Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 74 (1996)

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DOI: https://doi.org/10.5169/seals-56092

Large Compartment Fire Tests at Cardington and the Assessment of Eurocode 1

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Summary

This paper describes a series of large compartment fire tests performed at BRE's Cardington laboratory. One of the objectives of these tests was to collect high quality data to assess the fire recommendations in Eurocode 1 Part 2.2. This paper presents comparisons between the fire temperature-time relationships, predicted by Eurocode 1, and those predicted by the method of Pettersson, Magnusson and Thor, and the test results. To relate realistic fires to the standard fire exposure, Eurocode 1 gives recommendations to calculate the equivalent time of exposure for a real fire. Predictions for the equivalent time of the large compartment fire tests using the Eurocode 1 method are compared with the test results and also with predictions from other methods. Finally, a parametric study is conducted to compare the sensitivities of the maximum fire temperature to the material properties of the compartment lining, predicted using the Eurocode 1 method and the method of Pettersson et al.

1. Introduction

With the advance in fire safety engineering, the design of structures subject to fires is now moving away from the traditional prescriptive approach to a performance based methodology. In the performance based method, the fire is treated as a type of accidental loading and the structure is designed to sustain this loading without loss of stability.

Essentially, there are four steps in this new approach. The design starts with the specification of a fire load, obtained from a statistical analysis of actual fires. This is followed by a fire behaviour analysis based on the fire load and ventilation condition of the fire compartment which gives the fire exposure in the form of a fire temperature - time relationship for the fire. Using this relationship and the thermal properties of the building materials, a thermal calculation is then performed to obtain the temperature rise in the structural members. Finally, a structural design incorporating the strength and stiffness of the structural elements at high temperatures is carried out to check the stability of the structure.

Various parts of the Eurocode system give recommendations on the thermal response and structural behaviour of the different materials used in construction. For example, Eurocode 3 Part 1.2 [1] describes in detail the procedures for the determining the fire resistance of steel framed buildings.

The method for calculating the time-temperature relationship of the fire is given in Eurocode 1 Part 2.2 [2]. Various appendices give other details such as the fire load, the equations for calculating the fire temperature-time relationships inside and outside a compartment and the calculations for the equivalent time of the fire. The equations for the latter relate a realistic fire scenario to the traditional standard fire exposure.

Although the information contained in Eurocode 1 has a sound scientific basis, its validation was based on comparisons against fire tests performed in small compartments [3]. Clearly, the applicability of the method to the large open plan offices found in modern buildings needs critical examination. The main differences between fires in small compartments and those in large compartments are:

(a) The temperature distribution in a large compartment is generally more non-uniform than the temperature distribution in a small compartment;

(b) The air movement in a large compartment is generally more turbulent than the air movement found in a small compartment.

Against this background, the Building Research Establishment in conjunction with British Steel Technical carried out 9 large compartment fire tests in BRE's Cardington laboratory (referred to as BRE/BST tests in the paper). More recently, as part of an ambitious project to investigate the behaviour of a whole building under fire conditions, a fire test in a full scale 8-storey steel framed building (referred to as the BRE corner test) was carried out to examine the provisions of Eurocode 1 Part 2.2 [2].

The objectives of this paper are twofold: first, to briefly describe the above mentioned fire tests and secondly, to assess the recommendations given in Eurocode 1 Part 2.2. This assessment includes the following comparisons:

(a) A comparison between the temperature-time relationship of the compartment predicted using the recommendations given in Eurocode 1 Part 2.2 and the same relationship calculated using Pettersson et al's method. Both these predictions are also compared with the test results.

(b) The equivalent time of exposure of a fire calculated using Eurocode 1 Part 2.2 is compared with the test results and other empirical methods.

(c) An assessment is made on the sensitivity of the maximum fire temperature to the properties of the compartment lining materials $(k\rho c_p)^{1/2}$.

2. Description of fire tests

2.1 BRE/BST fire tests

A full description of these fire tests is given in a British Steel Technical report[5]. This paper gives a brief account of the more important test parameters and of the measurements taken.

The fire tests were conducted in a compartment built inside the BRE Large Building Test Facility (LBTF) at Cardington, to the north of London. Overall, the compartment measured nominally 23 m x 6 m x 3 m high. Test 7 was carried out in the 1/4 size compartment.

The compartment roof was constructed of 200 mm thick reinforced autoclaved aerated concrete slabs with two layers of 25 mm thick standard grade ceramic fibre blanket. Test 8 had an additional lining of two layers of 12.5 mm thick Fireline plasterboard. The walls of the compartment were made of 215 mm thick lightweight concrete blocks with the same lining as the ceiling. The floor of the compartment was 75 mm thick dense concrete covered with a 125 mm deep layer of fluid sand.

Fire load was uniformly distributed in the compartment. Ventilation was provided via an opening in one wall. Table 1 gives the fire load density and the opening width and height for each fire test.

During the fire, three crib lines in the compartment, one near the back, one in the middle and one near the front were adopted as measuring stations for monitoring the compartment air temperature. At each of these stations, an array of 3 mm thermocouples were used.

Short steel sections with and without fire protection were suspended below the compartment roof at the three monitoring stations and their temperatures recorded. These temperatures were used to determine the equivalent time of fire exposure and for validating thermal response analysis.

The mass loss of timber stacks (every other stack in the centre row) was monitored using 1 m square load cell platforms.

2.2 BRE fire test in the 8-storey building

The Building Research Establishment in collaboration with a number of European parties is carrying out an ambitious experimental programme to study the behaviour of whole buildings under fire conditions. These tests are being carried out in an eight storey three bay by five bay steel framed composite building erected in BRE's Cardington laboratory. Although the main objective of this programme is to provide high quality test data on the structural behaviour of the whole building under fire conditions, this data can also be used to calibrate the recommendations in Eurocode 1 Part 2.2 [2]. To date (January 1996), only two compartment fire tests using timber cribs have been carried out, one by the Building Research Establishment and one by British Steel Technical. Since the fire conditions of both these two tests are the same, only the BRE test is described here.

The BRE fire test was conducted in one corner of the building, simulating the dimensions of a typical office room. This room measured 9 m long, 6 m wide and 4.185 m high.

The floor of the building was constructed of in-situ concrete acting compositely with corrugated steel decking. The floor of the fire compartment was covered with sand to simulate the serviceability load and to protect the instrumentation. The external end wall was made of lightweight concrete blocks, while the window side of the compartment consisted of a 1.5 metre high wall of lightweight concrete blocks supporting a 2.685 m high aluminum frame sealed with double glazing. The remaining internal walls of the fire compartment were formed using plasterboard to give a two hour fire resistance.

The fire load consisted of 40 kg/m^2 of timber distributed uniformly over the compartment floor.

Various instruments were placed inside and outside of the fire compartment to record combustion gas temperatures, the steel beam and column section temperatures and the strains and displacements in various locations in the compartment.

3. Analysis of fire tests

In this paper, three types of analysis are conducted. First, combustion gas temperature-time curves from these tests are compared against various predictions. These predictions include the parametric temperature - time curves proposed in Eurocode 1 Part 2.2 [2], predictions according to the method of Pettersson et al [4] and a simple equation based on the observation that the hot gas flowing out of the compartment constitutes a significant proportion of the total heat release of the fire. Secondly, the equivalent times of fire exposure predicted by Eurocode 1 are compared against the test results and predictions by other methods. Thirdly, the sensitivity of the predicted maximum combustion gas temperature to the properties of the compartment lining materials is compared with that of the predictions using the method of Pettersson et al [4].

3.1. Compartment fire temperature-time relationship

3.1.1: Eurocode 1 parametric temperature-time curve

For convenience, the equations in the Eurocode 1 Part 2.2 [2] are reproduced here. The temperature-time curve of a compartment fire is divided into a heating phase and a cooling phase. The expression for the heating phase is given by:

$$T_g = 1325(1-0.325e^{-0.2t^*}-0.204e^{-1.7t^*}-0.472e^{-19t^*}) \qquad (1)$$

where T =the temperature in the fire compartment (C°),
t^* =t.Γ (h) with
t =fire exposure time in hours,
Γ $=(O/b)^2/(0.04/1160)^2$
in which b is the average value of $(k\rho c_p)^{½}$ of compartment structure within the range of $1000 \le b \le 2000$ ($J/m^2s^{1/2}K$)
O =opening factor $A_v\, h^{1/2}/A_t$ within the range of $0.02 \le O \le 0.2$ ($m^{1/2}$) with
A_v =area of vertical openings (m^2)
h =height of vertical openings (m)
A_t =total area of enclosure of the fire compartment (m^2), i.e. walls, ceiling and floor, including opening.

The fire exposure time t_d^* at which the fire temperature in the enclosure starts to decrease is given by the following expression:

$$t_d^* = 0.00013 q_{t,d} \Gamma / O \qquad (2)$$

in which $q_{t,d}$ is the fire load density related to the total area A_t of the fire compartment. During the cooling phase, the temperature is assumed to decrease linearly at a rate depending on the time t_d^*.

The combustion gas temperature-time curves for all the large compartment fire tests have been predicted using Eurocode 1 method. Typical results are shown in figures 1-4. For BRE/BSC fire tests 5 and 6, the ventilation factor was lower than the lower bound value of 0.02 ($m^{1/2}$) permitted in Eurocode 1 Part 2.2 [2]. However, using the test value seems to give better agreement with the test temperature-time curves than using this lower bound.

It seems that Eurocode 1 Part 2.2 [2] predicts the maximum combustion gas temperature reasonably well but grossly underestimates the time of fire exposure. This prediction would be acceptable for unprotected steel structures since their maximum temperatures would be very close to that of the fire. However, Eurocode 1 Part 2.2 [2] may significantly underestimate the temperature rise in other structures such as protected steel and concrete structures.

3.1.2: Predictions according to the method of Pettersson et al [4]

The method used by Pettersson et al [4] is the most widely quoted one in the fire safety engineering literature for the calculation of combustion gas temperatures in fully developed compartment fires. The method is based on the assumptions of a uniform temperature field and no-moving air in the fire compartment. While these assumptions are reasonable for fires in small enclosures, the results from the BRE/BST large compartment fire tests clearly show that the combustion gas temperature in the compartment is not uniform. For example, figure 5 shows the three time-temperature curves recorded at the three combustion gas measurement stations for BRE/BST Test 2.

However, including a non-uniform temperature distribution will make the study of the compartment fire behaviour very complicated. For applications to structural fire resistant design, this degree of complexity may not be necessary since the maximum temperature of a structural member may not be particularly sensitive to a non-uniform temperature field. For example, figure 6 shows the measured temperature-time curves of steel sections at the three recording stations of BRE/BST Test 2. Clearly, the differences in the maximum temperatures of steel at these locations are much smaller than the differences in fire temperatures at the same locations. It is therefore considered acceptable to use the average combustion gas temperature in the compartment for determining the temperature of the structural elements.

The method developed by Pettersson et al [4] is based on a heat balance: heat produced equals heat lost. The heat produced is the heat generated by combustion of the fire load. The heat lost is made up of: heat lost in escaping gases; heat absorbed by the structure and fabric of the compartment, heat lost by radiation through the ventilation opening and heat required to produce mass of volatile [3].

Clearly, the total rate of heat release in the fire is the most important parameter. In this study, this value was calculated from the measured burning rates of the timber cribs during steady burning and are given in table 2, which also includes the predicted burning rates using the equation known as the CIB equation [3].

The maximum heat release rate is obtained from the burning rate of timber cribs, assuming a combustion efficiency coefficient of 0.7 and a heat production of 18 MJ/kg for timber. The complete rate of heat release-time curve of the compartment fire is constructed from three parts: a linearly growth part consuming 10% of the fire load, a steady burning rate consuming 50% of the fire load and a parabolic cooling phase until complete burn-out of the fire load.

Studies in the 1950's and 1960's established an empirical burning rate of about $5.5A_v h^{1/2}$ kg wood/minute based on ventilation conditions and the maximum heat required for stoichiometric combustion. It is noticed from table 2 that in BRE/BST Tests 5 and 6, the burning rates of timber are significantly higher than this value. At present, there lacks a comprehensive theory to explain these higher burning rates. However, the equivalent heat of $5.5A_v h^{1/2}$ kg wood/minute may still be regarded as the maximum rate of heat release for the fire development.

Predicted combustion gas temperature-time curves are compared with the test results and also with the predictions from Eurocode 1 Part 2.2 [2] in figures 1-4. It seems that this method generally predicts more severe fires than Eurocode 1. However, the degree of over prediction using the method of Pettersson et al [4] is about the same as the degree of under prediction using the Eurocode 1 [2] method.

During the fire analysis using the method of Pettersson et al [4], it was observed that the heat loss due to hot gas flowing out of the fire compartment openings accounted for about 70%-80% of the total heat release. Since the fire compartments were highly insulated, this is in agreement with the observation of Thomas and Heselden [3] who noticed that radiation heat loss through opening was less than 30%. Since the mass rate of air flowing out of the compartment openings is expressed as[7]:

$$m_{air}=0.5A_v\sqrt{h} \qquad (3)$$

The combustion gas temperature can be determined from the following expression:

$$T_g=T_\infty+\frac{0.75*RHR}{0.5A_v\sqrt{h}C_a} \qquad (4)$$

where RHR is the total rate of heat release and the coefficient of 0.75 implies that 75% of the total rate of heat release of the fire flows out of the fire compartment openings as convective heat loss. T_∞ is the ambient temperature and C_a the specific heat of ambient air, C_a=1150 J/kg.°C.

Figures 1-4 compare the predicted fire temperature-time curves using equation (4) with the test results and predictions from Eurocode 1 [2] and the more complicated method of Pettersson et al[4]. The accuracy of equation (4) is comparable to that of the other two methods. However, equation (4) is much easier to use.

3.2: Equivalent time of fire exposure

Eurocode 1 [2] provides an equation to calculate the equivalent time of a realistic fire. This equivalent time is the time in the standard fire exposure (e.g. ISO 834 [7]) for a structural member to reach the maximum temperature obtained when the structural member is subjected to the realistic fire exposure.

Alternative methods to calculate the equivalent time of fire exposure are provided by Law [8] and Harmathy [9]. Results of the predicted equivalent times for the BRE/BST fire tests using these three methods are compared with the test results in table 4. The test equivalent times are obtained from measured temperatures of the protected steel sections.

Eurocode 1 [2] gives three different values of k_b (0.04-0.07) according to the value of $(k\rho c_p)^{½}$ of the compartment lining materials. However, using the value of 0.09 gives the best agreement.

Table 3 shows that while the methods of Eurocode 1 [2] and Law [8] are reasonably close to each other and to the test results, the predictions of Harmathy [9] are quite different. This is because there is a fundamental difference in the way Harmathy's [9] equations are derived.

The derivation of Harmathy's equations [9] was based on temperature calculations at the position of the reinforcement inside a concrete slab, while the methods of Eurocode 1 [2] and Law [8] were based on temperature calculations for steel sections.

In summary, the equivalent time of exposure of a fire may not be unique. Its values may depend on the construction material and the fire protection of the structural members.

3.3. Effect of $(k\rho c_p)^{½}$ of enclosure lining materials on maximum fire temperature

In Eurocode 1 [2], the property $(k\rho c_p)^{½}$ of the enclosure lining material plays an important role in the calculation of the parametric temperature-time curves. Whilst it is possible to check the accuracy of this recommendation by performing a series of experiments in which only the lining materials are varied, the cost of such a series of tests would be prohibitive. Instead, the method of Pettersson et al [4] is used. Although this method has not proved to be very accurate as shown in figures 1-10, it is thought that this is the result of inaccurate information on the rate of heat release of the fire. For comparative studies to check the influence of other parameters on the fire temperature development, this method is acceptable.

Table 4 compares the predicted maximum temperatures of a fire in an enclosure with different lining materials. Other conditions are the same as the BRE corner fire test. In the calculations using the Pettersson et al [4] method, the rate of heat release is unchanged.

Table 4 shows that for this range of lining materials, the maximum difference in the predicted maximum temperature using the Pettersson et al method [4] is only about 7%, whilst the maximum difference in the maximum temperatures predicted using Eurocode 1 [2] is about 30%.

The results of table 4 imply that the heat release rates of the same fire in enclosures with different lining materials will be different. However, existing prediction for the burning rate of a fire do not include this influence. Nevertheless, the effect of different enclosure lining materials on the fire temperature development as predicted using the Eurocode 1 [2] method should be explored further.

4. Conclusions

In this paper, a series of fire tests in large compartments in the BRE's Large Building Test Facility at Cardington are briefly described and results are analysed. The results are compared with predictions using Eurocode 1 [2] and other methods. From the results of the analyses, the following conclusions can be drawn:

(1) The Eurocode 1 [2] underestimates the temperature-time relationships for fires in large compartments. Generally, Eurocode 1 gives a reasonable prediction for the maximum

combustion gas temperature, but grossly underestimates the fire exposure time.

(2) The method of Pettersson et al [4] gives similar accuracy. It is thought the inaccuracy in the prediction is not in the method itself, but the assumption concerning the amount of energy released per unit mass of timber.

(3) Equation 4 may be used as a very simple way to estimate the combustion gas temperature. The accuracy of this equation is comparable to Eurocode 1 and Pettersson et al's method.

(4) The fire temperature is very sensitive to the properties of the compartment lining materials, according to Eurocode 1. However, predictions using the method of Pettersson et al [4] do not show such sensitivity. It is recommended that a thorough study is made to investigate the influence of lining materials on the fire temperature development, including a study on the influence of this parameter on the heat release rate.

(4) The equivalent time of exposure of a fire may not be a unique. Its values may depend on the construction material and fire protection of the structural members. A thorough study is required to validate the recommendations in Eurocode 1.

5. References

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Parameter	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Fire load density (kg/m^2)	40	20	20	40	20	20	20	20.6	20
Window width (m)	5.595	5.595	5.195	5.195	2.139	5.195	1.37	5.065	5.195
Window height (m)	2.75	2.75	1.47	1.47	1.73	0.375	2.75	2.68	2.75

Table 1: Fire load density and ventilation conditions for each test

Test	Test burning rate (kg/min)	CIB burning rate (kg/min)	test burning rate/A_vh ($kg/min.m^{3/2}$)
BRE/BST 1	84	59.7	3.55
BRE/BST 2	87	59.7	3.67
BRE/BST 3	36.6	36.3	3.95
BRE/BST 4	51.6	36.3	5.57
BRE/BST 5	40.2	26.5	8.25
BRE/BST 6	21.6	13.1	18.15
BRE/BST 7	30	32.9	4.8
BRE/BRE 8	60.6	55.2	2.73
BRE/BST 9	69	57.6	2.91
BRE corner	--	133.8	3.38

Table 2: Test and predicted burning rates

Equivalent time method:	test 1 min	test 2 min	test 3 min	test 4 min	test 5 min	test 6 min	test 7 min	test 8 min	test 9 min
Measured	118.0	71.5	81.5	142.0	99.8	110.5	54.3	67.5	74.0
Eurocode 1	101.2	50.6	79.0	157.9	100.6	112.1	50.6	57.0	53.7
Law	79.5	43.3	55.7	111.3	79.4	109.1	34.2	43.5	41.2
Harmathy	44.4	28.9	57.1	101.9	93.2	162.2	45.3	30.6	30.3

Table 3: Equivalent times of exposure, BRE/BST fire tests

$(k\rho c_p)^{1/2}$ of lining material/ (1160 $J/m^2\ s^{1/2}\ ^\circ K$)	Maximum combustion gas temperature (°C)	
	Pettersson prediction	EC1 Part 2.2 prediction
0.5	927.4	1253.6
0.6	921.8	1201.3
0.7	915.7	1152.7
0.8	909.1	1110.9
0.9	902.6	1075.3
1.0	895.6	1044.3
1.1	889.3	1016.4
1.2	882.4	990.7
1.3	872.5	966.7
1.4	869.5	944.0
1.5	863.5	922.8

Table 4: Predicted maximum combustion gas temperature

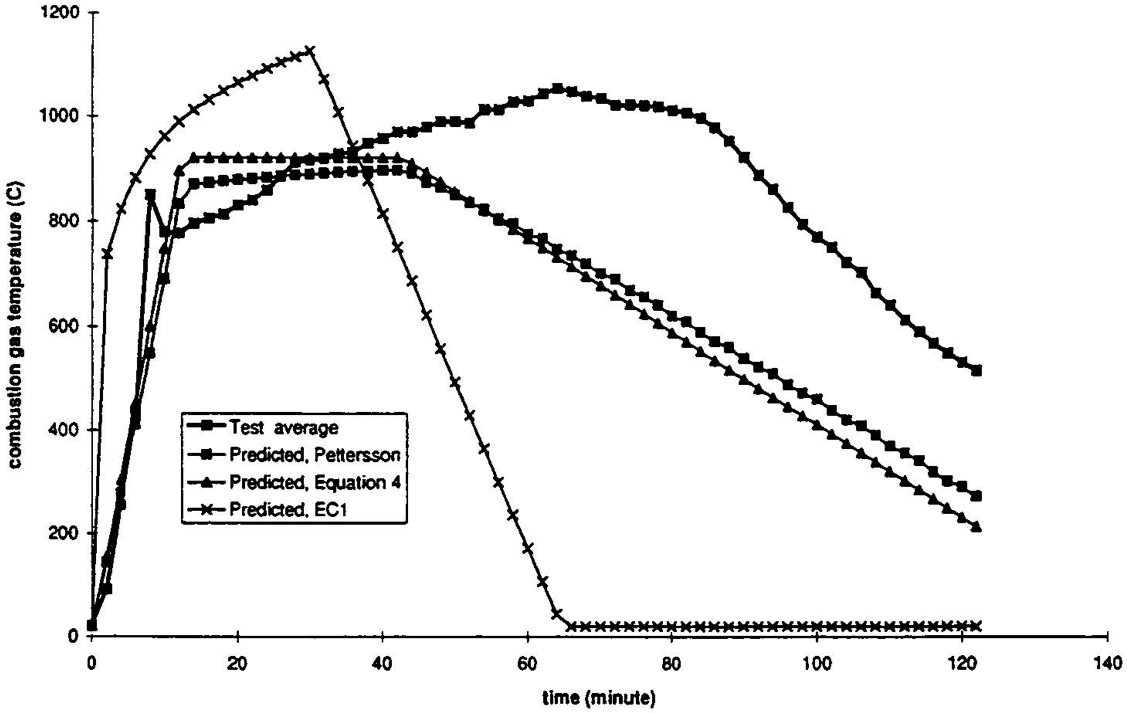

Figure 1: Comparison of combustion gas temperatures, BRE/BST Test 1

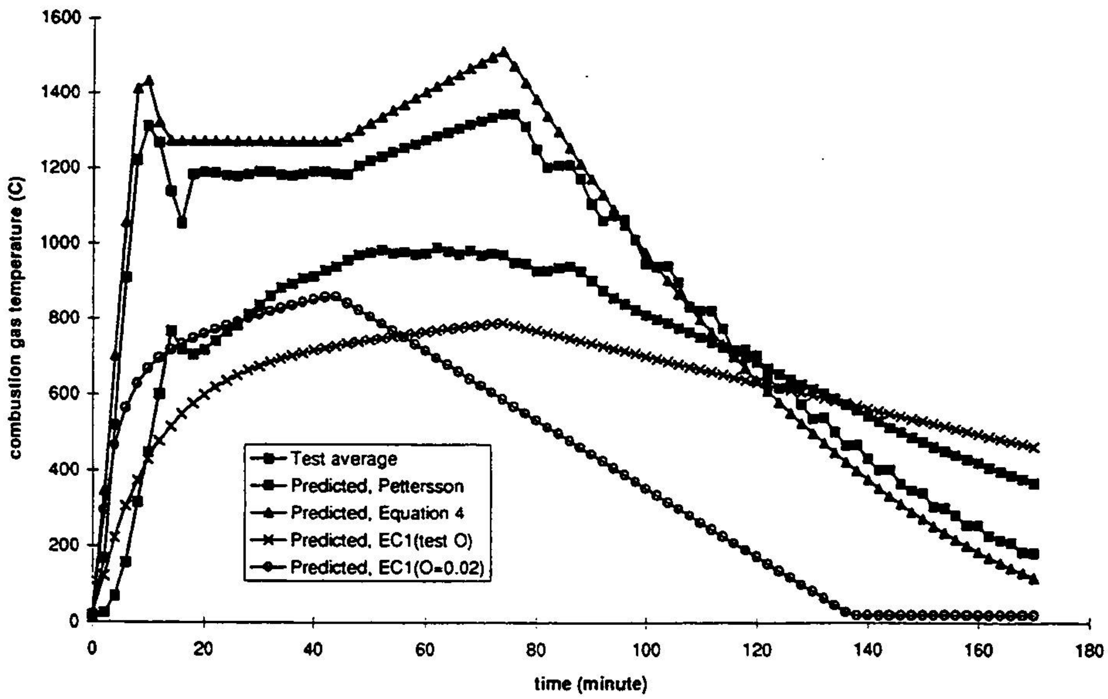

Figure 2: Comparison of combustion gas temperatures for BRE/BST Test 5

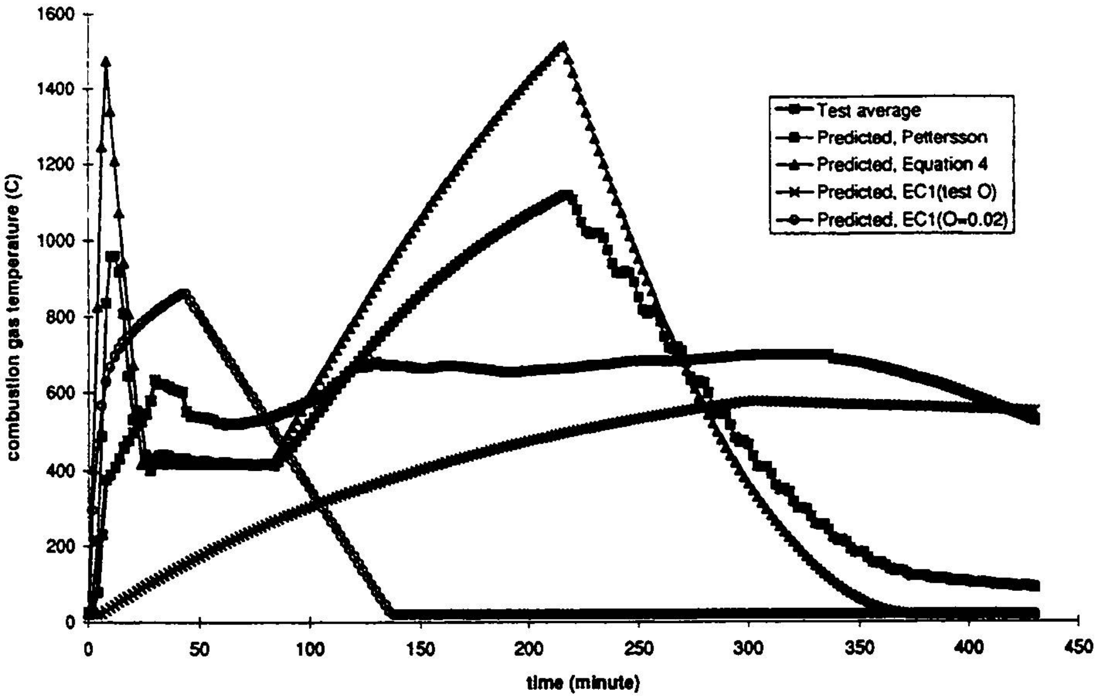

Figure 3: Comparison of combustion gas temperatures for BRE/BST Test 6

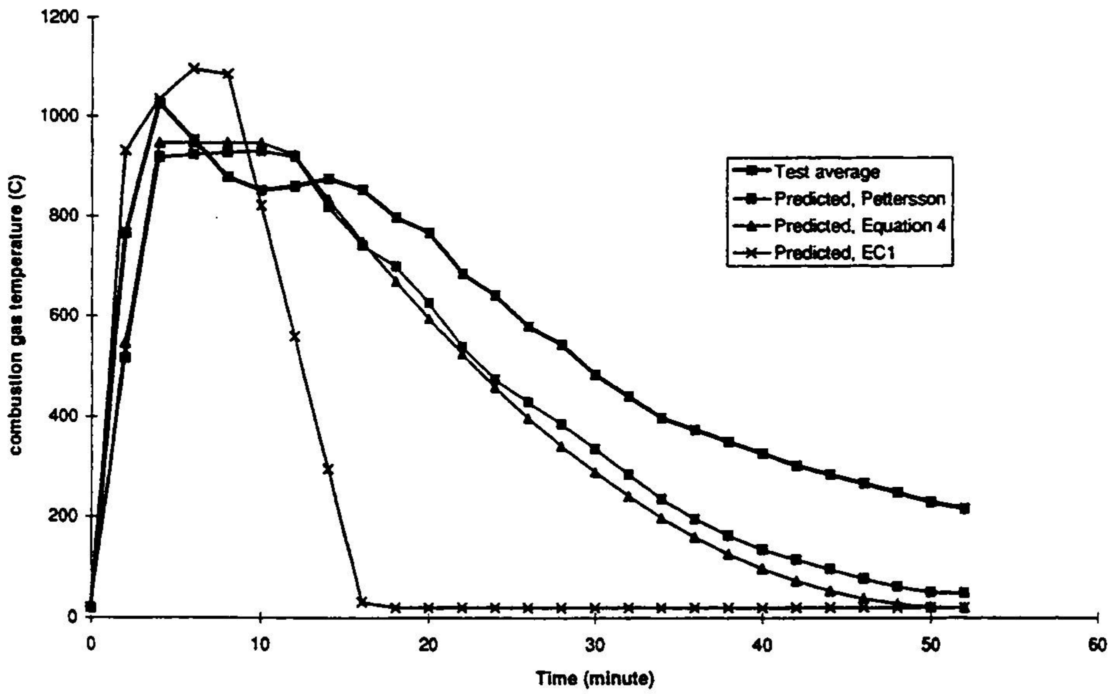

Figure 4: Comparison of combustion gas temperatures for BRE corner test

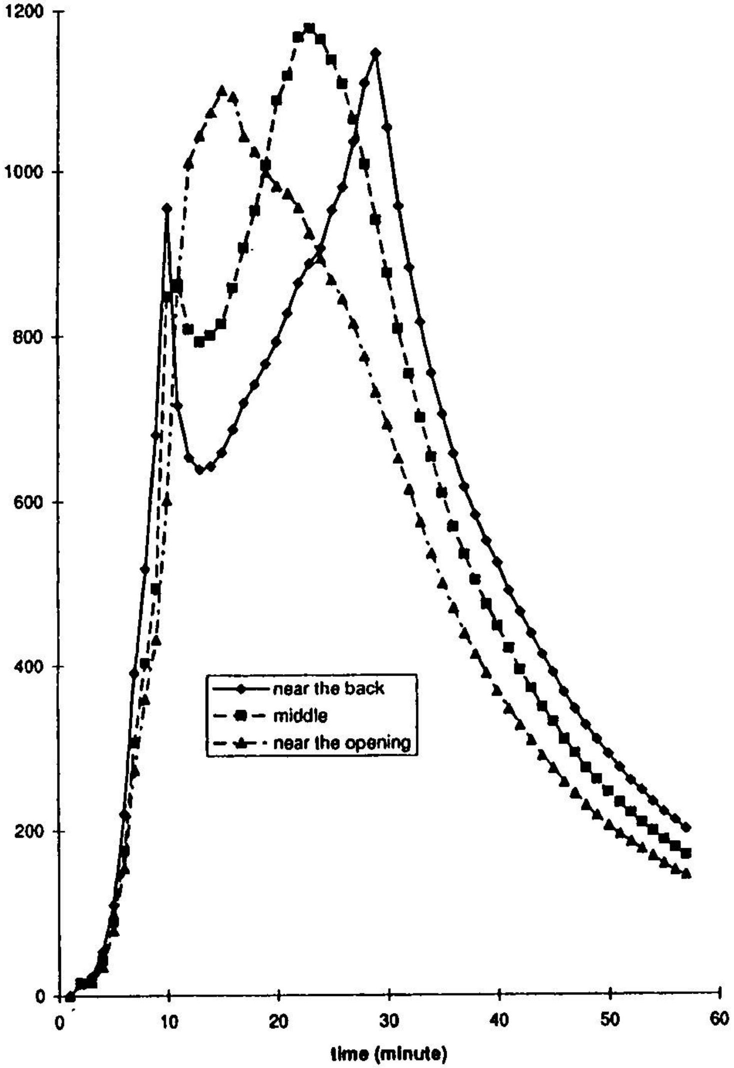

Figure 5: Combustion gas temperatures at three recording positions

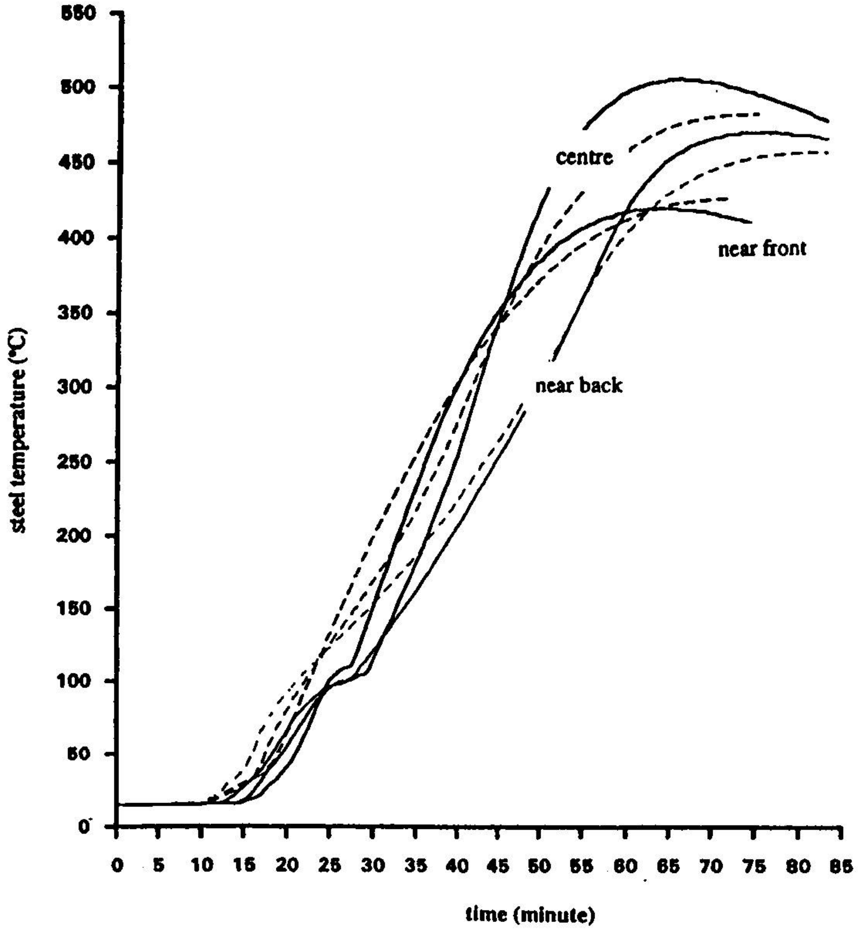

Figure 6: Measured and calculated steel temperatures, BRE/BST Test 2

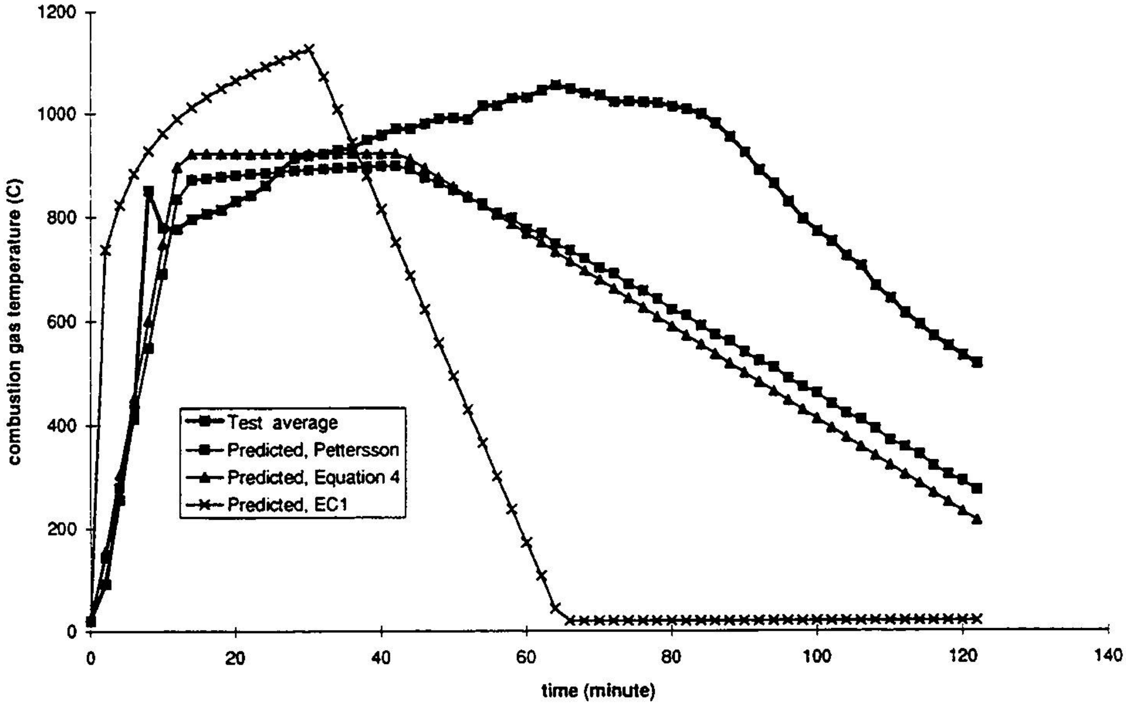

Figure 1: Comparison of combustion gas temperatures, BRE/BST Test 1

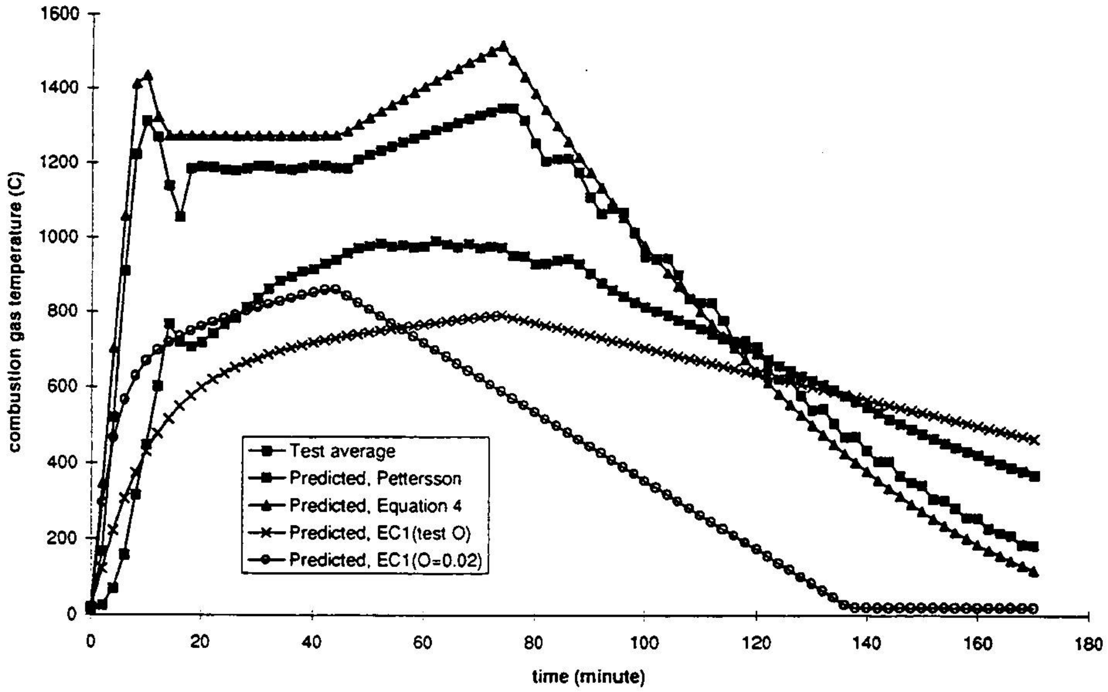

Figure 2: Comparison of combustion gas temperatures for BRE/BST Test 5

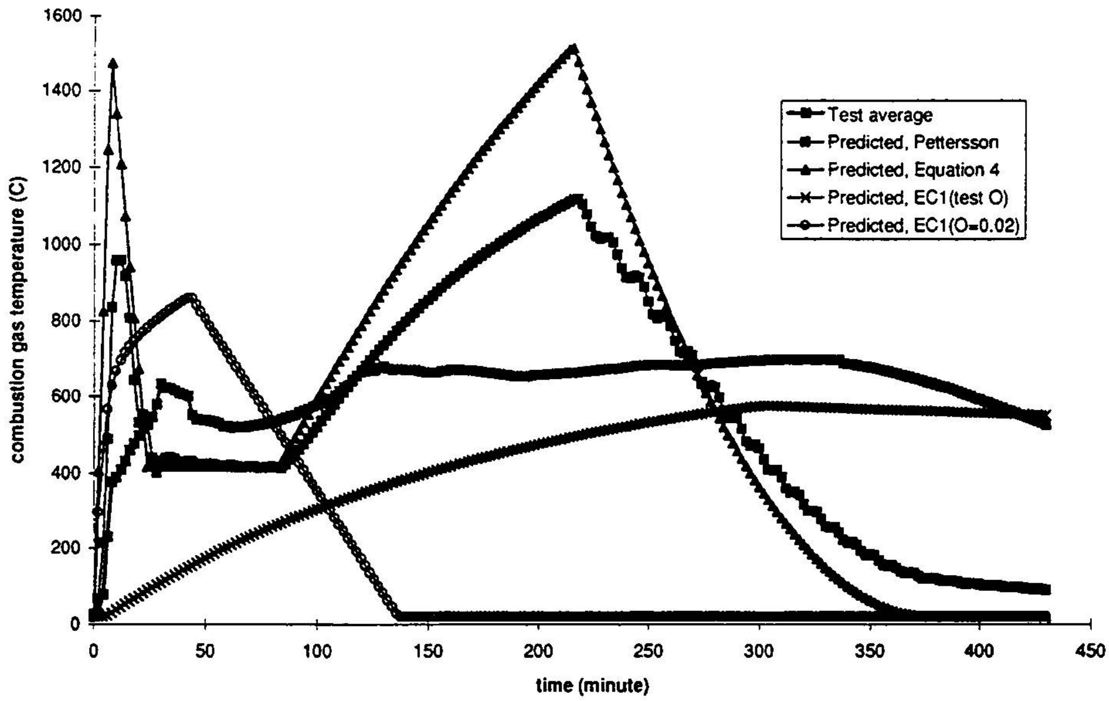

Figure 3: Comparison of combustion gas temperatures for BRE/BST Test 6

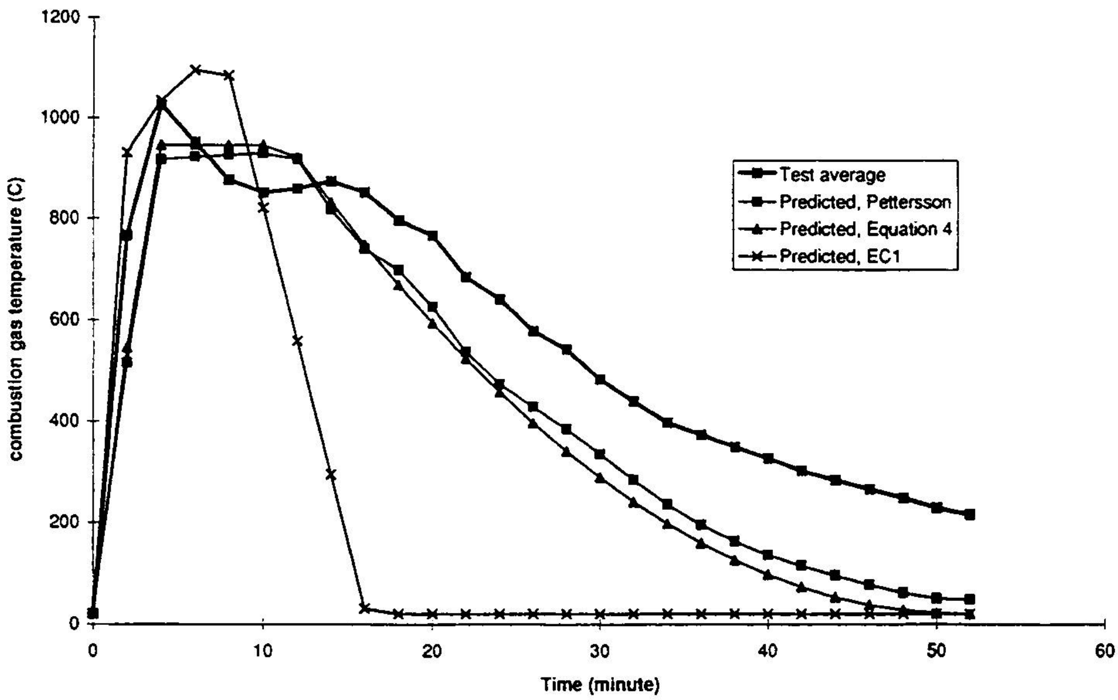

Figure 4: Comparison of combustion gas temperatures for BRE corner test

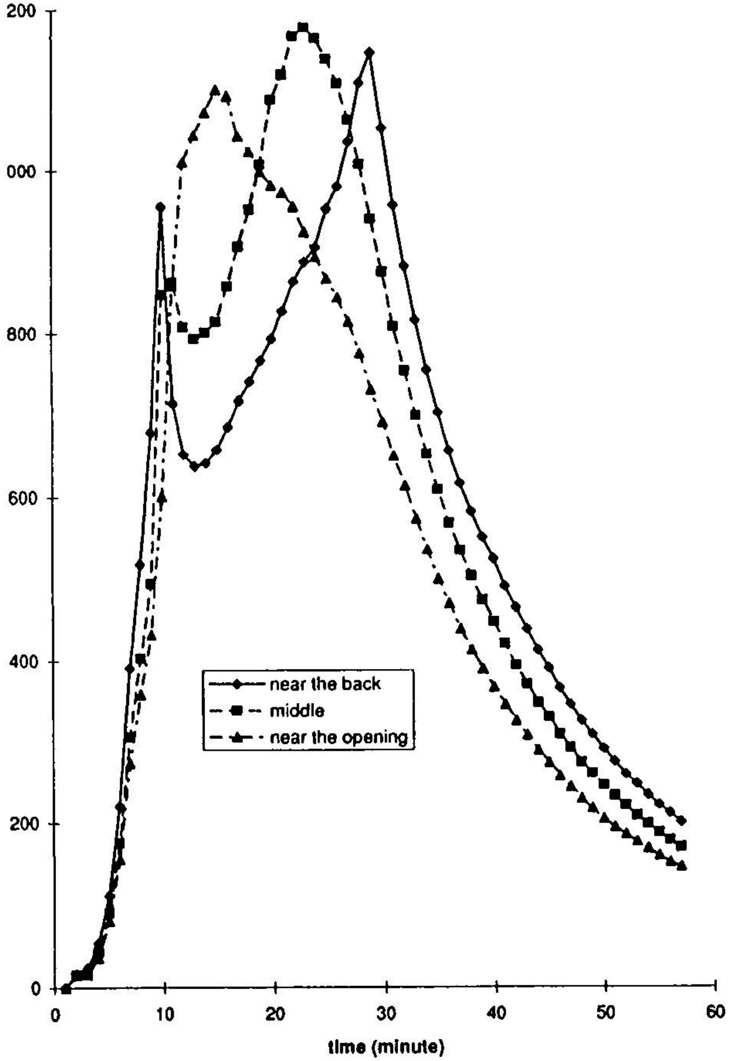

Figure 5: Combustion gas temperatures at three recording positions

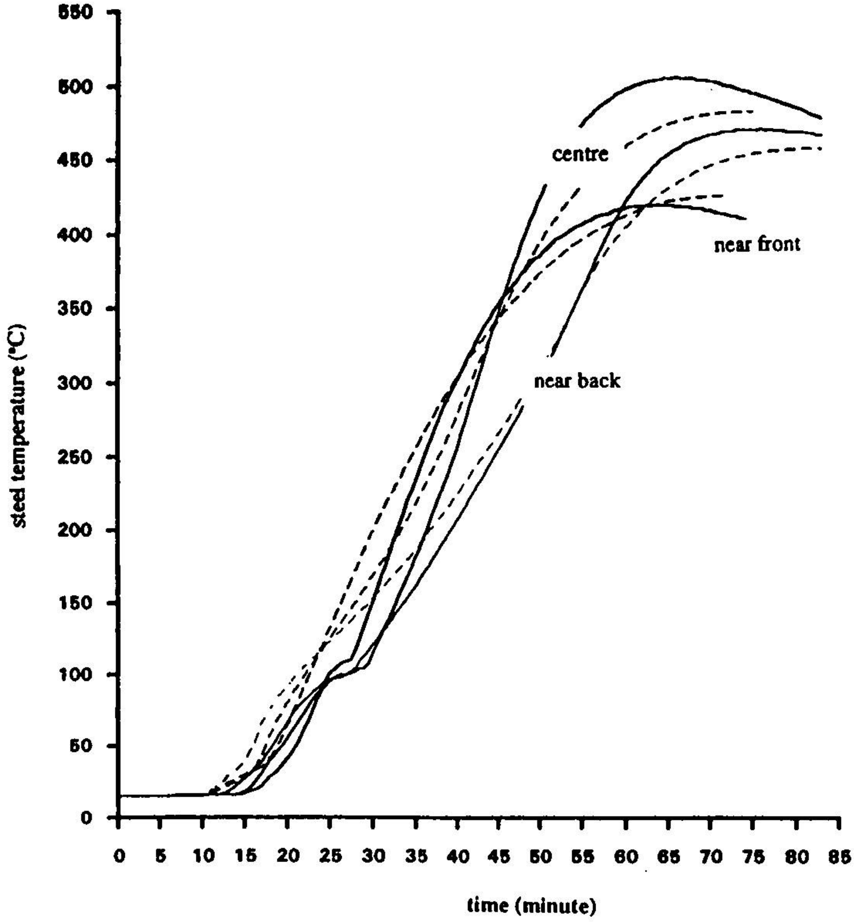

Figure 6: Measured and calculated steel temperatures, BRE/BST Test 2

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