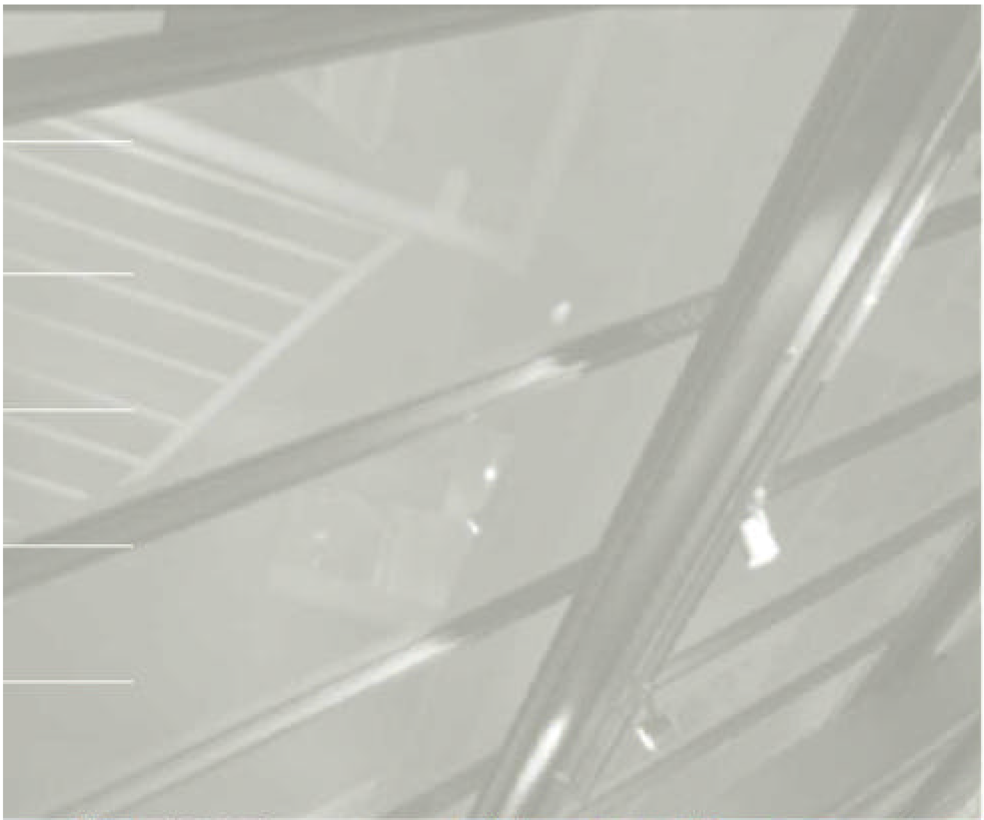


Client Report :

Results and observations from full-scale fire test at BRE Cardington, 16 January 2003

Client report number 215-741

Prepared for :

Mr J Dowling
Commercial Manager
Corus

February 2004

Prepared on behalf of BRE by

Signature	
Name	Mr T Lennon
Position	Principal Consultant

Approved on behalf of BRE by

Signature	
Name	Dr D B Moore
Position	Director
Date	

BRE
Construction Division
Bucknalls Lane
Garston
Watford
WD25 9XX

Tel : 01923 664200
Fax : 01923 664096

Email : construction@bre.co.uk
Website : www.bre.co.uk

Executive Summary

This report has been prepared for Mr J Dowling of Corus Construction following discussions with Dr D B Moore of the Centre for Structural and Geotechnical Engineering, BRE. This document and the associated CDs details the results and observations from a full-scale fire test carried out on the steel-framed building at Cardington in January 2003. The data is presented in a form suitable for subsequent analysis and interpretation by others.

Contents

Introduction	1
Description of the test	4
Instrumentation locations and channel allocation	8
Detailed test results	37
References	52
Appendix A – Imposed load	
Appendix B - Fire design parameters	

Introduction

This report has been prepared at the request of Mr J Dowling of Corus Construction to document the results and observations from a full-scale fire test carried out on the steel framed building at BRE's Cardington laboratory in January 2003. Corus Construction are interested in gaining access to the test results in order to further develop their understanding of the behaviour of steel structures in fire and to promote the effective use of steel in construction. The test took place as a result of a collaborative research project between BRE, the University of Prague, the University of Coimbra and the University of Bratizlava. Funding was provided through the European Commission through a training programme and additional support was provided by the Association for Specialist Fire Protection (ASFP).

The information from the test is summarised in this report with the detailed results and observations included on the associated CDs. For the purposes of subsequent interpretation and analysis of the data the format of the report is as follows:

- Description of the test – This includes the specification of the relevant parameters in terms of compartment location and geometry, extent and nature of protected elements, fire design scenario including fire load density and ventilation conditions.
- Instrumentation locations and channel allocations – Drawings showing the location of the instrumentation used to monitor the thermal and structural response of the building are provided together with an associated channel allocation allowing researchers to identify the relevant instrument from the raw and processed data. This document provides a road map to access the drawings and excel files included in the associated CDs.
- Detailed test results – Both the raw and processed data files are included on the associated CDs. Indicative graphical output is provided in the form of excel files dealing with:

  compartment time-temperature response

  temperature distribution through structural members

  vertical and horizontal displacements of the steel members and the composite floor slab

  strain in the structural elements

  strain in the reinforcement and the surface of the slab

- Audio-visual record – All photographs are allocated descriptive titles and assigned to either pre-test, during the test or post-test categories.

Table 1 below provides a road map to access the relevant files included on the associated CD (CD1).

Directory	Filename	Description
Raw data/burn	Dis.dat	Displacement test data files – raw data
Raw data/burn	Str.dat	Strain test data files – raw data
Raw data/burn	TC1.dat	Temperature test data – raw data for channels 401-475
Raw data/burn	TC2.dat	Temperature test data – raw data for channels 477-557
Raw data/cool	Dis.dat	Displacement cool down data – raw data
Raw data/cool	Str.dat	Strain cool down data – raw data
Raw data/cool	TC1.dat	Temperature cool down data – raw data for channels 401-475
Raw data/cool	TC2.dat	Temperature cool down data – raw data for channels 477-557
Excel	Displacements_Raw_data.xls	All displacement data – excel file
Excel	Strains_Raw_data.xls	All strain data – excel file
Excel	Temperatures_Raw_data.xls	All temperature data – excel file
Chanal	revCopy of Logger sheet Displacement v3.xls	Channel allocation – displacements
Chanal	revCopy of Logger sheet Gauges v9.xls	Channel allocation - strains
Chanal	revCopy of Logger sheet Thermocouples final-version.xls	Channel allocation - temperatures
AV/pre-test	*.jpg	All photographs related to activities preceding the fire test
AV/test	*.jpg	All photographs related to activities during the test
AV/post-test	*.jpg	All photographs related to damage following the test
AV/presentations	Frantisek.ppt	Powerpoint presentations

Table 1 “Road map” for accessing the CD1

Description of the test

The test was carried out as part of a European collaborative research project "tensile membrane action and robustness of structural steel joints under natural fire" (EC FP5 HPRI – CV5535). The objective of the project was to investigate the global structural integrity of a realistic fire compartment within a real building subject to realistic levels of imposed load and a natural fire. Specific objectives were to determine the temperature distribution in the structural elements and connections, the internal forces in the connections and the transfer of forces through the composite slab.

The detailed construction of the 8 storey steel framed building at Cardington is very familiar to the client and has been the subject of a number of other papers[1, 2]. It is therefore not discussed in this report.

Test Compartment

The fire test was undertaken on the 4th floor of the building (fire load on the third floor) in an area measuring 11m by 7m in plan. The location of the compartment on the building is illustrated in figure 1 below.

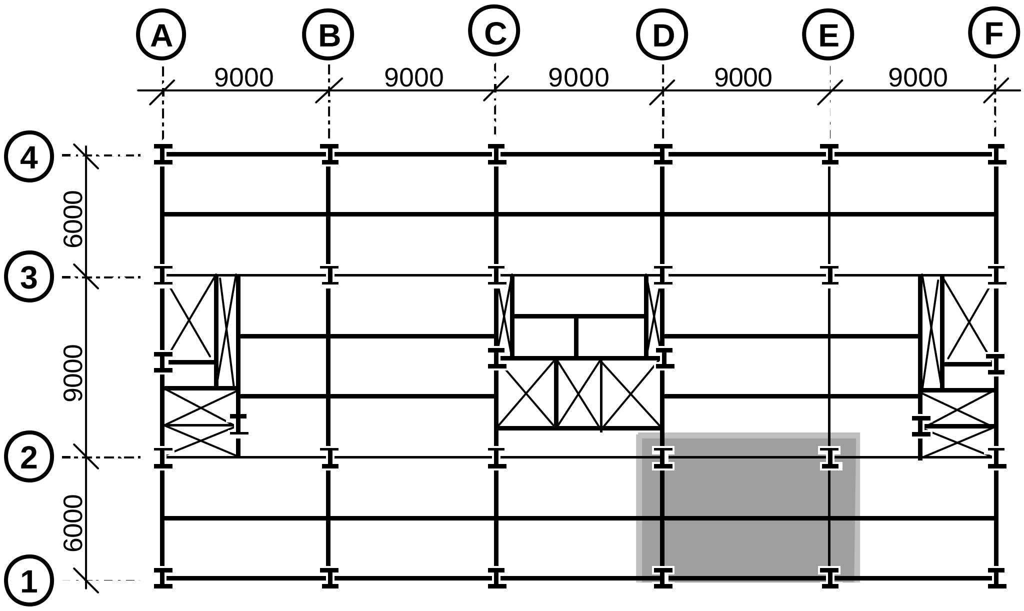


Figure 1 Location of test compartment

The compartment was formed using three layers of plasterboard (15mm+12.5mm+15mm) with a thermal conductivity of between 0.19 and 0.24 W/mK on three sides of the test area. Over the existing window opening a single layer of fire resistant plasterboard of full height (2.4m) was fixed to the existing 0.9m high dado wall to contain the fire within the test area. An allowance of approximately 500mm was made for vertical deformation of the floor slab above the compartment walls. The gap between the top of the compartment wall and the underside of the floor slab was sealed using ceramic fibre blanket which prevented the escape of flames and hot gases whilst allowing unrestricted vertical deflection of the floor slab. The situation is illustrated in figure 2 and 3 below.

Figure 2 Compartment wall parallel to gridline E – external and internal view

Figure 3 Fireline plasterboard over window opening

Mechanical Load

The imposed load was simulated using sandbags each weighing 110kN applied over an area of 18m by 10.5m on the 5^{th} floor. The location and distribution of sandbags on the fifth floor is illustrated in figure 4 below. The complete layout of the applied load on the floors above the fire compartment is illustrated in Appendix A. Together the self load of the structure and the sandbags represent 100% of the permanent actions (dead load), 100% of the variable permanent actions (partitions and services) and 56% of the live load. This is considerably higher than the value of load adopted in the previous full-scale fire tests undertaken on this structure.

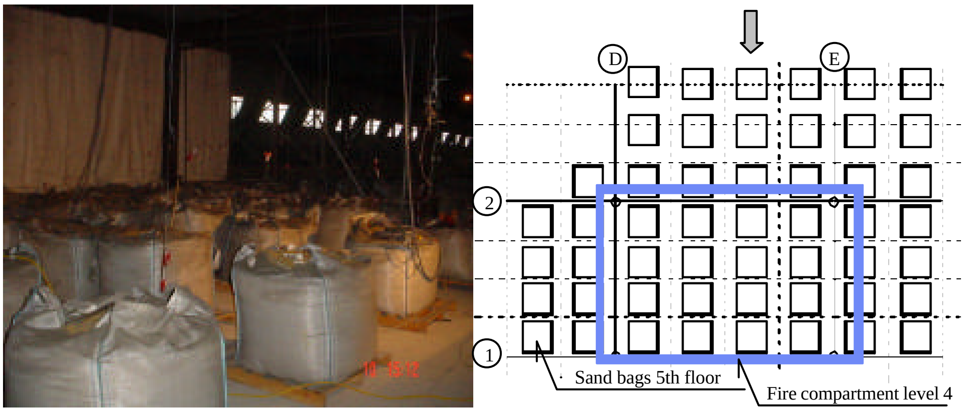


Figure 4 Sandbag layout on 5^{th} floor

Fire Load

The fire load was provided by 40 kg of wood per m^2 of floor area in the form of wooden cribs (average moisture content < 14 %) placed in a uniform manner within the test area. The ventilation area consisted of a single opening 1.27 m high and 9 m in length. The original open area was reduced to give rise to a fire of sufficient duration and temperature to provide the required thermal input to the structural members. The fire design parameters are summarised in Appendix B which also includes the predicted time-temperature response according to the latest version of the fire part of the Eurocode for Actions[3]. The ventilation opening and the wooden cribs are shown in figure 5 below.

Figure 5 Restricted ventilation and fire load

Protection to structural elements

All columns were protected using CAFCO C300 sprayed fire protection for a 90 minute fire resistance period based on a limiting temperature of 550°C. The incorporation of two perimeter columns within the fire compartment allowed for two different methods of protection. One of the columns was protected with the thickness based on the Yellow Book[4] on all faces while the other utilised the same amount of material in total although it was only applied on three sides with the external flange remaining unprotected. The unprotected face can be clearly seen in figure 3.

The internal columns (D2 and E2) had protection applied up to the underside of the connecting beams with the actual connection area remaining unprotected. This situation is illustrated in figure 6 below. The perimeter columns were protected full height up to and including the connection and also for a short length of the connecting beams to look at the need for "coatback" where unprotected members frame into protected members. This situation is illustrated in figure 7 below.

Figure 6 Internal column (D2) protection to underside of connecting beams

Figure 7 Perimeter column protection including connections and "coatback" length

Instrumentation locations and channel allocation

Approximately 300 individual instruments were used to record the thermal and structural response of the building throughout the test and for a considerable period following the test. In order to evaluate and analyse the data it is necessary to uniquely locate each instrument and to refer the location back to the channel allocation in the data files. A series of drawings have been produced to identify the positions of the individual instruments within the building (both in plan and, where appropriate, on the cross-section). The channel allocations are classified according to the type of response being measured i.e. strain, displacement and temperature and refer to the figures for reference. In this way it should be possible for researchers to identify both the location of the measuring device and the type of instrument referred to in order to interrogate the data files.

Table 2 below shows which drawings relate to the measurement of strain, displacement and temperature respectively.

Type of measurement	Drawing reference
Strain	8,9,10,11,13,16,17
Displacement	18,19
Temperature	8,9,10,11,12,14,15,20

Table 2 Relationship between drawings and type of measurement

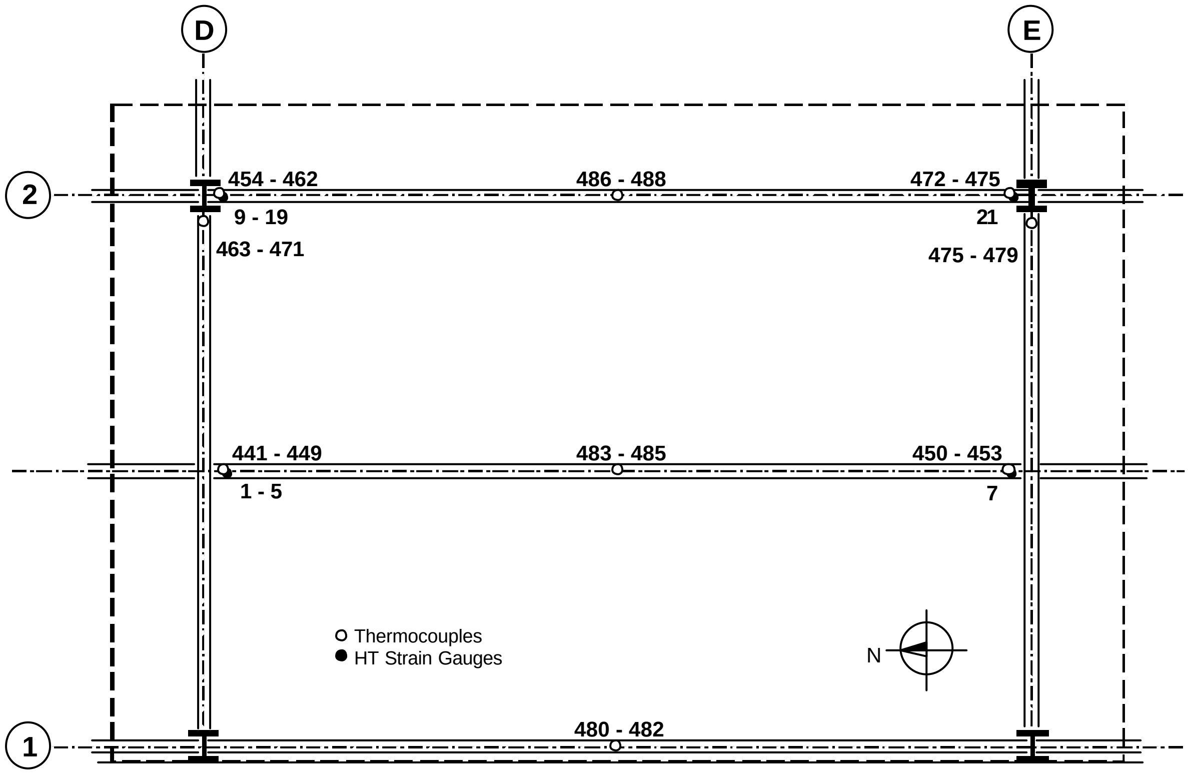


Figure 8 instrument locations beams and connection details general view on third floor

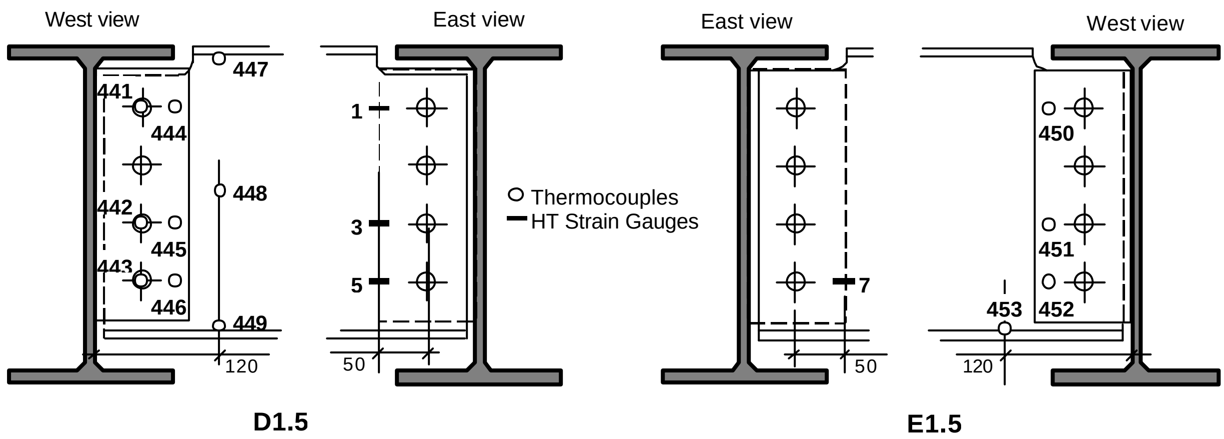


Figure 9 instrument locations fin plate connections

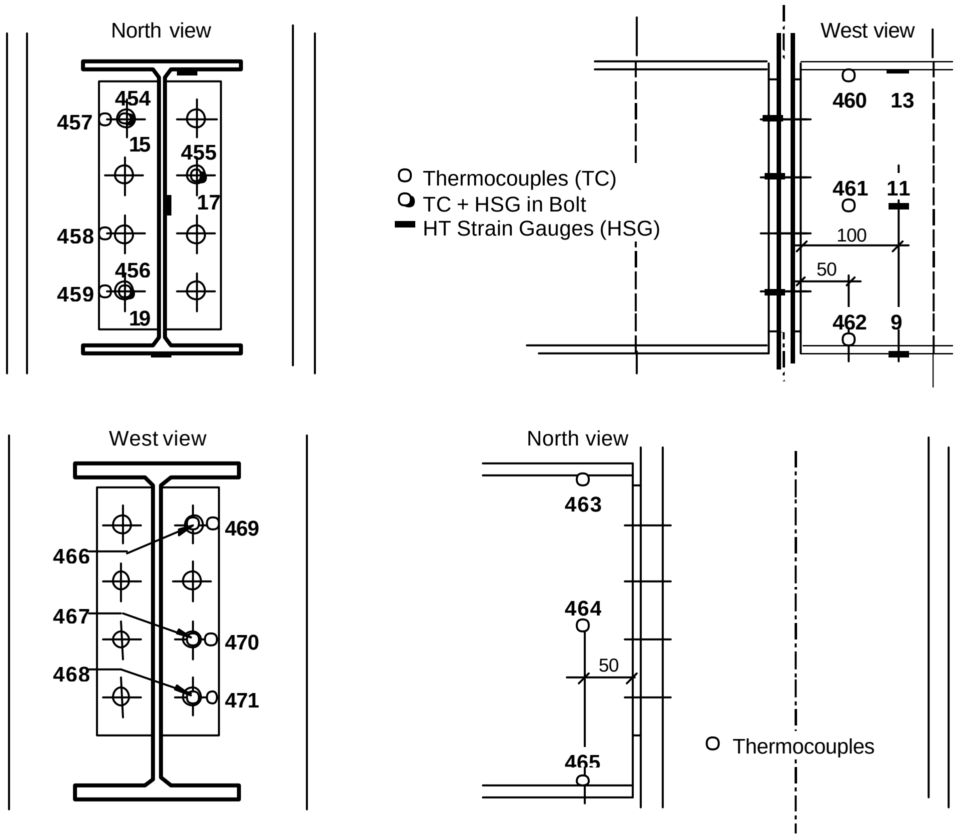


Figure 10 Partial depth end plate connections (D2)

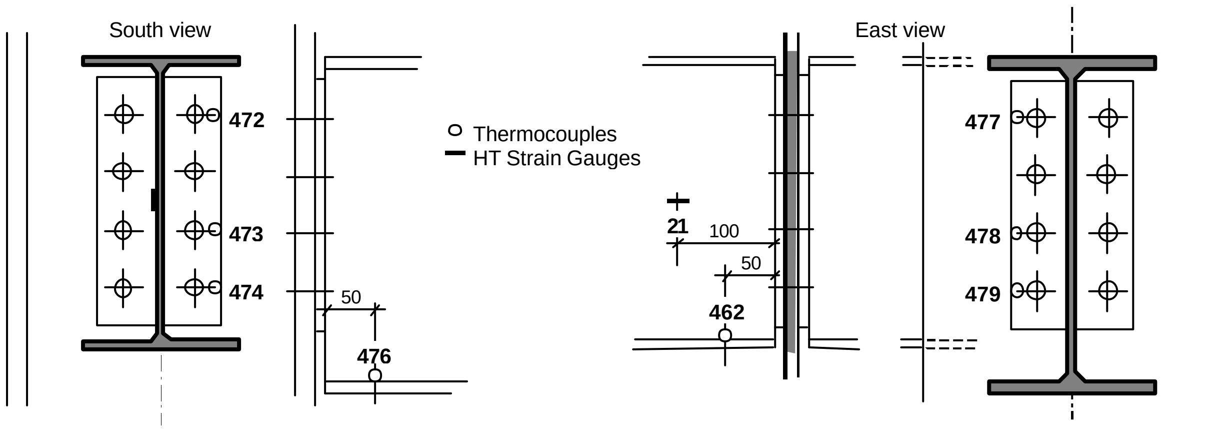


Figure 11 Partial depth end plate connections (E2)

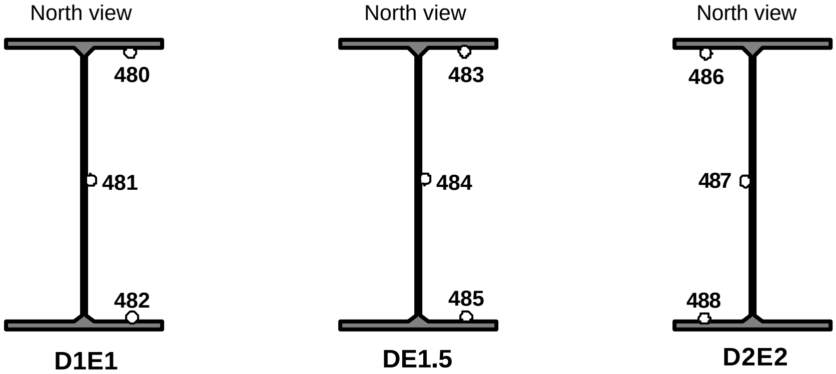


Figure 12 instrument locations – mid-span beam thermocouples (D1E1; DE1.5; D2E2)
NB flange thermocouples mid-way between edge of flange and flange/web junction

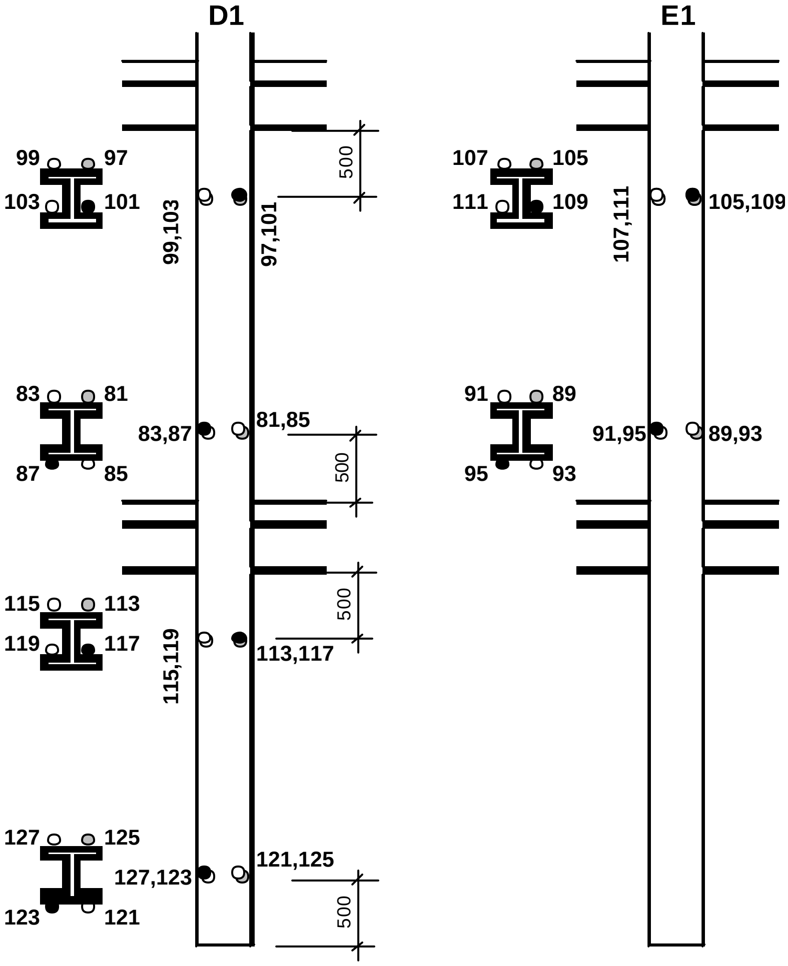


Figure 13 instrument locations – strain gauges in columns (centre line of strain gauges 10mm from edge of column flange)

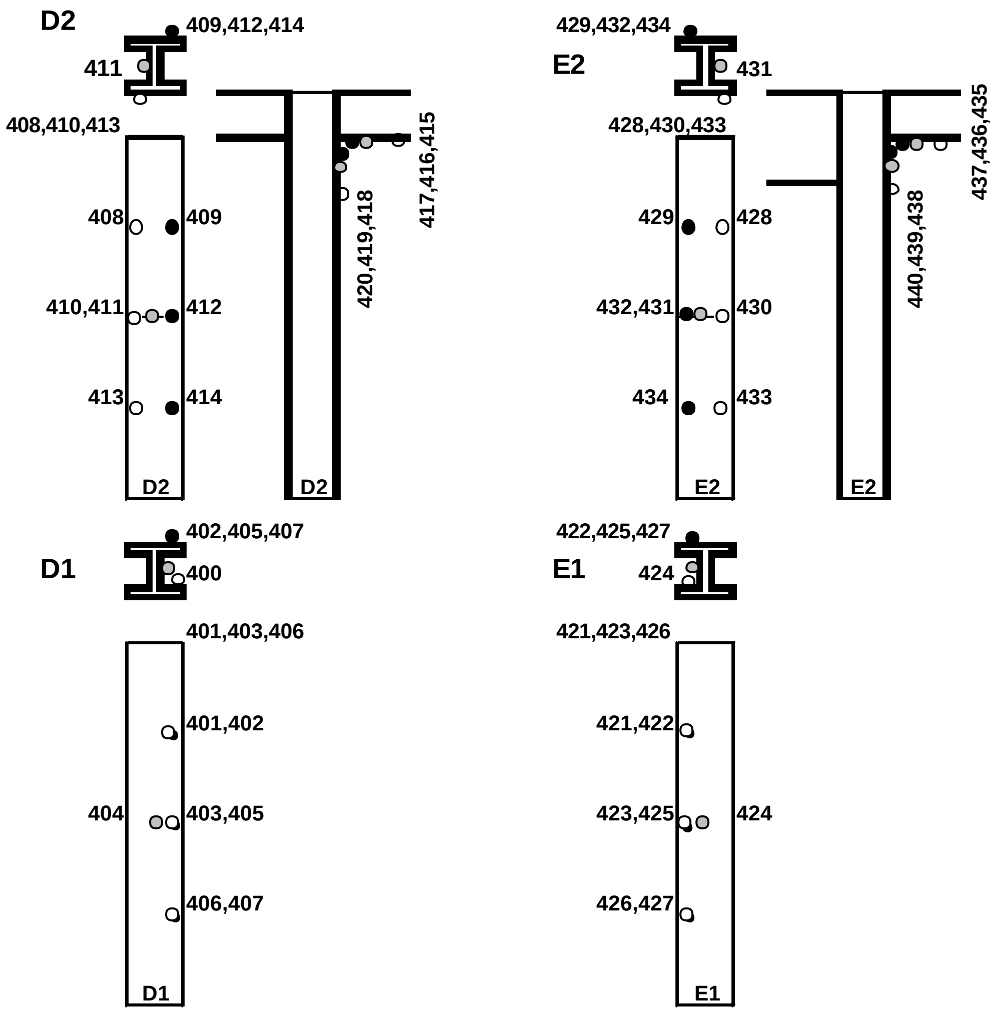


Figure 14 Location of thermocouples in columns (flange thermocouples mid-way between edge of flange and flange/web junction)

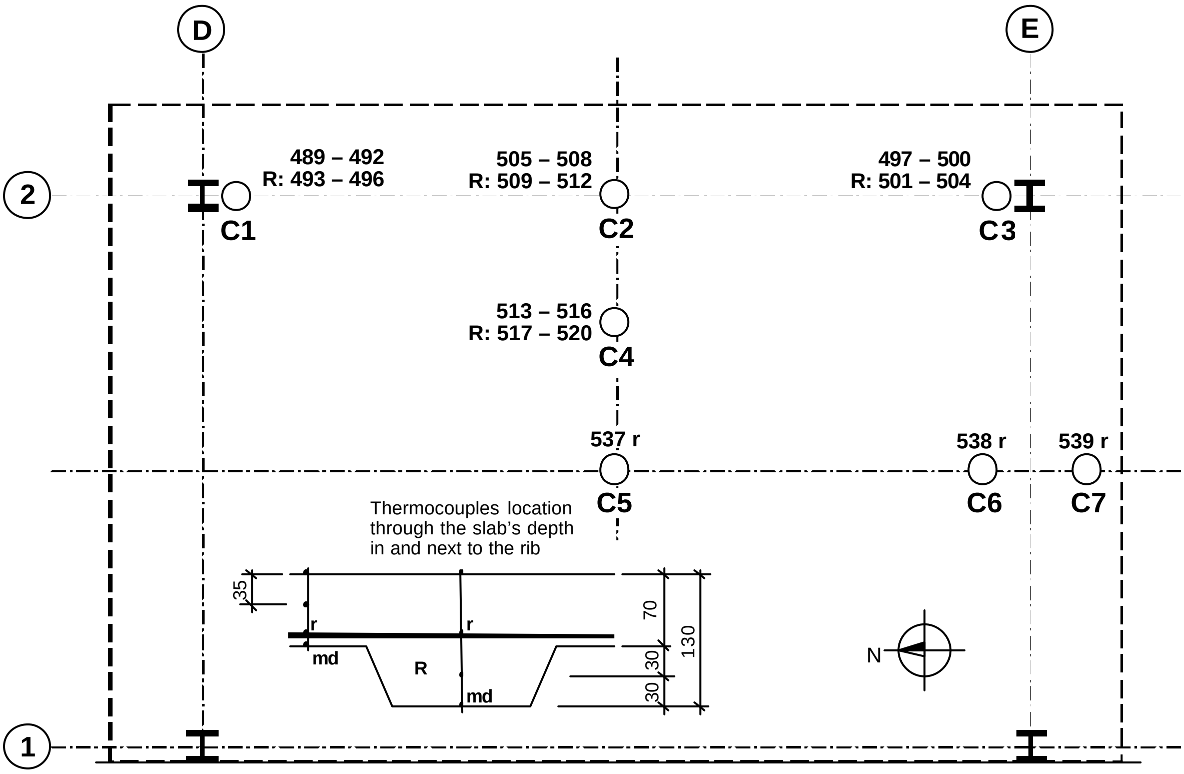
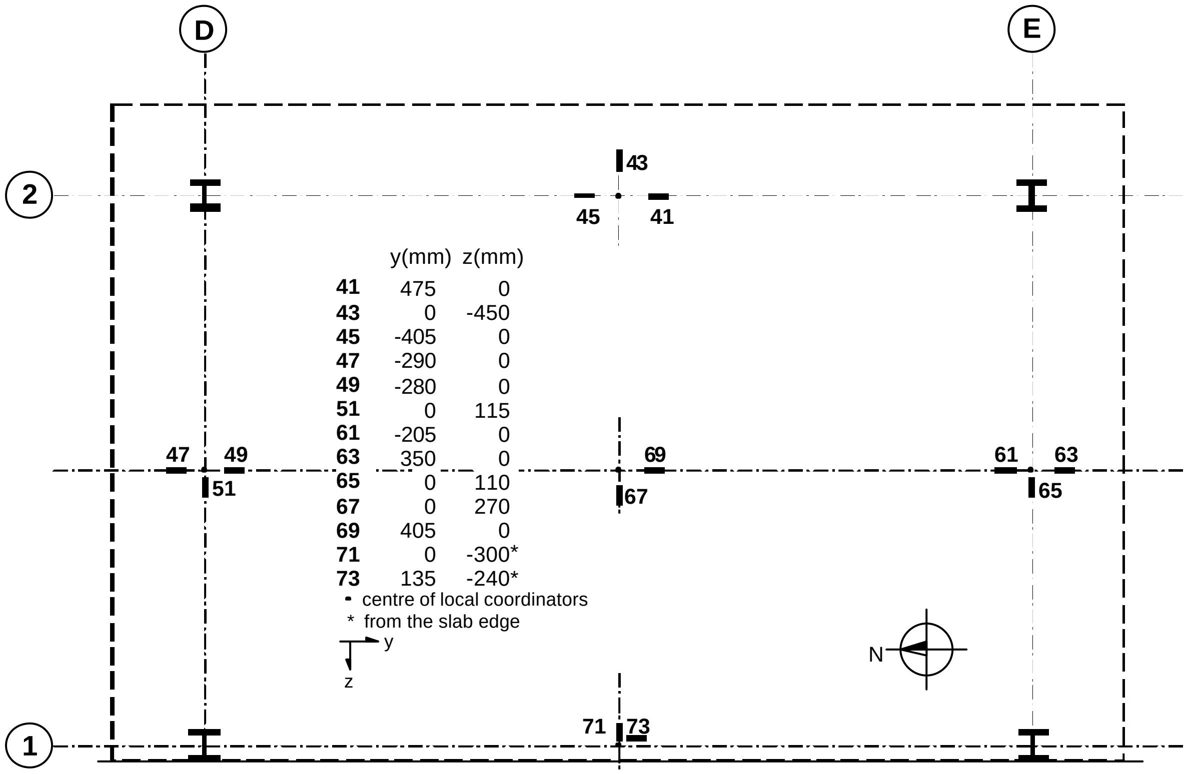


Figure 15 Location of thermocouples in slab 4th floor (centre of cavity 50mm from local co-ordinate system – see figure 17)



	y(mm)	z(mm)
41	475	0
43	0	-450
45	-405	0
47	-290	0
49	-280	0
51	0	115
61	-205	0
63	350	0
65	0	110
67	0	270
69	405	0
71	0	-300*
73	135	-240*

Figure 16 Location of strain gauges in slab 4th floor

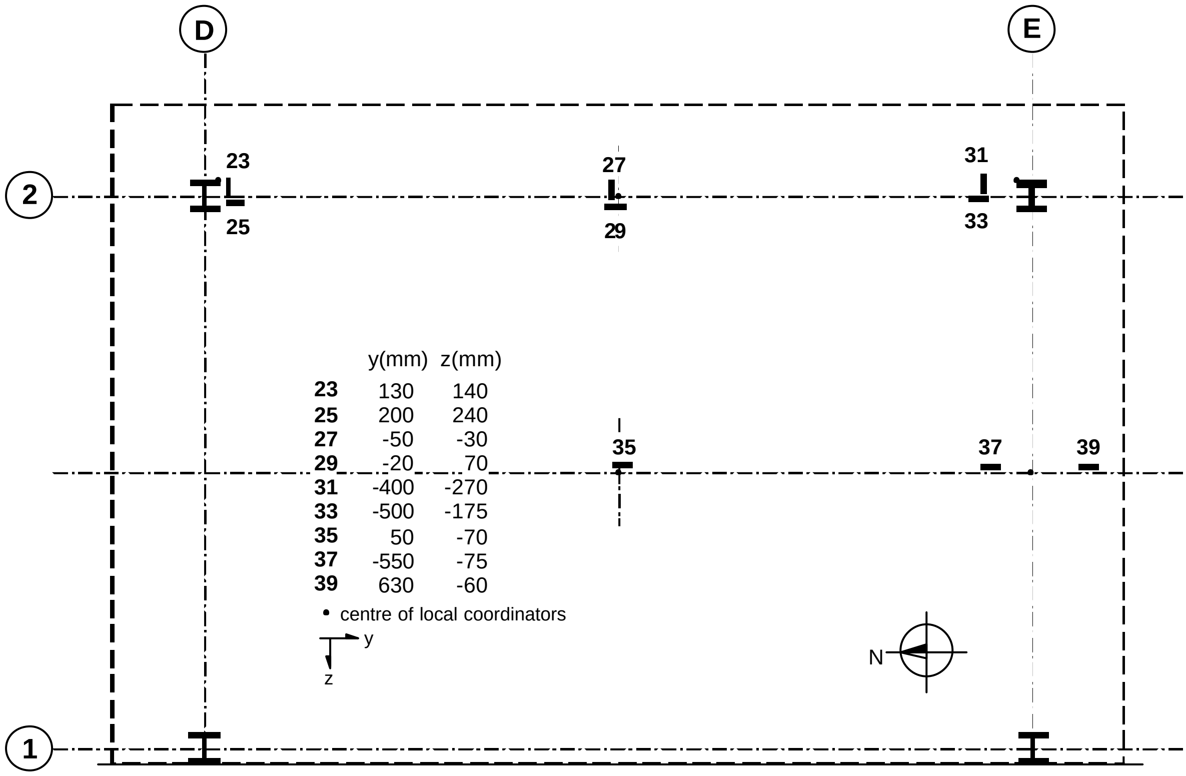


Figure 17 Location of strain gauges in reinforcing mesh 4th floor

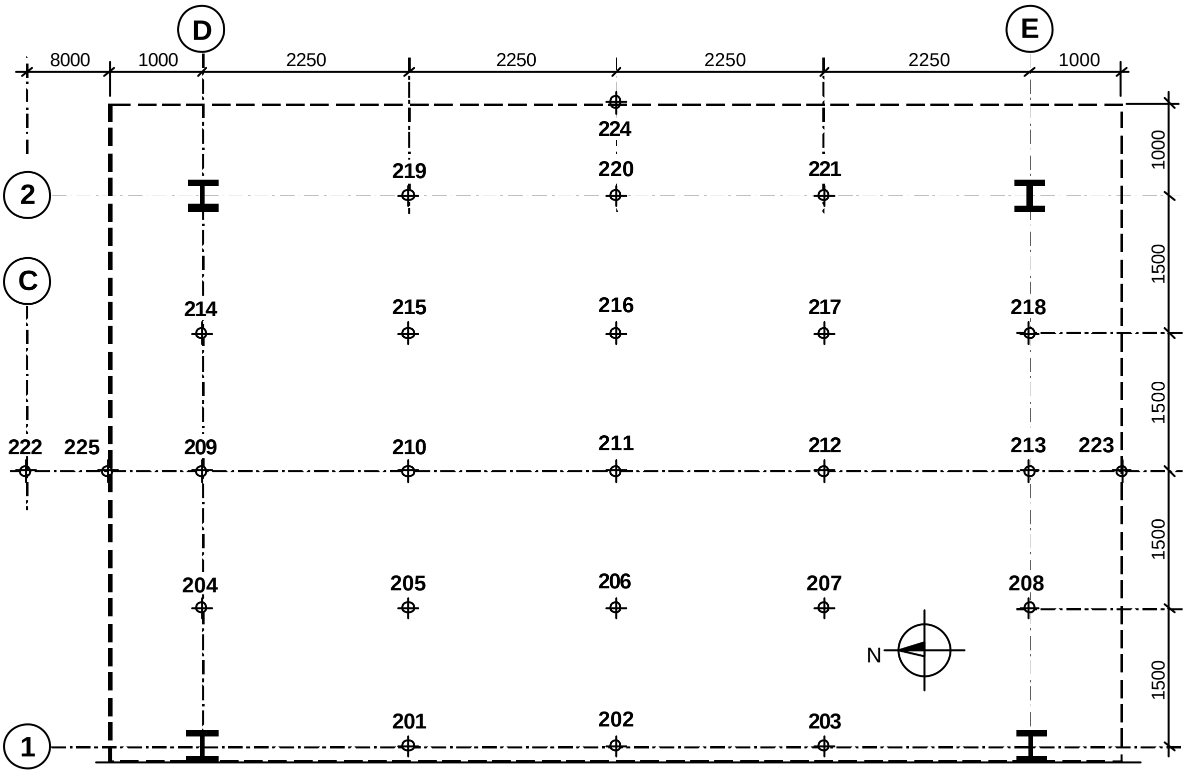


Figure 18 Location of vertical displacements 4th floor slab

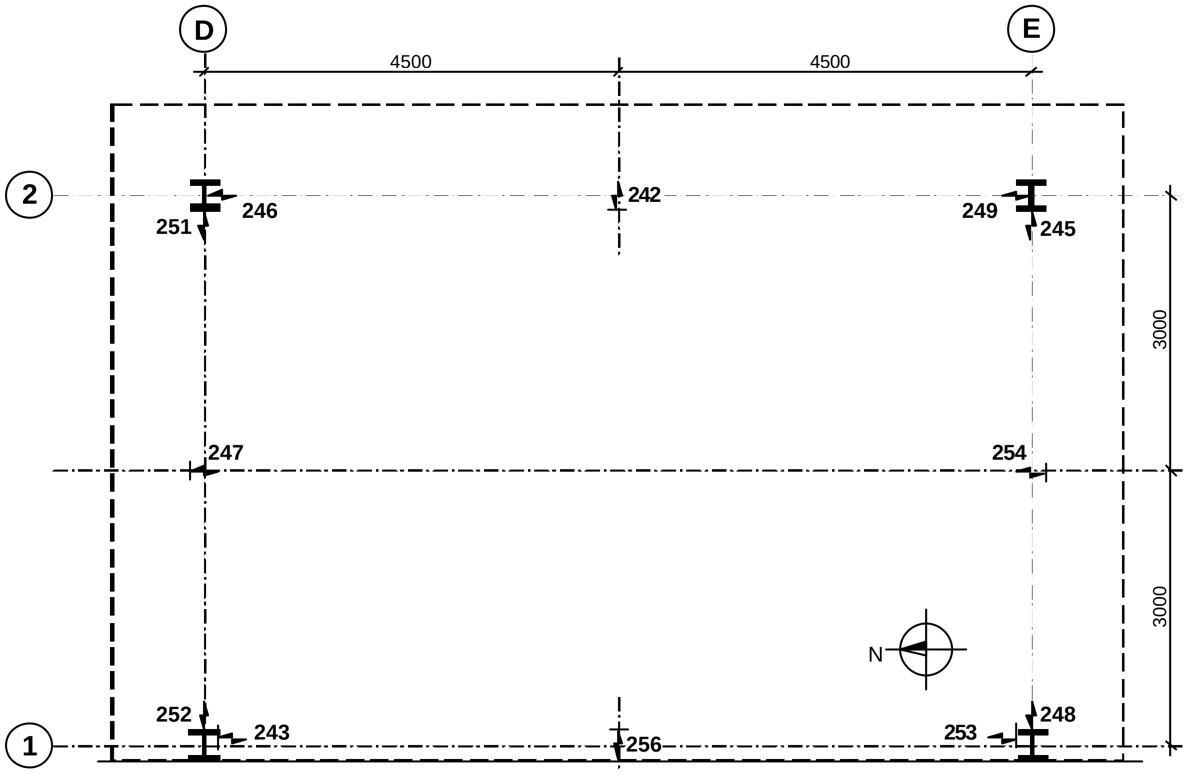


Figure 19 Location of horizontal displacements – 4th floor slab (measurements taken from RHS laid on floor slab – measurement position approximately 300mm from surface of slab)

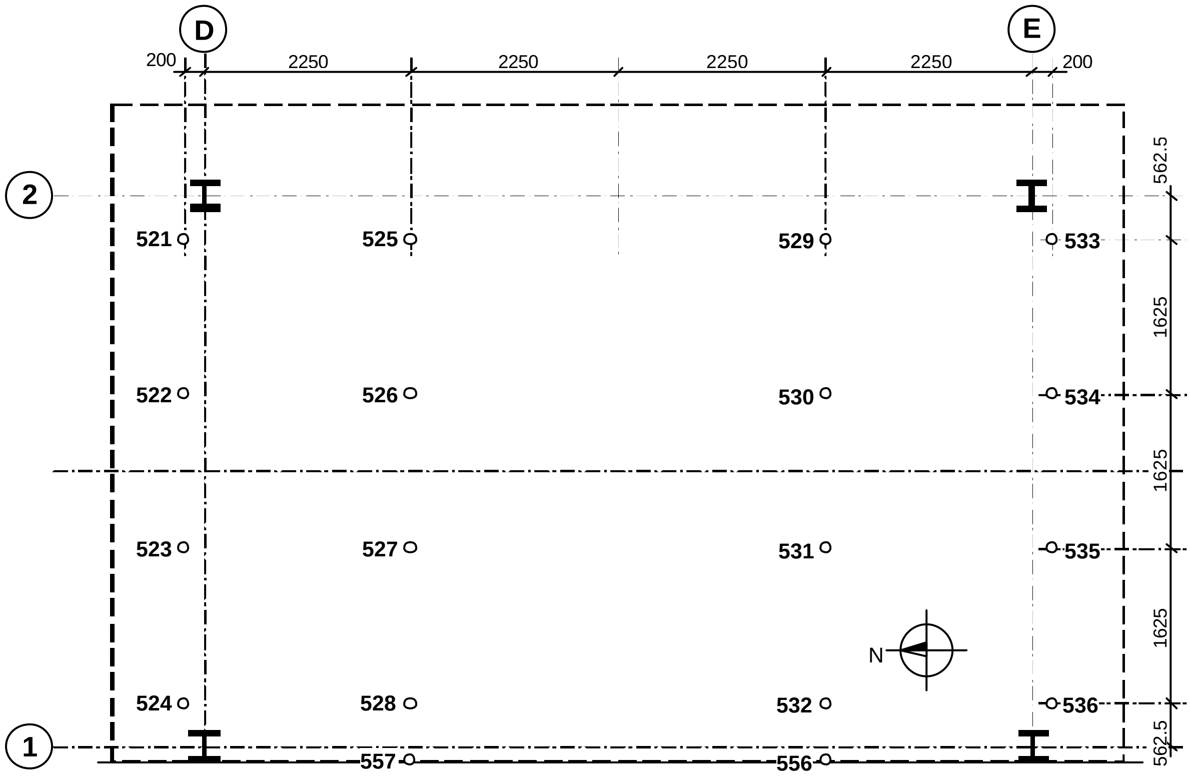


Figure 20 Location of atmosphere thermocouples in compartment 300mm below ceiling

The channel allocations contain all the information required (used together with the drawings above) to interrogate the data files strain.xls, displacements.xls, temperature.xls included in the associated CD. For each of the data files the data has been investigated to identify missing/erroneous data. In the final column of the channel allocation an "X" relates to data that is either not present or is clearly not reading from the outset of the test. A "?" identifies a possible problem with the data but this may have been a problem which occurred during the test (e.g. instrument over range, cables burnt through) but does not necessarily invalidate the readings for the entire period of the test. It can clearly be seen that the vast majority of instruments are providing reliable results for the duration of the test.

Logger Channel	Card Channel	Drawing Ref	Gauge Resistance	Location Key	Gauge Factor	User Dummy	Comments	OK
1	1	fig 8,9		D1.5	1.36		Fin plate, SE side aligned with the 1st bolt row	
3	3	fig 8,9		D1.5	1.36		Fin plate, SE side aligned with the 3rd bolt row	
5	5	fig 8,9		D1.5	1.36		Fin plate, SE side aligned with the 4th bolt row	
7	7	fig 8,9		E1.5	1.36		Fin plate, NE side aligned with the 4th bolt row	X
9	9	fig 8,10		Beam D2-E2	1.36		Center of bottom flange 100 mm from D2	
11	11	fig 8,10		Beam D2-E2	1.36		E side of web centre 100 mm from D2	
13	13	fig 8,10		Beam D2-E2	1.36		E upper flange 100 mm from D2	X
15	15	fig 8,10		D2	1.36		W bolt of 1st bolt row	
17	17	fig 8,10		D3	1.36		E bolt of 2nd bolt row	
19	19	fig 8,10		D4	1.36		W bolt of 4th bolt row	

Table CA1 Strain gauges

Logger Channel	Card Channel	Drawing Ref.	Gauge Resistance	Location Key	Gauge Factor	User Dummy	Comments	OK
21	1	fig 6,9		Beam D2-E2	1.36		E middle of web 100 mm from E2	
23	3	fig 15,17	120	Cavity C1	2.1		Slab reinforcement WE direction	
25	5	fig 15,17	120	Cavity C1	2.1		Slab reinforcement NS direction	
27	7	fig 15,17	120	Cavity C2	2.1		Slab reinforcement WE direction	
29	9	fig 15,17	120	Cavity C2	2.1		Slab reinforcement NS direction	
31	11	fig 15,17	120	Cavity C3	2.1		Slab reinforcement WE direction	
33	13	fig 15,17	120	Cavity C3	2.1		Slab reinforcement NS direction	
35	15	fig 15,17	120	Cavity C5	2.1		Slab reinforcement NS direction	
37	17	fig 15,17	120	Cavity C6	2.1		Slab reinforcement NS direction	
39	19	fig 15,17	120	Cavity C7	2.1		Slab reinforcement NS direction	

Table CA2 Strain Gauges

Logger Channel	Card Channel	Drawing Ref	Gauge Resistance	Location Key	Gauge Factor	User Dummy	Comments	OK
41	1	fig 16	120	DE2 slab	2.1		NS direction S of axis, 60 mm gauge	
43	3	fig 16	120	DE2 slab	2.1		WE direction E of axis, 60 mm gauge	
45	5	fig 16	120	DE2 slab	2.1		NS direction N of axis, 60 mm gauge	
47	7	fig 16	120	D12 slab	2.1		NS direction N of axis, 70 mm gauge	
49	9	fig 16	120	D12 slab	2.1		NS direction S of axis, 70 mm gauge	
51	11	fig 16	120	D12 slab	2.1		WE direction W of axis, 70 mm gauge	
53	13							
55	15							
57	17							
59	19							

Table CA3 Strain gauges

Logger Channel	Card Channel	Drawing Ref	Gauge Resistance	Location Key	Gauge Factor	User Dummy	Comments	OK
61	1	fig 16	120	E12 slab	2.1		NS direction N of axis, 70 mm gauge	
63	3	fig 16	120	E12 slab	2.1		NS direction S of axis, 70 mm gauge	?
65	5	fig 16	120	E12 slab	2.1		WE direction W of axis, 70 mm gauge	
67	7	fig 16	120	DE1.5 slab	2.1		WE direction W of axis, 70 mm gauge	X
69	9	fig 16	120	DE1.5 slab	2.1		NS direction S of axis, 70 mm gauge	
71	11	fig 16	120	DE1 slab	2.1		WE direction E of axis, 70 mm gauge	
73	13	fig 16	120	DE1 slab	2.1		NS direction S of axis, 70 mm gauge	X
75	15							
77	17							
79	19							

Table CA4 Strain Gauges

Logger Channel	Card Channel	Drawing Ref	Gauge Resistance	Location Key	Gauge Factor	User Dummy	Comments	OK
81	1	fig 13	120	D1	2.1		Unprotected column on 4th floor, SE flange 500 mm above the floor	
83	3	fig 13	120	D1	2.1		Unprotected column on 4th floor, NE flange 500 mm above the floor	
85	5	fig 13	120	D1	2.1		Unprotected column on 4th floor, SW flange 500 mm above the floor	
87	7	fig 13	120	D1	2.1		Unprotected column on 4th floor, NW flange 500 mm above the floor	
89	9	fig 13	120	E1	2.1		Unprotected column on 4th floor, SE flange 500 mm above the floor	
91	11	fig 13	120	E1	2.1		Unprotected column on 4th floor,NE flange 500 mm above the floor	
93	13	fig 13	120	E1	2.1		Unprotected column on 4th floor, SW flange 500 mm above the floor	
95	15	fig 13	120	E1	2.1		Unprotected column on 4th floor, NW flange 500 mm above the floor	
97	17	fig 13	120	D1	2.1		Unprotected column on 4th floor, SE flange 500 mm below the beam	
99	19	fig 13	120	D1	2.1		Unprotected column on 4th floor, NE flange 500 mm below the beam	

Table CA5 Strain gauges

Logger Channel	Card Channel	Drawing Ref	Gauge Resistance	Location Key	Gauge Factor	User Dummy	Comments	OK
101	1	fig 13	120	D1	2.1		Unprotected column on 4th floor SW flange 500 mm below the beam	
103	3	fig 13	120	D1	2.1		Unprotected column on 4th floor NW flange 500 mm below the beam	
105	5	fig 13	120	E1	2.1		Unprotected column on 4th floor SE flange 500 mm below the beam	
107	7	fig 13	120	E1	2.1		Unprotected column on 4th floor NE flange 500 mm below the beam	
109	9	fig 13	120	E1	2.1		Unprotected column on 4th floor SW flange 500 mm below the beam	
111	11	fig 13	120	E1	2.1		Unprotected column on 4th floor NW flange 500 mm below the beam	
113	13	fig 13	120	D1	2.1		Protected column SE flange 500 mm below the beam	
115	15	fig 13	120	D1	2.1		Protected column NE flange 500 mm below the beam	
117	17	fig 13	120	D1	2.1		Protected column SW flange 500 mm below the beam	
119	19	fig 13	120	D1	2.1		Protected column NW flange 500 mm below the beam	

Table CA6 Strain gauges

Logger Channel	Card Channel	Drawing Ref	Gauge Resistance	Location Key	Gauge Factor	User Dummy	Comments	OK
121	1	fig 13	120	D1	2.1		Protected column SW flange 500mm above the floor	
123	3	fig 13	120	D1	2.1		Protected column NW flange 500 mm above the floor	
125	5	fig 13	120	D1	2.1		Protected column SE flange 500 mm above the floor	
127	7	fig 13	120	D1	2.1		Protected column NE flange 500mm above the floor	
129	9							
131	11							
133	13							
135	15							
137	17							
139	19							

Table CA7 Strain gauges

Logger Channel	Card Channel	Drawing Ref.	Instrument Type	Location Key	Convers Factor	Offset	Comments	OK
201	1	Fig 18	ASM 10	Gridline 1	100	64.55	1/4 span D-E	
202	2	Fig 18	ASM 27	Gridline 1	100	52.357	Midspan D-E	
203	3	Fig 18	ASM 33	Gridline 1	100	56.189	3/4 span D-E	
204	4	Fig 18	ASM 35	Line 1/4 span D1-D2	100	73.777	Gridline D	?
205	5	Fig 18	ASM 37	Line 1/4 span D1-D2	100	87.427	1/4 span D-E	
206	6	Fig 18	ASM 47	Line 1/4 span D1-D2	100	66.514	Midspan D-E	
207	7	Fig 18	ASM 52	Line 1/4 span D1-D2	100	28.073	3/4 span D-E	
208	8	Fig 18	ASM 55	Line 1/4 span D1-D2	100	34.994	Gridline E	
209	9	Fig18	ASM 59	Gridline 1.5	100	73.659	Gridline D	
210	10	Fig 18	ASM 60	Gridline 1.5	100	63.065	1/4 span D-E	
211	11	Fig 18	ASM 63	Gridline 1.5	100	75.368	Midspan D-E	
212	12	Fig 18	ASM 66	Gridline 1.5	100	55.632	3/4 span D-E	
213	13	Fig 18	ASM 67	Gridline 1.5	100	70.886	Gridline E	
214	14	Fig 18	ASM 68	Line 3/4 span D1-D2	100	4.6606	Gridline D	
215	15	Fig 18	ASM 69	Line 3/4 span D1-D2	100	69.48	1/4 span D-E	
216	16	Fig 18	ASM 71	Line 3/4 span D1-D2	100	34.102	Midspan D-E	
217	17	Fig 18	ASM 73	Line 3/4 span D1-D2	100	78.496	3/4 span D-E	
218	18	Fig 18	ASM 74	Line 3/4 span D1-D2	100	43.284	Gridline E	
219	19	Fig 18	ASM 75	Gridline 2	100	53.536	1/4 span D-E	
220	20	Fig 18	ASM 77	Gridline 2	100	25.554	Midspan D-E	

Table CA8 Displacements

Logger Channel	Card Channel	Drawing Ref.	Instrument Type	Location Key	Convers Factor	Offset	Comments	OK
221	1	fig 18	ASM 78	Gridline 2	100	65.145	1/4 span D-E	
222	2	fig 18	ASM 79	Gridline C	100	25.315	Midspan	
223	3	fig 18	ASM 83	S comprt. wall	100	18.533	Midspan	
224	4	fig 18	ASM 84	W comprt. wall	100	74.957	Midspan	
225	5	fig 18	ASM 87	N comprt. wall	100	23.444	Midspan	
226	6							
227	7							
228	8							
229	9							
230	10							
231	11							
232	12							
233	13							
234	14							
235	15							
236	16							
237	17							
238	18							
239	19							
240	20							

Table CA9 Displacements

Logger Channel	Card Channel	Drawing Ref	Instrument Type	Location Key	Convers Factor	Offset	Comments	OK
241	1							
242	2	fig 19	SAKI,2	Gridline DE	10	-48.989	Midspan D2-E2	
243	3	fig 19	SAKI,3	D1	10	-63.46	S column web	
244	4							
245	5	fig 19	SAKI,5	E2	10	-52.585	W column flange	
246	6	fig 19	SAKI,6	D2	10	-39.93	S column web	
247	7	fig 19	SAKI,7	Gridline 1.5	10	-43.301	Gridline D	
248	8	fig 19	SAKI,8	E1	10	-32.078	E column flange	
249	9	fig 19	SAKI,9	E2	10	-60.013	N column web	
250	10							
251	11	fig 19	SAKI,11	D2	10	-56.365	W column flange	
252	12	fig 19	SAKI,12	D1	10	-31.69	E column flange	
253	13	fig 19	SAKI,13	E1	10	-42.815	N column web	
254	14	fig 19	SAKI,14	Gridline 1.5	10	-45.837	Gridline E	
255	15							
256	16	fig 19	SAKI,16	Gridline DE	10	-39.07	Midspan D1-E1	
257	17							
258	18							
259	19							
260	20							

Table CA10 Displacements

Logger Channel	Card Channel	Drawing Ref.	TC Type	Location Key	Comments	OK
401	1	fig 14	K,1	D1,BREdwg1	Protected Column 3/4 height SW flange	
402	2	fig 14	K,2	D1,BREdwg1	Protected Column 3/4 height SE flange	
403	3	fig 14	K,3	D1,BREdwg1	Protected Column 1/2 height SW flange	
404	4	fig 14	K,4	D1,BREdwg1	Protected Column 1/2 height S Web	
405	5	fig 14	K,5	D1,BREdwg1	Protected Column 1/2 height SE flange	
406	6	fig 14	K,6	D1,BREdwg1	Protected Column 1/4 height SW flange	
407	7	fig 14	K,7	D1,BREdwg1	Protected Column 1/4 height SE flange	
408	8	fig 14	K,8	D2,BREdwg1	Protected Column 3/4 height SW flange	
409	9	fig 14	K,9	D2,BREdwg1	Protected Column 3/4 height SE flange	
410	10	fig 14	K,10	D2,BREdwg1	Protected Column 1/2 height NW flange	
411	11	fig 14	K,11	D2,BREdwg1	Protected Column 1/2 height N Web	
412	12	fig 14	K,12	D2,BREdwg1	Protected Column 1/2 height SE flange	
413	13	fig 14	K,13	D2,BREdwg1	Protected Column 1/4 height NW flange	
414	14	fig 14	K,14	D2,BREdwg1	Protected Column 1/4 height SE flange	
415	15	fig 14	K,29	Beam D1-D2	Bottom of N flange 200 mm from D2	
416	16	fig 14	K,30	Beam D1-D2	Bottom of N flange 100 mm from D2	X
417	17	fig 14	K,31	Beam D1-D2	Bottom of N flange 50 mm from D2	
418	18	fig 14	K,32	D2,BREdwg1	NW flange 200 mm below Beam D1-D2	
419	19	fig 14	K,33	D2,BREdwg1	NW flange 200 mm below Beam D1-D2	
420	20	fig 14	K,34	D2,BREdwg1	NW flange 200 mm below Beam D1-D2	

Table CA11 Thermocouples

Logger Channel	Card Channel	Drawing Ref.	TC Type	Location Key	Comments	OK
421	1	fig 14	K,15	E1,BREdwg1	Protected Column 3/4 height NW flange	
422	2	fig 14	K,16	E1,BREdwg1	Protected Column 3/4 height NE flange	
423	3	fig 14	K,17	E1,BREdwg1	Protected Column 1/2 height NW flange	
424	4	fig 14	K,18	E1,BREdwg1	Protected Column 1/2 height N Web	
425	5	fig 14	K,19	E1,BREdwg1	Protected Column 1/2 height NE flange	
426	6	fig 14	K,20	E1,BREdwg1	Protected Column 1/4 height NW flange	
427	7	fig 14	K,21	E1,BREdwg1	Protected Column 1/4 height NE flange	
428	8	fig 14	K,22	E2,BREdwg1	Protected Column 3/4 height SW flange	
429	9	fig 14	K,23	E2,BREdwg1	Protected Column 3/4 height NE flange	
430	10	fig 14	K,24	E2,BREdwg1	Protected Column 1/2 height SW flange	
431	11	fig 14	K,25	E2,BREdwg1	Protected Column 1/2 height S Web	
432	12	fig 14	K,26	E2,BREdwg1	Protected Column 1/2 height NE flange	
433	13	fig 14	K,27	E2,BREdwg1	Protected Column 1/4 height SW flange	
434	14	fig 14	K,28	E2,BREdwg1	Protected Column 1/4 height NE flange	
435	15	fig 14	K,35	Beam E1-E2	Bottom of S flange 200 mm from D2	X
436	16	fig 14	K,36	Beam E1-E2	Bottom of S flange 100 mm from D2	
437	17	fig 14	K,37	Beam E1-E2	Bottom of S flange 50 mm from D2	
438	18	fig 14	K,38	E2,BREdwg1	SW flange 200 mm below Beam D1-D2	
439	19	fig 14	K,39	E2,BREdwg1	SW flange 200 mm below Beam D1-D2	
440	20	fig 14	K,40	E2,BREdwg1	SW flange 200 mm below Beam D1-D2	

Table CA12 Thermocouples

Logger Channel	Card Channel	Drawing Ref.	TC Type	Location Key	Comments	OK
441	1	fig 8,9	K,41	D1.5	top 1st bolt	
442	2	fig 8,9	K,42	D1.5	3rd bolt	
443	3	fig 8,9	K,43	D1.5	bottom 4th bolt	
444	4	fig 8,9	K,44	D1.5	SW Fin Plate aligned with the 1st bolt row	
445	5	fig 8,9	K,45	D1.5	SW Fin Plate aligned with the 3rd bolt row	X
446	6	fig 8,9	K,46	D1.5	SW Fin Plate aligned with the 4th bolt row	
447	7	fig 8,9	K,47	Beam DE1.5	Bottom of W top flange 120 mm from D1.5	
448	8	fig 8,9	K,48	Beam DE1.5	Middle of W web 120 mm from D1.5	
449	9	fig 8,9	K,49	Beam DE1.5	Bottom of W flange 120 mm from D1.5	
450	10	fig 8,9	K,50	E1.5	NW Fin Plate aligned with the 1st bolt row	
451	11	fig 8,9	K,51	E1.5	NW Fin Plate aligned with the 3rd bolt row	
452	12	fig 8,9	K,52	E1.5	NW Fin Plate aligned with the 4th bolt row	
453	13	fig 8,9	K,53	Beam DE1.5	Bottom of W flange 120 mm from E1.5	
454	14	fig 8,10	K,54	D2	W 1st bolt, S minor axis connection	
455	15	fig 8,10	K,55	D2	E 2nd bolt, S minor axis connection	
456	16	fig 8,10	K,56	D2	W 4th bolt, S minor axis connection	
457	17	fig 8,10	K,57	D2	SW End plate aligned with 1st bolt, minor axis	
458	18	fig 8,10	K,58	D2	SW End plate aligned with 3rd bolt, minor axis	
459	19	fig 8,10	K,59	D2	SW End plate aligned with 4th bolt, minor axis	
460	20	fig 8,10	K,60	Beam D2-E2	Top flange W bottom surface 50mm from D2	

Table CA13 Thermocouples

Logger Channel	Card Channel	Drawing Ref.	TC Type	Location Key	Comments	OK
461	1	fig 8,10	K,61	Beam D2-E2	W web, middle height 50 mm from D2	
462	2	fig 8,10	K,62	Beam D2-E2	Bottom flange W upper surf. 50 mm from D2	
463	3	fig 8,10	K,63	Beam D1-D2	Top flange S bottom surface 50mm from D2	
464	4	fig 8,10	K,64	Beam D1-D2	S web, middle height 50 mm from D2	
465	5	fig 8,10	K,65	Beam D1-D2	Bottom flange S upper surf. 50 mm from D2	X
466	6	fig 8,10	K,66	D2	S 1st bolt, W major axis connection	
467	7	fig 8,10	K,67	D2	S 3rd bolt, W major axis connection	
468	8	fig 8,10	K,68	D2	S 4th bolt, W major axis connection	
469	9	fig 8,10	K,69	D2	WS End plate aligned with 1st bolt, major axis	
470	10	fig 8,10	K,70	D2	WS End plate aligned with 3rd bolt, major axis	
471	11	fig 8,10	K,71	D2	WS End plate aligned with 4th bolt, major axis	
472	12	fig 8,11	K,72	E2	NW End plate aligned with 1st bolt, minor axis	
473	13	fig 8,11	K,73	E2	NW End plate aligned with 3rd bolt, minor axis	
474	14	fig 8,11	K,74	E2	NW End plate aligned with 4th bolt, minor axis	
475	15	fig 8,11	K,75	Beam D2-E2	Bottom flange W upper surf. 50 mm from E2	
476	16	fig 8,11	K,76	Beam D1-D2	Bottom flange N upper surf. 50 mm from E2	X
477	17	fig 8,11	K,77	E2	WN End plate aligned with 1st bolt, major axis	
478	18	fig 8,11	K,78	E2	WN End plate aligned with 3rd bolt, major axis	
479	19	fig 8,11	K,79	E2	WN End plate aligned with 4th bolt, major axis	
480	20	fig 8,12	K,80	Beam D1-E1	Mid-span, E top flange	

Table CA14 Thermocouples

Logger Channel	Card Channel	Drawing Ref.	TC Type	Location Key	Comments	OK
481	1	fig 8,12	K,81	Beam D1-E1	Mid-span, middle of the E web	
482	2	fig 8,12	K,82	Beam D1-E1	Mid-span, E bottom flange	
483	3	fig 8,12	K,83	Beam DE1.5	Mid-span, E top flange	
484	4	fig 8,12	K,84	Beam DE1.5	Mid-span, middle of the E web	
485	5	fig 8,12	K,85	Beam DE1.5	Mid-span, E bottom flange	
486	6	fig 8,12	K,86	Beam D2-E2	Mid-span, W top flange	
487	7	fig 8,12	K,87	Beam D2-E2	Mid-span, middle of the W web	
488	8	fig 8,12	K,88	Beam D2-E2	Mid-span, W bottom flange	
489	9	fig 15	K,89	Cavity C1	Next to rib, slab surface	
490	10	fig 15	K,90	Cavity C1	Next to rib 35 mm below the top surface	X
491	11	fig 15	K,91	Cavity C1	Reinforcement next to rib	?
492	12	fig 15	K,92	Cavity C1	Next to rib, steel decking	?
493	13	fig 15	K,93	Cavity C1	Rib, slab surface	
494	14	fig 15	K,94	Cavity C1	Reinforcement in the rib	?
495	15	fig 15	K,95	Cavity C1	Rib 100 mm below the top surface	
496	16	fig 15	K,96	Cavity C1	Rib, steel decking	X
497	17	fig 15	K,97	Cavity C3	Next to rib, slab surface	
498	18	fig 15	K,98	Cavity C3	Next to rib 35 mm below the top surface	
499	19	fig 15	K,99	Cavity C3	Reinforcement next to rib	
500	20	fig 15	K,100	Cavity C3	Next to rib, steel decking	?

Table CA15 Thermocouples

Logger Channel	Card Channel	Drawing Ref.	TC Type	Location Key	Comments	OK
501	1	fig 15	K,101	Cavity C3	Rib, slab surface	
502	2	fig 15	K,102	Cavity C3	Reinforcement in the rib	?
503	3	fig 15	K,103	Cavity C3	Rib 100 mm below the top surface	
504	4	fig 15	K,104	Cavity C3	Rib, steel decking	?
505	5	fig 15	K,105	Cavity C2	Next to rib, slab surface	
506	6	fig 15	K,106	Cavity C2	Next to rib 35 mm below the top surface	
507	7	fig 15	K,107	Cavity C2	Reinforcement next to rib	
508	8	fig 15	K,108	Cavity C2	Next to rib, steel decking	?
509	9	fig 15	K,109	Cavity C2	Rib, slab surface	
510	10	fig 15	K,110	Cavity C2	Reinforcement in the rib	
511	11	fig 15	K,111	Cavity C2	Rib 100 mm below the top surface	
512	12	fig 15	K,112	Cavity C2	Rib, steel decking	?
513	13	fig 15	K,113	Cavity C4	Next to rib, slab surface	
514	14	fig 15	K,114	Cavity C4	Next to rib 35 mm below the top surface	
515	15	fig 15	K,115	Cavity C4	Reinforcement next to rib	
516	16	fig 15	K,116	Cavity C4	Next to rib, steel decking	?
517	17	fig 15	K,117	Cavity C4	Rib, slab surface	
518	18	fig 15	K,118	Cavity C4	Reinforcement in the rib	
519	19	fig 15	K,119	Cavity C4	Rib 100 mm below the top surface	
520	20	fig 15	K,120	Cavity C4	Rib, steel decking	?

Table CA16 Thermocouples

Logger Channel	Card Channel	Drawing Ref.	TC Type	Location Key	Comments	OK
521	1	fig 20	K,121	gridline D	500 mm from D2	
522	2	fig 20	K,122	gridline D	2125 mm from D2	
523	3	fig 20	K,123	gridline D	2125 mm from D1	
524	4	fig 20	K,124	gridline D	500 mm from D1	
525	5	fig 20	K,125	2250 mm N from midspan	500 mm from gridline 2	
526	6	fig 20	K,126	2250 mm N from midspan	2125 mm from gridline 2	
527	7	fig 20	K,127	2250 mm N from midspan	2125 mm from gridline 1	
528	8	fig 20	K,128	2250 mm N from midspan	500 mm from gridline 1	
529	9	fig 20	K,129	2250 mm S from midspan	500 mm from gridline 2	
530	10	fig 20	K,130	2250 mm S from midspan	2125 mm from gridline 2	
531	11	fig 20	K,131	2250 mm S from midspan	2125 mm from gridline 1	
532	12	fig 20	K,132	2250 mm S from midspan	500 mm from gridline 1	
533	13	fig 20	K,133	gridline E	500 mm from E2	
534	14	fig 20	K,134	gridline E	2125 mm from E2	
535	15	fig 20	K,135	gridline E	2125 mm from E1	
536	16	fig 20	K,136	gridline E	500 mm from E1	
537	17	fig 15	K,137	Cavity C5	Reinforcement in the rib	
538	18	fig 15	K,138	Cavity C6	Reinforcement in the rib	?
539	19	fig 15	K,139	Cavity C7	Reinforcement in the rib	
540	20					

Table CA17 Thermocouples

Logger Channel	Card Channel	Drawing Ref.	TC Type	Location Key	Comments	OK
541	1	Red 1	K,141	Indicative 2	Thermocouple 1	
542	2	Red 2	K,142	Indicative 2	Thermocouple 2	
543	3	Red 3	K,143	Indicative 2	Thermocouple 3	
544	4	Red 4	K,144	Indicative 1	Thermocouple 1	
545	5	Red 5	K,145	Indicative 1	Thermocouple 2	
546	6	Red 6	K,146	Indicative 1	Thermocouple 3	X
547	7	Red 7	K,147	Indicative 3	Thermocouple 1	
548	8	Red 8	K,148	Indicative 3	Thermocouple 2	
549	9	Red 9	K,149	Indicative 3	Thermocouple 3	
550	10	Red 10	K,150	Indicative 4	Thermocouple 1	
551	11	Red 11	K,151	Indicative 4	Thermocouple 2	
552	12	Red 12	K,152	Indicative 4	Thermocouple 3	
553	13	Red 13	K,153	Indicative 5	Thermocouple 1	
554	14	Red 14	K,154	Indicative 5	Thermocouple 2	
555	15	Red 15	K,155	Indicative 5	Thermocouple 3	
556	16	Red 16	fig 20	Window	Close to gridline D	X
557	17	Red 17	fig 20	Window	Close to gridline E	
558	18					
559	19					
560	20					

Table CA18 Thermocouples

Detailed test results

The test results presented here are indicative plots taken from the main data files and illustrate how the files can be interrogated to provide specific information related to thermal or structural response.

Compartment time-temperature results

The compartment time-temperature results may be found in the main temperature data files. The time-temperature response for the position of maximum recorded atmosphere temperature is given in figure 19 below. The average compartment temperature for thermocouples 525-527 and 529-531 (see figure 18) is shown in figure 20.

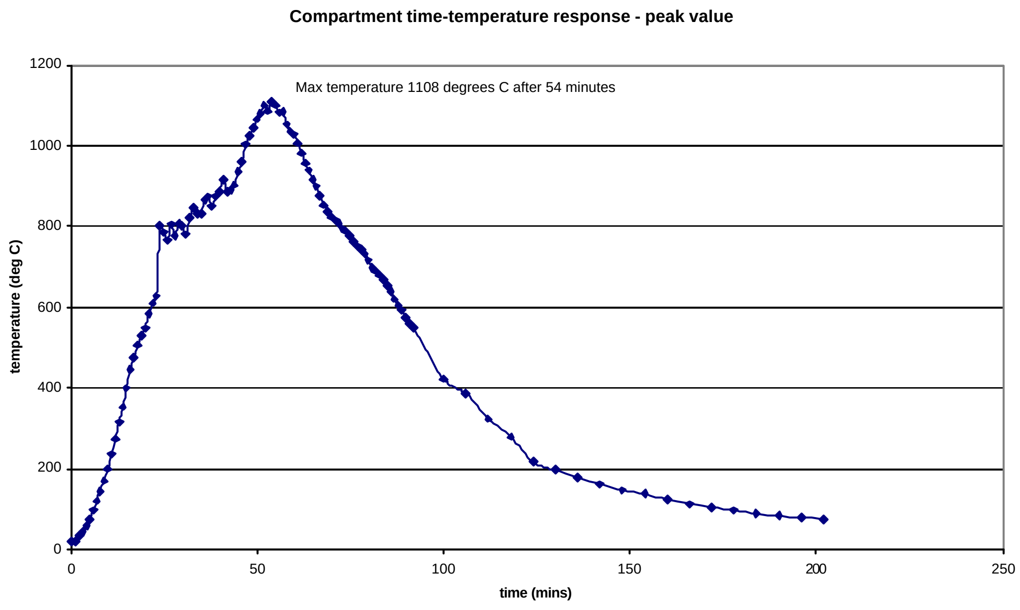


Figure 19 Compartment time-temperature response for position of maximum measured temperature

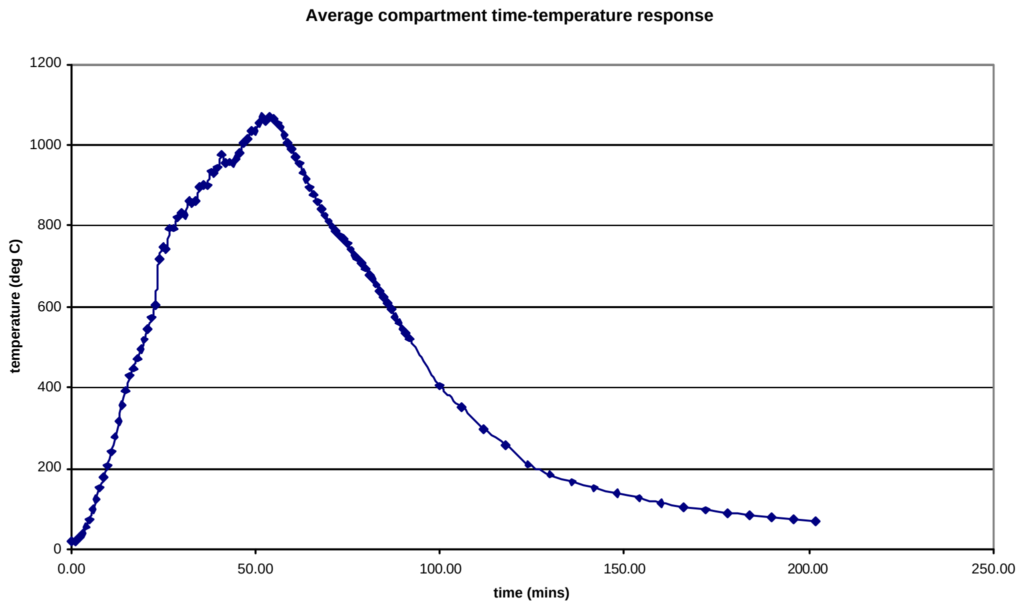


Figure 20 Average compartment time-temperature response

Temperature distribution through structural members

Protected column temperatures

The temperatures of the protected columns may be found in the main temperature data files. The relevant channels are 401-440. Figure 21 shows the temperatures of the internal and perimeter columns compared to the compartment gas temperatures and unprotected steel sections.

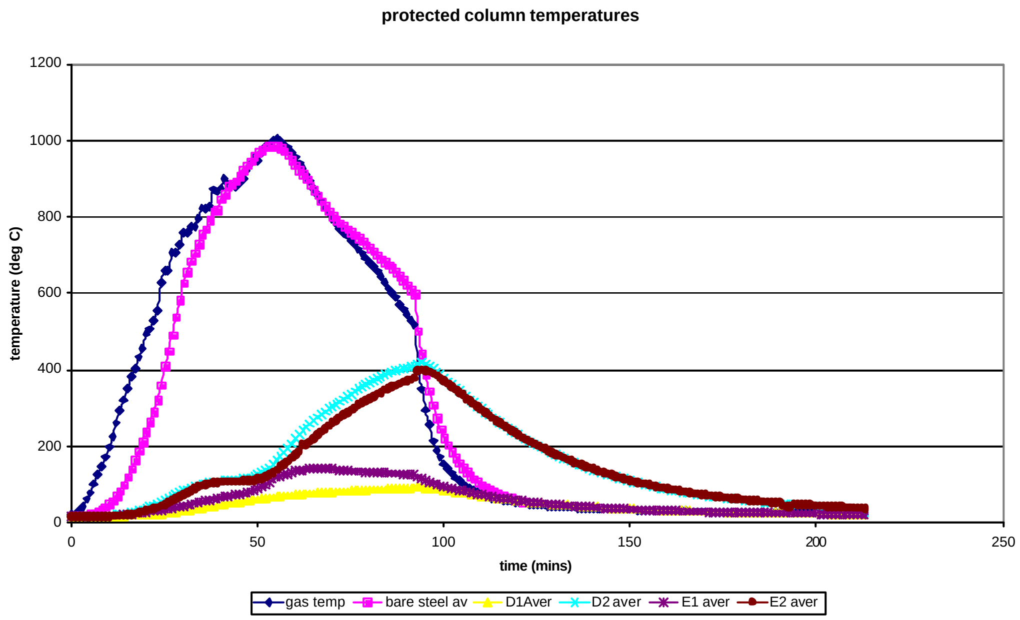


Figure 21 Protected column temperatures

Bolt temperatures and end plate temperatures

Bolt temperatures are included in the main temperature data files. The relevant channels are 441-443 for the fin plate beam to beam connection, 454-456 for the end plate minor axis connection and 466-468 for the partial depth end plate (header plate) major axis connection. Figure 22 shows the temperatures of the bolts in the fin plate and major axis end plate connections.

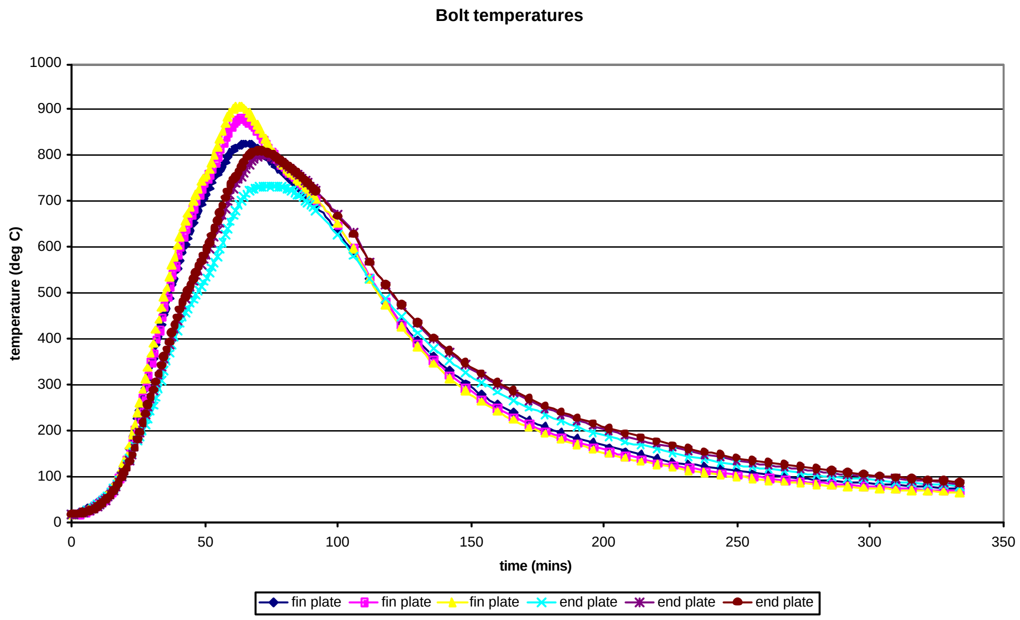


Figure 22 Bolt temperatures

The associated connection temperatures for both the fin plate and the major and minor axis end plate connections are in the temperature data files (channels 444-446, 450-452, 454-459, 469-474, 477-479). Figure 22 shows the temperatures for all the connections.

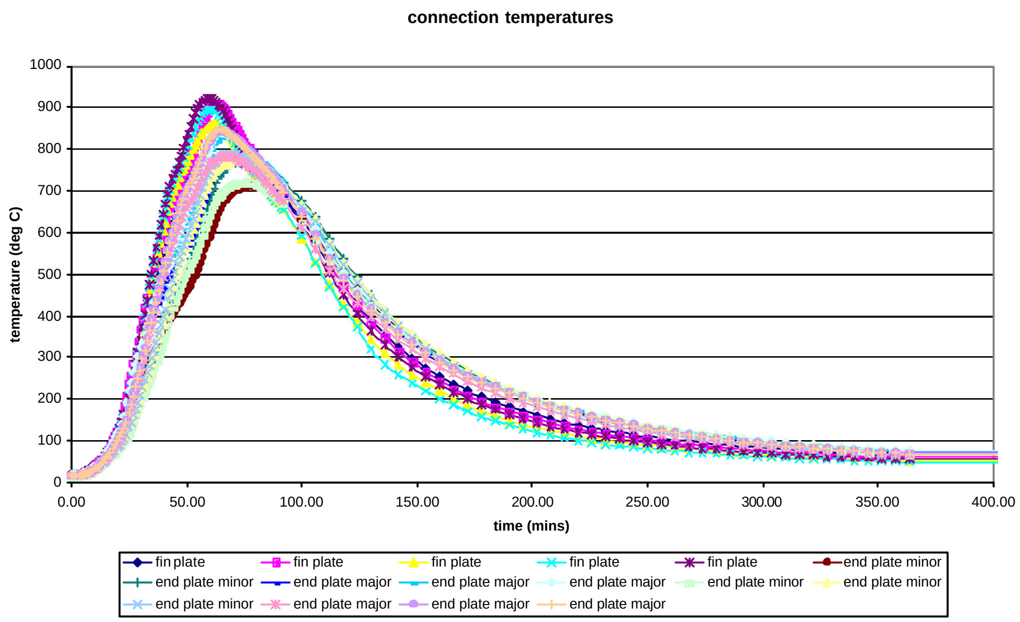


Figure 22 Connection temperatures

Beam Temperatures

The temperatures of the beams can be found in the main data file or alternatively in the file beamtemps.xls. The temperature of the beams within the compartment is shown in figures 23-26 below.

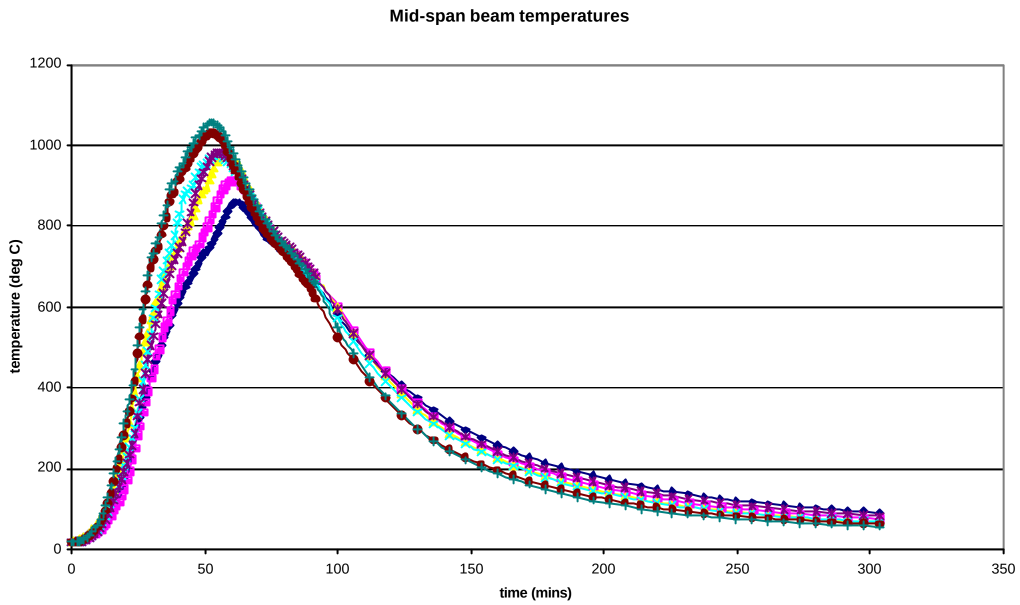


Figure 23 Mid-Span beam temperatures

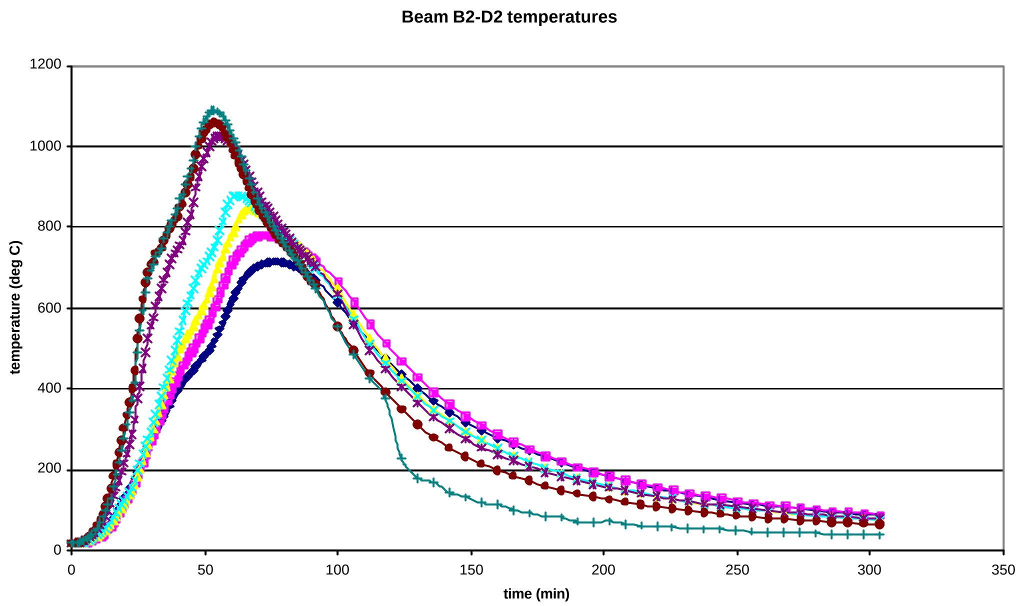


Figure 24 Temperatures of beam D2-E2

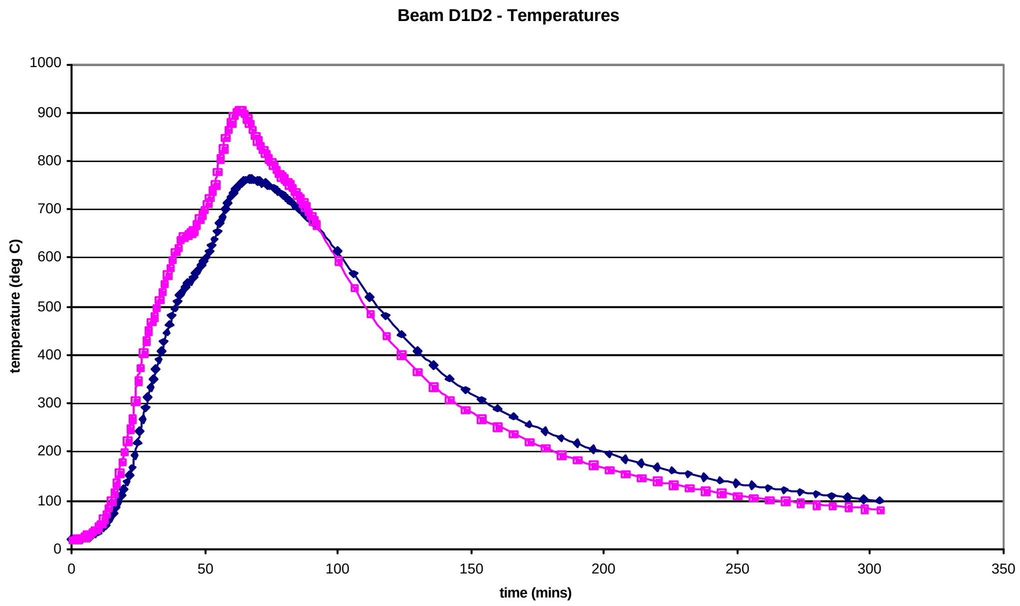


Figure 25 Temperatures of beam D1-D2

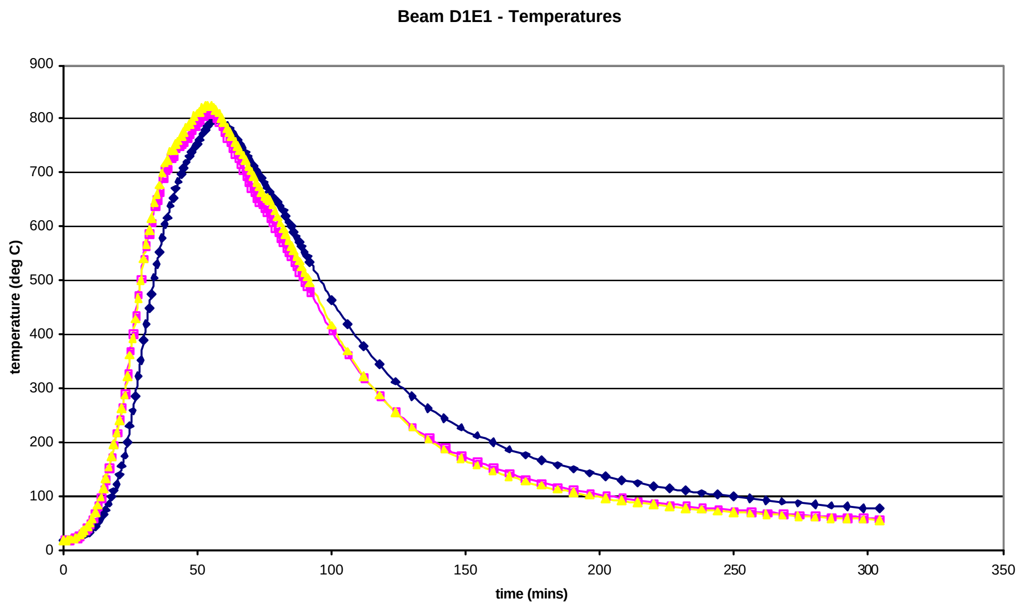


Figure 26 Temperatures of beam D1-E1

Slab temperatures

The temperatures through the depth of the slab in the locations shown in figure 13 are given in the main data file and additionally in the file slabtc.xls. The measured temperatures are shown below in figures 27-32.

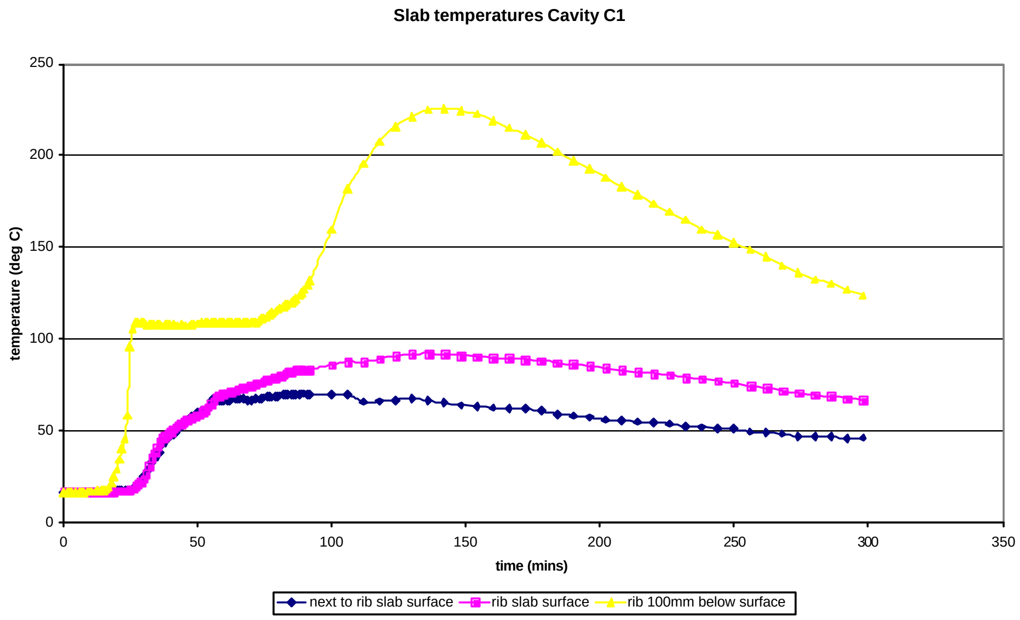


Figure 27 Slab temperatures Cavity C1

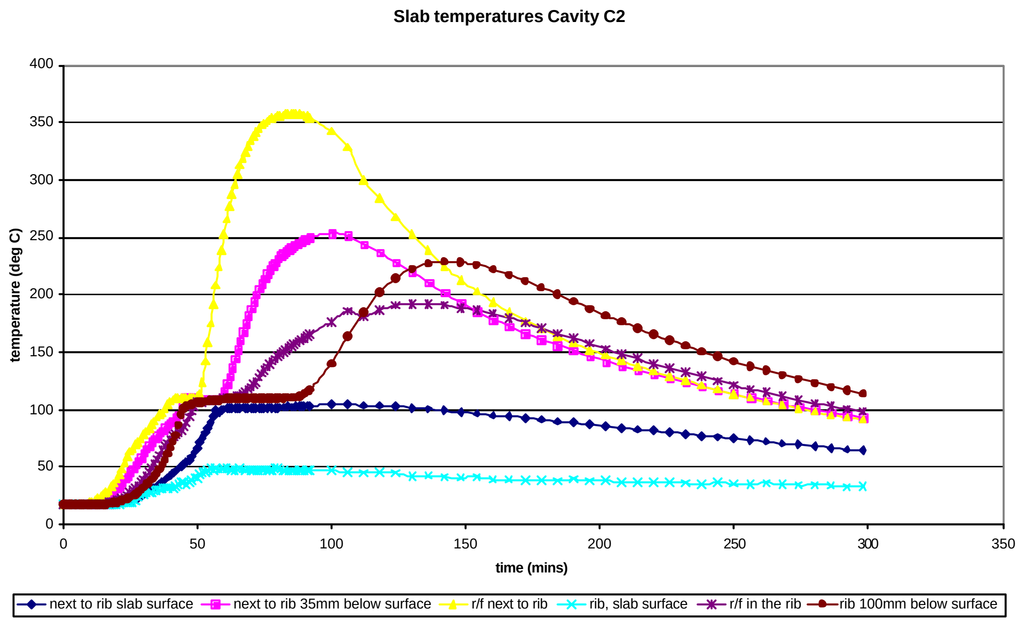


Figure 28 Slab temperatures Cavity C2

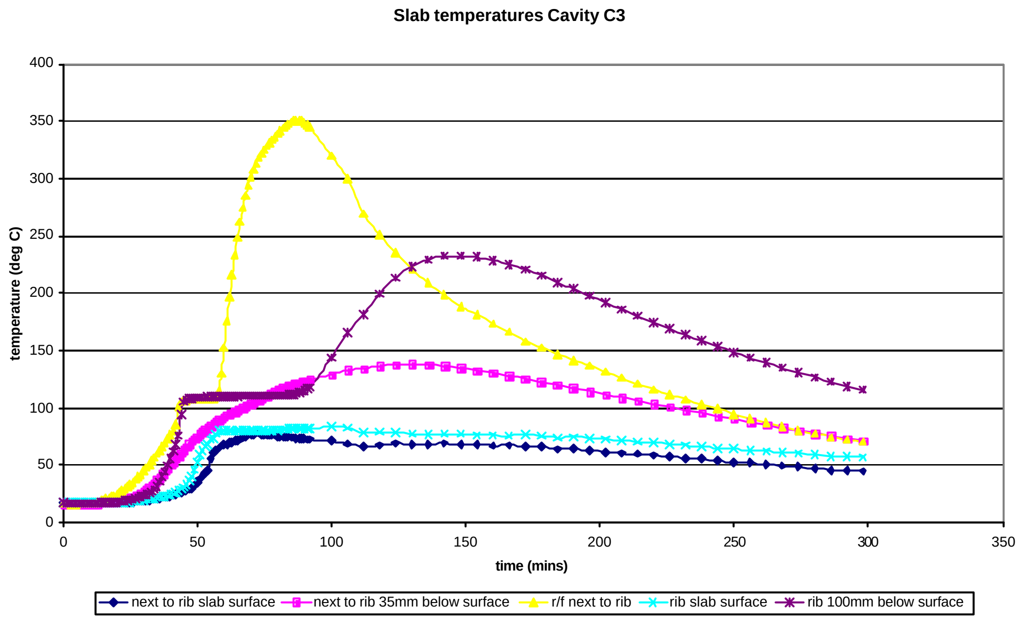


Figure 29 Slab temperatures Cavity C3

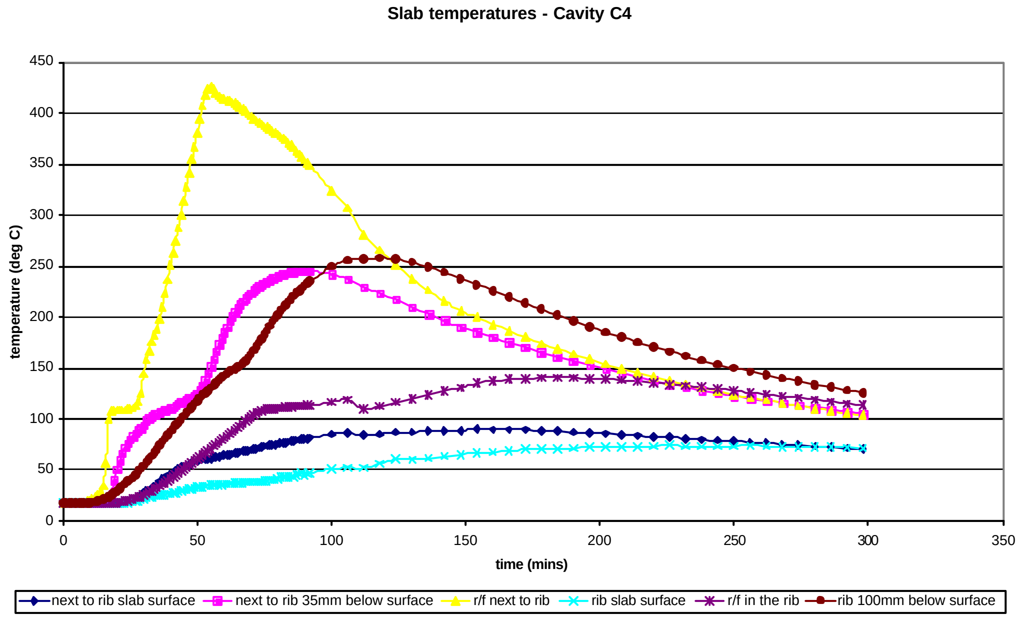


Figure 30 Slab temperatures Cavity C4

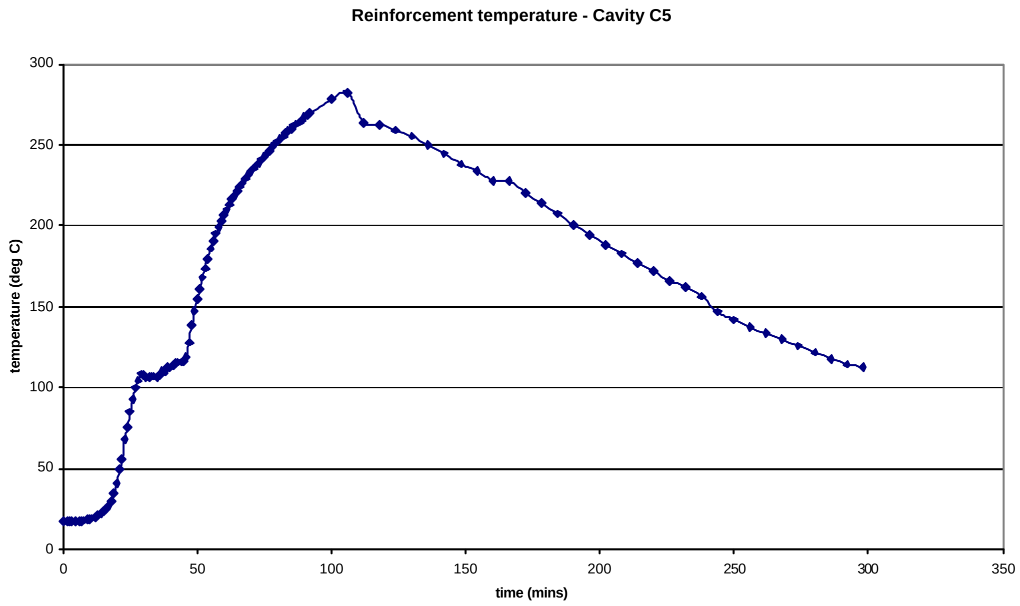


Figure 31 Reinforcement temperature Cavity C5

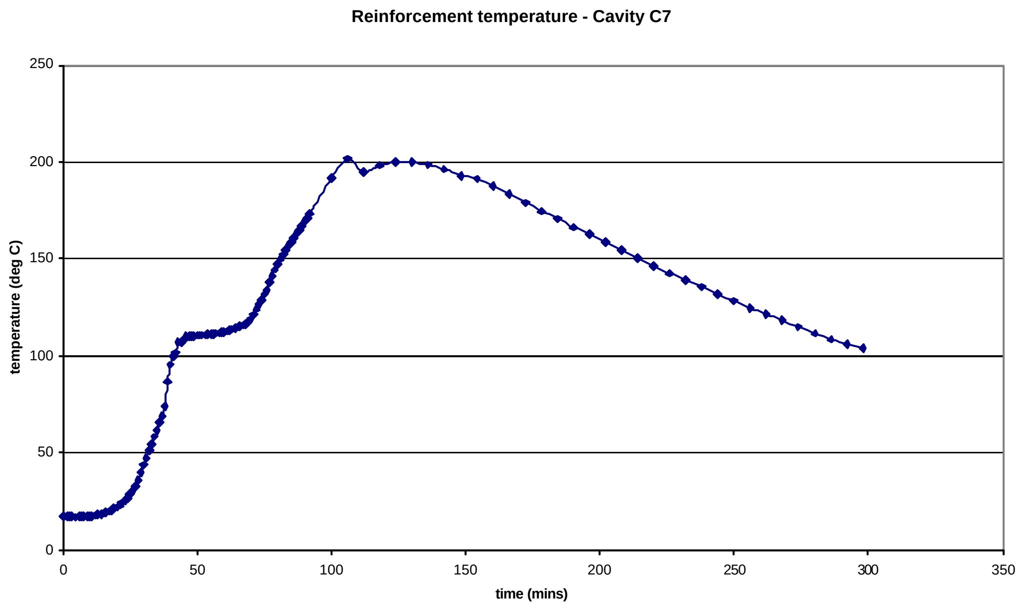


Figure 32 Reinforcement temperature Cavity C7

Vertical and horizontal displacements

The vertical and horizontal deflection measurements are located in the main displacement data file. Additional information may be found in vertdeflection.xls. Figures 33 and 34 show the vertical deflection profile across the east-west and north-south centre lines of the compartment respectively. The positions of the individual measurement points are illustrated in figure 16. The deflection profile is only plotted for the first 100 minutes as after this point the readings tend to tail off. It should be pointed out that in certain cases the maximum travel of the transducer had been reached (when the initial offset is taken into account) and the instruments were left hanging from the floor above. Therefore displacements in excess of those recorded took place during and immediately after the test.

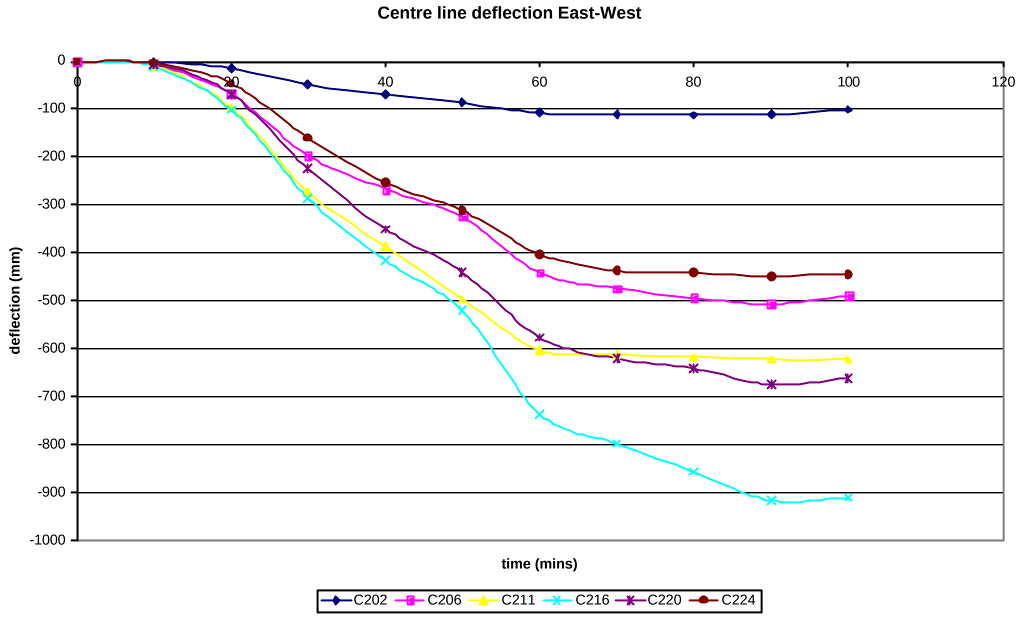


Figure 33 Centre line deflection profile (E-W) for first 100 minutes

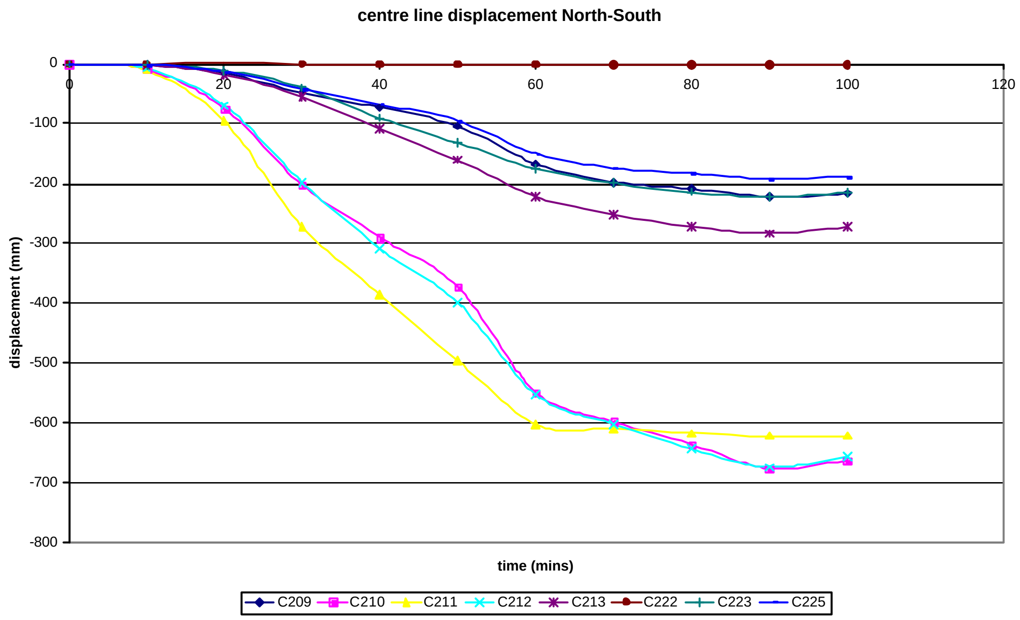


Figure 34 Centre line deflection profile (N-S) for first 100 minutes

The lateral movement of the two internal columns E2 and D2 is illustrated in figure 35 below.

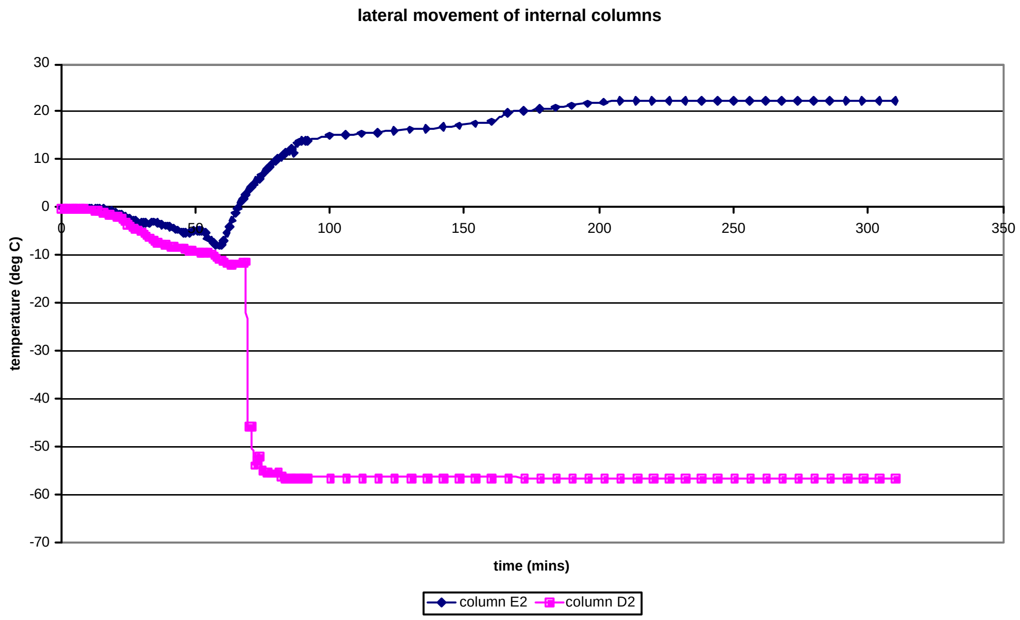


Figure 35 Lateral movement of internal columns (E-W direction)

Figure 36 shows the measured lateral movement of the internal and perimeter beams at mid-span.

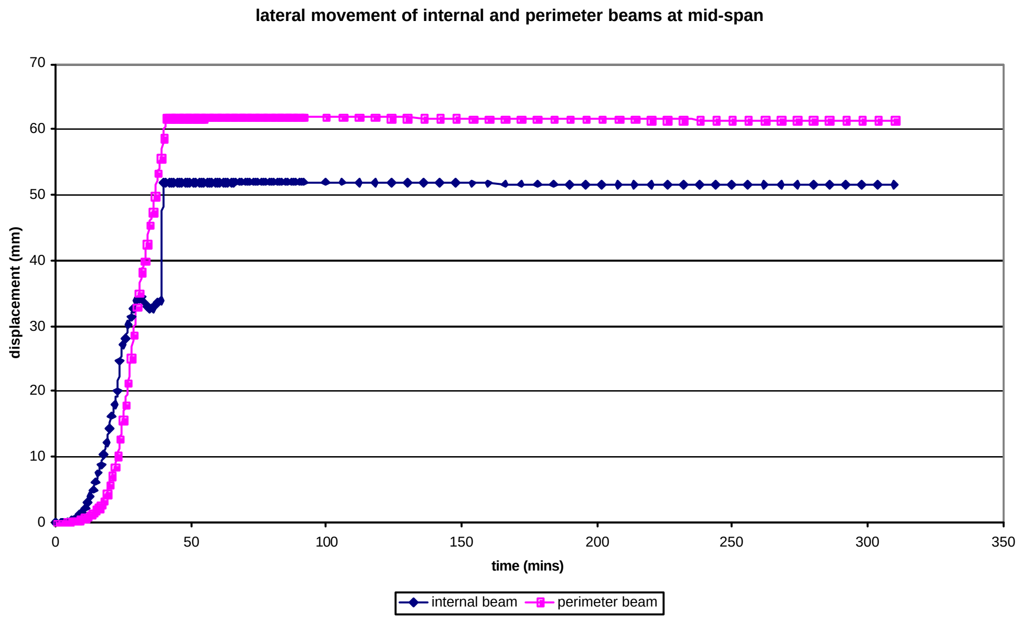


Figure 36 Lateral movement of internal and perimeter beams at mid-span

Strain in the structural elements

Strain measurements were taken for many of the structural elements in the immediate vicinity of the fire compartment including high temperature measurements within the fire compartment. The analysis and interpretation of strain data is a complex task. All the raw data is available in the main strain data file. Figures 37-39 are included as examples for illustrative purposes. Any conclusions based on this data should take into account the full duration of the test including the entire cool down period and the interaction between structural elements.

In the graphs readings have been discontinued at a value of 2500 microstrain. At this level the steel will have yielded and so the results cannot be relied on. The actual yield point is dependent on the grade of steel and the quality of the material. Data is available to the client on the material properties for the Cardington building and is summarised in table 3 below.

Figure 37 shows the development of strain in the bolts to the minor axis end plate connection at D2. Figure 38 shows the strain in the reinforcement in the positions identified in figure 15. Here the cut-off point of 2500 microstrain may be unduly conservative as the yield stress of the mesh is quite high. The full analysis should investigate the complete data files using appropriate material properties. The measured strains on the surface of the slab are shown in figure 39.

Material/Grade	Ultimate stress (N/mm²)		Yield stress (N/mm²)		Compressive strength (N/mm²)/ Tensile strength (N/mm²)	
	Nominal	Measured	Nominal	Measured	Nominal	Measured
Steel/S275	430	469	275	303		
Steel/S355	510	544	355	396		
Plate/grade 43	430		275			
Bolts/grade 8.8	800	869	640			
Concrete/ LW 35/40					35/3.2	37.01
Reinforcement/ A142 mesh T6@200mm						

Table 3 Material properties

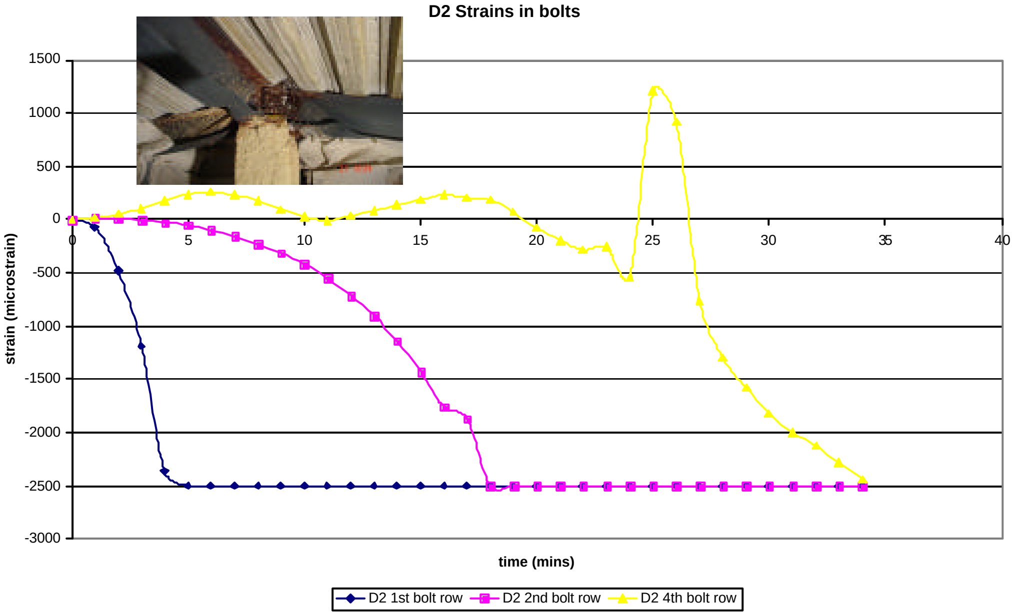


Figure 37 Strains in bolts on minor axis end plate connection D2

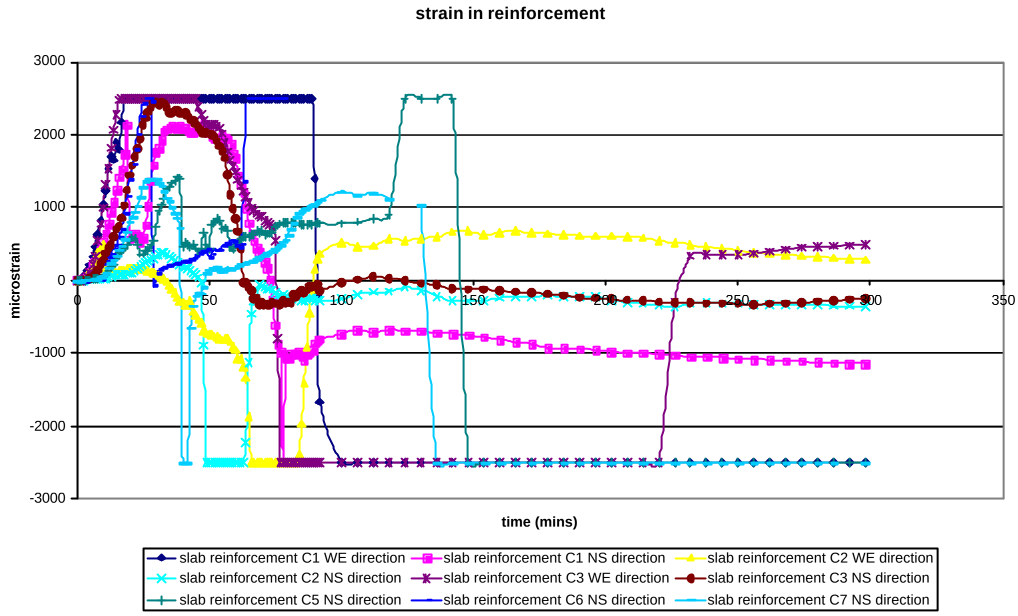


Figure 38 Strains in the reinforcement for test duration

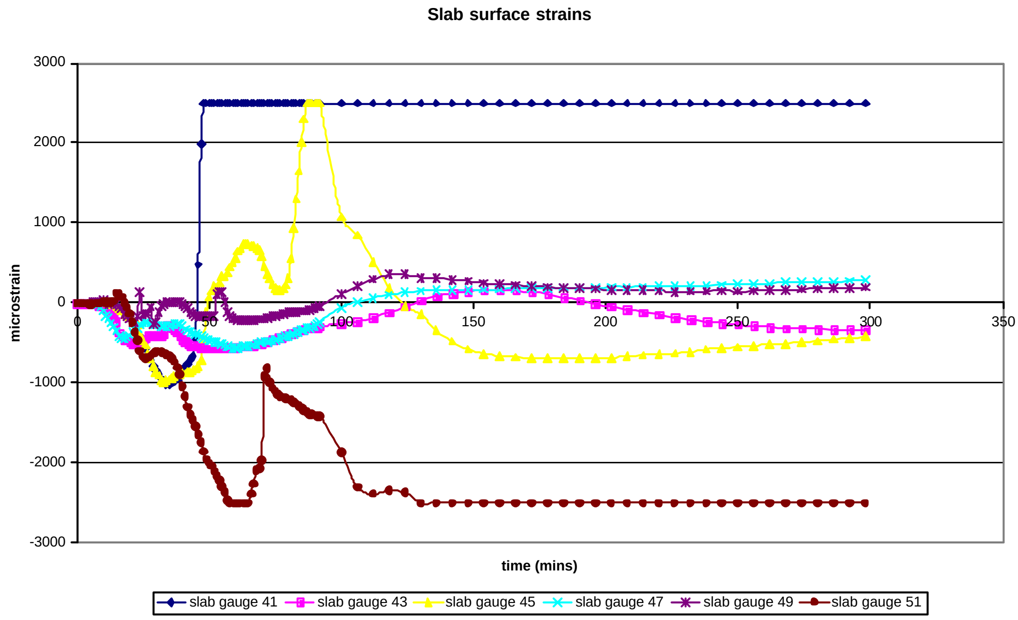


Figure 39 Slab surface strains

Audio-Visual Record

The attached CD (CD1) provides a detailed breakdown of the available photographic records from before during and after the tests. Each individual image (in jpg format) is given a unique description to facilitate subsequent use. In many cases, such as photographs taken during the fire itself, the images are very similar to each other. Where this occurs the description will be followed by an identification number. The second CD (CD2) contains a powerpoint presentation that includes linked video footage of the test including the output from the thermal imaging cameras.

Acknowledgements

This report has been prepared with the assistance of colleagues from the Czech Technical University in Prague, the University of Coimbra and the Slovak Technical University. Their assistance is gratefully acknowledged.

References

1. Newman G M, Robinson J T and Bailey C G, Fire Safe Design: A New Approach to Multi-Storey Steel-Framed Buildings, SCI Publication P288, the Steel Construction Institute, Ascot 2000
2. Moore D B and Lennon T, Fire engineering design of steel structures, Progress in Structural Engineering and Materials, Vol. 1 No. 1, September 1997, pp 4-9
3. BS EN 1991-1-2:2002, Eurocode 1: Actions on structures – Part 1.2: General actions – Actions on structures exposed to fire, British Standards Institution, November 2002
4. Association for Specialist Fire Protection, Steel Construction Institute, Fire Test Study Group, Fire protection for structural steel in buildings, Third Edition

Appendix A – Imposed load

The building was designed for a dead load of 3.65 kN/m^2 and an imposed load of 3.5 kN/m^2.

Floor loadings:			
	Dead:	Slab	2.60 kN/m^2
		Raised floor	0.40 kN/m^2
		Services	0.25 kN/m^2
		Ceiling	0.15 kN/m^2
		Steel self-weight	0.25 kN/m^2
	Live:	Imposed	2.50 kN/m^2
		Partitions	1.00 kN/m^2

Uniform loading of 3.05 kN/m^2 corresponding to a fire situation was simulated using sandbags. Sandbags each of 1.1 ton are applied over an area of 18 m by 10.5 m on the 4th floor.

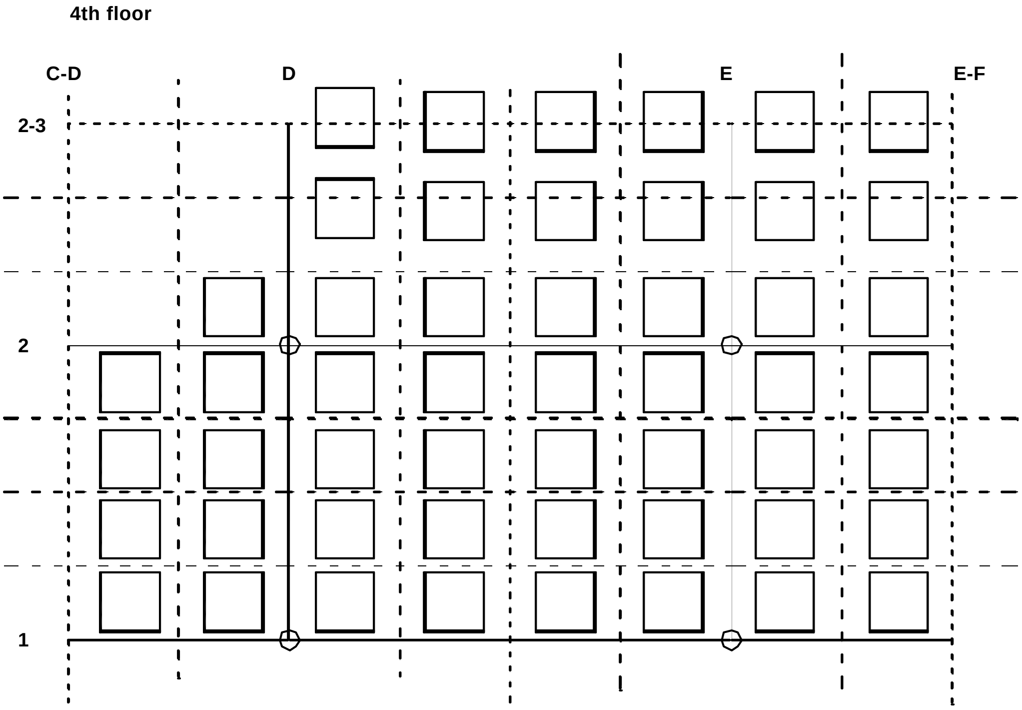


Figure A1 Location of sandbags on the 4th floor

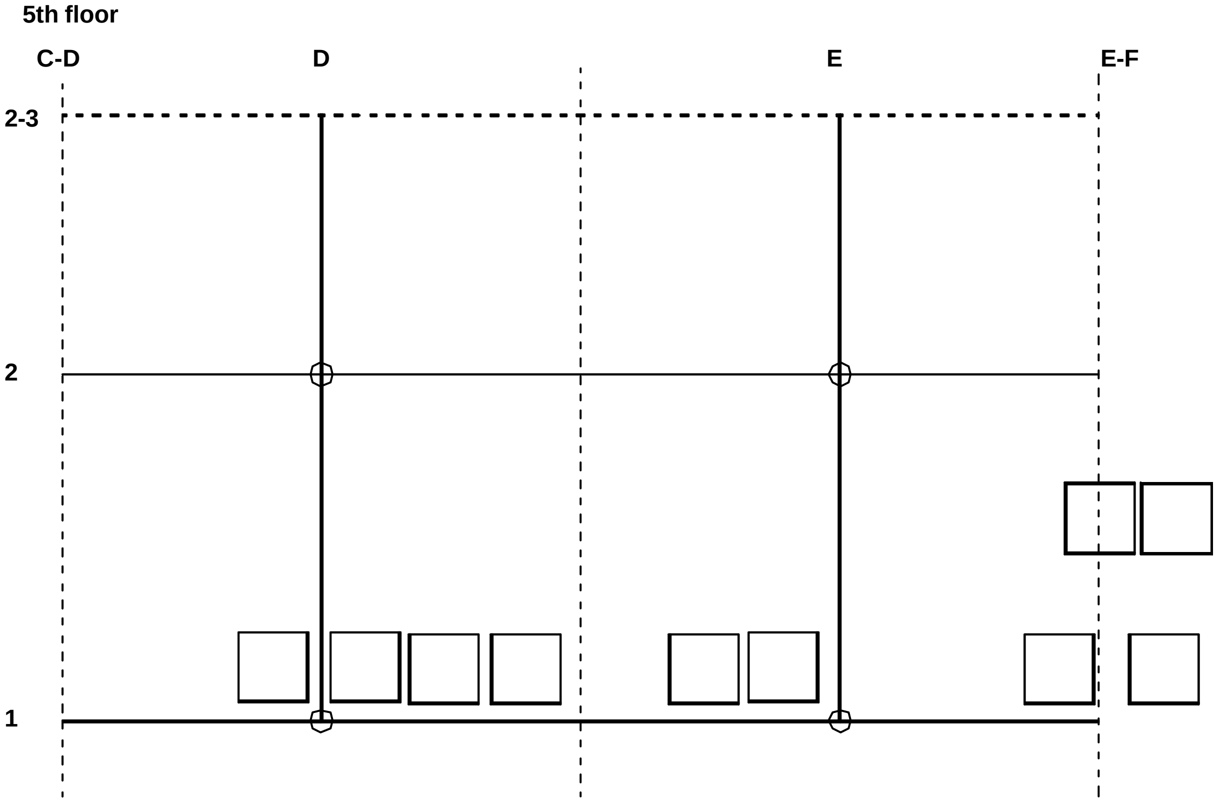


Figure A2 Location of sandbags on 5th floor

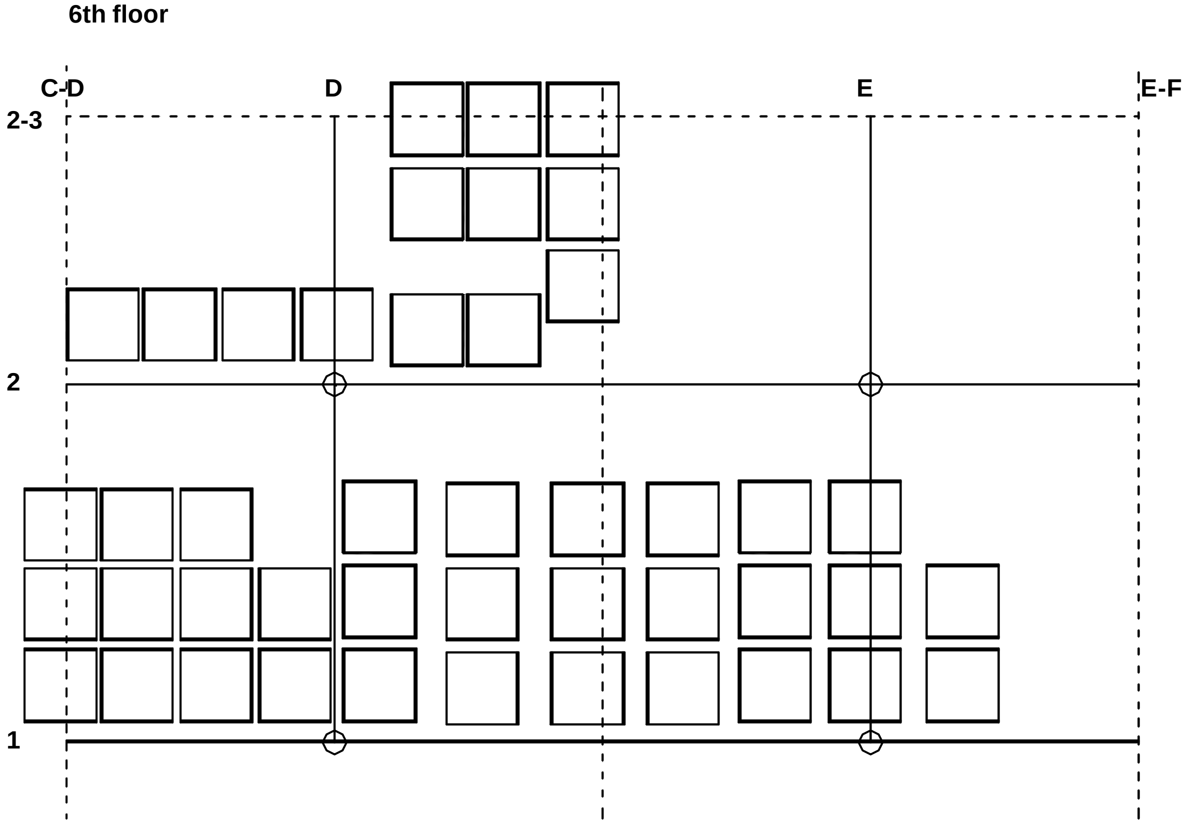


Figure A3 Location of sandbags on 6th floor

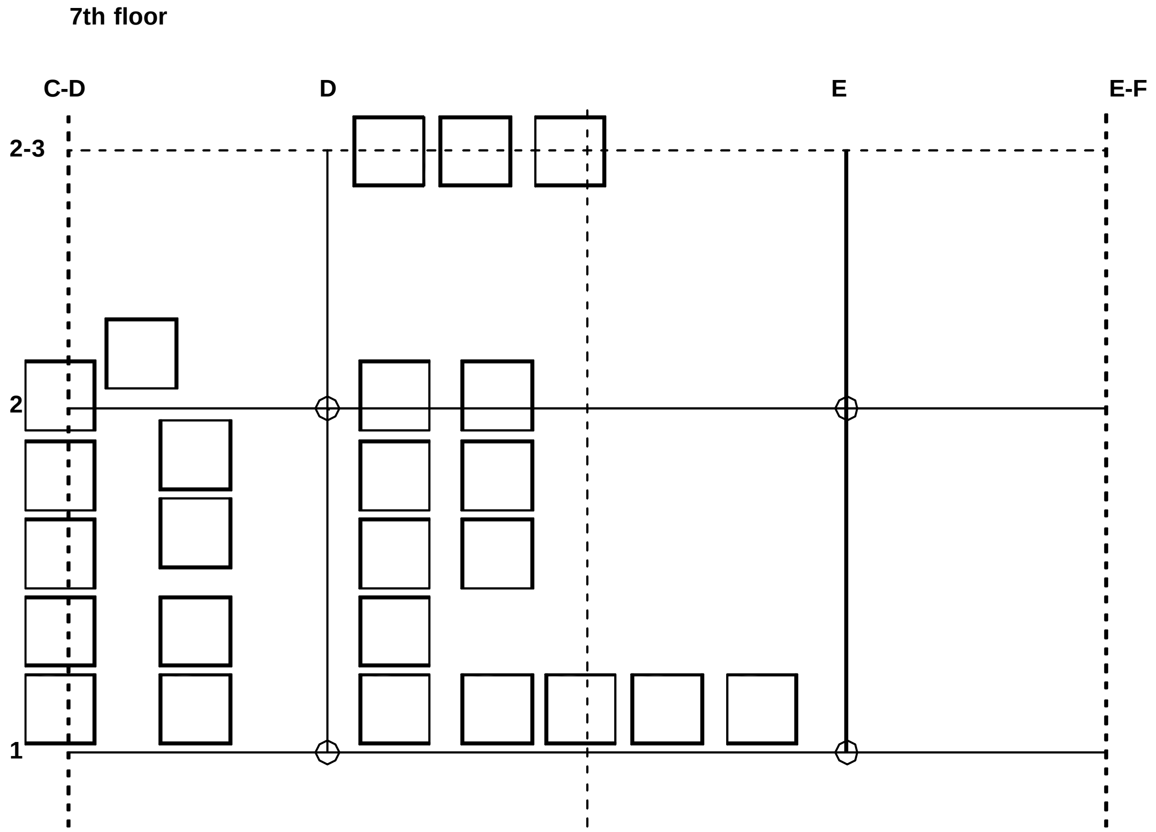


Figure A4 Location of sandbags on 7^{th} floor

8th floor

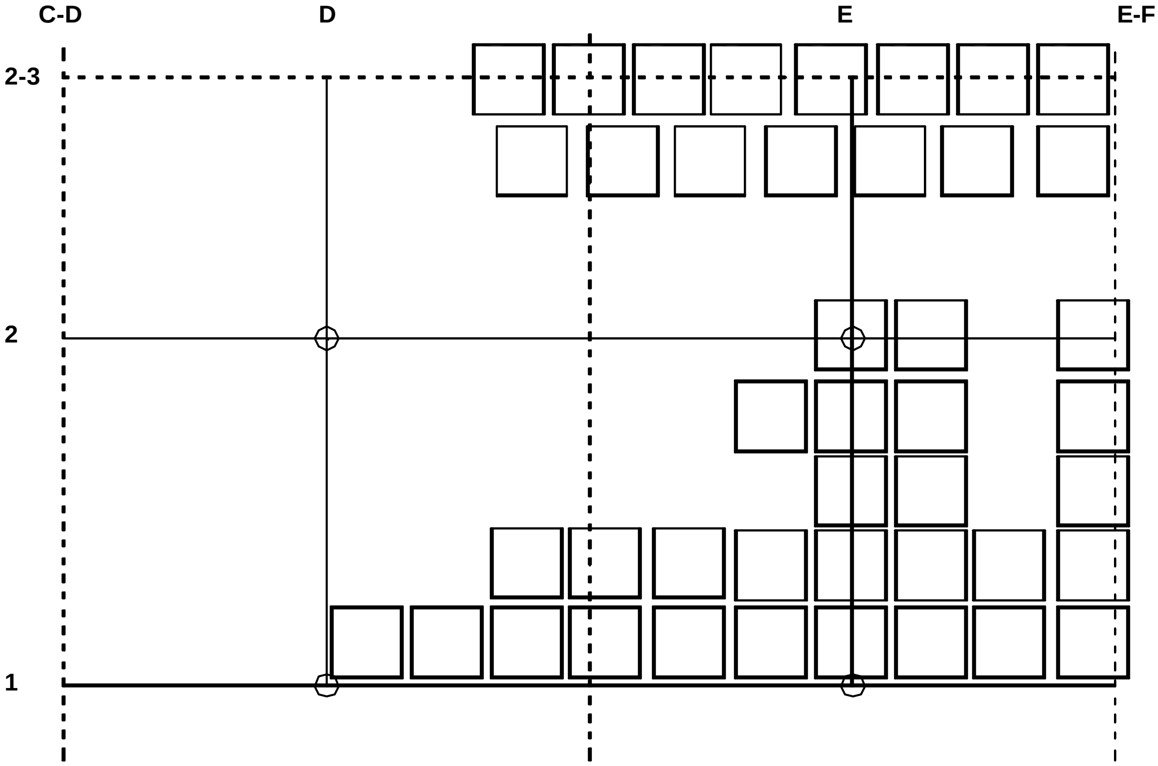


Figure A5 Location of sandbags on 8th floor

Appendix B- Fire design parameters

A_f = 11x7 = 77m²

A_v = 1.27x9 = 11.43m²

a_v = 0.148

O = 0.043m^{½}

Fire load density = 40kg/m² = 720MJ/m²

Thermal properties:

	bj	Aj	bjAj
Floor	560	77	43120
Walls	560	126	70560
Ceiling	1120	77	86240

b = SAjbj/Sbj = 720 J/m²s^{½K}

w_f = 1.11

t_{eq} = 720x0.09x1.11 = 72 minutes

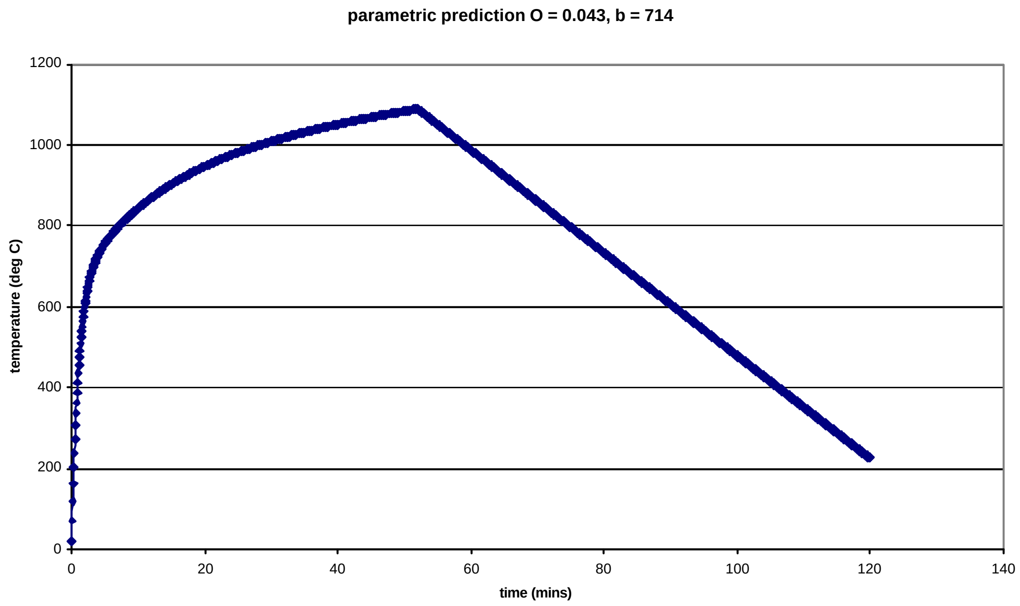


Figure B1 Parametric time-temperature curve