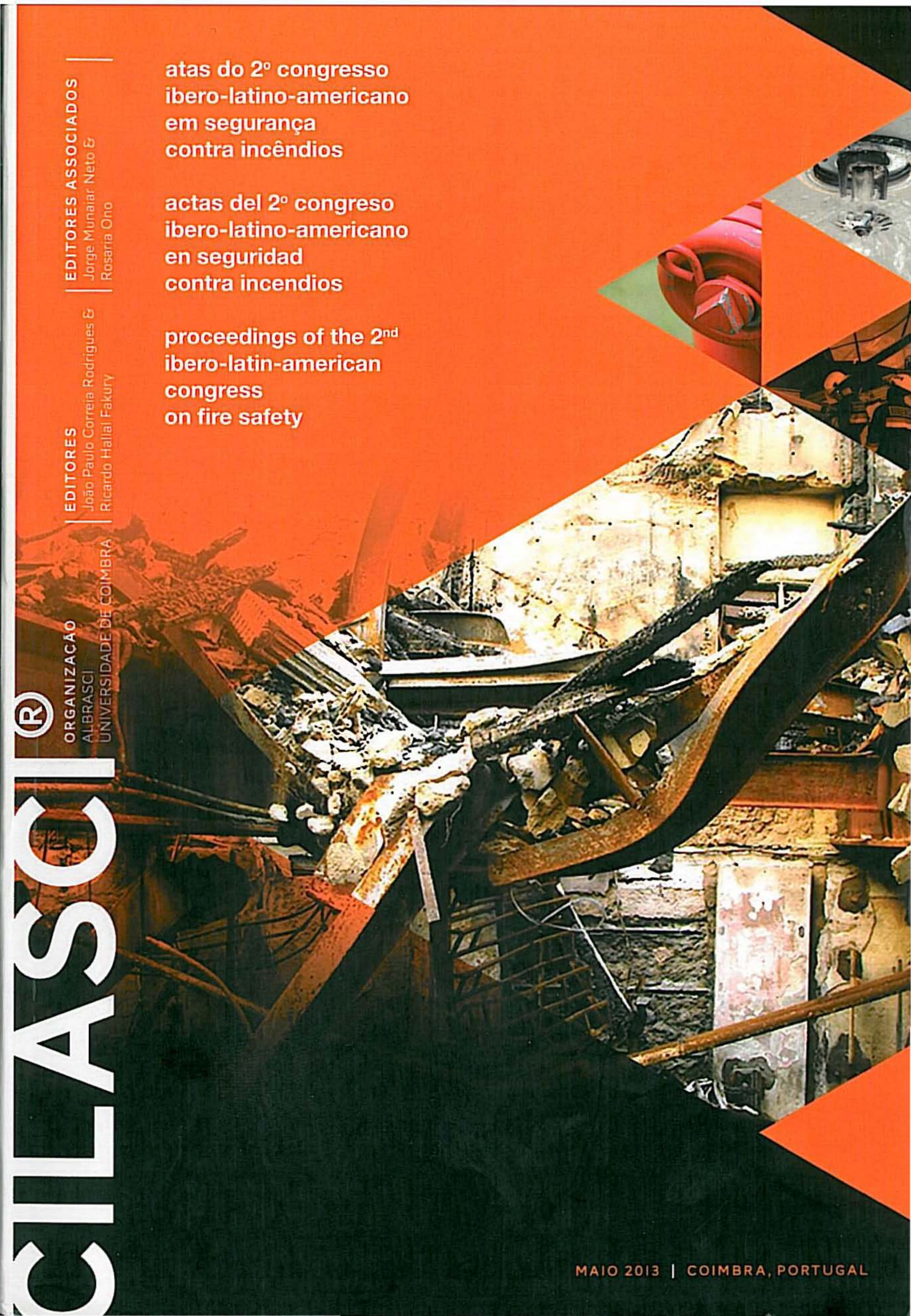

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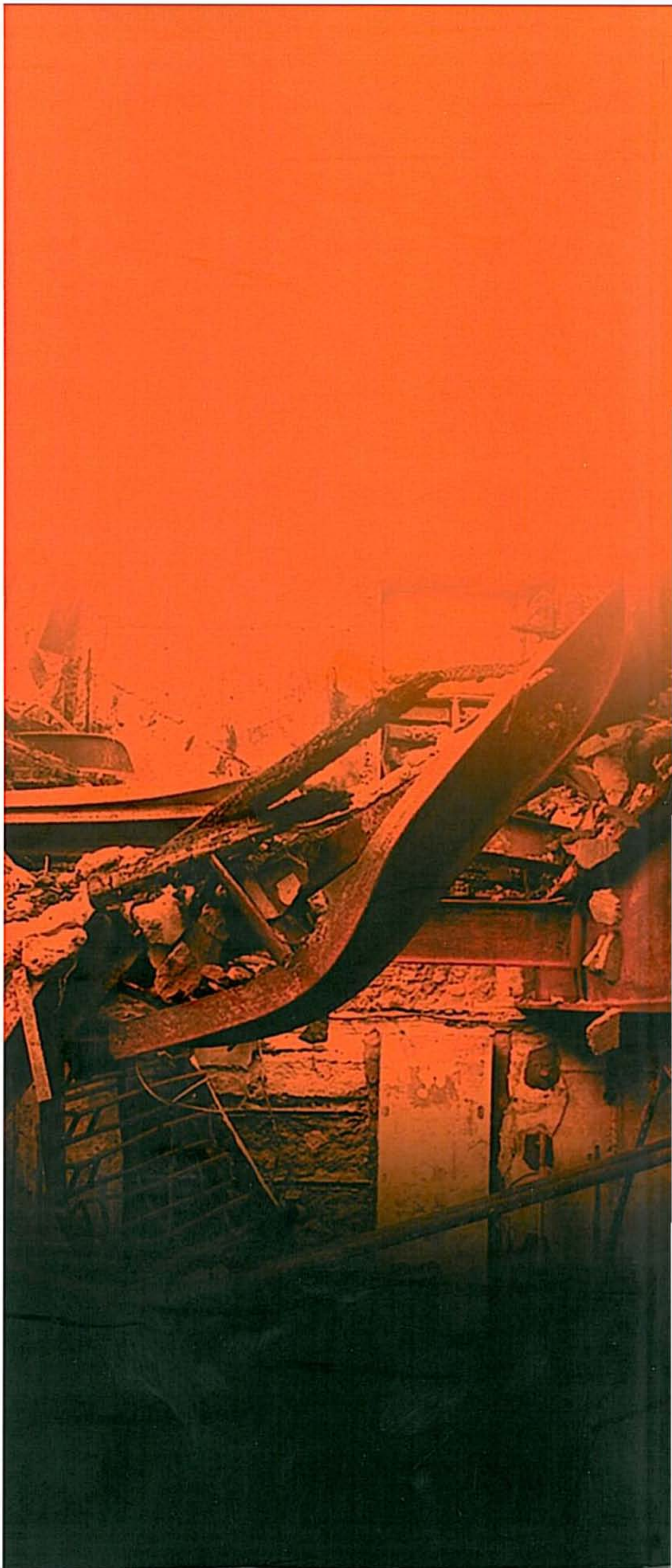

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EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF PARTIALLY ENCASED BEAMS AT ELEVATED AND ROOM TEMPERATURE

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Keywords: Partially Encased Beams; Elevated temperature, Experimental tests, Bending resistance.

1. INTRODUCTION

Partially Encased Beams (PEB) are composite steel and concrete elements that present several advantages with respect to bare steel beams. They are usually built with hot rolled sections with encased concrete between flanges. There are different design solutions, considering the arrangement of longitudinal reinforcement of concrete, stirrup configuration and material strength. The reinforced concrete between flanges is responsible for increasing fire resistance, load bearing and stiffness, without enlarging the overall size of bare steel cross section. Fire design, according to European standard EN1994-1-2 [1], is valid for composite beams, based on tabulated methods (considering simple supporting conditions and standard fire exposure) based on prescriptive geometry to a certain fire rating (time domain). The simple calculation method may also be applied to PEB, using fire resistance on load domain, assuming no mechanical resistance of the reinforced concrete slab (considering simple supporting conditions and standard heating from three sides). The effect of fire on the material characteristics is taken into account, either by reducing the dimensions of the parts or by reducing the characteristic mechanical properties of materials.

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Partially Encased Beams (PEB) and Columns (PEC) have been widely tested at room temperature, but only a small number of experiments under fire and elevated temperature conditions have been reported. Kindmean et al. [2], performed thirteen tests on PEB with and without concrete slabs, showing the importance of the reinforced concrete between flanges in determining the ultimate bending moment. Hosser et al. [3], carried out four experimental tests on simply supported composite PEB, connected to reinforced concrete slabs, under fire conditions. Temperature changes were registered at different locations, including the PEB cross section. Authors concluded that the effective width of the slab depends on the transversal longitudinal shear reinforcement. Lindner and Budassis [4], tested lateral instability at room temperature using twenty two full-scale PEB with two different steel sections under three-point bending test. A new design proposal for lateral torsional buckling was proposed, taking into consideration the torsional stiffness of concrete. Maquoi et al. [5], improved and implemented the knowledge on lateral torsional buckling of beams, including PEB, and prepared design rules that were not satisfactorily covered by the existing standards. Assi et al. [6], developed a theoretical and experimental study on the ultimate moment capacity of PEB, performing twelve bending tests on specimens with four different IPE cross sections, to investigate the contribution of different types of concrete. Makamura et al. [7], tested three partially encased girders with longitudinal rebars and transversal rebars (welded (W) and not welded (NW) to flanges). The bending strength of the partially encased girder was almost two times higher than conventional bare steel girders. Authors concluded that the specimen with rebar not welded (NW) to flanges presented a decrease of 15 % for maximum load bearing when compared to the welded rebar (W) specimen. More recently, Kodaira et al. [8], decided to determine fire resistance of eight PEB, with and without concrete slabs. Authors demonstrated that reinforcement is effective during fire. In 2008, Elghazouli and Treadway [9], performed ten full scale tests on PEB. The experimental analysis was focused on inelastic performance, considering major and minor-axis bending tests. Authors discussed several parameters related with the capacity and ductility with relevance to design and assessment procedures. Nardin and El Debs [10], studied the static behaviour of three composite PEB under flexural loading at room temperature, testing some alternative positions for shear studs, using one type of mono-symmetric steel section. Experimental results confirmed that studs are responsible for the composite action and increase bending resistance, especially when the studs are vertically welded on the bottom flange. A. Correia and João P. Rodrigues [11], studied the effect of load level and thermal elongation restraint on PEC, built with two different cross sections, under fire conditions. They concluded that the surrounding stiffness had a major influence on fire element behaviour for lower load levels. The increasing of the surrounding stiffness was responsible for reducing critical time. Critical time remained practically unchanged for higher load levels. Recently, Paulo Piloto et al [12], tested fifteen PEB under fire conditions (small series) using three-point bending test to determine fire resistance. Results revealed the dependence of fire resistance on load level. Particular emphasis was given to the critical temperature on the composite section.

The experimental tests presented in this paper aim to analyse the bending performance of partially encased beams using four point bending test set-up, heated from two sides (top and bottom flanges), after stabilizing temperature level (200, 400 and 600 ºC). The bending resistance of PEB is also compared with bare steel beams at room temperature. Two different beam lengths were considered (medium and large series), using one cross section type

(IPE100) with two different shear conditions between stirrups and the web of the profile (W- welded and NW- not welded).

2. EXPERIMENTAL PROGRAMME

Twenty seven specimens were tested, divided into ten series. Two or three tests were considered for repeatability in each series and the results agree very well. Specimens were tested using a steel portal reaction frame, with two fork supports, see figure 1. Room temperature tests were developed in one single stage, using small increments of load, while elevated temperature tests were developed in two stages. The first stage was used to heat the beam along the length "Lf", using a constant heating rate of 800 °C/h and a specific dwell time to achieve constant temperature. During the second stage, temperature was kept constant using small increments of load.

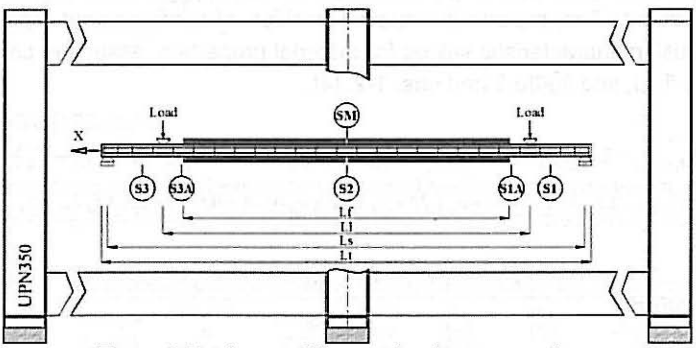


Figure 1: Testing conditions and main cross sections.

Tests developed at elevated temperature used electro-ceramic resistances to increase and sustain temperature during loading. Five different cross sections were defined to measure temperature (S1, S1A, S2, S3A and S3), and one cross section (SM) was defined to measure strain, displacements (vertical Z_G, lateral Y_G) and cross section rotation θ_G.

2.1 Specimens

PEB were prepared by filling the space between the flanges of a steel IPE100 profile, using reinforced concrete (RC). Partially encased sections achieve higher fire resistance when compared to bare steel sections. The increase in fire resistance is due to the encased material, reducing the exposed steel surface area, introducing concrete which has a low thermal conductivity. Higher fire resistance can also be achieved by increasing the amount of reinforcement to compensate for the reduction of steel strength in case of fire. Two different shear conditions for stirrups were defined (W and NW), both represented in figure 2. According to EN1994-1-1 [13], this composite steel and concrete section is classified as class 1.

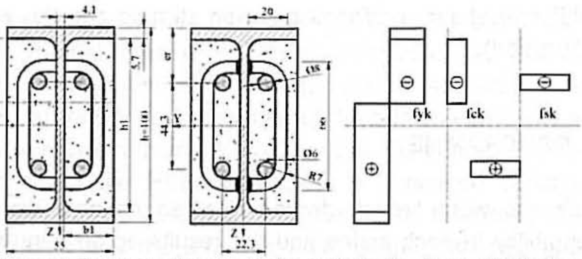


Figure 2: Cross section geometry and plastic stress distribution.

PEB were made of IPE100 with steel S275 JR, using encased concrete with siliceous aggregates. Four longitudinal steel B500 rebar were applied with diameter of 8 mm. Stirrups were designed with B500 rebar with a diameter of 6 mm, spaced every 167 mm. Stirrups were also partially welded to the longitudinal steel reinforcement, as represented in figure 2. The plastic neutral axis is referred to "epl", reinforced concrete block dimensions are represented by "b1" and "h1", while "er" represents the relative position of reinforcement. The plastic moment was calculated using characteristic values for material properties, assuming certain hypotheses based on stress field, see figure 2 and eqs. 1-2, [4].

$$M_{pl} = W_{pl,y}.f_{yk} - 2.f_{yk}.t_w.\left(0.5h_1 - e_{pl}\right)^2/2 + f_{ck}.2.b_1.e_{pl}\left(0.5h_1 - 0.5e_{pl}\right) + 2.A_r.\left(f_{sk} - f_{ck}\right)\left(h - 2.e_r\right) \quad (1)$$

$$M_{pl,\theta} = W_{pl,y}.f_{yk}.k_{y\theta} - 2.f_{yk}.k_{y\theta}.t_w.\left(0.5h_1 - e_{pl}\right)^2/2 + f_{ck}.k_{c\theta}.2.b_1.e_{pl}\left(0.5h_1 - 0.5e_{pl}\right) + 2.A_r.\left(f_{sk}.k_{s\theta} - f_{ck}.k_{c\theta}\right)\left(h - 2.e_r\right) \quad (2)$$

2.2 Instrumentation

PEB were prepared to be tested at room temperature, measuring strain in central section (SM), over steel flange and web, in hot rolled section (SM-WS and SM-FS) and over concrete (SM-RS1 and SM-RS2). Whereas perfect bond was considered between concrete and reinforcement, concrete strain was measured on steel reinforcement; for the latter measurement, rebars were machined 1 mm in depth and 15 mm in length, in respect to the dimensions of the electrical strain gauge. Five strain gauges (HBM reference 1-LY11-6/120) were used. All strain gauges were protected with gloss (Vishay reference M-coat A) and special viscous putty (HBM reference Ak22) against moisture, water and mechanical damage. PEB were also prepared to be tested at elevated temperatures, using thermocouples type K positioned in five sections along the length of the beam. Thermocouples were positioned in place, using the spot welding machine. For the concrete temperature measurements, positions Si-IC and Si-OC (nor represented), thermocouples were welded to a small steel washer, wrapped in concrete.

2.3 Materials

Each steel material was characterized according to international standards [14] for hot rolled and cold formed steel. Three samples were collected from the web of steel hot rolled profile and two more samples were collected from steel reinforcement. The average value for the elastic modulus of the steel profile was 197.9 GPa and the average values for the ReH- upper yield strength (f_{yk}) was 302 MPa. The values for the cold formed steel (reinforcement) were respectively 203 GPa and 531 MPa.

Concrete was made with Portland cement, sand and siliceous aggregates. The concrete mixture was prepared for one cubic meter of concrete with sand mass equal to 1322.7 [kg], aggregate mass equal to 451.1 [kg], water equal to 198 [l] and cement equal to 466.7 [kg]. The ratio water/cement was 45 %. Aggregates were characterized by the sieving method and tested according to European standard [15] to determine particle size dimension. Due to the small size of the steel section and considering the space available to cover the stirrups, the concrete used small-sized aggregates. The percentage of aggregates with diameters between 4-6 mm was 90%, while the percentage of sand with diameters between 0.063-0.5 mm was 80%. The aggregate dimensions limit the value of the compressive resistance of concrete ($f_{ck,cube}$ =21.45 [MPa] and f_{ck} =20.36 [MPa]), as concluded by Keru et al, [16]. The high level of permeability at elevated temperature was responsible to decrease pore pressure. This fact justifies the absence of explosive spalling.

3. BENDING TEST RESULTS

Four-point bending tests were performed to evaluate bending performance of PEB at elevated and room temperature, see table 1. Bending resistance was compared to bare steel beams.

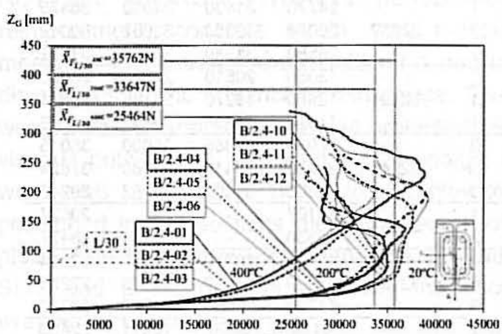
Table 1: List of tested partially encased beams (specimens) and force events.

Series	Specimen	Length Ls [m]	Stirrups [W/NW]	Temp. [ºC]	Max. Imp [mm]	F_{Mpl} [N] (1)(2)	F_p [N]	F_y [N]	$F_{L/30}$ [N]	F_u [N]
1	B/2.4-01	2,4	W	400	2	32191	11910	18890	24932	38864
	B/2.4-02				2		13627	21760	26583	31533
	B/2.4-03				2		12540	19920	24878	33568
2	B/2.4-04	2,4	W	200	1	32877	24770	31430	34060	36875
	B/2.4-05				2		26030	30350	32953	39042
	B/2.4-06				1		26580	31380	33930	34712
3	B/2.4-07	2,4	NW	400	1	32191	13050	20610	24898	29000
	B/2.4-08				1		12960	19270	25135	40861
	B/2.4-09				1		11920	20850	25722	33246
4	B/2.4-10	2,4	W	room	2	32968	27050	34966	35000	35015
	B/2.4-11				0,5		25960	35410	36360	37624
	B/2.4-12				3		26600	34600	35962	39246
5	B/2.4-11A	2,4	-	room	1	26271	16107	-	-	29627
	B/2.4-12A				2		15530	-	-	28477
6	B/3.9-01	3,9	W	400	2	32191	11190	16370	22126	30204
	B/3.9-02				5		11920	16360	22715	27290
	B/3.9-03				3		11700	14850	22573	28337
7	B/3.9-04	3,9	W	600	2	15086	4110	9620	12641	22456
	B/3.9-05				2		4360	9750	12996	21662
	B/3.9-06				5		4090	9110	12025	22770
8	B/3.9-07	3,9	NW	400	5	32191	11170	15260	22665	23591
	B/3.9-08				5		13160	16540	24237	32642
	B/3.9-09				2		10720	15400	23200	24815
9	B/3.9-11	3,9	W	room	2	32968	26500	31350	35405	38718
	B/3.9-12				5		29020	32010	36159	36264
10	B/3.9-11A	3,9	-	room	1	26271	15023	-	-	19436
	B/3.9-12A				3		15331	-	-	21272

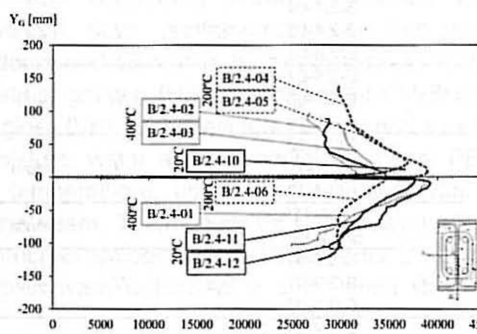
Tests developed at room temperature used quasi-static load increments. Strain, displacement and cross section rotation were determined at central section (SM). Vertical and lateral displacements (Z_G, Y_G) as well as cross section rotation (θ_G) were determined based on measurements of three wire potentiometric displacement transducers. Some important load events were recorded for each test. The proportional limit force (F_p), the force (F_y) using the intersection method between two straight lines drawn from linear and non-linear interaction of the vertical displacement; the load event for the displacement limit ($F_{L/30}$); and the maximum load level for the asymptotic behaviour of lateral displacement (F_u).

3.1 Bending of medium series at elevated temperature

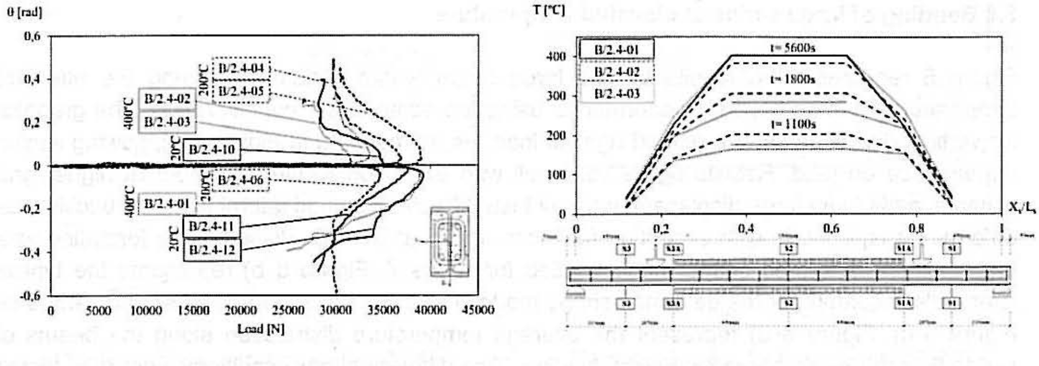
Figure 3 presents the results for the medium length series, showing the temperature effect on bending using the same shear condition (W). The measured load versus vertical displacement is represented on figure 3a), sowing similar dependence on load. Results agree very well with exception to the ultimate loads (very large displacements). All tested beams reached lateral torsional buckling (LTB) as deformed shape mode. Figure 3 b) represents the lateral displacement. This graphic helped to determine the ultimate limit load (Fu). The cross section rotation is represented on Figure 3 c). Figure 3 d) represent the average temperature distribution in each cross section along the beam, for three time events and for series 1, before loading. Similar evolutions were recorded for the other series. Temperature is not uniform along the length of the beams due to heat flow from central sections to the extremities (supports) and also due to the reduced insulation near beam ends. At the end of the tests, the insulation material was removed and infrared thermography proved an almost constant value of temperature distribution along the heating length (Lf). Two different shear conditions were also tested. Figure 3e) and 3f) compares the vertical and lateral displacement for both types of shear condition. No significant differences were detected, but the average load for $F_{L/30}$ and for the ultimate load F_u seemed to be a little smaller for NW shear condition.



a) Vertical displac., for medium series (W).

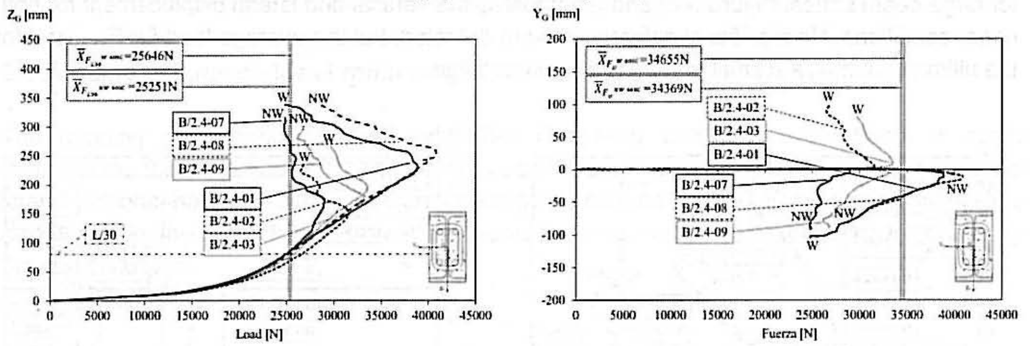


b) Lateral displac., for medium series (W).



c) Cross section rot., for medium series (W).

d) Temperature dist. and evol. for series 1.



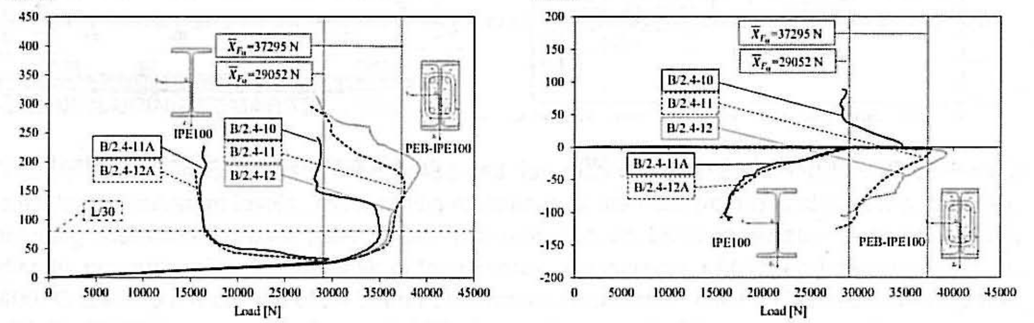
e) Vertical displac., for medium series (W/NW).

f) Lateral displac., for medium series (W/NW).

Figure 3: Bending behaviour at elevated temperature for medium series.

3.2 Bending of medium series at room temperature, using PEB and bare steel beam

The bending performance of PEB was also compared with the performance of bare steel beam at room temperature, using the same steel profile. The deflection behaviour if different, besides both attained the lateral torsional buckling as deformed shape mode, see figure 4. The bending stiffness is also higher for the case of PEB. Bare steel beams behaved on the elastic and plastic domain, as verified by the strain records.



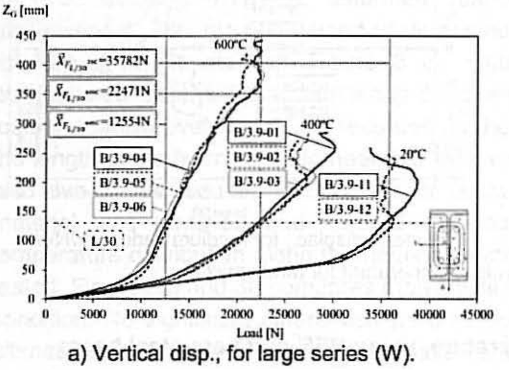
a) Vertical displac., for series 4 and 5.

b) Lateral displac., for series 4 and 5.

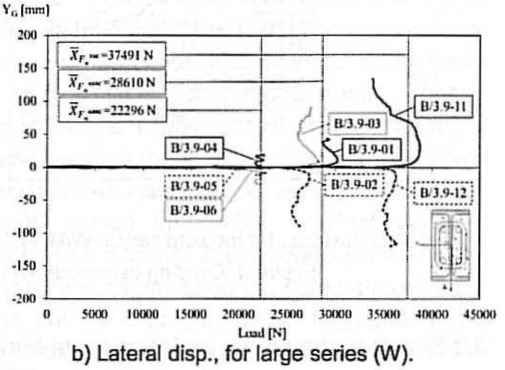
Figure 4: Bending at room temperature for medium series. Comparison between PEB and bare steel beam.

3.3 Bending of large series at elevated temperature

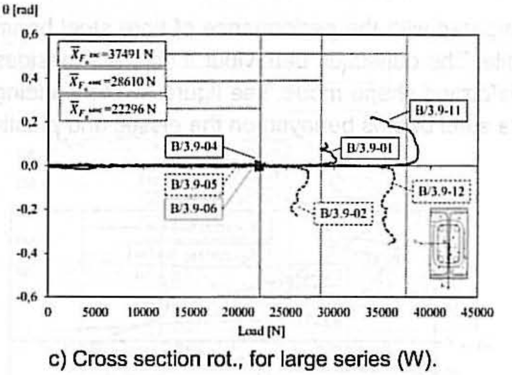
Figure 5 represents the results for the large beam length series, comparing the effect of temperature level on bending performance using the same shear condition (W). The graphics for vertical displacement are plotted against load, as represented in Figure 5 a), sowing similar dependence on load. Results agree very well with exception to the behaviour at higher and ultimate loads (very large displacements). All tested beams reached lateral torsional buckling as deformed shape mode with exception for those tested at 600 ºC. Plastic hinge formation was the dominant deformed shape mode verified for series 7. Figure 5 b) represents the typical lateral displacement for the deformed shape mode. The cross section rotation is represented on Figure 5 c). Figure 5 d) represent the average temperature distribution along the beams of series 5, for three time events, before loading. Two different shear conditions were also tested for large beam series. Figure 5 e) and f) compares the vertical and lateral displacement for both shear conditions. No significant differences were detected, but the average load for $F_{L/30}$ and for the ultimate load F_u are smaller for NW shear condition.



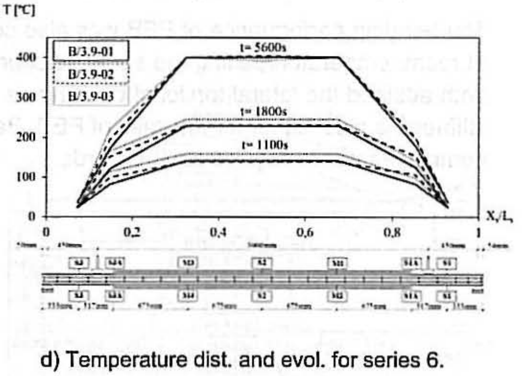
a) Vertical disp., for large series (W).



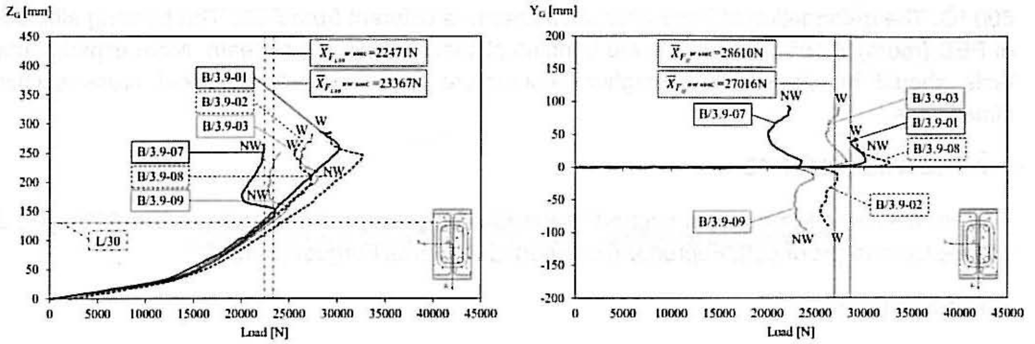
b) Lateral disp., for large series (W).



c) Cross section rot., for large series (W).



d) Temperature dist. and evol. for series 6.

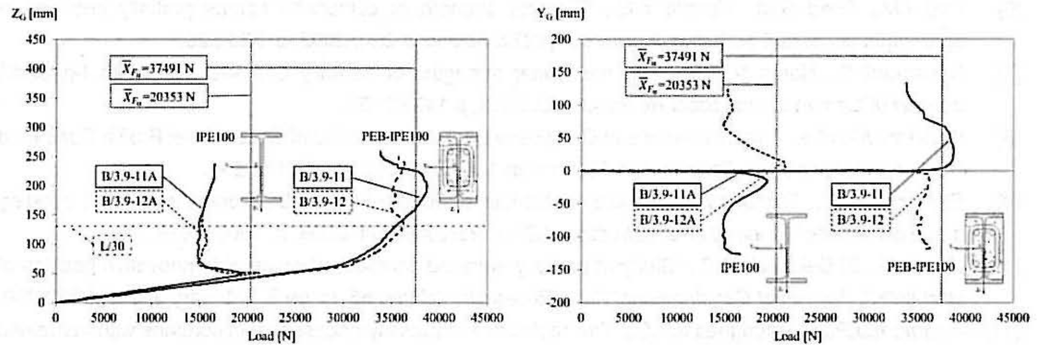


e) Vertical displac., for large series (W/NW). f) Lateral displac., for large series (W/NW).

Figure 5: Bending behaviour at elevated temperature for large series.

3.4 Bending of large series at room temperature, using PEB and bare steel beam

The bending performance of PEB was also compared with bare steel beam at room temperature, for the large series. The deflection behaviour is different, besides both attained the lateral torsional buckling (LTB) as deformed shape mode, see figure 6. The bending stiffness is also higher for the case of PEB. Bare steel beams behaved on the elastic domain, as verified by the strain records.



a) Vertical displac., for series 9 and 10. b) Lateral displac., for series 9 and 10.

Figure 6: Bending at room temperature for large series. Comparison between PEB and bare steel beam.

4. CONCLUDING REMARKS

Twenty seven bending tests were presented for medium and large series of PEB, using elevated temperature levels. The bending resistance of the PEB (room) is almost two times the bending resistance of bare steel beam. The reduction on bending resistance of PEB is not directly proportional to the increase of temperature. An increase of temperature from 200ºC to 400 ºC leads to a reduction of 24 % on FL/30 for medium series, while an increase from room to 400ºC, 600ºC leads to a reduction of 37 % and 64% on FL/30, respectively. The deformed shape mode was LTB for all tested PEB and bare steel beams, with exception to those tested at

600 °C. The deformation of large bare steel beams is different from PEB. The bending stiffness of PEB (room) is 15% higher than the bending stiffness of bare steel beam. More experimental tests should be developed at higher temperature level and with different cross section dimensions.

5. AKNOWLEDGMENTS

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