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NATURAL FIRES IN LARGE SCALE COMPARTMENTS

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ABSTRACT

British Steel plc**,** Swinden Technology Centre has recently carried out a programme of tests with the UK Fire Research Station in order to simulate the behaviour of natural fires in large scale compartments.

By studying a range of fire severity conditions, it was found that one of the more recently developed relationships for calculating time equivalent presented in the September 1992 draft of Eurocode 1: Actions on Structures Exposed to Fire, can provide safe realistic predictions. However, in a later draft of ECI the factors used for describing the thermal properties of the compartment, were amended resulting in unsafe solutions. It is advocated they revert back to those given in the September 1992 draft.

From the various temperature measurements made of the atmosphere and indicative steel sections included in the tests, other aspects of the Eurocodes on Fire Actions were investigated. In particular, these included the proposed relationships for calculating heat transfer to protected steel members (EC3) and parametric time temperature curves for the combustion gases.

1. INTRODUCTION

National and International structural building codes and standards on fire safety have been developed around the standard furnace test (BS 476:Part 20 [1], ISO 834 [2]) and as a result, a very large body of data has been generated on the behaviour of both protected and unprotected loadbearing elements. In order to utilise this information in association with designing for the real fire, engineers have strived to develop a methodology whereby the severity of the real fire and its effect upon the structure, can be quantified in terms of a period of heating in the furnace test. This is generally referred to as 'Time Equivalent of Fire Exposure'.

Historically, from the early work of Ingberg [3] through the post war National Building Studies of 1946 [4] and to the present time, various relationships have been established, to quantify the severity of a real fire upon a structure. Those more recently developed and frequently used are popularly referred to by the originators as:

Law [5]:

$$t_e = k \frac{L}{(A_v A_t)^{\frac{1}{2}}} \quad (1)$$

Pettersson [6]:

$$t_e = 0.067 q_{tf} \left(\frac{A_v \sqrt{h}}{A_T} \right)_f^{-\frac{1}{2}} \quad (2)$$

Harmathy [7]:

$$t_e = 0.11 + 0.16 \times 10^{-4} H' + 0.13 \times 10^{-9} (H')^2 \quad (3)$$

CIB W14 [8]:

$$t_e = q_f cw \quad (4)$$

The equation given in Reference 8 originated from DIN 18230 [9].

In the September 1992 draft of Eurocode 1: Actions on Structures Exposed to Fire [10] an adaptation of the CIB W14 equation was included given by the relationship:

$$t_{e,d} = q_{fd} \cdot c' \cdot w_f \cdot y_{n1} \cdot y_{n2} \ldots \min \quad (5)$$

where

q_{fd}	=	design fire load density per unit floor area, MJ/m^2
c'	=	conversion factor which takes account of the thermal properties of the enclosure, min/(MJ/m^2)
w_f	=	ventilation factor
$y_{n1,n2}$	=	safety factors

At the time of drafting no specific values of $y_{n1,n2}$ were assigned and later were removed since they would be implicit within the design process for calculating k_b.

The potential advantage of such an expression is that it provides the designer with a method for determining fire severity which is independent of the size and type of structural members, the material and thickness of protection but, unlike some previously developed relationships, apart from fire load and ventilation, also takes into account the thermal properties of the compartment boundaries.

Since the equation in Eurocode 1 had not been verified for compartments having large depth to height ratios such as those found in modern office buildings, a programme of tests were carried out to validate its applicability.

However, the equivalent time of fire exposure was subsequently revised in the April 1993, draft of EC1 to:

$$t_{e,d} = q_{fd} \cdot k_b \cdot w_f \qquad (6)$$

where

q_{fd} and w_f	=	as before
k_b	=	conversion factor to account for the thermal properties of the enclosure *but were assigned new values.*

The April 1993 draft of EC1 contained amendments dated June 1993 and the relevant section has since been re-issued as ENV 1991: Part 2.2: 1994 [11].

In recent years, relationships have also been developed for calculating the thermal response of steel members protected by passive fire protection systems. Separate formulae for lightly and heavily protected systems have been in existence with the latter taking into account the heat capacity of the insulation itself. These have been brought together in EC3: Part 1.2 [12] in the form of a single expression whereby the temperature rise $\Delta\theta_{a,t}$ of an insulated member can be calculated from:

$$\Delta\theta_{a,t} = \frac{\lambda p/dp}{c_a \rho_a}\frac{A_p}{V}\left[\frac{1}{1+\Phi/3}\right]\left(\theta_{g,t} - \theta_{a,t}\right)\Delta t - \left(e^{\Phi/10} - 1\right)\Delta\theta_{g,t}$$

$$\text{but } \Delta\theta_{a,t} \geq 0 \qquad (7)$$

in which:

$$\Phi = \frac{c_p \rho_p}{c_a \rho_a} d_p \frac{A_p}{V}$$

As part of the overall analysis of this investigation, a validation exercise was carried out to assess the accuracy of the above relationship for large scale natural fires.

Within EC1: Part 2.2, the thermal history for the compartment fire can be derived using a parametric expression for the heating and cooling phases given by:

$$\theta_g = 1325(1 - 0.325\,\exp^{-0.2t*} - 0.204\,\exp^{-1.7t*} - 0.472\,\exp^{-19*} \qquad (8)$$

$\theta_g = \theta_{max} - 625\,(t^* - t_d^*)$ for $t_d^* \leq 0.5$ h

$\theta_g = \theta_{max} - 250\,(3 - t_d^*)\,(t^* - t_d^*)$ for $0.5\text{ h} \leq t_d^* \leq 2\text{h}$

$\theta_g = \theta_{max} - 250\,(t^* - t_d^*)$ for $t_d^* \geq 2\text{h}$ (9)

However, since Equations (8) and (9) are limited by the working range of the thermal diffusivity for the materials used in the construction of the compartment, an appraisal was conducted to assess whether the parametric time temperature relationships could be extended beyond its current limits.

2. TEST DETAILS

2.1 Compartment Construction and Dimensions

A series of nine fire tests were conducted in a compartment built inside the BRE large experimental building facility at Cardington in Bedfordshire. Overall, the compartment measured 23.120 m long × 6.125 m wide × 3.075 m high and was designed to represent a 'slice' through a much larger compartment 46 m deep, of infinite width and having an effective (internal) depth to height ratio of 16:1. A general view of the structure is shown in Fig. 1.

Fig. 1: General view of the test compartment

In the construction of the compartment and its linings the following materials were used:

Roof

Structure: Reinforced autoclaved aerated concrete slabs, 6.0 × 0.7 × 0.200 m thick.

Lining: 2 × 25 mm layers of standard grade ceramic fibre blanket (ρ = 128 kg/m^3) fixed with stainless steel pins.

Additionally for Test 8 only:
2 × 12.5 mm = sheets of Fireline plasterboard fixed onto 47 × 75 mm timber studs at 400 mm centres.

Walls

Structure: Lightweight concrete blocks, 440 × 215 × 215 mm thick.

Lining: 2 × 25 mm layers of standard grade ceramic fibre blanket (ρ = 128 kg/m^3) fixed with stainless steel pins.

Additionally for Test 8 only:
2 × 12.5 mm sheets of Fireline plasterboard fixed onto 47 × 47 mm timber studs at 600 mm centres.

Floor

Structure: Dense concrete ~75 mm thick.

Lining: 125 mm deep layer of fluid sand, $\rho \approx$ 1750 kg/m^3.

Details on the relevant physical properties for each material are given in Table 1.

Table 1: Ambient temperature thermal properties of the material used in the test compartment

Structure	Material	Density ρ kg/m^3	Specific Heat c_p J/kg ^{o}K	Thermal Conductivity λ W/m ^{o}K	$b = \sqrt{\lambda \rho c_p}$ W h^{½}/m^2 ^{o}K (J/m^2 s^{½} ^{o}K)
Walls	Lightweight concrete blocks	1375	753	0.42	11.01 (660.6)
Roof	Autoclaved aerated concrete slabs	450	1505	0.16	4.59 (275.4)
Floor	Fluid sand	1750	800	1.0	19.75 (1185)
Lining (1)	Ceramic fibre	128	1130	0.02	0.898 (53.88)
Lining (2)	Fireline plasterboard	900	1250	0.24	8.68 (520.8)

Taking into account the lining materials, the internal dimensions of the compartment were as follows:

Test 1-6, 9	Length =	22.855 m
	Height =	2.750 m
	Width =	5.595 m
Test 7 (¼ size - square)	Length =	5.595 m
	Height =	2.750 m
	Width =	5.595 m
Test 8 (Fireline plasterboard)	Length =	22.780 m
	Height =	2.680 m
	Width =	5.465 m

Ventilation was provided at one end only with a maximum opening being the full width and height of the compartment. Lightweight concrete blocks were used to construct temporary walls to reduce the ventilation from fully open, 1/1, to 1/8 of the available ventilation area. In the reduced size compartment, Test 7, the ventilation conditions of ¼ opening represent the same ventilation area with respect to floor area as adopted in Tests 1 and 2. Fig. 2 illustrates how the ventilation conditions were achieved. Note however, from Test 3 onwards, an insulated steel column with an overall width of 400 mm was placed directly against the opening and has been taken into account when calculating the horizontal dimensions of the openings.

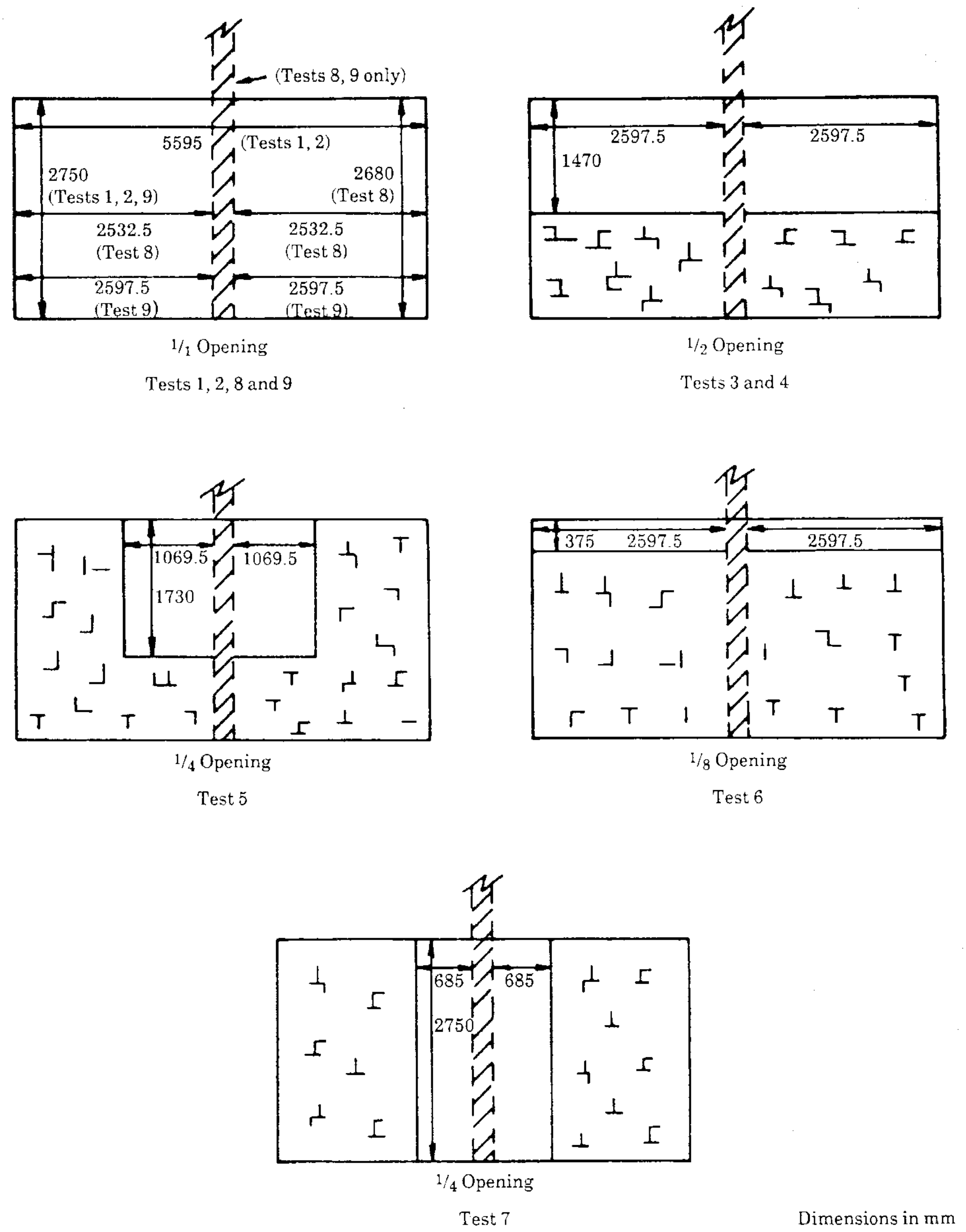

Fig. 2: Dimensions of the ventilation opening conditions

2.2 Fire Loading

Fig. 3 shows the general layout of 33 × 1 m square cribs distributed to provide a uniform fire load density. In the reduced size compartment, Test 7, nine cribs were used.

Each crib was constructed using 1 m lengths of 50 × 50 mm softwood kiln dried to 10% moisture content. These were stacked with alternate layers at right angles leaving a gap of 50 mm between each stick, see Fig. 4. On average, a 1 m length of softwood weighed 1 kg.

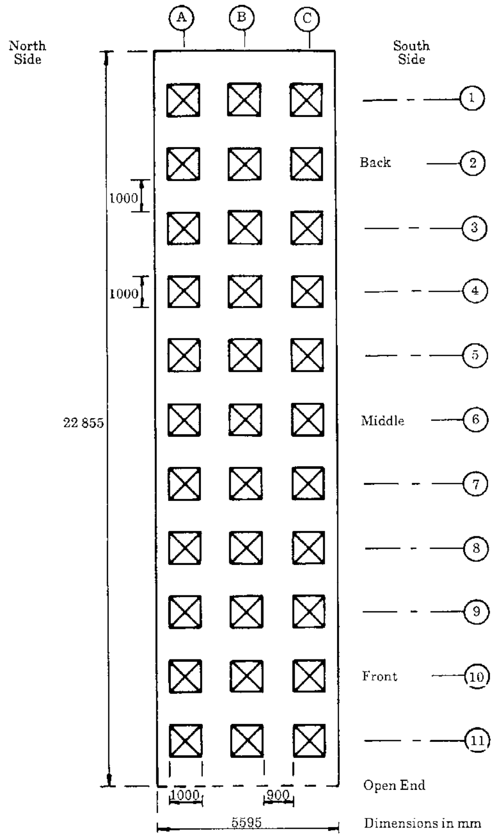

Fig. 3: Compartment plan showing the layout of the cribs with the back, middle and front measuring stations

Fig. 4: Construction of the timber cribs

2.3 Atmosphere and Steel Temperatures

The atmosphere temperature profiles in the horizontal plane (Fig. 5) were measured across the width of the compartment along crib lines 2, 6 and 10 by positioning the hot junctions of eleven 3 mm diameter chromel/alumel thermocouples 300 mm below the roof.

The vertical atmosphere temperature profiles were also measured directly above cribs 2B, 6B and 10B as well as mid centre to cribs B-C and 5-6. In each case, a series of five thermocouples were attached at intervals of 300 mm to a steel bar suspended from the roof.

For the purpose of determining values of 'Time Equivalent of Fire Exposure' 254 × 146 mm × 43 kg/m universal beams and 203 × 203 mm × 52 kg/m universal columns were selected. These particular section sizes are commonly used in the UK test furnaces for measuring fire resistance and therefore thermal data are available on both protected and unprotected members.

A total of twelve short lengths of beams and columns were fixed to the underside of the insulated roof slabs along the three measuring stations 2, 6 and 10. These were distributed so that a beam section alternated with a column section across the width and along the length of the compartment. In each case, the steel members were positioned either directly over, or equidistant between the cribs.

In order to simulate as near as possible the thermal effects of beams supporting a dense concrete floor, paving slabs 50 mm thick were placed upon the upper flanges with a thin layer (~0.2 mm) of cement paste between the concrete and steel surfaces. By using threaded bar, the assemblies could then be secured against the underside of the roof.

The steel sections were instrumented with 3 mm diameter chromel/alumel thermocouples placed in tight fit holes drilled into the flanges and web. This method of fixing had proven itself in the past and avoided problems concerning reliability resulting from repeated exposure to high temperatures and iron oxide, scale detachment.

When the members were finally positioned, the lower flange of the beams and the complete temperature profile across the column sections were all located approximately 300 mm below the roof, i.e. in the same horizontal plane as thermocouples used to measure the atmosphere temperatures. Associated with each beam and column, the hot junction of an atmosphere thermocouple was also placed on both sides of the member, approximately 125 - 150 mm from either a flange surface or flange tip. In the subsequent heat transfer calculations, these are referred to as 'local' atmosphere temperatures.

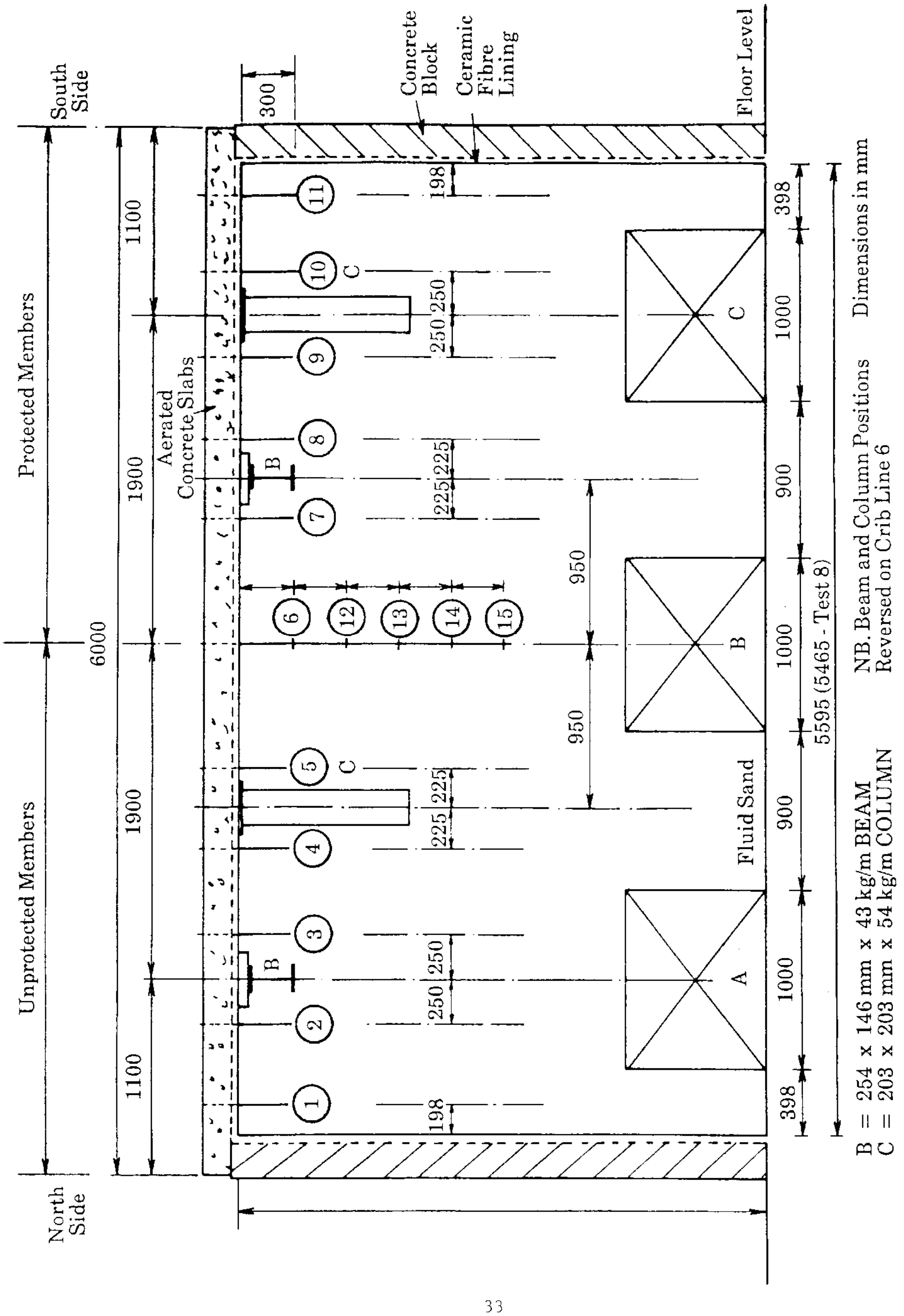

Fig. 5: Section through the compartment on crib lines 2, 6 and 10 showing the position of steel members and thermocouple locations

2.4 Fire Protection

Along one side of the compartment, the beams and columns were fire protected with 20 mm and 30 mm Vicuclad boarding respectively, Fig. 6. This was supplied and fitted by Promat Fire Protection Ltd. using normal fixing methods, although the detailing was modified to ensure that the position of the noggings did not influence the steel temperatures around the thermocouple positions.

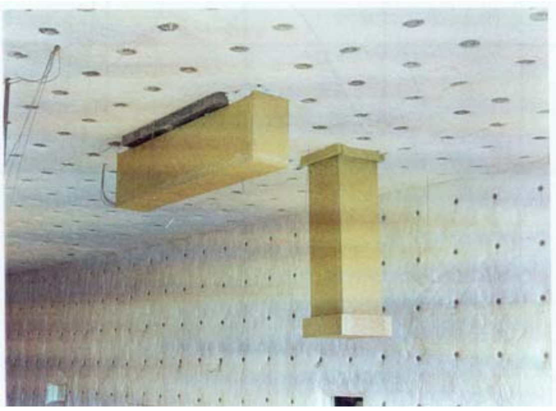

Fig. 6: Beam and column protected with Vicuclad

In Tests 1 and 2 Vicuclad Grade 900 was used. However, as a result of the duration and severity of the fires being well in excess of those for which the protection was intended to experience, resulting in loss of integrity, the Vicuclad was subsequently supplied to a higher specification, Grade 1050. In addition, since only thermal data were required, the fire protection was supported mechanically using nichrome wire and chicken wire mesh. No further problems regarding loss in integrity were experienced.

During the programme it was found that the temperatures attained by the unprotected steel members were in the main too high to be correlated with available fire resistance data. Consequently, in Tests 6, 8 and 9, 70 mm Vicuclad board was fixed to the unprotected column on grid line 10 in the same manner as the columns protected with 30 mm board.

Test 7 was carried out in a reduced size compartment and therefore only the steelwork located on crib line 10 was exposed to fire. In this particular test, both pairs of beams and columns were protected using the 20 mm and 30 mm Vicuclad.

Throughout the programme fire protection was removed following each test and the steel members cleaned from adhesive and loose scale before refitting.

2.5 Test Programme

A total of nine tests were conducted as follows:

Tests 1-6 were carried out in the full size compartment lined with ceramic fibre in which the fire load densities were generally either 20 or 40 kg of wood/m^2 while the ventilation varied from fully open at the front (l/1) to (l/8) opening. In each test, up to three cribs were ignited at the rear of compartment along grid line 1 and the fire allowed to progress naturally.

In Test 7 a reduced size compartment 25% of its original plan area was used. With respect to the variables given in the Eurocode time equivalent formula, the fire conditions were designed to replicate those of Test 2 by incorporating a fire load density of 20 kg/m^2 of floor area and for the same opening height, a constant ratio of ventilation area to floor area. The fire loading was distributed between nine cribs and these were ignited simultaneously.

Test 8 was designed to demonstrate the influence of a plasterboard lining on fire severity. However, due to the room taken up by the plasterboard, the internal dimensions of the compartment were slightly reduced. In addition, part of the timber framing system became directly involved in the fire and effectively increased the fire loading to 26 kg/m^2.

Test 9 was carried out to study the influence on fire behaviour between a growing fire whereby only three cribs were ignited and a fire in which all the cribs were ignited simultaneously. In this comparison, both the fire loading and ventilation conditions adopted in Test 2 were repeated.

The entire test programme is summarised in Table 2 together with values assigned to each of the various parameters for calculating t_e given in the September 1992 and April 1993 drafts of EC1.

3. RESULTS AND DISCUSSION

3.1 General Observations

With the exception of Tests 7 and 9, the fires were ignited at the rear of the compartment on crib line 1 and in all cases, the pattern of growth was similar to the thermal cycles shown in Fig. 7.

Table 2: Summary of the parameters adopted in the natural fires tests programme and the time equivalent predictions based upon Eurocode 1 drafts dated (a) September 17, 1992 and (b) April 1993

Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Compartment Size	Full Size	Full Size	Full Size	Full Size	Full Size	Full Size	¼Size	Full Size	Full Size
Wall and Ceiling Lining	Ceramic Fibre	Ceramic Fibre	Ceramic Fibre	Ceramic Fibre	Ceramic Fibre	Ceramic Fibre	Ceramic Fibre	Plaster-board	Ceramic Fibre
Fire Load Density, kg/m^2 of Floor	40	20	20	40	20	20	20	26	20
Ventilation×	1/1	1/1	1/2	1/2	1/4	1/8	1/4	1/1	1/1
Ventilation Factor, w_f	1.4795	1.4795	2.3087	2.3087	2.9396	3.2760	1.4790	1.5737	1.4795
Fire Load Density, q_f (MJ/m^2 of Floor)	759.9	380.1	380.1	759.9	380.1	380.1	380.1	507.2	380.1
Ignition/Fire Progress*	Growing	Growing	Growing	Growing	Growing	Growing	Simultaneous	Growing	Simultaneous

(a) Eurocode 1: Actions on Structures Exposed to Fire Part 10A: General Principles and Nominal Thermal Actions September 17, 1992

Thermal Properties: $b = \sqrt{\rho c_p \lambda}$ (W $h^{½}m^2$ °K)	<12	<12	<12	<12	<12	<12	<12	<12	<12
Insulation Factor: c	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Time Equivalent t_e (minutes)	101.2	50.6	79.0	157.9	100.6	112.1	50.6	71.9	50.6

(b) Eurocode 1:Part 2.7 Actions on Structures Exposed to Fire ENV 1991-2-7, April 1993

Thermal Properties: $b = \sqrt{\rho c_p \lambda}$ (W $h^{½}m^2$ °K)	<720	<720	<720	<720	<720	<720	<720	<720	<720
Insulation Factor: c	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Time Equivalent t_e (minutes)	76.7	39.4	61.4	122.8	78.2	87.2	39.4	55.9	39.4

× Represents fraction of front wall open

* Growing fire initiated by igniting up to three cribs on crib line 1

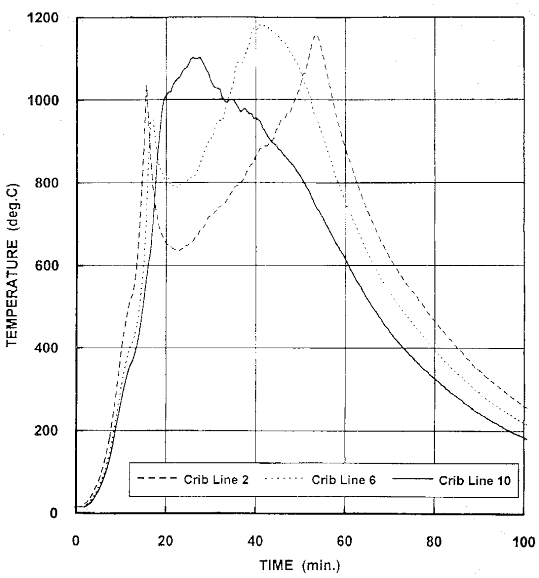

Fig. 7: Average atmosphere temperature profiles Test 2: Fire load = 20 kg/m^2, Ventilation = 1/1

In general, fire spread to adjacent cribs was initially slow followed by a period of rapid development towards crib line 11 at the front. Once the fire had fully developed, the cribs from the middle to the rear of the compartment were starved of oxygen, with the result that combustion ceased. Preferential burning continued near the opening and as the fuel was consumed, the fire progressed slowly back towards the rear. Although the cribs in Test 9 were ignited simultaneously, once the fire had established itself, the pattern of behaviour displayed in the growing fires was repeated.

Fig. 8 shows typical horizontal temperature distributions measured across the width of the compartment near the back, middle and front (see Fig. 3) at three intervals in time. Apart from reflecting the even rates of combustion at each measuring station, they further illustrate the cyclic behaviour of the fire along the length of the compartment.

Photographs illustrating the various fire conditions at different stages during the tests are shown in Figs. 9 - 12.

T/c	Cr2	Cr6	Cr10
1	1029	706	562
2	1007	689	561
3	1004	702	559
4	990	717	560
5	1006	702	563
6	1055	661	529
7	1057	686	552
8	1053	699	565
9	1057	727	570
10	1045	721	579
11	1047	729	586

Cr2	Cr6	Cr10
642	797	1047
639	781	1041
638	784	1046
643	791	1045
642	798	1048
646	789	1079
630	787	1062
624	797	1057
622	794	1062
630	802	1052
632	820	1041

Cr2	Cr6	Cr10
1152	945	725
1153	970	725
1155	976	724
1155	961	738
1158	951	742
1172	942	744
1166	954	734
1163	947	729
1163	954	749
1145	949	754
1147	944	748

11 Thermocouple positions across compartment

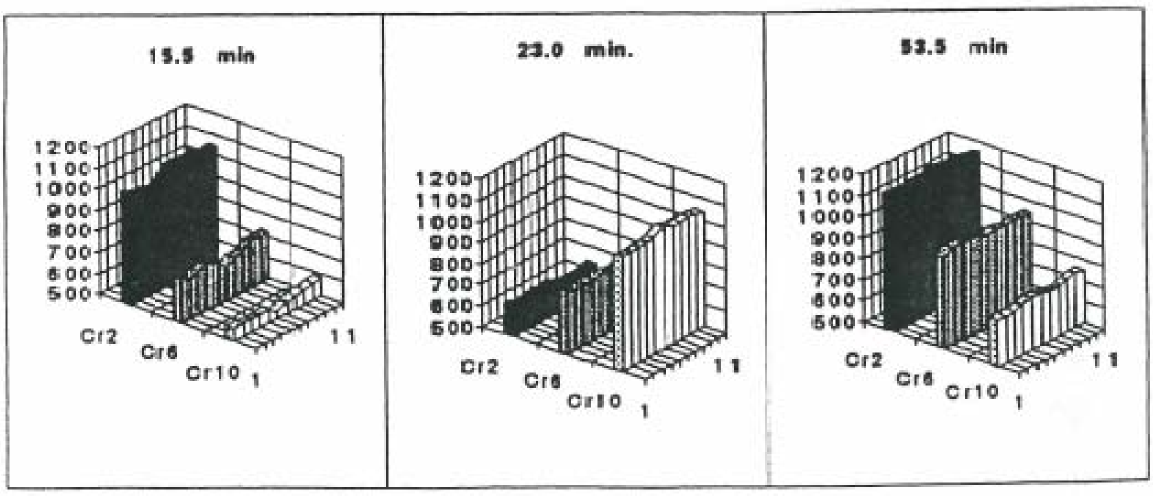

Fig. 8: Test 2: Horizontal temperature profiles of the hot gases on the crib lines 2, 6 and 10

Fig. 9: Test 2: Ignition of the cribs on crib line 1

Fig. 10: Test 4: Fully developed fire, 1/2 ventilation

Fig. 11: Test 6: Fully developed fire, 1/8 ventilation

Fig. 12: Complete combustion of the fire loading

3.2 Time Equivalent

Table 3 presents a summary of the results in which maximum temperatures recorded by the steel members are given (beams:average lower flange, columns:average flange and/or web) together with the corresponding times to achieve identical temperatures in the BS 476 fire resistance test, i.e. time equivalent. This process for determining the measured Time Equivalent is illustrated in Fig. 13.

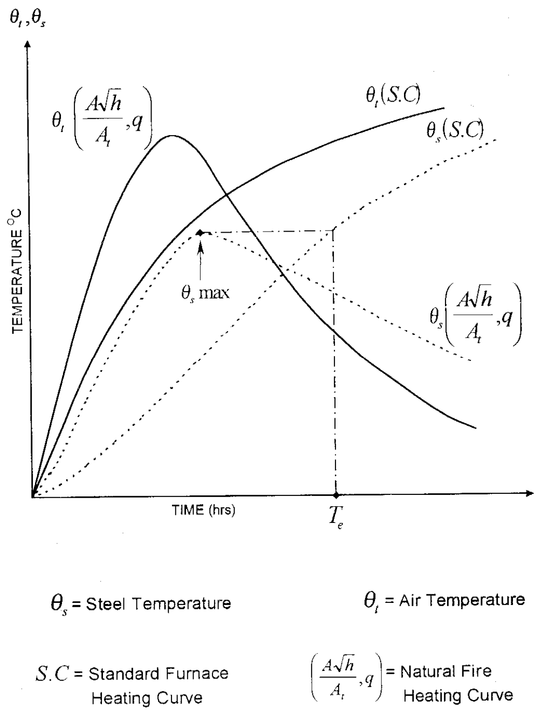

Fig. 13: Measurement of equivalent fire duration T_e

Table 3: Summary of test results comparing the measured time equivalents to predicted values based upon Eurocode 1:drafts dated Sept 1992 and April 1993

Location/Steel Member Type	Maximum Temperatures (°C) and Equivalent Fire Resistance, t_e (min)												
	Test 1	Test 2	Test 3	Test 4	Test 5	Test6		Test 7		Test 8		Test 9	
	South Side	South Side	South Side	South Side	South Side	North Side	South Side	North Side	South Side	North Side	South Side	North Side	South Side
BACK													
Beam, °C min	* 	470.5 73	506.5 80	705.5 144	568.5 94	744.0† 32	639.5 114	N/A	N/A	-	427.5 66.5	-	493.5 78
Column, °C min	588.0 155	378.0 72	400.5 75	616.5 121	493.0 92	742.0† 32	605.0 119	N/A	N/A	-	361.0 69.5	-	379.0 72
MIDDLE													
Beam, °C min	*	505.0 80	572.0 95	742.0 160	602.5 103	713.5† 27.5	623.0 109	N/A	N/A	-	454.0 70	-	541.0 88
Column, °C min	*	428.5 79	442.0 81.5	653.0 127.5	521.5 98	-	590.0 116	N/A	N/A	-	382.0 72.5	-	403.5 76.5
FRONT													
Beam, °C min	*	420.0 64	507.5 80	759.0 168	625.0 110	741.5† 32	580.5 97	B (342.0) 53.5	350.0 55	-	403.5 62	-	440.0 68
Column, °C min	616.5 121	308.0 61	418.0 77.5	678.5 132	538.0 102	A (450.8) 195	559.5 108	C (265.5) 55	258.0 54	A (248.8) 129.5	330.0 64	A (222.5) 122	308.5 61
Average Time Equivalent, t_e Measured	118	71.5	81.5	142	99.8	-	110.5	54.3		-	67.5	-	74
t_e Calculated using c = 0.09 (Eurocode 1: September 1992)	101.2	50.6	79.0	157.9	100.6	-	112.1	50.6		-	71.8	-	53.7
t_e Measured / Calculated	1.17	1.41	1.03	0.90	0.99	-	0.99	1.07		-	0.94	-	1.38
t_e Calculated using k_b = 0.07 (Eurocode 1: April 1993)	76.7	39.4	61.4	122.8	78.2	-	87.2	39.4		-	55.9	-	41.8
t_e Measured / Calculated	1.54	1.82	1.33	1.16	1.27	-	1.27	1.38		-	1.21	-	1.77

* Integrity of Fire Protection Lost

( ) Fire Protected with : A = 70 mm Vicuclad

B = 20 mm Vicuclad } Duplicate of South Side and Included in the Averaging
C = 30 mm Vicuclad }

† Unprotected Steel

Values of t_e measured for the individual members protected with 20 and 30 mm Vicuclad (South side) have been averaged to obtain the overall time equivalent for each test. These are compared with t_e calculated using a thermal inertia for the compartment which equates to c = 0.09, as implied in the September 2 draft of the Eurocode.

In order to check the validity of the Eurocode time equivalent equations, the measured values of t_e are compared with the theoretical values.

In the first six tests by adopting a value of c = 0.09 values of t_e measured/calculated are around 1.0 for Tests 3-6, but are significantly greater than 1.0 in the fully ventilated fires, viz. Tests 1 and 2. In particular, the calculated value of t_e for Test 2 underestimates the measured fire severity by 41% and therefore implies that using c = 0.09 is unconservative. This should however, be examined in terms of the practical solutions which may be envisaged in building design. By including a ceramic fibre lining on the inner surface of the test rig, the thermal behaviour of the compartment was more comparable to a furnace rather than a room in a building. This can be seen by comparing the thermal absorptivity of ceramic fibre [$\sqrt{(\lambda \rho \, c_p)}$ = 0.898 W $h^{½}/m^2$ ^oK] with the upper limit given in Eurocode 1 (12.0 W $h^{½}/m^2$ ^oK) for a room to be classed as a well 'insulated' compartment i.e. c = 0.09. The difference is at least an order of magnitude. Even allowing for the concrete walls and roof in calculating the overall thermal absorptivity, the total structure is still regarded as being well insulated.

The influence of a less thermally insulated compartment of fire severity using a plasterboard lining, but sufficiently high to still warrant a value of c = 0.09, is demonstrated by the results obtained from Test 8 containing the plasterboard lining. In Test 8, similar fire conditions of those adopted in Test 2 were repeated since these showed the greatest variance with respect to the calculated behaviour. The calculated time equivalent for Test 8 = 71.8 min compares with measured average t_e of 67.5 min. This provides a value of the ratio t_e measured/ calculated of 0.94. Therefore, for this particular set of fire conditions adopting a value of c = 0.09 for an 'insulated' compartment using conventional construction materials is on the safe side and reasonable. It follows therefore, that had a plasterboard lining been included in Tests 1 and 3-6 there would have been a significant reduction in measured fire severity resulting in values of t_e measured/calculated much less than unity.

Since the use of c = 0.09 appears valid for insulated compartments it is reasonable to adopt values of c = 0.07 and c = 0.05 for categories of compartment with poorer thermal performance as recommended in the CIB W14 report [8] and DIN 18230: Part 1: 1982 [9]. The use of c = 0.06 which is recommended for the general case, does not appear appropriate.

In the more recent draft of Eurocode 1 dated April 1993, the influence of thermal absorptivity on fire severity is described by the factor 'k_b' in which values of 0.04, 0.055 and 0.07 are recommended with the latter being adopted for the general case. It is clear from Table 3 that assigning 0.07 to k_b and consequently 0.055 and 0.04 for less insulating compartment is questionable and therefore should revert back to the original values given in the September 1992 draft of EC1.

Investigation by the authors as to the basis for adopting values of c and k_b = 0.6 and 0.55 respectively have found little technical support for these.

The correlations between calculated time equivalent and measured fire severity have been based upon beams and columns protected with 20 and 30 mm Vicuclad. These thicknesses of protection have been evaluated in the BS 476 fire resistance test for periods up to 150 min and would generally be applied to structural elements requiring up to 2 h fire resistance.

While the temperatures attained by the unprotected members in the majority of the test programme were considerably higher than the available data, in Tests 6 and 8 comparisons could be made between the calculated and measured behaviour. In each case, t_e measured for the unprotected steelwork was considerably lower than the calculated value and therefore for the normal failure temperatures expected by steel structure, analysis based upon the 20 and 30 mm thicknesses of fire protection provide conservative solutions. In contrast however, the introduction of 70 mm Vicuclad in Tests 6, 8 and 9 shows the measured values of t_e were considerably greater than the calculated response. While a fire protection thickness of 70 mm would normally be applied to members requiring much higher levels of fire resistance than 2 h, the disparity between calculation and measurement implies that the Eurocode method of determining the equivalent fire resistance does not provide a unique value for each set of compartment conditions but must partly depend upon whether the members are protected and the level of protection. This suggests that in the analysing the time equivalent of fire severity approximate conservative values may be easily obtained by using the Eurocode formula but for a more accurate analyses, additional factors should be included such as the limiting (critical) temperature of the structural element as well as the thickness and thermal properties of the insulation itself. The approach described is not new but is covered in the work by Pettersson et al [13] and should be re-examined. Reference 13 presents a detailed graphical analysis in which the equivalent time of fire severity can be determined from a knowledge of: fire load density, ventilation, thermal properties of the compartment and are all linked to: the temperature of the structural element and a combined factor for the fire protection and geometric properties of the section:

$$\frac{\lambda_i}{d_i}\frac{A_i}{V_s}$$

where

λ_i = thermal conductivity of the insulation

d_i = thickness of insulation

A_i = internal surface area of the insulation/unit length

V_s = volume of steel/unit length

3.3 Growing Fire v Simultaneous Ignition

In Test 9, the fire conditions of Test 2 were repeated to establish whether a growing fire would result in a significant difference in equivalent fire severity as opposed to simultaneous ignition. The former would be more representative of fires in large compartments in which ignition would normally occur at one source.

From Table 3, values of t_e measured/calculated for Tests 2 and 9 are 1.41 and 1.38 respectively - a variance of approximately 2%. In terms of conducting fire tests this is not regarded as significant.

3.4 Large v Small Compartment

Test 7 repeated the fire conditions of Test 2 as defined by the parameters presented in the Eurocode. While the atmosphere temperatures in Test 7 were higher, >1260°C, the ratios of t_e measured/calculated were 1.41 and 1.07 for the large and small compartments respectively. In practice, for the fire conditions evaluated, this suggests that the Eurocode calculation for small compartments will be conservative. One possible explanation could be that in small shallow compartment the aspect ratio between the ventilation height and compartment depth is much greater than in large compartments. This will give rise to a higher rate of burning with a greater amount of heat lost through the openings as opposed to remaining inside the compartment and heating the structure.

3.5 Heat Transfer Calculation Methods - Protected Members

The results of the test programme have been used to assess whether the relationship for calculating the temperature rise of protected steel members given in EC3: Part 1.2 [12], is appropriate to severe natural fires.

For the Vicuclad fire protection, it was initially found that using the ambient temperature thermal properties grossly underestimated the maximum steel temperatures attained during the tests. However, by modifying the thermal conductivity parameter for Vicuclad with values representative of its elevated temperature response, reasonable agreement was obtained between calculated and recorded results. In the analysis, the thermal conductivity for the Vicuclad was based upon the mean temperature between the ‘local’ atmosphere and the corresponding steel member.

Fig. 14 compares the calculated and recorded heating curves in Test 4 for the steel beams protected with 20 mm Vicuclad and is typical of the correlations obtained from analyses of all the data. Out of a total of 51 protected members studied, the variances between calculated and recorded maximum steel temperatures were within the following temperature bands:

$>50^oC$ = 4 members
$\geq 35^oC \leq 50^oC$ = 9 members
$<35^oC$ = 38 members

The evaluation conducted therefore provides confidence in the methodology.

3.6 Parametric Time Temperature Relationship

The parametric time temperature relationship given in EC1 Part 2.2, may be used to describe the thermal history of the combustion gases within a compartment. In its scope of application, certain limits are placed upon the physical parameters e.g. maximum compartment floor area = 100 m^2, permitted range of thermal absorptivity, $\sqrt{(\lambda\rho c_p)}$ = 1000-2000 J/m^2 S^{½} ^{o}K, opening factor, $\left(A_v\sqrt{h}/A_T\right)$, between 0.02 and 0.2 m½. While for the most part, the parameters adopted in the test programme fell outside these limits an assessment was made therefore, as to whether the relationship could be extended to cover the test conditions evaluated.

Fig. 15 is typical of the comparison between measured and calculated response. For all the tests conducted, the parametric expression was found to grossly underestimate the thermal histories of the compartment fires.

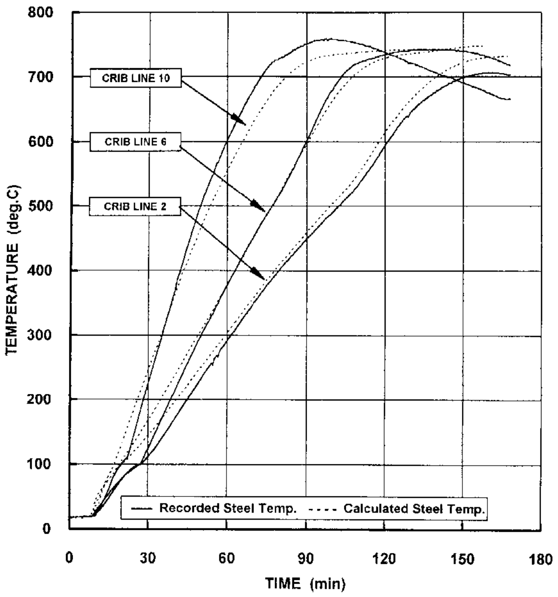

Fig. 14: Comparison between the recorded and calculated heating curves for the protected beams in Test 4

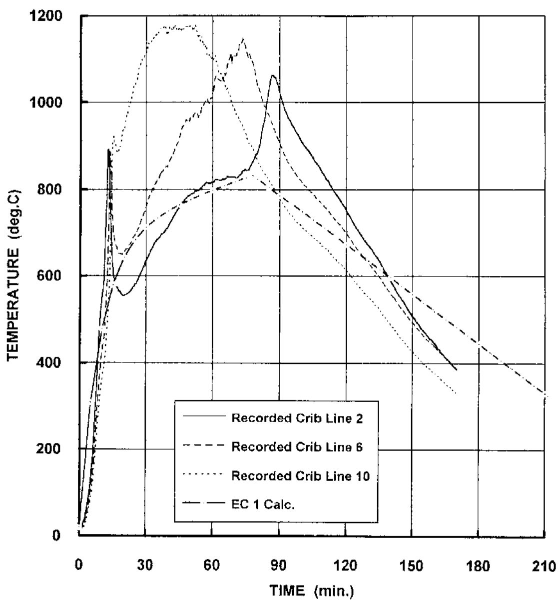

Fig. 15: Comparison of atmospheric heating cycles between measured behaviour and calculated responses using the eurocode parametric relationship

4. CONCLUSIONS

A programme of natural fire tests has been carried out with the main purpose of assessing whether the relationship for time equivalent of fire severity, t_e given in Eurocode 1: 'Actions on Structures Exposed to Fire', is appropriate to large scale compartments. From the results and analysis the following conclusions have been reached.

1. In the September 1992 draft of EC1 the equivalent time of fire severity was calculated from the relationship $t_{ed} = q_{fd}\ c' w_f$. For the parameter 'c', which represents the thermal characteristics of the compartment boundaries, it was generally assumed that reference could be made to DIN 18230: Part 1: 1982 [9] and CIB W14 [8] in which values of 0.05, 0.07 and 0.09 could be assigned for specific ranges of thermal inertia. The results have shown the relationship provides safe solutions when c = 0.09 for insulated compartments constructed with the type of materials normally used in buildings. This has been validated for equivalent periods of fire severity up to 150 min.

2. Based upon the results for an insulated compartment, it is considered that the formula given in the September 1992 draft would also provide safe solutions when values of c = 0.05 and 0.07 are used for compartment boundaries with higher ranges of thermal inertia. However, the use of c = 0.06 proposed in the Eurocode for the general case cannot be supported.

3. In the April 1993 draft of EC1, t_e is determined from q_{fd}, k_b, w_f in which 'k_b' replaced 'c' given in the September draft. New values representing the thermal inertia for the compartment are introduced as 0.04, 0.055 and 0.07 with 0.07 being applied to both insulated compartments and the general case. In this study, from the results obtained for the insulated compartment fires, these new values cannot be supported and it is recommended that k_b should be reassigned values of 0.05, 0.07 and 0.09 for the appropriate ranges of thermal inertia as originally given in the September 1992 draft.

   In summary, the recommended values for k_b should be:

   0.09 for heavily insulated compartments and the general case,
   0.07 for medium insulated compartments,
   0.05 for poorly insulated compartments.

Examples of the construction materials providing the levels of insulation within the categories given above are:

k_b = 0.09

Floors: lightweight concrete (ρ = 650kg/m^3).

Walls: plasterboard with mineral fibre infill.

k_b = 0.07

Floors: dense concrete ($\rho \geq$ 1850kg/m^3).

Walls: blockwork (ρ = 450 – 1350 kg/m^3) and plasterboard with no fibre infill.

k_b = 0.05

Floors: dense concrete ($\rho \geq$ 2200 kg/m^3).

Walls: combination of uninsulated steel sheet cladding (50%) and concrete, blockwork or brickwork ($\rho \geq$ 1350 kg/m^3).

4. Correlations between the measured and calculated values of t_e have been made on the basis of protected steel elements using Vicuclad in thicknesses of 20 and 30 mm. However, in several of the later tests in which similar analyses could also be made using unprotected steel and steel protected with 70 mm Vicuclad, results of the former gave lower values of equivalent fire severity, whereas those of the heavily protected members, were greater than the calculated response. This implies that the equivalent fire severity is not a unique value for a specific set of fire conditions as described in the Eurocode, but may also be linked to other parameters such as: the critical temperature of the structural element as well as the properties and section factor the insulation. While the Eurocode equation is still valid, and has been shown to provide safe solutions for large scale compartment, with unprotected steel or lightly protected members, there is a case for re-examining the parameters in the manner described in Pettersson's analysis for a more universal solution.

5. The influence of a growing fire on equivalent fire severity was not found to be significant compared with the same fire conditions involving simultaneous ignition.

6. Reducing the compartment size to approximately ¼ of its floor area reduced the measured fire severity by approximately 25% for the same fire loading and ventilation conditions as defined by the Eurocode formula. Calculations based upon small compartment geometries would therefore provide conservative answers.

7. Analysis of the data was extended to examining whether the heat transfer calculation method given in EC3: Part 1.2 for protected steel elements, could be applied to severe natural fire, heating conditions. In general, good agreement could be obtained between the calculated and measured response for the thicknesses of Vicuclad used provided the elevated temperature properties of thermal conductivity were adopted.

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NOMENCLATURE

t_e	equivalent time of fire exposure(min)
t_{ed}	design equivalent of fire exposure (min)
k	a constant, usually taken as unity for large scale experimental fires (min.m^2/kg)
L	fire load (kg of wood)
A_f	area of floor (m^2)
A_v	area of ventilation (m^2)
A_t	area of walls and roof but not including openings (m^2)
A_T	area of walls, floor and roof (m^2)
q_{tf}	elective fire load density (MJ/m^2 of bounding surfaces)
q_f	fire load density (MJ/m^2 of floor area)
q_{fd}	design fire load density (MJ/m^2 of floor area)
h	height of ventilation - weighted mean (m)
c	conversion factor to take account of the thermal properties of the compartment boundaries (min/(MJ/m^2))
w_f	ventilation factor
$y_{n1,\,n2}$	safety factors

k_b	conversion factor to take account of the thermal properties of the compartment boundaries (min/(MJ/m^2))
A_p / V	section factor for steel members insulated by fire protection material
A_p	area of the inner surface of the fire protection material per unit length of the member (m^2)
V	volume of the member per unit length (m^3)
c_a	specific heat of steel (J/kg ^oK)
c_p	specific heat of the fire protection material (J/kg ^oK)
d_p	thickness of the fire protection material (m)
Δt	time interval (seconds)
$\theta_{g,t}$	ambient gas temperature at time t
$\theta_{a,t}$	steel temperature at time t
$\Delta\theta_{g,t}$	increase of the ambient temperature during the time interval Δt
$\Delta\theta_{a,t}$	increase of the steel temperature during the time interval Δt (^oC)
λp	thermal conductivity of the fire protection material (W/m ^oK)
ρ_a	unit mass of steel = 7850 kg/m^3
ρ_p	unit mass of the fire protection material (kg/m^3)
θ_g	temperature in the fire compartment (^oC)
θ_{max}	maximum temperature in the heating phase (^oC)
t*	t r
t	time (h)
r	$(0/b)^2$
0	opening factor (m½)
b	thermal diffusivity (J/m^2 $s^{½}$ ^oK)
t_d*	0.13×10^{-3} q_{td} /σ r (h)
q_{td}	$q_{fd} \times \frac{A_f}{A_T} \left(MJ / m^2\right)$
H '	normalised heat load for mainly cellulosic fires ($s^{½}$ ^oK)

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