Temperature of Steel Columns under Natural Fire

F. Wald, P. Studecká, L. Kroupa

Current fire design models for time-temperature development within structural elements as well as for structural behaviour are based on isolated member tests subjected to standard fire regimes, which serve as a reference heating, but do not model natural fire. Only tests on a real structure under a natural fire can evaluate future models of the temperature developments in a fire compartment, of the transfer of heat into the structure and of the overall structural behaviour under fire.

To study overall structural behaviour, a research project was conducted on an eight storey steel frame building at the Cardington Building Research Establishment laboratory on January 16, 2003. A fire compartment 11×7 m was prepared on the fourth floor. A fire load of 40 kg/m² was applied with 100 % permanent mechanical load and 65 % of imposed load. The paper summarises the experimental programme and shows the temperature development of the gas in the fire compartment and of the fire protected columns bearing the unprotected floors.

Keywords: steel structures, fire design, fire test, compartment temperature, protected steel, natural fire.

1 Introduction

The BRE's Cardington Laboratory is a unique facility for advancement of the understanding of whole-building performance, see [1]. This facility is located at Cardington, Bedfordshire, UK, and consists of a former airship hangar with dimensions 48 m×65 m×250 m. The Cardington Laboratory comprises three experimental buildings: a six storey timber structure, a seven storey concrete structure, and an eight storey steel structure. The steel test structure was built in 1993. It is a steel framed structure using composite concrete slabs supported by steel decking in composite action with the steel beams. It has eight storeys (33 m) and is five bays wide (5×9 m = 45 m) by three bays deep (6+9+6 = 21 m) in plan. The structure was built as non-sway with a central lift shaft and two end staircases providing the necessary resistance to lateral wind loads. The main steel frame was designed for gravity loads, the connections consisting of flexible end plates for beam-to-column connections and fin plates for beam-to--beam connections, designed to transmit vertical shear loads. The building simulates a real commercial office in the Bedford area, and all the elements were verified according to British Standards and checked for compliance with the provisions of the Structural Eurocodes. The building was designed for a dead load of 3.65 kN m^{-2} and an imposed load of 3.5 kN m^{-2}. The floor construction consists of a steel deck and a light-weight in-situ concrete composite floor, incorporating an anti-crack mesh of 142 mm^2 m^{-1} in both directions, see [2]. The floor slab has an overall depth of 130 mm and the steel decking has a trough depth of 60 mm. Seven large-scale fire tests at various positions within the experimental building were conducted, see [3], and there is still a place for two more tests.

The main aim of these compartment fire tests was to assess the behaviour of structural elements with real restraint in a natural fire. The structural integrity fire test (large test No.7) was carried out in a centrally located compartment of the building, enclosing a plan area of 11 m by 7 m on the 4th floor [4]. The preparatory works took four months. The fire compartment was bounded with walls made of three layers of plasterboard (15 mm + 12.5 mm + 15 mm) with thermal conductivity (0.19–0.24) W $m^{-1}K^{-1}$. In the external wall the plasterboard was fixed to a 0.9 m high brick wall. The opening 1.27 m in hight and 8.7 m in length simulated an open window to ventilate the compartment and allow for observation of the element behaviour. The ventilation condition was chosen to result in a fire of the required severity in terms of maximum temperature and overall duration.

The steel structure exposed to fire consists of two secondary beams (section 305×165×40UB, steel S275 measured f_y = 303 MPa; f_u = 469 MPa), an edge beam (section 356×171×51UB), primary beams (section 336×171×51UB, steel S350 measured f_y = 396 MPa; f_u = 544 MPa) and columns, internal section 305×305×198UC and external 305×305×137UC, steel S350. The joints were a cruciform arrangement of a single column with three or four beams connected to the column flange and web by the header plate connections, steel S275. The beam to beam connections were created by fin plates, steel S275. The composite behaviour was achieved by a concrete slab (lightweight concrete LW 35/38; experimentally by a Schmidt hammer 39.4 MPa) over beams cast on shear studs (∅19–95; f_u = 350 MPa). The geometry and material properties of the measured section are summarized in Table A1, see [2, 5].

The mechanical load was simulated using sandbags, 1100 kg of each, applied over an area of 18 m by 10.5 m on the 5th floor. The sand bags represent the mechanical loadings; 100 % of permanent actions, 100 % of variable permanent actions and 56 % of live actions. The mechanical load was designed to reach the collapse of the floor, based on analytical and FE simulations. Wooden cribs with 14 % moisture content provided the fire load of 40 kg/m^2 of the floor area, see Fig. 1a,b.

The columns, external joints and connected beam (about 1.0 m from the joints) were fire protected to prevent global structural instability. The material protection used was 20 mm of Cafco300 vermiculite-cement spray, based on vermiculite and gypsum, see Table A2 and Fig. 1c, d. It was applied as a single package factory controlled premix, with a thermal conductivity of 0.078 W $m^{-1}K^{-1}$.

Fig. 1: a) Fire load in compartment; b) fire load around column D2; c) protection of internal column D2 (after test), d) protection of external column (after test)

The paper describes the temperature development in the fire protected columns. The temperatures predicted analytically and by 2D FEM simulation are compared to the measured values.

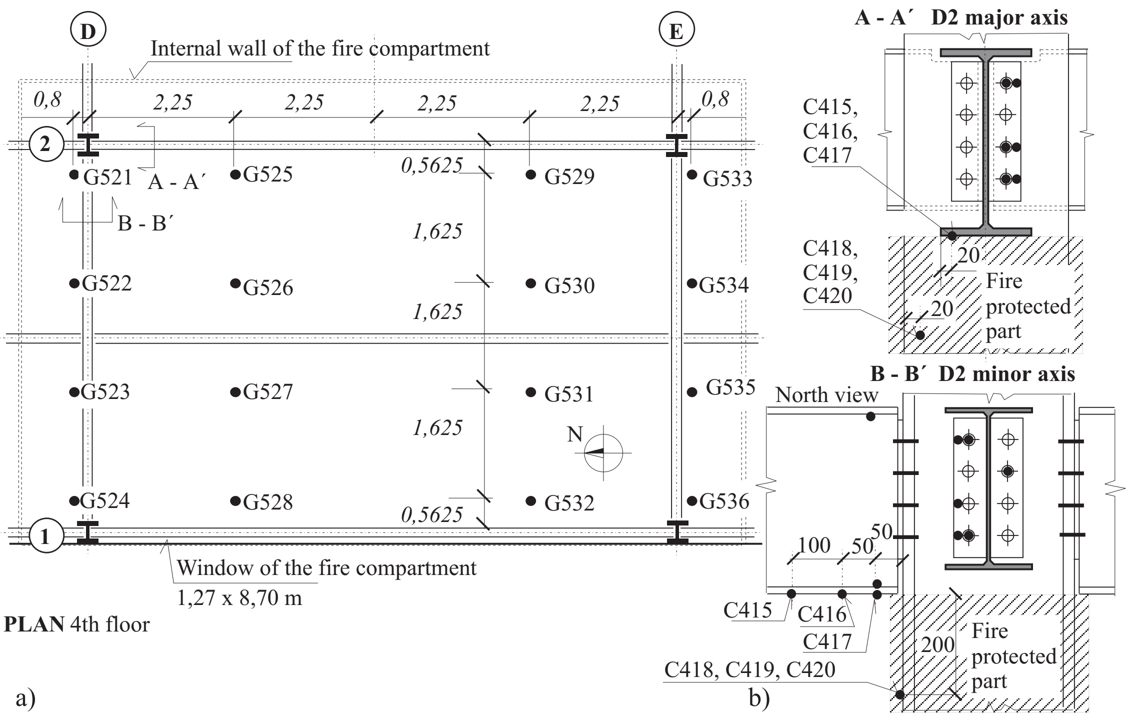

Fig. 2: a) Location of thermocouples in a compartment 300 mm below the ceiling; b) thermocouples on the beam and column end round the connection

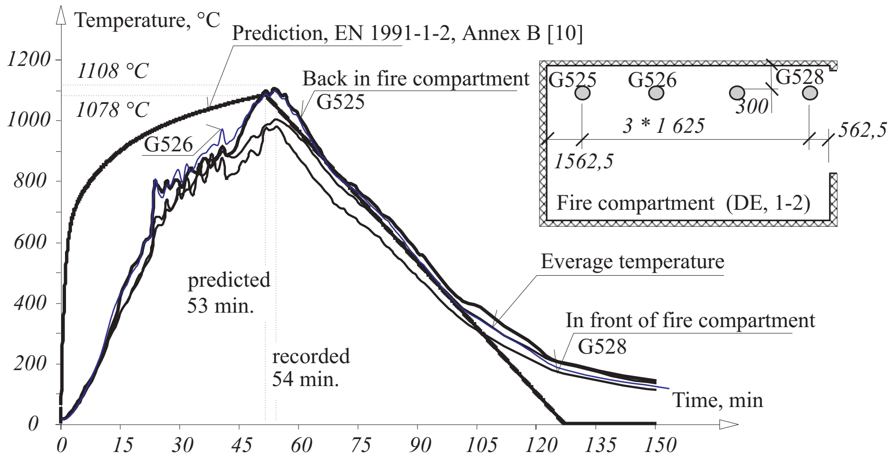

Fig. 3: Comparison of the prediction of the gas temperature with the measured temperatures, for values see Table B1

2 Instrumentation

The instrumentation used included thermocouples, strain gauges and displacement transducers. A total of 133 thermocouples monitored the temperature of the connections and beams within the compartment, the temperature distribution through the slab and the atmospheric temperature within the compartment, see Fig. 2a. An additional 14 thermocouples measured the temperature of the protected columns, see Fig. 5. Two different types of gauge were used, high temperature and ambient temperature, to measure the strain in the elements. In the exposed and unprotected elements (fin plate and end plate - minor axis) nine high temperature strain gauges were used. In the protected columns and on the slab a total of 47 ambient strain gauges were installed. 25 vertical displacement transducers were attached along the 5th floor to measure the deformation of the concrete slab. An additional 12 transducers were used to measure the horizontal movement of the columns and the slab. Ten video cameras and two thermo-imaging cameras recorded the fire and smoke development, the deformations and the temperature distribution, see [5].

3 Fire development

The quantity of thermal load and the dimensions of the opening on the facade wall were designed to achieve a representative fire in the office building. The openings allowed the fire to develop without a flashover managed by combustible timber sticks, see [4]. The temperature grew to reach the plateau of the time temperature curve in about 18 minutes, with a peak at 54 min., after which cooling began, see Fig. 3. The maximum recorded compartment temperature near the wall (2 250 mm from D2) was 1107.8 °C after 54 minutes. The predicted value was 1078 °C in 53 min, see [5]. During heating the temperature was distributed regularly, see Fig. 4. The measured differences of gas temperature decreased during cooling from 200 °C to 20 °C in 120 min. The measured

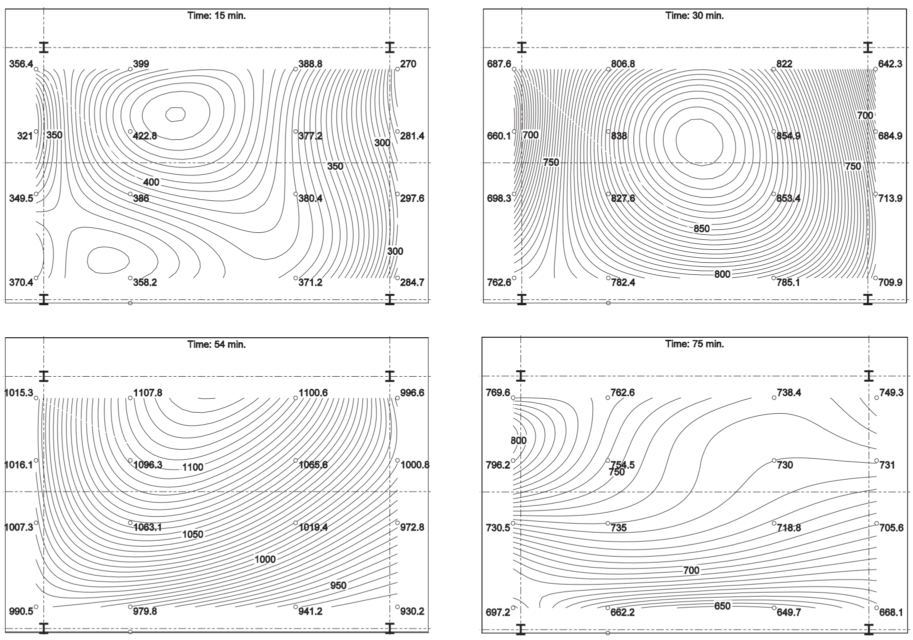

Fig. 4: Isotherms in the compartment with thermocouples 300 mm under the ceiling, the input data are summarised in Table B1

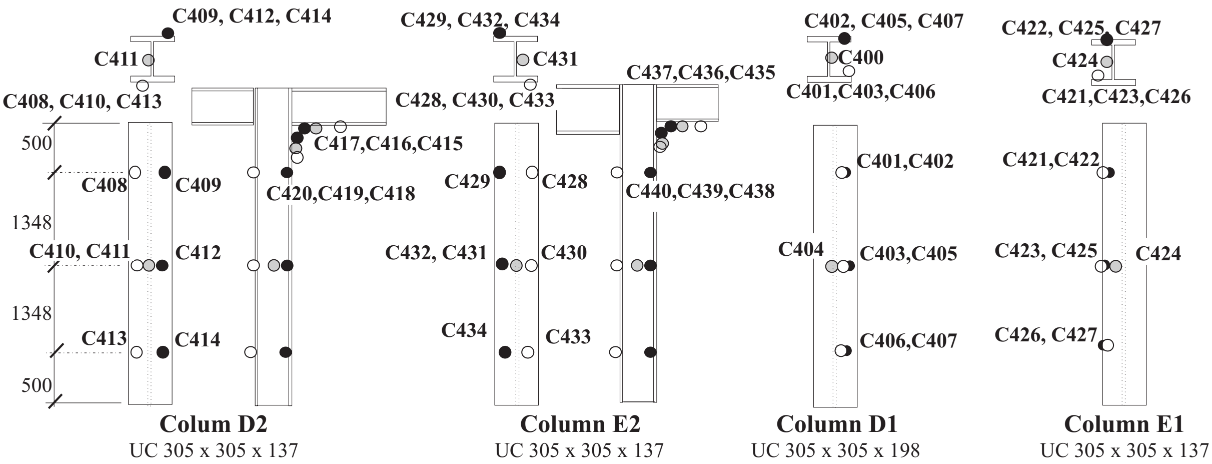

Fig. 5: Location of thermocouples on columns/beams, on flanges 20 mm from edge, on web in centreline

maximum gas temperatures are summarised in tab. B1 in the time intervals. The average gas temperature is calculated from all sixteen thermocouples.

4 Column temperatures

The temperatures in the columns in the fire compartment were measured at middle of the compartment's height, 500 mm from the floor, and 500 mm below the ceiling at both flanges and at its web, and in the connections, see Figs. 2b and 5, Table B2. The columns were fire protected except the joint area, where the primary and secondary beams were connected. A selection of the temperatures recorded at column D1 and D2 is presented in Figs. 6 and 7, where they compared to the gas temperature, the beam mid-span temperature, the beam end temperature as well as the column end temperature. The fire created a homogeneous gas temperature, and both columns were heated almost equally. The maximum re-

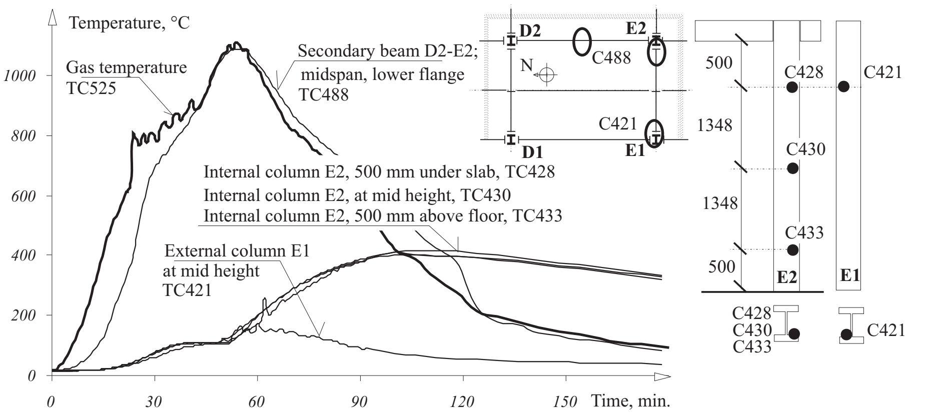

Fig. 6: Comparison of the measured temperature along the column length to the gas and connected beam temperature (column D2) and external column temperature (D1)

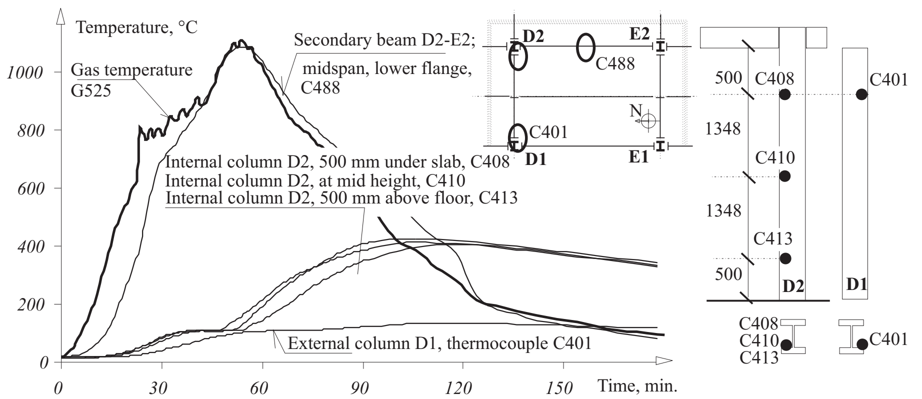

Fig. 7: Comparison of the measured temperature along the column length with the gas and connected beam temperature (column E2) and external column temperature (E1)

ported temperature in the insulated part of the middle column was 426.0 C, which occurred after 106 minutes of fire. The values reached at the middle height of column and in the upper part of the column were similar. The gradient of the temperatures along the column changed in the course of time. The differences of the measured temperature cross sections were insignificant, see Table B2.

The accurate and simple step-by-step calculation procedure is based on the principle that the heat entering the steel over the exposed surface area in a small time step Δt (taken as 30 seconds maximum) is equal to the heat required to raise the temperature of the steel by $\theta_{a,t}$ (at time t) assuming that the steel section is a lumped mass at uniform temperature, so that

$$\dot{q}'' F\, \Delta t = \rho_a\, c_{a,t}\, V\, \Delta\theta_{a,t}\,, \tag{1}$$

where ρ_a is the unit mass of steel, $c_{a,t}$ is the temperature dependent specific heat of steel, V is the volume of the member per unit length, and $\dot{q}''$ is the heat transfer at the surface, given by

$$\dot{q}'' = h_c(\Delta\theta_{g,t} - \Delta\theta_{a,t}) + \sigma\varepsilon(\Delta\theta_{g,t}^4 - \Delta\theta_{a,t}^4), \tag{2}$$

where h_c is the convective heat transfer coefficient, σ is the Stefan-Bolzman constant (56.7 10^{-12} kW m^{-2} K^{-4}), ε is the resultant emissivity, and $\Delta\theta_{g,t}$ is the increase of the ambient gas temperature during the time interval Δt. Eqs (1) and (3) may be rearranged to give

$$\Delta\theta_{a,t} = \frac{\dfrac{A_m}{V}}{c_a\,\rho_a}\Big[h_c(\Delta\theta_{g,t} - \Delta\theta_{a,t}) + \sigma\varepsilon(\Delta\theta_{g,t}^4 - \Delta\theta_{a,t}^4)\Big]\Delta t\,, \tag{3}$$

where A_m/V is the section factor for unprotected steel members, A_m is the surface area of the member per unit length. The convective heat transfer coefficient is recommended to have a value of 25 W m^{-2} K^{-1}. The iterative procedure for protected steelwork is similar to that for unprotected steel. The equation does not require heat transfer coefficients because it is assumed that the external surface of the insulation is at the same temperature as the fire gases. It is also assumed that the internal surface of the insulation is at the same temperature as the steel. The equation is

$$\Delta\theta_{a,t} = \frac{A_p}{V}\,\frac{k_p}{d_p\, c_{a,t}\,\rho_a}\,\frac{c_{p,t}\,\rho_p}{c_{a,t}\,\rho_a + \dfrac{A_p}{V}\,\dfrac{d_p\, c_{p,t}\,\rho_p}{2}} \times \\ \times(\theta_{g,t} - \theta_{a,t})\Delta t, \tag{4}$$

where A_p/V is the section factor for steel members insulated by fire protection material, k_p is the thermal conductivity of the insulation, d_p is the thickness of the fire protection material, $c_{p,t}$ is the temperature independent specific heat of the fire protection material, λ_p is the thermal conductivity of the fire protection system, ρ_p is the unit mass of the fire protection material. ECCS, see [6], suggested ignoring the heat capacity of the insulation if it is less than half of that of the steel section, such that $c_{a,t}\,\rho_a\, A/2 > c_{p,t}\,\rho_p\, A_i$, where A_i is the cross-section area of the insulating material and A is the cross-section area of the steel. This prediction is used in EN 1993-1-2: 2003 par. 4.2.5.2 [7], taking constant 3 instead of constant 2 in the heavy insulations term to allow calculations for the temperature gradient across the insulation material, in the form

$$\Delta\theta_{a,t} = \frac{\lambda_p\,\dfrac{A_p}{V}}{d_p\, c_a\,\rho_a}\,\frac{(\theta_{g,t} - \theta_{a,t})}{\left(1 + \dfrac{\phi}{3}\right)}\Delta t - \\ -(e^{\phi/10} - 1)\,\Delta\theta_{g,t} \quad (\text{but } \Delta\theta_{a,t} \ge 0 \textit{ if } \Delta\theta_{g,t} > 0) \tag{5}$$

with $\phi = \dfrac{c_{p,t}\,\rho_p}{c_{a,t}\,\rho_a}\, d_p\, \dfrac{A_p}{V}$, where A_p is the appropriate area of fire protection material per unit length of the member, which should generally be taken as the area of its inner surface, but for a hollow encasement with a clearance around the steel member the same value as for a hollow encasement without a clearance may be adopted. For prediction we used fire protection material thickness $d_p = 0.018$ m; unit mass $\rho_p = 310$ kg m^{-3}; specific heat $c_p = 1200$ J kg^{-1} K^{-1}; and thermal conductivity $\lambda_p = 0.078$ W m^{-1} K^{-1}. Fig. 9 compares of the predicted and measured temperatures. The internal column was exposed from four sides, the external column from two sides only. The prediction is based on the measured gas temperature in thermocouple G525, on the calculated parametric temperature, see [8] and [9], and also on the nominal temperature, see [10].

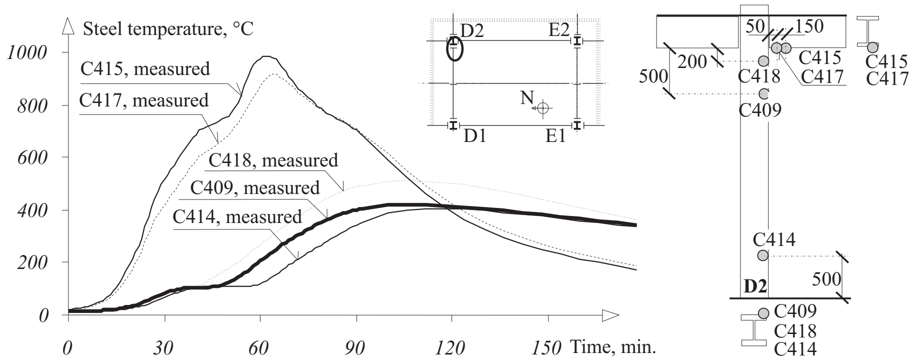

Fig. 8: Measured temperatures along a column length, column D2, and at a beam end

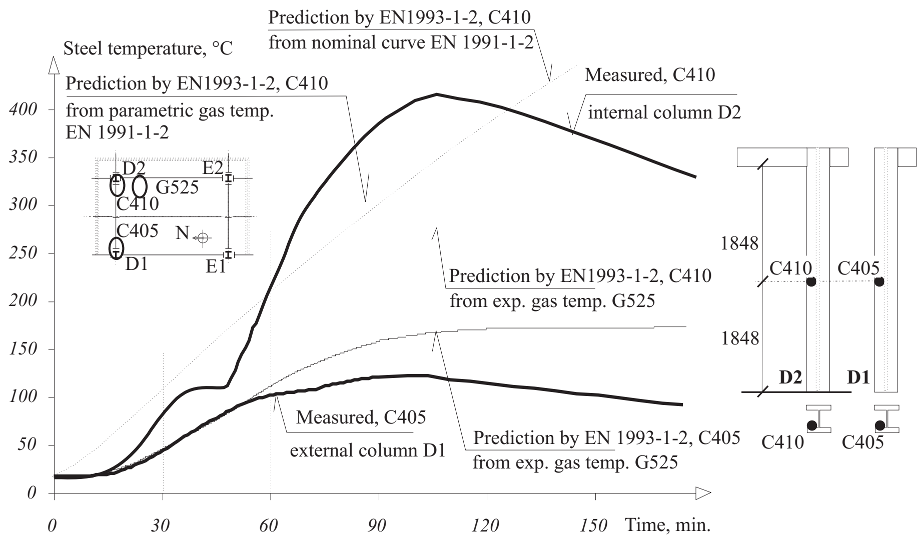

Fig. 9: Comparison of column calculated temperatures based on prediction by EN 1993-1-2 with measured temperatures, thermocouple C410

The results of modelling the heat transfer into the columns by the 2-dimensional FE code are shown in Fig. 10. The Super-Tempcalc code [11], taking into account the above listed parameters, was used for prediction. In the code, the differential equation is derived for 2-dimensional heat flow from conservation of energy, based on the fact that total inflow per unit time equals the total outflow per unit time. The constitutive relation invoked is Fourier's law of heat conduction, which describes heat flow within a material. The spatial and time domains are discretized by the weighted residual approach. Boundary conditions implemented include convective and radiative heat flow and heat exchange within enclosures. 3-node triangular finite elements were used. The thermal properties of the materials are described as temperature dependent. The temperature distribution within the protected column is presented during heating, after 30 min. of fire, and during cooling, after 120 min. of fire in Fig. 11. A temperature difference of 40 °C only was reached in the section. The comparison of the analytical and numerical results confirms the good quality of the presented analytical model.

5 Conclusions

The collapse of the structure or parts of the structure was not reached during the experiment for a fire load of 40 kg m^{-2}, which represents the fire load in a typical office building, together with a mechanical load greater than standard approved cases. The structure showed good structural integrity. The test results supported the concept of unprotected beams and protected columns as a viable system for composite floors. The connections do not need to be fire protected from the point of view of its resistance, see Fig. 11b, where only moderate local buckling is visible.

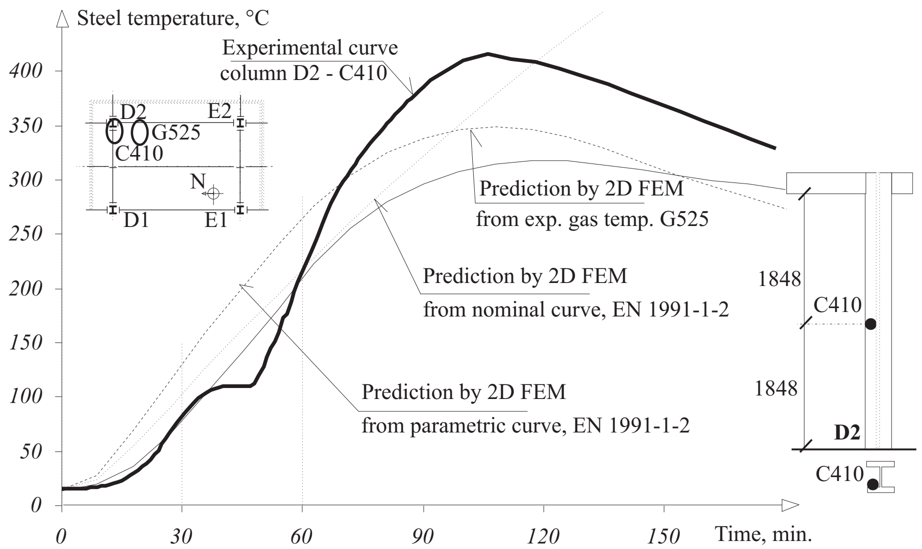

Fig. 10: Comparison of column calculated temperatures based on prediction by Tempcalc code to measured temperatures, thermocouple C410

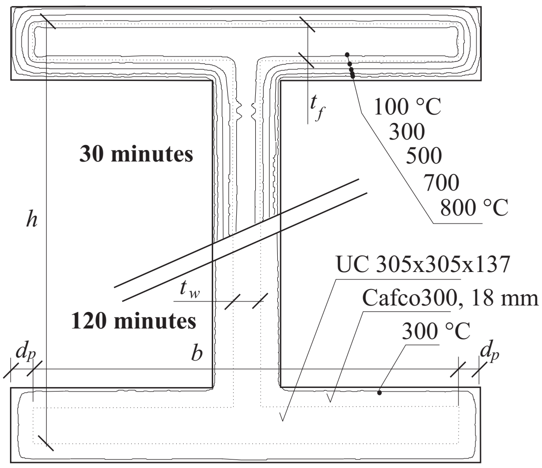

Fig. 11: a) Temperature distribution within the protected column during heating (after 30 min.) during cooling (after 120 min.) by Tempcalc code; b) local buckling of column flange E2

The test in at Cardington on January 16, 2003 documents that the incremental analytical models in prEN-1993-1-2: 2003 [7] allows predict the column temperature from the gas temperature during the heating phase with good accuracy, see Figs. 3, 9 and 10. From the nature of the heat transferred from the connected unprotected beams it is clear that the 3D solution is sufficient to describe the transfer of heat into the protected columns under the unprotected floors. An approximation based on 2D calculations is acceptable for design up to 60 minutes of fire only. Accurate analytical prediction of the temperature of the structure during its cooling will enable optimization of the application of the fire protective material on the compressed member of the structure only.

6 Acknowledgment

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Prof. Ing. František Wald, CSc.
phone: +420 224 354 757, +420 233 334 766
e-mail: wald@fsv.cvut.cz

Department of Steel Structures

Ing. Petra Studecká
phone: +420 224 353 877
e-mail: studecká@fsv.cvut.cz

Ing. Lukáš Kroupa
phone: +420 224 354 624
e-mail: lukaskroupa@fsv.cvut.cz

Czech Technical University in Prague
Faculty of Civil Engineering
Thákurova 7
166 29 Praha 6, Czech Republic

Annex A – Measured Geometrical Properties of Columns

Table A1: Geometry of column, [5] Fig. 2

Profile	Column	h_l	h_r	b_{upp}	b_{low}	t_w	$t_{f,upp,l}$	$t_{f,upp,r}$	$t_{f,low,l}$	$t_{f,low,r}$
		mm		mm		mm	mm			
UC305×305×137	nominal	320.5		309.2		13.8	21.7			
	D2	318.1	316.6	308.2	309.6	–	21.2	21.9	21.2	21.6
	E1	318.1	317.6	307.2	309.8	–	21.4	21.6	21.2	21.7
	E2	320.2	318.6	309.2	309.6	–	21.4	21.9	21.1	21.5
UC305×305×198	nominal	339.9		314.5		19.1	31.4			
	D1	336.0	336.8	312.3	312.5	–	32.0	30.8	31.4	31.1

Symbols, see Fig. 11:
h_l height of the column section on the left side, h_r height of the column section on the right side, b is the width of the column section, $_{upp}$ upper measured value, $_{low}$ lower measured value, t_w thickness of the column web, t_f thickness of column flange

Table A2: Thickness of the thermal protection of the column d_p (mm), [5], Fig. 11

Column	Above floor	West (outer) flange prot. thickness		East (inner) flange prot. thickness		hickness of prot. on web		Average of cross section	Average on column
		max.	min.	max.	min.	max.	min.		
E1	1000	18	15	18	22	18	20	19	18
	2000	18	19	15	20	20	15	18	
E2	1000	13	19	23	16	19	21	19	19
	2000	22	14	18	20	26	20	20	
D1	1000	23	13	18	20	18	16	18	18
	2000	22	15	19	18	22	13	18	
	3000	12	18	15	21	16	–	16	
	4000	19	13	18	21	22	–	19	
D2	1000	22	26	24	–	32	–	26	25
	2000	26	19	20	–	30	–	24	

Annex B – Measured Temperature

Table B1: Maximum gas temperatures (°C) in time intervals, thermocouples 300 mm under ceiling, number of thermocouples, see Fig. 2 [5]

Thermocouple Time interval, min.	C 521	C 522	C 523	C 524	C 525	C 526	C 527	C 528	aver.
10–15	356.40	321.00	349.50	370.40	399.00	422.80	386.00	358.20	373
25–30	687.6	660.1	698.3	762.6	806.8	838.0	827.6	782.4	805
40–45	810.5	777.3	834.8	851.1	935.0	971.6	964.5	885.9	966
0–180	1 015.3	1 016.1	1 007.3	990.5	1 107.8	1 096.3	1 063.1	979.8	1 074
75–80	769.6	796.2	730.5	697.2	762.6	754.5	735.0	662.2	761
90–95	567.1	579.7	576.9	528.7	560.3	535.0	555.1	475.1	555

Table B2: Steel beam temperatures (°C), numbers of thermocouples, see Figs. 2 and 5 [5]

Column Time, min.	D1 **C 401**	D2 **C 408**	D2 **C 409**	D2 **C 410**	D2 **C 411**	D2-D1 **C 415**	D2 **C 418**	E2 **C 428**	E2 **C 430**	E2 **C 433**
0	17.6	17.6	16.9	16.1	16.3	22.6	18.4	15.9	15.9	15.9
15	18.0	23.2	22.2	23.4	23.2	106.2	26.6	19.8	20.8	21.2
30	31.0	85.0	82.9	82.5	89.4	521.2	84.8	73.3	74.6	76.2
45	61.3	106.9	106.8	109.9	107.4	726.0	141.7	107.3	107.6	109.0
60	88.7	191.5	205.5	215.1	208.8	976.0	266.6	174.3	197.8	202.7
90	95.2	408.8	401.3	385.8	421.7	704.6	489.4	377.8	380.3	385.8
106	92.5	426.0	421.8	415.9	434.9	522.2	511.2	400.0	402.3	416.6
124	84.6	413.1	410.8	402.5	408.7	365.6	495.5	392.2	390.9	408.1
160	73.2	367.4	367.3	355.0	354.1	215.2	411.5	352.1	345.7	358.7
Maximal	95.3	426.0	421.8	415.9	436.3	985.8	511.2	410.4	402.3	416.6
Position	3/4 SW	3/4 SW	3/4 SE	1/2 NW	1/2 N	**BF	*NW	3/4 SW	1/2 SW	1/4 SW

The thermocouples were located 20 mm from the column/beam edge; * 200 mm below secondary beam; ** on the beam lower flange of the beam, 200 mm from the column face.