

Fire resistance of steel members protected with intumescent coatings

L. Mesquita^{a,*}, P. Piloto^a, S. Roque^a, M. Vaz^b

^a IPB- Polytechnic Institute of Bragança
Campus Sta Apolonia Apartado 1134
5300-857 Bragança, Portugal

^b FEUP- Faculty of Engineering of the University of Porto
Rua Dr. Roberto Frias, s/n
4200-465 Porto, Portugal

*Corresponding author: lmesquita@ipb.pt

Abstract. *The required intumescent coating thicknesses needed for fire resistance are proposed by the paints manufactures based on the results of a limited number of standard fire resistance tests, considering different steel section factors and DFTs. This work presents a set of 50 experimental fire resistance tests made in a pilot gas furnace and considering: (i) different member cross-sections (IPE, SHS, CHS, LNP), (ii) analysis at ambient temperature and fire conditions, (iii) application of a mechanical loading in a three-point bending setup, (iv) different utilization degree level (30%, 50%, 70%) and (v) different intumescent thicknesses. Results show that increasing intumescent fire protection thickness an increase in fire resistance time is achieved. For the same nominal protection thickness the critical temperature and fire resistance time decreases with increasing degree of utilisation. The results from the unprotected fire tests are compared with the ones obtained by the Eurocode 3 part 1.2 simplified calculation method. Taking into account the nominal properties only the CHS section experimental results shows unsafe fire resistance times in comparison to the Eurocode values.*

Keywords: Fire resistance, Fire tests, Fire Protection, Intumescent Paint.

1 INTRODUCTION

Steel structures are widely used in building construction due to its high mechanical strength, ductility and execution times. However, due to deterioration of mechanical properties with temperature, it is essential that the whole structure and its elements have the necessary fire resistance to prevent a collapse caused by fire.

One of the measures used to design a structure with the required fire resistance but without applying any fire resistance material is to use higher cross-section elements, better quality steels or fire resistance steels. The alternative is the application of passive fire protection systems such as concrete, plaster boards, mineral fibbers or intumescent paints.

When protected, the steel temperature rise is mainly due to the conduction heat transfer mode, since the steel is not directly exposed to radiation from the fire or in contact with the surrounding gases (Lewis, KR, 2000). The application of intumescent coatings as fire protection depends on its physical and thermal properties, member section factor and the required fire resistance time. An increase of the fire resistance time can be achieved applying higher intumescent dry film thickness (DFT), or for the same DFT using sections with smaller section factors.

The advantages of this protection includes the reduced overweight compared to other materials, off-site application and a good surface finishing, which can be improved with the application of decorative films. On the other hand, its implementation requires a high level of experience with high quality control and frequent coating

measures. Its application in the erection phase is only possible with good weather, causing interruptions in erection which might lead to an increase in the total cost of fire protection.

To reduce the total cost of fire protection through the application of thin film intumescent paints Longton et al [1] conducted a study focused on paint formulation and properties needed to be applied off-site and go to the site in the same day of coating. This can be achieved with reduced cure time coatings, improved durability, and resistance to damage during transport and erection. Extra care is needed when the damage put the steel visible since the tests show that, in these cases, the damage remains uncovered after intumescence and that there is no lateral expansion.

The need to develop environmentally friendly paints compelled paints manufactures to produce water-based intumescent paints with a significant reduction of volatile organic compounds (VOC). These have faster drying times and supports thicker coats, being more versatile than the solvent-based, resulting in surfaces of higher hardness, minimizing the damage caused by handling of protected elements.

The growing demand of fire protection measures and materials require the knowledge of the behaviour of this passive fire protection material. The intumescent fire reaction is responsible for an increase in the thermal resistance, increasing the fire resistance time of protected members. Thus the material thermal behaviour and efficiency influences the overall thermo-mechanical behaviour of structural elements under fire conditions.

The current methodology for fire design prescribed in the European standard [2], see Equation (1), does not take into account the material increasing thickness or the thermal and physical properties variation with temperature, not describing the real fire behaviour.

$$\Delta T_s = \frac{k_p A_p / V (T_g - T_s)}{c_s \rho_s d_p \left(1 + \frac{\phi}{3}\right)} \Delta t - \left(e^{\phi/10} - 1\right) \Delta T_g \quad ; \Delta T_s \geq 0 \text{ e } \Delta T_g \geq 0 \quad (1)$$

In previous equation $\phi = c_p \rho_p d_p / c_s \rho_s (V/A_p)$ and $\Delta t \leq 30s$ for protected steel elements. This equation is based on the differential heat conduction equation solution with non-homogeneous boundary conditions and admits several simplifying assumptions. These assumptions constrain its application to materials with temperature independent properties, as is the case of gypsum boards, mineral fibres and vermiculite. In equation (1) ΔT_s , represents the increase in steel temperature when submitted to an external temperature variation, based on standard fire curves, ΔT_g . When considering materials with thermal and physical temperature dependent properties an update is mandatory mainly on the thermal conductivity and protection thickness during the fire action, introducing $\lambda_p(t)$ and $d_p(t)$ over time or with the intumescent mean temperature.

For elements subjected to fire conditions whose resistance is directly proportional to the steel yield strength, the critical temperature can be determined by the degree of utilization, μ_0 , see equation (2). In other cases, elements subjected to instability phenomena, an iterative procedure must be used.

$$\theta_{a,cr} = 39,19 \ln \left[\frac{1}{0,9674 \mu_0^{3,833}} - 1 \right] + 482 \quad (2)$$

For a particular design the minimum coating thickness of protection is normally recommended by the paints manufacturers and presented in tables or graphs for different critical temperatures, section factors and different fire resistance periods, see Figure 1. These data are based on the fire resistance test results performed in fire resistance furnaces of certified laboratories using structural elements (beams and columns), with and without mechanical load. The results are usually kept confidential due to the coatings manufactures commercial nature, which limit a full characterization of the intumescent physical and thermal properties.

Recent studies on passive fire protection materials present analytical results of temperature evolution of protected materials based on simplified differential equations [3-7]. In these formulae the protection layer thickness variation are not considered.

Bailey [8] made a set of fire resistance tests on solid and cellular beams, with circular holes, protected with intumescent paint. The results comparison shows that the temperatures in the web of cellular beams are higher

than the measured temperature in the equivalent solid beams. The author justifies this difference due to intumescence shrinkage around the hole perimeter, but he also refers the lack of protection within the holes, consistent with a deficient coating.

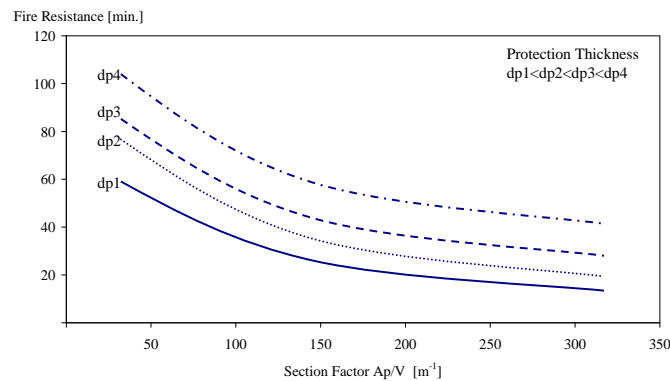


Figure 1 – Fire protection thicknesses for different fire resistance times and section factors.

Han et al [9] tested a solvent based intumescent coating applied to steel plates protected with dry film thicknesses from 0.3 to 1.2 [mm] and exposed to different radiative heat fluxes in a cone calorimeter. When a heat flux of 50 [kW/m²] is applied and for protection thicknesses higher than 0.5 [mm] the intumescence expansion ratio decreases, indicating that, for this thermal action, the protection is not fully decomposed into a carbonised material.

The aim of this work is to present a study made on steel elements protected with intumescent coatings. The protection efficiency is analysed considering elements with different cross sections (IPE, CHS, SHS and LNP), different utilization degrees (30%, 50% and 70 %) and protection thicknesses. The fire resistance tests are made in a fire resistance furnace under constant mechanical load and thermal conditions as prescribed by standard fire curve [10].

2 MATERIAL PROPERTIES CHARACTERIZATION

The steel mechanical properties was determined by tensile tests made on machined specimens obtained from the web, in the case of IPE, from the largest leg, in the case of angles and away from the weld for the tubular profiles. For each profile type at least three tensile tests were carried out according to the standard NPEN10002-1 [11]. The results aim to determine the value of the modulus of elasticity, E , the proof stress at 0.2% of deformation, $R_{p,0.2\%}$, upper and lower yield strength, R_{eH} , R_{eL} , tensile strength, R_m , and total deformation at rupture, A_t .

shows the comparison between experimental results and nominal values for each section and steel grade, where the yield strength was considered equal to the averaged upper yield strength, except for the CHS section in which was considered the 0.2% proof strength. With the exception of this section, the average yield stress of the remaining sections is higher than the nominal value.

Table 1 – Comparison between nominal and experimental geometric and material properties.

		A [mm ²] x10 ²	Iz [mm ⁴] x10 ⁴	Iy [mm ⁴] x10 ⁴	It [mm ⁴] x10 ⁴	Iw [mm ⁶] x10 ⁹	$W_{pl,y}$ [mm ³] x10 ³	f_y [MPa]
IPE	Nom	10,30	15,9	171,00	1,20	0,35	39,40	275
	Real	10,59	15,35	177,85	1,28	0,35	40,46	302,47
L	Nom	11,40	12,70	12,3	2,42	1,40	30,68	275
	Real	11,36	14,07	12,99	2,82	1,56	32,21	311,22
SHS	Nom	15,20	236,30	236,30			55,33	235
	Real	16,11	249,70	249,70			58,24	352,00
CHS	Nom	12,41	145,00	145,00			37,80	235
	Real	11,11	130,50	130,50			34,25	200,99

Cross section dimensions were measured in several sections along elements length for each cross section type. Average values were used to determine geometric properties needed for plastic resistance design and lateral torsional buckling design accordingly to the member collapse mode, and later real degree of utilisation update, see Table 1 and Table 4.

3 EXPERIMENTAL SETUP AND ELEMENT INSTRUMENTATION

The conventional method of determining fire resistance of protected and unprotected structural elements is by standard fire tests. This test consists into determine the time in which the element continues stable when supports a mechanical load, usually constant, and a thermal load defined by a prescribed standard fire curve. Fire resistance is defined by the time elapsed from the beginning of the heating until the element can not support the load and its collapse is close.

The set of experimental tests performed at the Polytechnic Institute of Bragança to evaluate the behaviour of beams in fire and assess the protection thickness and utilization degree influence is the presented in Table 2. For comparison and determination of the load capacity (collapse load) tests were also done in elements at room temperature and in fire without fire protection. The test consists into determine the load bearing element capacity, i.e., the element ability to support the test load and maintaining its stability when exposed to fire without exceeding a specified criteria, usually based on the deflection and/or deflection rate.

The fire furnace has interior dimensions of $1 \times 1 \times 1$ [m³], insulated with refractory bricks and ceramic fibber. Is a gas furnace with four gas burners in which the temperature evolution follows the specifications of the standard EN1363-1 [10] and is controlled by a plate thermocouple, see Figure 2.

The elements are subjected to a constant mechanical load and subsequent fire action accordingly to ISO834 standard fire curve, determining for each degree of utilisation and fire protection thickness the corresponding critical temperature and fire resistance time. The elements have a total length (L_t) of 1370 [mm], a length between supports (L) of 1210 [mm] and a length exposure to fire (L_f) equal to 1000 [mm].

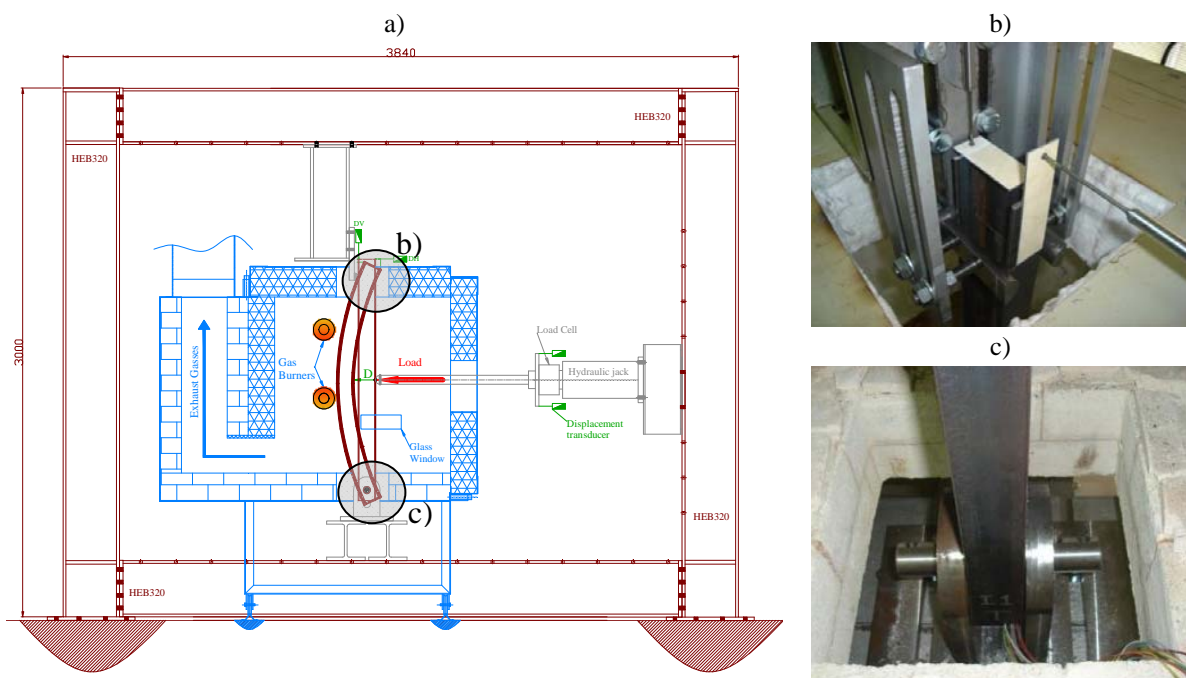


Figure 2 – a) Experimental test setup. b) Upper fork support. c) Lower end pinned support.

Table 2 – Experimental tests set and results.

Section	Test n°	Ap/V [m ⁻¹]	Fire Cond	μ_0	Q [kN]	dn [mm]				EC3 Resist.		Exp. Resist.	
						DFT	Std.dev.	Max.	Min.	T [°C]	t [s]	T [°C]	t [s]
IPE 100 S275	I1	387	RoomT.	-	31,84*	-	-	-	-	-	-	-	-
	I2	387	RoomT.	-	31,84*	-	-	-	-	-	-	-	-
	I3	387	ISO834 30%	5,34	-	-	-	-	663,78	745,56	751,20	1156	-
	I4	387	ISO834 50%	9,18	-	-	-	-	584,67	562,96	684,47	749	-
	I5	387	ISO834 70%	12,94	-	-	-	-	525,78	473,19	659,01	632	-
	I6	387	ISO834 30%	5,34	974	193	1253	445	663,78	-	722,71	2505	-
	I7	387	ISO834 30%	5,34	975	170	1287	576	663,78	-	727,57	2570	-
	I8	387	ISO834 50%	9,18	1012	185	1342	560	584,67	-	701,02	2331	-
	I9	387	ISO834 50%	9,18	1055	202	1528	490	584,67	-	701,88	2467	-
	I10	387	ISO834 70%	12,94	998	148	1268	653	525,78	-	695,31	2341	-
	I11	387	ISO834 70%	12,94	989	193	1360	501	525,78	-	690,21	2295	-
	I12	387	ISO834 50%	9,18	1824	156	2140	1440	584,67	-	676,52	2867	-
	I13	387	ISO834 50%	9,18	1832	194	2270	1440	584,67	-	747,46	3127	-
SHS 100x100x4 S235	S1	250	RoomT.	-	42,98*	-	-	-	-	-	-	-	-
	S2	250	RoomT.	-	42,98*	-	-	-	-	-	-	-	-
	S3	250	ISO834 30%	13,62	-	-	-	-	663,78	766,13	722,56	1032	-
	S4	250	ISO834 50%	22,25	-	-	-	-	584,67	583,56	641,95	693	-
	S5	250	ISO834 70%	30,09	-	-	-	-	525,78	492,36	594,02	573	-
	S6	250	ISO834 30%	13,62	1105	115	1310	854	663,78	-	687,79	2444	-
	S7	250	ISO834 30%	13,62	1094	113	1338	777	663,78	-	685,53	2411	-
	S8	250	ISO834 50%	22,25	1141	100	1309	944	584,67	-	617,08	2060	-
	S9	250	ISO834 50%	22,25	1141	104	1350	909	584,67	-	608,73	2047	-
	S10	250	ISO834 70%	30,09	1144	114	1482	886	525,78	-	555,69	1812	-
	S11	250	ISO834 70%	30,09	1131	92	1270	854	525,78	-	562,24	1836	-
	S12	250	ISO834 50%	22,25	1932	112	2210	1730	584,67	-	651,64	1967	-
	S13	250	ISO834 50%	22,25	1933	144	2310	1700	584,67	-	No Collapse	-	-
CHS 101,6x4,05 S235	C1	246,9	RoomT.	-	29,37*	-	-	-	-	-	-	-	-
	C2	246,9	RoomT.	-	29,37*	-	-	-	-	-	-	-	-
	C3	246,9	ISO834 30%	9,31	-	-	-	-	663,78	769,61	602,27	540	-
	C4	246,9	ISO834 50%	15,20	-	-	-	-	584,67	587,01	499,42	376	-
	C5	246,9	ISO834 70%	20,56	-	-	-	-	525,78	495,56	255,64	164	-
	C6	246,9	ISO834 30%	9,31	997	114	1270	800	663,78	-	560,26	1414	-
	C7	246,9	ISO834 30%	9,31	1004	111	1187	818	663,78	-	562,23	1861	-
	C8	246,9	ISO834 50%	15,20	1026	143	1330	770	584,67	-	No Collapse	-	-
	C9	246,9	ISO834 50%	15,20	1006	93	1140	810	584,67	-	472,24	1144	-
	C10	246,9	ISO834 70%	20,56	1071	143	1306	754	525,78	-	169,12	146	-
	C11	246,9	ISO834 50%	20,56	1120	178	1439	785	525,78	-	490,75	1411	-
	C12	246,9	ISO834 50%	15,20	1896	200	2190	1490	584,67	-	563,47	1378	-
	C13	246,9	ISO834 50%	15,20	1807	210	2270	1430	584,67	-	512,00	1261	-
LNP 100x50x8 S275	L1	250	RoomT.	-	21,69*	-	-	-	-	-	-	-	-
	L2	250	RoomT.	-	21,69*	-	-	-	-	-	-	-	-
	L3	250	ISO834 30%	5,84	-	-	-	-	663,78	766,13	822,55	1743	-
	L4	250	ISO834 50%	9,83	-	-	-	-	584,67	583,56	761,68	1297	-
	L5	250	ISO834 70%	13,61	-	-	-	-	525,78	492,36	745,66	1210	-
	L6	250	ISO834 30%	5,84	1041	91	1205	898	663,78	-	983,42	4692	-
	L7	250	ISO834 30%	5,84	1026	107	1309	850	663,78	-	1015,19	4655	-
	L8	250	ISO834 50%	9,83	1053	108	1318	898	584,67	-	747,38	3382	-
	L9	250	ISO834 50%	9,83	1063	96	1271	825	584,67	-	760,49	3533	-
	L10	250	ISO834 70%	13,61	1135	118	1420	882	525,78	-	756,97	3801	-
	L11	250	ISO834 70%	13,61	1114	110	1377	953	525,78	-	600,68	1937	-

The mechanical load corresponds to a predetermined degree of utilization in bending where the design fire resistance at time $t=0$, $R_{f,d,0}$, was based in the lateral torsional buckling resistance moment, for the sections IPE and LNP, and in the plastic moment resistance of the gross section in the case of SHS and CHS sections.

The load is applied via an hydraulic jack with a load cell at its end. Its value depends on the desired degree of utilisation and is applied incrementally until it reaches the requested value and kept constant during the fire action. Steel temperature are measured by thermocouples type K welded to the steel profile in three sections along its length, and in these at different cross section points, as specified in the standard prEN13381-8 [12] and represented in Figure 3. As the standard does not specify the thermocouples location for angle sections the distribution adopted was the presented in Figure 3. The thermocouple wires are protected with a small steel angle (9x9 [mm]) to avoid exposure to temperatures higher than the ones at measuring points.

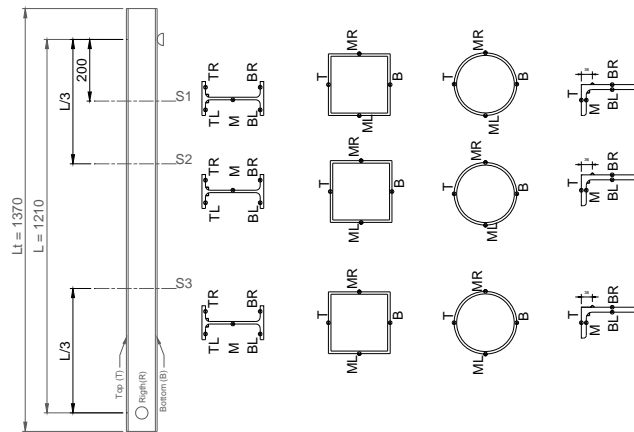


Figure 3 – Thermocouple locations for measuring steel temperatures.

Additionally the top element horizontal (HD) and vertical (DV) displacements were measured by two LVDT and the mid-span displacement (D) at the load application point using wire potentiometric transducers.

The elements were spray painted following the manufacturer's recommendations, presented in the data sheet, applying several coats and controlling its thickness using a wet film thickness gauge. After coating, the elements were conditioned under controlled temperature (23 ° C) and humidity (50%) for 8 days. Following this curing time the dry film thickness was measured in five sections in the element length and at the points indicated in Figure 4, complying with the prEN 13381-8 [12] requirements.

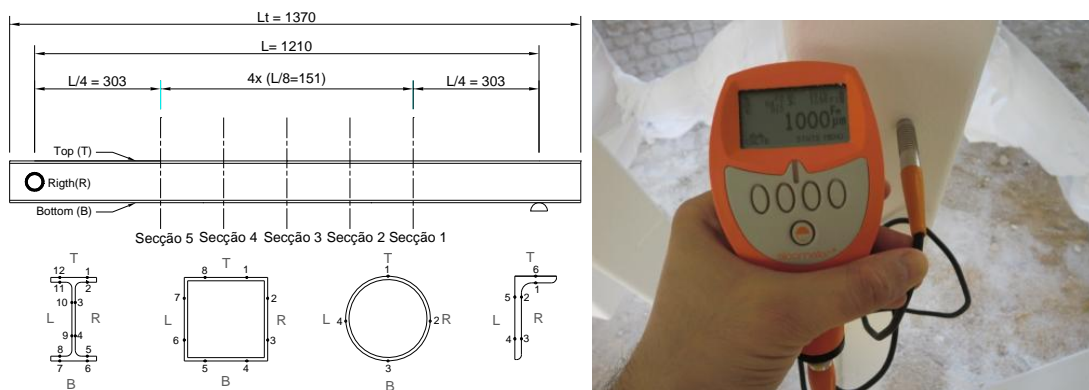


Figure 4 – Cross section thickness measuring points locations. Dry film thickness measuring device.

Table 2 shows the fire protection characterization, where the mean arithmetic dry film thickness, standard deviation, maximum and minimum measured values are presented.

4 COLLAPSE CRITERIA AND FIRE RESISTANCE

An element is regarded as having a fire resistance equal to the elapsed time between the beginning of heating and

the end of heating or until it fails to meet the load bearing capacity criterion, whichever occurs sooner. The standard EN 1363-1 [10] specifies a failure criteria for columns and beams. For the first type of elements failure occurs when both the following criteria have been exceeded: (i) vertical contraction, $C = h/100$ [mm] and (ii) rate of vertical contraction, $dC/dt = 3h/1000$ [mm/min], where h is the initial column height in [mm]. Beams are deemed to have failed when both of the following criteria are exceeded: (i) deflection of $L^2/400d$ and (ii) rate of deflection = $L^2/(9000d)$ [mm/min]. The rate of deflection limit shall not apply before a deflection of $L/30$ is exceeded.

When the British Standard is used [13-14] the criteria is slightly different. For beams failure is defined by: (i) deflection of $L/20$ or (ii) rate of deflection of $L^2/(9000d)$ [mm/min], whichever is exceeded first. L is the span of the element (in mm) and d is the distance from the top of the structural section to the bottom of the design tension zone (in mm). Also the rate of deflection limit shall not apply before a deflection of $L/30$ is exceeded.

The standard EN 1363-1 differs from the BS 476 since it requires both a deflection limit and a deflection rate limit to be exceeded for failure, while in BS 476 failure occurs when if either criterion is exceeded. This implies that applying the BS 476 criteria leads to the same or a more conservative failure time and temperature [15].

For the studied sections, with $d=100$ [mm], the deflection limit criteria occurs when $D=36.6$ [mm], giving a displacement equivalent to $L/33$. From the analyses of time vs mid-span displacement curves one can see that the rate of deflection criteria is reached before the deflection of $L/30$ is exceeded, so the fire resistance is established by the time (rounded down to the nearest minute) when the deflection is equivalent to $L/30$.

5 ROOM TEMPERATURE TESTS RESULTS

The load bearing capacity at room temperature was determined experimentally performing two tests in each cross section. The load was applied incrementally until the element leaves to support the load resulting in a large deformation. The load vs displacement curves presented in Figure 5 show a typical collapse mode due to instability phenomenon by lateral torsional buckling in IPE and angles sections and a mid span plastic hinges in SHS and CHS elements. Considering these collapse modes and for fire resistance comparison proposes, the load capacity was defined as the applied load when an equivalent displacement of $L/30$ was reached, in the cases of IPE and angles elements, and the maximum load at time when the plastic hinge is detected. The values are presented in Table 3 and compared with the results obtained from the Eurocode 3 part 1.2 [2] using the specified collapse mode formulae and the nominal and real values of the yield strength and cross section dimensions.

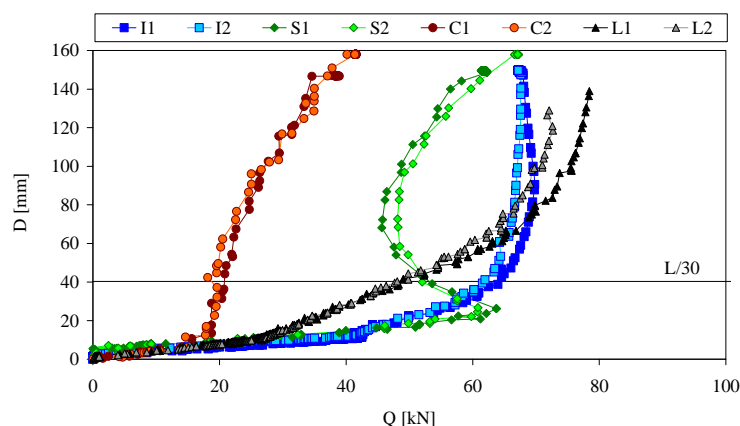


Figure 5 - Load vs displacement curves at room temperature.

6 EXPERIMENTAL TESTS IN FIRE WITHOUT FIRE PROTECTION

All sections in study were tested under fire conditions without fire protection and an applied constant mechanical load representative of the required degree of utilisation. The critical temperature determined from the Eurocode simplified calculation method, using equation (2), for degrees of utilisation equal to 30%, 50% and 70%, are 663.78 [C], 584.67 [C] and 525.78 [C], respectively. Using the simplified equation for the temperature evolution

of unprotected elements gives a fire resistance time of 12, 9 and 7 minutes for the IPE100 section, respectively, and for the remaining sections, with section factors close to 250 [m^{-1}], a fire resistance of 12, 9 and 8 minutes, see Table 2 and Table 4. These values can be compared with experimental results, in time and temperature domains, where the collapse criteria were based on the L/30 equivalent displacement, as stated before.

Table 3 – Comparison between the experimental results and the one obtained by the Eurocode 3 part 1.2.

Section	Test n°	Resistance EC3-1.1		Q_{exp}	Q_{exp}	Collapse mode
		Nom.	Real	L/30 [kN]	Max [kN]	
IPE 100	I1	31,84	34,99	64,22	69,82	LTB
	I2	31,84	34,99	61,76	67,78	LTB
SHS	S1	42,98	66,23	53,11	63,73	Plast. hinge
	S2	42,98	66,23	52,01	67,19	Plast. hinge
CHS	C1	29,37	22,76	20,78	38,91	Plast. hinge
	C2	29,37	22,76	18,70	41,61	Plast. hinge
LNP	L1	21,69	25,45	48,78	78,44	LTB
	L2	21,69	25,45	48,06	72,67	LTB

Table 4 – Critical temperature and fire resistance time comparison between Eurocode and unprotected experimental tests.

		Degree of Utilisation%			Tcr-EC3 [°C]			Time-EC3			Tcr-Exp. [°C] / Time [min]		
IPE	Nom	30	50	70	663,78	584,67	525,78	12	9	7	751,20/19	684,47/12	659,01/10
	Real	29,17	47,71	64,38	668,02	592,17	541,72	12	9	8			
SHS	Nom	30	50	70	663,78	584,67	525,78	12	9	8	722,56/17	641,95/11	594,02/9
	Real	20,10	32,82	44,40	724,15	659,07	610,82	17	12	10			
CHS	Nom	30	50	70	663,78	584,67	525,78	12	9	8	602,27/9	499,42/6	255,64/2
	Real	40,89	66,77	90,32	625,45	536,21	443,98	11	8	6			
L	Nom	30	50	70	663,78	584,67	525,78	12	9	8	822,55/29	761,68/21	745,66/20
	Real	29,17	47,71	64,38	668,02	592,17	541,72	12	9	8			

The results presented in Table 2 and Table 4 show that the critical temperature and the fire resistance time obtained from the IPE and LNP cross sections are higher than the ones determined from the Eurocode 3 part 1.2, despite the degree of utilisation. The critical temperature and fire resistance are inversely proportional to the degree of utilisation applied in the element. Regarding the SHS and CHS sections the results from Eurocode 3 Part 1.2 are higher than those obtained experimentally, with a maximum difference of one minute fire resistance for the SHS. For the CHS the difference between both methods increases with the degree of utilisation, even comparing with the real geometric and material properties.

Figure 6 presents the steel temperature evolution with time considering the arithmetic mean of all thermocouples in the three measuring sections.

7 EXPERIMENTAL TESTS IN FIRE WITH FIRE PROTECTION

The experimental setup and methodology used in this set of tests is similar to the one used in the previous section. To avoid direct contact between the load application component and the protected element, a thermal insulation, consisting of ceramic fibber, was applied. However in the contact area the coating intumescence is limited. Figure 7 shows the intumescence development, from the carbonaceous layer initial formation to the total intumescence oxidation and degradation, turning at the end of the test in a white porous foam layer.

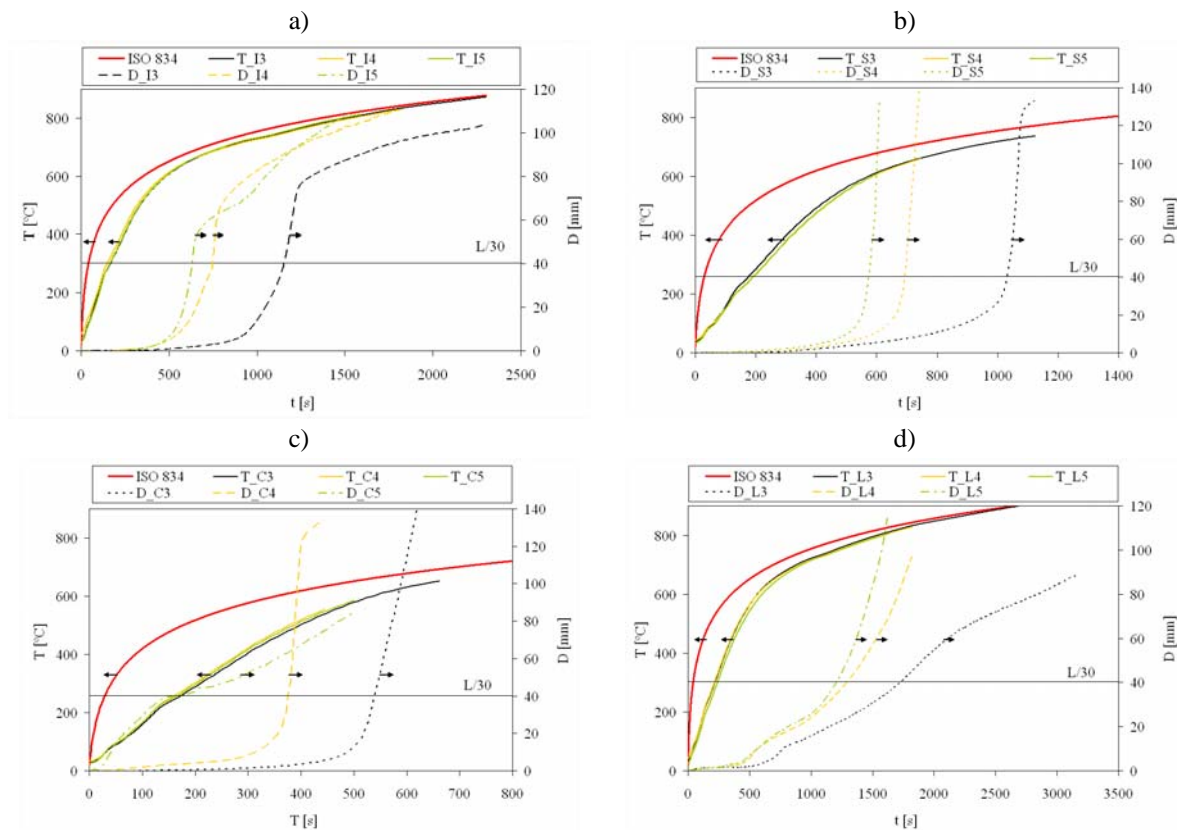


Figure 6 – Experimental steel temperature evolution and mid span displacement results of members without fire protection. a) IPE sections. b) SHS sections. c) CHS sections. d) LNP sections.

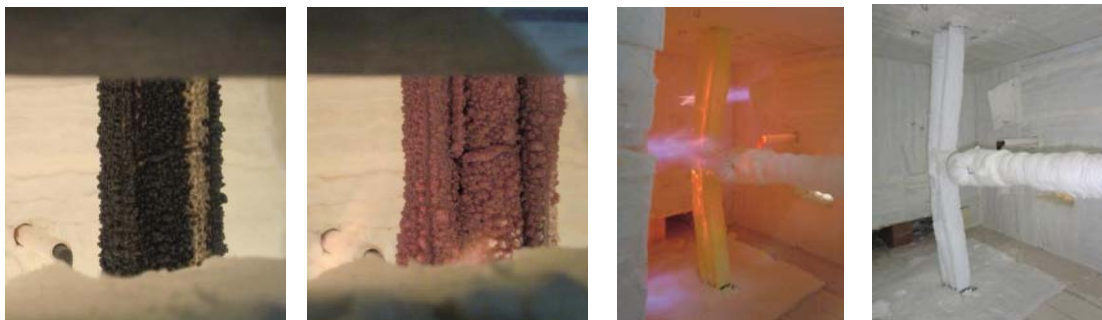


Figure 7 – Intumescence development and final state of test I7.

The fire tests results of members protected with intumescent coating are presented in Figure 10, where they can be compared with the tests results of members without fire protection. The temperatures presented are mean values of all measured temperatures in the element. The temperature behaviour of IPE sections show a clear distinction between the elements protected with nominal DFT of 1000 [μm] and 2000 [μm], and there is no clear influence of the degree of utilisation on the temperature evolution. For SHS and CHS sections the influence of the protection thickness on the coating performance is only clear for short exposure times. When these elements are protected with 2000 [μm] nominal DFT, with increasing exposure times and the consequent intumescence char expansion there is a partial detachment, and sometimes total detachment, leaving the steel with a reduced fire protection or even with no protection at all. This becomes less favourable in comparison to thicknesses of 1000 [μm], resulting in higher steel temperatures. Due to the high load bearing capacity of the LNP sections with a time of fire resistance of approximately one hour, when protected with 1000 [μm] and subjected to a degree of

utilisation of 50%, tests with higher thicknesses were not done.



Figure 8 – Local shrinkage of test C9.



Figure 9 – Local shrinkage of test L11.

Critical temperature and fire resistance time were determined by the collapse criterion, which corresponds to the steel temperature and the time when the mid span displacement is equivalent to $L/30$. The numerical values are presented in Table 2 and the displacement time evolution, for protected and unprotected elements, presented in Figure 11. The figure shows the protection efficiency by increasing fire resistance time when compared to the equivalent unprotected element and same degree of utilisation. In the case of C9 and L11 tests this increase was not as significant due to a local intumescence shrinkage that leaves the steel in direct contact to the fire hot gases, as can be seen in Figure 8 and Figure 9. As the real degree of utilisation of the sections CHS turns to be higher than the initially expected, e.g. the nominal 70% represents a real value of 90.32%, the C10 test reach the collapse criteria after only 146 [s], before the intumescent paint starts to react. Therefore the test C11 was tested with a degree of utilisation of 50%.

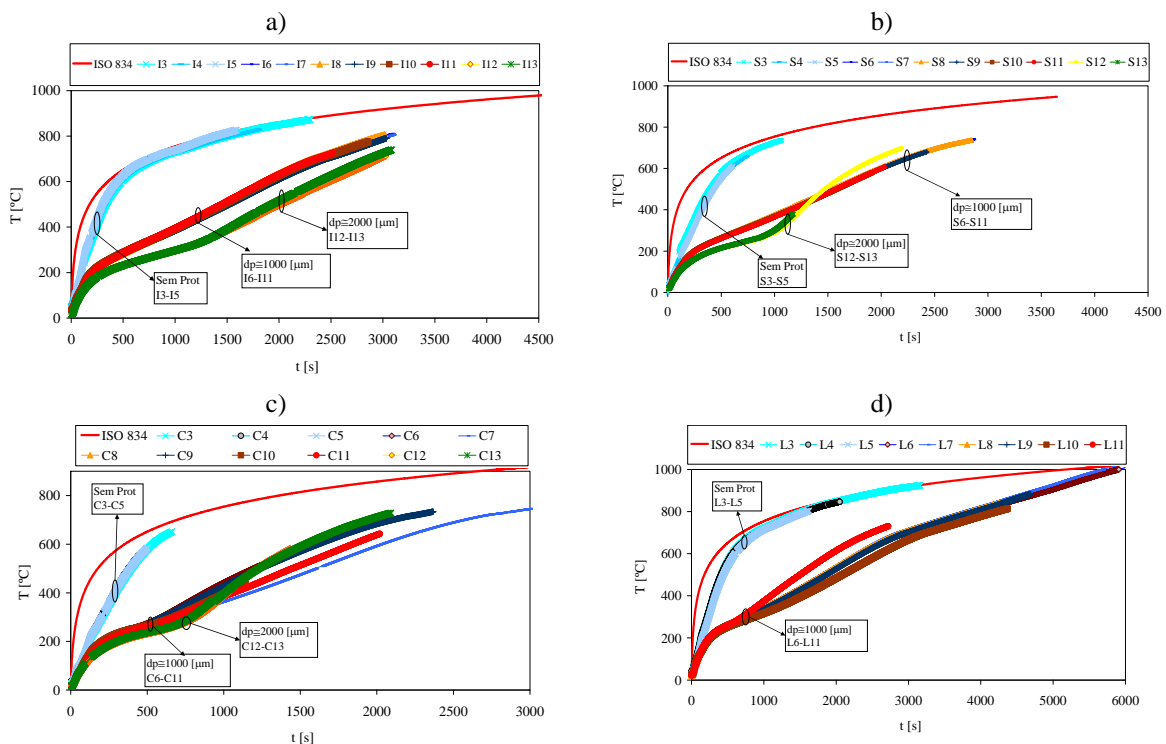


Figure 10 – Experimental steel temperature evolution of fire protected elements. a) IPE sections. b) SHS sections. c) CHS sections. d) LNP sections.

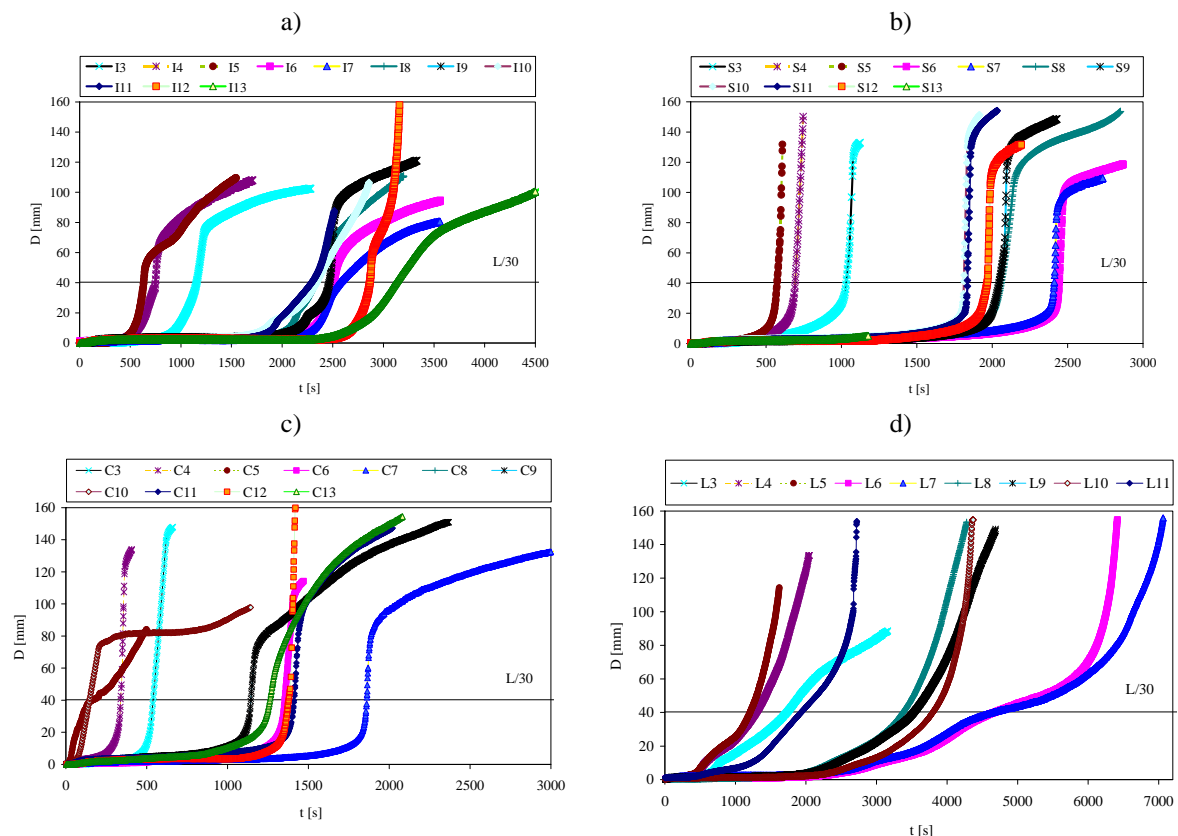


Figure 11 – Experimental mid span displacement of members with and without fire protection. a) IPE sections. b) SHS sections. c) CHS sections. d) LNP sections.

8 CONCLUSIONS

To study the influence of the intumescent coating thickness, the degree of utilisation and the cross section type, a set of 50 tests were done in a fire resistance furnace using elements subjected to bending. Of these, and for comparison proposes, 8 were performed at room temperature and the others under fire conditions using the standard fire curve and nominal degrees of utilisation of 30%, 50% and 70% applied in protected and unprotected elements.

In the case of tests without fire protection a comparison is made between experimental results and the values obtained by the Eurocode 3 part 1.2 simplified method. Taking into account the nominal properties only the CHS section experimental results shows unsafe fire resistance times in comparison to the Eurocode values.

Increasing intumescent fire protection thickness an increase in fire resistance time is achieved. For the same nominal protection thickness the critical temperature and fire resistance time decreases with increasing the degree of utilisation. In the SHS and CHS protected sections a partial detachment and intumescence shrinkage was sometimes observed leaving steel with reduced protection or even unprotected.

ACKNOWLEDGMENTS

The authors acknowledge financial support from the Portuguese Science and Technology Foundation, project PTDC/EME-PME/64913/2006, “Assessment of Intumescent Paint Behaviour for Passive Protection of Structural Elements Submitted to Fire Conditions”, and fellowship SFRH/BD/28909/2006. The authors also acknowledge the contribution from the paints manufactures: CIN and Nullifire.

REFERENCES

- [1] Longton, P.J., C. Houyoux, B. Zhao, and B. Chico, Development of alternative technologies for off-site

- applied intumescent coatings. 2005, European Commission: Luxembourg.
- [2] EN1993-1-2, Eurocode 3: Design of Steel Structures, Part 1-2: General rules, Structural fire design. 2005, European Committee for Standardization
 - [3] Wong, M.B. and J.I. Ghojel, Sensitivity analysis of heat transfer formulations for insulated structural steel components. *Fire Safety Journal*, 2003. 38(2): p. 187-201.
 - [4] Tan, K.h., Z. Wang, and S.K. Au, Heat transfer analysis for steelwork insulated by intumescent paint exposed o standard fire conditions, in *Third international Workshop Structures in fire*. 2004: Ottawa.
 - [5] Silva, V.P.E., Determination of the steel fire protection material thickness by an analytical process - a simple derivation. *Engineering Structures*, 2005. 27(14): p. 2036-2043.
 - [6] Wang, Z.-H., S.K. Au, and K.H. Tan, Heat transfer analysis using a Green's function approach for uniformly insulated steel members subjected to fire. *Engineering Structures*, 2005. 27(10): p. 1551-1562.
 - [7] Wang, Z.H. and K.H. Tan, Sensitivity study of time delay coefficient of heat transfer formulations for insulated steel members exposed to fire. *Fire Safety Journal*, 2006. 41(1): p. 31-38.
 - [8] Bailey, C., Indicative fire tests to investigate the behaviour of cellular beams protected with intumescent coatings. *FIRE SAFETY JOURNAL*, 2004: p. 689-709.
 - [9] Han, Z., A. Fina, G. Malucelli, and G. Camino, Testing fire protective properties of intumescent coatings by in-line temperature measurements on a cone calorimeter. *Progress in Organic Coatings*, 2010. 69(4): p. 475-480.
 - [10] CEN, EN1363-1: Fire resistance tests. General requirements. 1999, European Committee for Standardization
 - [11] IPQ, NP EN 10002-1: Materiais metálicos, Ensaio de tracção. Parte 1: Método de ensaio. 1990, Instituto Português da Qualidade.
 - [12] prEN13381-8, Test methods for determining the contribution to the fire resistance of structural members. Applied reactive protection to steel members. 2007, European Committee for Standardization
 - [13] BS476-20, Fire tests on building materials and structures - Part 20: Method for determination of the fire resistance of elements of construction (general principles), in BS 476-20. 1987, CEN.
 - [14] BS476-21, Fire tests on building materials and structure — Part 21: Methods for determination of the fire resistance of loadbearing elements of construction, in BS 476-21. 1987, CEN.
 - [15] Gardner, L. and N.R. Baddoo, Fire testing and design of stainless steel structures. *Journal of Constructional Steel Research*, 2006. 62(6): p. 532-543.