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The Influence of Design Stress on the Performance of Unprotected Steel Beams and Columns Built into a Fire Resistant Wall

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Research Organisation

CONTENTS PAGE

1.	INTRODUCTION	1
2.	EXPERIMENTAL PROCEDURE	2
3.	RESULTS	3
4.	DISCUSSION	5
5.	CONCLUSIONS	6
6.	REFERENCES	7

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THE INFLUENCE OF DESIGN STRESS ON THE PERFORMANCE OF UNPROTECTED STEEL BEAMS AND COLUMNS BUILT INTO A FIRE RESISTANT WALL

SYNOPSIS

A BS476:Part 8 fire test has been performed on a pair of BS4360:Grade 43A, 203 x 203 mm x 52 kg/m columns built into a double skin cavity wall. One flange and part of the web of the unprotected steel section were exposed to the fire. The section was loaded to 115% of the maximum permissible design stress and the test discontinued after 30 min when the outer wall revealed horizontal cracks.

A similar test was carried out in which the columns were replaced by a pair of BS4360:Grade 50, 356 x 171 mm x 67 kg/m beams in which one flange and all the web were protected from direct radiant heat. The section was loaded to 40% of the maximum permissible design stress and the test was discontinued after 180 min.

Both these results and information obtained in earlier work suggest that partial protection of the steelwork can have a beneficial effect on fire resistance time and should be considered in any fire engineering design. Early indications suggest that it may be possible to achieve a 1 h fire reistance time for a bare column used in this way.

1. INTRODUCTION

The heating rate of a steel section in a fire depends on its location in relation to the flames. Recent laboratory experiments carried out on composite structures have shown that partially exposed steel elements can have significant fire resistance times as measured in the BS476:Part 8 test. This is particularly the case where heat transfer is restricted to thermal conduction along the relatively thin web. A form of building construction frequently encountered is that of a steel column built into a cavity wall. A BS476:Part 8 fire test on a pair of unprotected 203 x 203 mm x 52 kg/m columns built into a double skin and block wall and loaded to a nominal 50% of the maximum design stress gave a fire resistance of 103 min[1]. It was of interest to understress the columns by this amount since in the upper levels of a multistorey building they would always be subjected to loads less than the allowable maximum.

This form of construction may incorporate different column (or beam) sizes, a variety of wall systems and a range of load levels. Therefore, although the preliminary test results were encouraging there was a need to assess the fire resistance of other composite structures. The present report describes two further tests, the first using a pair of BS4360:Grade 43A, 203 x 203 mm x 52 kg/m columns loaded notionally to the maximum permissible design stress and the second using BS4360:Grade 50B beams (acting as columns) with a nominal 50%

loading. No load was applied to the wall. The heating rates and deflections of the columns were monitored and the significance of the results from all three 'columns in walls' tests are discussed. A subsequent examination of the loading procedure used on the standard FIRTO equipment culminated in a reappraisal of the actual test loads applied in all three experiments.

2. EXPERIMENTAL PROCEDURE

A total of three tests have been carried out on columns built into walls. The first of these has been described in an earlier report[1]. The more recent experiments are presented below.

2.1 Fabrication of Steelwork

Each test was carried out in the wall furnace at FIRTO, Borehamwood. In order that the load could be applied axially it was necessary to test two identical steel sections located at the $^1/3$ and $^2/3$ positions across the furnace. The steel sections comprised two 203 x 203 mm x 52 kg/m columns (BS4360:Grade 43A) and two 356 x 171 mm x 67 kg/m (BS4360:Grade 50B) beams acting as columns. The test length was 3 m. Steel end plates, 406 x 406 mm x 20 mm thick, were welded across the ends of the columns and each pair was then welded, in an upright position, to a 580 x 3048 mm x 20 mm steel base plate. A non-structural concrete mix was cast covering the base of the structure to form a 250 mm thick block which offered protection and additional fixity to the steel base. A second steel plate was welded across the top of both sections to ensure a uniform load distribution and to restrict their lateral movement.

2.2 Wall Construction

(a) Columns

A non load bearing cavity wall was built on the concrete base so that one flange of each column was contained within the void of the cavity. The outer fletton brick wall was positioned approximately 12 mm from this flange surface. The inner wall was constructed from Thermalight blocks which partially covered the webs while forming a cavity 50 mm wide. Wire wall ties were evenly spaced at every sixth course of fletton bricks. A gap approximately 30 mm left between the tops of the walls and the steel restraining plate was filled with mineral fibre. Figures 1 and 2 show a schematic illustration and photographs respectively of the test conditions.

(b) Beams

Due to the depth of the beams the fletton brick wall was erected approximately 22 mm away from the concealed flange. In this test the webs of the beam were completely protected by the lightweight concrete block bricks used for the inner wall. This was achieved by keying alternate courses, adjacent to the web of the beam, into the inner wall for added stability. Figures 3 and 4 show a schematic illustration and photograph respectively of the construction.

The part of the upper restraining plate exposed to the fire in each test was protected with mineral fibre blanket strapped to edge and lower surface.

2.3 Instrumentation

Twenty thermocouples were attached to each steel section to monitor the heating rates of the steel. Their positions are shown in Figs. 5 and 6. Five thermocouples were embedded in each flange and ten thermocouples were located in the web in both the exposed and protected areas. The atmosphere heating rate was measured by six thermocouples placed adjacent to those used to control the furnace.

The BS476:Part 8 fire test for vertical separating elements has an insulation requirement. This states that failure is deemed to occur if the maximum and mean temperature of the unexposed surface of the construction increases by more than 180 or 140^{o}C respectively above the ambient temperature. Six copper/constantan thermocouples, soldered to copper discs and covered with asbestos pads, were therefore fixed to the external surface of the fletton brickwork by FIRTO personnel to monitor the temperature rise.

The average longitudinal extension of each pair of test sections was measured throughout the test by displacement transducers fitted to the crosshead of the loading frame. The lateral deflection at mid-height of the unexposed flange of one steel section during each test was measured by reference to a metal rod attached to the flange and protruding through the brickwork to bear on a dial gauge.

2.4 Steel Supply

The columns and beams were obtained from a local steel stockholder. Following the fire tests, samples for chemical analysis and room temperature tensile properties were taken from the length of section embedded in the concrete base. The chemical compositions were within the limits specified by BS4360:1972 as shown in Table 1. Similarly, the respective strength properties of the Grade 43A columns and the Grade 50B beams were within specification, as shown in Table 2.

2.5 Testing Method

The test furnace is in the form of a sandwich; one half comprises the loading frame and is fixed in position whilst the other half, housing the gas burners at right angles to the wall, is moveable. Once the load is applied the furnace is lit and the test begins when the two halves are brought together. The gas temperature follows the standard time-temperature curve as per ISO 834 or BS476:Part 8.

The load on any column in a building is made up of a number of components depending on the situation and building type. The principal components arise from dead loads, superimposed floor and roof loads, and wind loads. At the time of a fire it is realistic to assume that many of these would be reduced. Therefore it was decided in the first test to understress the 203 x 203 mm x 52 kg/m columns in walls by 50% of their capacity. The current work using the same column size aimed at applying the maximum design load. With regard to the BS4360:Grade 50 beams built into the walls the intention was to load them to 50% of the design load.

In the current work, the actual loads of 1940 kN on the columns and 940 kN on the beams were applied by a pair of hydraulic rams at either side of the furnace which acted through lightweight concrete pads. A close examination of the loading path resulted in an estimate of the end conditions pertaining to the composite construction and the loading calculations are given in the Appendix.

3. RESULTS

3.1 203 x 203 mm x 52 kg/m Columns in Walls

The test performed at an applied load of 1939 kN was stopped after 30 min at which time the rate of deflection of the column was greater than the maximum crosshead speed of the loading frame.

The longitudinal extension of the columns is shown in Fig. 7 indicating a small thermal expansion during the first 20 min of the test followed by a progressive 'contraction'. The lateral deflection measurements, presented in Fig. 8 showed that during the first 20 min the columns bowed to a maximum displacement of 15 mm towards the furnace. However, as the apparent axial contraction occurred the columns reversed the direction of bowing giving a total deflection of 56 mm at failure. For safety precautions a pinch load was maintained on completion of the test which resulted in additional distortion of the columns.

The temperature measurements recorded from the columns, the furnace atmosphere and the unexposed brick wall surface during the test are given in Figs. 9 to 13. At the end of the test the outer flanges of both columns were heated to temperatures in the range of 666-783°C. The mean temperature of 742°C was approximately 30°C greater than that measured after the corresponding time in the first test[1]. The unexposed flanges were much cooler with temperatures in the range of 35 to 140°C. At the exposed web locations the measured temperatures were in the range of 517-670°C, whilst the unexposed positions were in the range of 96-253°C. A detailed summary of the steel heating data is presented in Table 3.

The temperature of 13°C recorded at the end of the test on the unexposed surface of the fletton brick wall remain unchanged and satisfied the insulation requirements of the BS476 fire test.

The furnace heating rates are compared with the BS476:Part 8 curve in Fig. 13. The temperatures recorded on the right hand side of the furnace were lower than the standard curve for part of the test but were still within the permitted tolerances of the specification.

Due to partial disintegration of the concrete plinth on which the test structure was sitting the reload test could not be carried out satisfactorily. Measurements made before the reload test was attempted indicated that the test load had pivoted at both the top and bottom by approximately 40 mm on the furnace side of the loading frame. It was clear that the loading had been eccentric and in consequence this altered the effective length used in calculating the ratio of slenderness of the compression member as governed by BS449:Clause 31. This meant that a load higher than the maximum permitted design load had been applied. The walls had also been pushed together at the centre of the construction corresponding with the maximum deflection of the columns. This resulted in the formation of two parallel horizontal cracks along the top and bottom of the central fletton brick course, producing gaps of 10 mm between brick and mortar.

Photographs of the construction after the fire test are given in Fig. 14, highlighting the cracking in the unexposed wall and the buckling pattern of the columns.

3.2 356 x 171 mm x 67 kg/m Beams in Walls

The test performed at an applied load of 939 kN (approximately 40% of the maximum design stress) was terminated after 180 min at the point when the rate of deflection exceeded that of the crosshead movement of the loading frame.

The longitudinal extension of the beams is given in Fig. 15 showing a similar pattern of behaviour to that observed in the column tests. The maximum thermal expansion of 3.7 mm was recorded after a time interval of 30 min. The lateral deflection measurements, presented in Fig. 16 showed that during the first 93 min the beams bowed a maximum displacement of 20 mm towards the furnace; the direction of bowing was then reversed giving a total deflection of 108 mm at failure.

The temperature measurements recorded from the beams, the furnace atmosphere and the unexposed brick wall surface during the test are given in Figs. 17 to 21. At the end of the test the outer flanges of both beams were heated to temperatures in the range of 960-1064°C, with a mean of 1048°C; the concealed flanges recorded temperatures of 107-225°C, with a mean of 162°C. The temperatures of the web in the parts which protruded into the furnace but which were protected by lightweight block brick were in the range of 690-979°C but the portions of the web contained within the block brick wall recorded much lower temperatures in the range of 152-291°C. A detailed summary of the steel heating data is presented in Table 4.

The temperatures recorded at the end of the test on the unexposed surface of the fletton brick wall satisfied the insulation requirements of the fire test, with maximum and mean temperatures of 47 and 37°C respectively.

The furnace atmosphere heating rate is compared with the International temperature-time curve in Fig. 21 which shows that the heating rates followed the standard curve throughout the test.

On completion of the fire test it was observed that the construction had tilted away from the furnace leaving a 6 mm gap between the bottom steel restraining plate and the loading frame. The walls were intact; only the fletton brick wall showed any damage with a horizontal and diagonal stepwise crack running away from the central brick course. Photographs of the construction after testing are presented in Fig. 22.

A reload test on the beams in walls construction was carried out successfully since the bottom concrete plinth of the FIRTO loading frame had been replaced for this test by protected fabricated steel sections.

4. DISCUSSION

The applied loads originally selected for this work were to achieve approximately 50 and 100% of the maximum design load specified by BS449:1972 for BS4360:Grade 43A steel sections. The load calculations rely principally on the effective length of the stanchion used in determining the slenderness ratio and the actual length that is measured between the centres of intersections. It has been shown that instability under load is dictated by deformation about the y-y axis of the column (or beam). The preliminary calculations carried out before the original 'column in wall' test was carried out used an effective length of 0.75 for the y-y condition and an actual length of column that ignored the depth of concrete cover at its base (250 mm)[1]. However, close observation of the test procedure suggests that neither the columns, nor the Grade 50 beams were effectively held in position and restrained in direction at both ends. In consequence it was considered more realistic to use an effective length factor of 1.00, which according to BS449:Clause 31 is appropriate for stanchions held in position at both ends but not restrained in direction. Therefore, the axial loads as a percentage of the maximum permissible design loads for Grade 43A members were respectively 56.5%, 115% and 50% for the two column tests and the beam test. (If the exposed length of the vertical steel member is taken as the 'actual length' in the calculations the above percentages are reduced by approximately 3%.)

The axial stress imposed on the 203 x 203 mm x 52 kg/m Grade 43A columns at the start of each test were 71.8 N/mm^2 and 146.1 N/mm^2 and hence they were loaded to 56.5 and 115% of the maximum design value. The axial stress on the 356 x 171 mm x 67 kg/m Grade 50 beam was 55.0 N/mm^2 loaded to 39.3% of its maximum design value, corresponding to 50% of the maximum design load for a Grade 43A member.

A summary of the behaviour of 203 x 203 mm x 52 kg/m Grade 43A columns in a standard BS476:Part 8 fire test is presented in Fig. 23 for a range of conditions. The fire resistance time is assumed to be zero at an applied axial stress equivalent to the room temperature yield stress of the steel. In the absence of test data on an unprotected column the fire resistance has been estimated from tensile tests at 2% permanent strain and at a heating rate of 10^{o}/min. Experience has shown that a realistic emissivity factor for the furnace conditions utilised is 0.4. On this basis the failure temperature and time for a fully loaded column with an $^{H}P/A$ value of 180 m^{-1} are 570°C and 13 min; at 50% design load these values become 680°C and 18 min respectively. By protecting the column with Vicuclad board the fire resistance increased dramatically[2,3].

Between these extremes lie the columns in walls tests, demonstrating that partially protected structures can have a useful fire resistance. The wall prevents flame impingement on the concealed flange and this part of the section is only heated by conduction through the web. In the absence of bending the thermal gradient through the section enables the cooler areas of the section to carry higher imposed loads. It is rare for the axial loading of columns in multistorey buildings to exceed 80% of the maximum permissible design load. The current work suggests that (within the realms of experimental error) such a limiting condition imposed on 203 x 203 mm x 52 kg/m columns embedded in a similar composite wall construction would achieve a fire resistance time of 1 h.

No BS476:Part 8 fire tests had previously been carried out on unprotected BS4360:Grade 50 beams acting as columns. The 356 x 171 x 67 kg/m beams built into the walls had an $^{H}P/A$ value of 162 m^{-1}. By using the same calculation approach as described for the columns the failure temperature and time for a fully loaded section would be 640°C and 17 min, increasing to 780°C and 29 min for a 40% design load, as used in the 'beams in walls' test. In the latter situation the block wall construction provided complete protection to the web of each beam. This resulted in a significant improvement in fire resistance by extending the load carrying capacity of each beam to 180 min.

A summary of the average temperature profiles across the central cross section of the unprotected steel column and beam built into a fire resisting wall exposed to BS476:Part 8 heating is given in Fig. 24. The experiments have shown a similar pattern of behaviour to that observed in recent FRS work where columns bow initially towards the heat source, then straighten out and eventually fail by bowing in the reverse direction[4]. Such opposite bowing is believed to be caused by movement of the neutral axis away from the heated flange and may also be influenced by a phase transformation in the heated steel flange.

The work to date has been based on only one form of composite construction and under a simple loading situation that ignores the additional stresses set up in the columns as a result of the expansion of a connecting beam. The single storey portal frame incorporates a cavity wall to half the height of the column and plastic coated steel above this level. The experimental fire testing of all such building methods in terms of structural stability is expensive and time consuming. Efforts are being directed towards a mathematical approach to the problem, in which a thermal model is used to specify the temperature gradients through the section followed by a structural model to determine the load bearing capacity.

Preliminary work into thermal modelling has produced a simple computer program[5] which predicts the thermal response of a steel column built into a cavity wall, by incorporating the temperatures recorded in the first of the columns in walls tests[1]. Several modes of heat transfer have been considered but variables such as furnace emissivity and convective heat transfer coefficient and the contact coefficient between the column and the blockwork could not be actuately defined. The values given to these variables were adjusted to provide a reasonable fit between the calculated results and the experimentally measured temperatures. The predicted temperatures in a 203 x 203 mm x 52 kg/m column built into the wall at the completion of a 30 min fire test and the recorded values are shown in Fig. 25. The agreement is very close, discrepancies being due possibly to different furnace heating rates from the ISO curve used in the model and local radiation effects.

An attempt has been made to use the thermal information to predict structural behaviour using the FASBUS II program released by the American Iron & Steel Institute to analyse beam and floor deflection and load bearing characteristics. This program is the only structural model that has been available to Sheffield Laboratories and is not designed specifically to handle columns in walls 'per se'. Therefore the prediction of column deflection has only been partly successful. More work needs to be done to specify the column end effects in mathematical terms.

5. CONCLUSIONS

A BS476:Part 8 fire test has been performed on a pair of unprotected BS4360:Grade 43A, 203 x 203 mm x 52 kg/m columns built into a double skin brick and block wall. The flange and part of the web of the columns were exposed to the fire and they were loaded to 115% of the maximum permissible design stress. The fire test was discontinued after 30 min and although the columns were deformed they still supported the test load at this time. The exposed flanges had attained a mean temperature of 742°C and the concealed flanges a mean temperature of approximately 88°C.

A similar fire test was performed on a pair of BS4360:Grade 50 beams 356 x 171 mm x 67 kg/m built into walls in which one flange and the complete depth of the beam were protected from radiant heat. The beams were loaded to 40% of the maximum permissible axial stress. The fire test was terminated after 180 min. The exposed flanges recorded a mean temperature of 1048°C and the concealed 162°C. A reload test was carried out successfully.

A mathematical model designed to specify temperature gradients based on data derived in an earlier columns in walls test gave predictions in close agreement with recorded data.

The use of partially protected steel members can have a significant influence on their fire resistance. The limited data obtained on the 203 x 203 mm x 52 kg/m columns in walls suggest that for an axial load equivalent to 80% of the maximum permissible design load, a fire resistance time approaching 1 h might be possible.

6. REFERENCES

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TABLE 1 CHEMICAL COMPOSITION OF STEEL SECTIONS USED IN TESTS

Code No.	Test	C	Si	Mn	P	S	Cr	Mo	Ni	V	Ti	Cu	Nb	Zr	Tot. Al	N_2
RS386	203 x 203 mm x 52 kg/m column	0.27	0.04	0.94	0.012	0.020	<0.02	<0.005	0.02	<0.005	<0.005	0.02	<0.005	<0.005	<0.005	0.0042
	356 x 171 mm x 67 kg/m beam	0.17	0.02	1.24	0.011	0.018	0.01	<0.005	0.02	0.075	<0.005	0.04	<0.005	<0.005	0.008	0.006
BS4360:Grade 43A requirements		0.30 max.	0.55 max.	1.70 max.	0.06 max.	0.06 max.										
BS4360:Grade 50B requirements		0.29 max.	0.55 max.	1.60 max.	0.06 max.	0.06 max.				0.003/ 0.10			0.003/ 0.10			

TABLE 2 TENSILE TEST DATA FROM THE FLANGE OF STEEL SECTIONS USED IN THE TESTS

Code No.	Test Section	Yield Stress N/mm^2	Tensile Strength N/mm^2	Elongation %
RS386	203 x 203 mm x 52 kg/m column	266	506	29.0
	356 x 171 mm x 67 kg/m beam	379	526	28.0
BS4360:Grade 43A requirements		255 min.	430/540	20.0
BS4360:Grade 50B requirements		355 min.	490/620	18.0

TABLE 3 COLUMNS IN WALLS TEST - 115% DESIGN LOAD
(COMPRISING OF AN EXTERNAL FLETTON BRICK WALL AND A BLOCKWORK BRICK WALL INTO WHICH TWO UNIFORMLY SPACED BS4360:GRADE 43A 203 x 203 mm x 52 kg/m COLUMNS WERE BUILT)

BSC Test No. 56, Data Sheet 32, FIRTO No. TE4413, Test Date 7.12.82

	Flange
Yield Stress, N/mm^2	266
Tensile strength, N/mm^2	506
Elongation (200 mm GL), %	29.0

Code No.	Composition, %													
	C	Si	Mn	P	S	Cr	Mo	Ni	V	Ti	Cu	Nb	Tot. Al	N_2
RS386	0.27	0.04	0.94	0.012	0.020	<0.02	<0.005	0.02	<0.005	<0.005	0.02	<0.005	<0.005	0.0042

Failure time: 30 min

Thermocouple Location		Temperature, °C, At Various Times, min									
		3	6	9	12	15	18	21	24	27	30
Unexposed flange	21	18	27	38	49	60	69	82	97	118	140
	22	12	13	16	20	26	35	46	70	81	101
	23	11	13	16	20	28	38	52	71	80	91
	24	11	12	15	19	25	33	42	52	69	83
	25	11	11	12	14	17	21	26	32	39	46
Mean		13	15	19	24	31	39	50	64	77	92
Exposed flange	36	125	215	304	390	475	558	626	664	700	740
	37	114	197	294	392	487	582	654	684	719	745
	38	114	194	291	388	480	568	644	667	714	746
	39	120	210	290	379	461	547	614	637	707	749
	40	74	137	228	334	438	534	586	572	666	702
Mean		109	191	281	377	468	558	625	645	701	736
Unexposed web	26	35	52	69	86	105	127	152	190	223	253
	27	16	24	35	49	68	87	101	118	161	189
	28	16	24	34	48	64	82	104	127	148	168
	29	14	21	33	46	61	76	82	102	125	150
	30	13	16	22	32	46	60	77	87	101	114
Mean		19	27	39	52	69	86	103	125	152	175
Exposed web	31	110	179	248	317	385	455	524	579	622	668
	32	73	137	206	284	365	451	528	576	621	670
	33	76	130	203	280	360	446	524	560	605	648
	34	70	132	202	271	345	426	493	530	594	648
	35	52	79	148	248	340	426	473	464	547	584
Mean		76	131	201	280	359	441	508	562	598	644
Furnace atmosphere	1	500	559	642	683	743	774	802	749	862	869
	2	549	637	630	692	752	803	822	722	904	894
	3	411	582	656	723	771	797	797	668	899	826
	4	511	578	606	655	731	767	794	780	936	873
	5	405	540	610	604	690	749	764	594	884	810
	6	434	533	584	653	715	769	793	688	859	837
Mean		468	591	621	668	734	776	795	700	891	851
ISO curve RT 13oC		495	596	656	698	731	759	782	801	819	834

TABLE 4 BEAMS IN WALLS TEST - 40% DESIGN LOAD
(COMPRISING OF AN EXTERNAL FLETTON BRICK WALL AND A BLOCKWORK BRICK WALL INTO WHICH TWO UNIFORMLY SPACED BS4360:GRADE 50B 356 x 171 mm x 67 kg/m BEAMS WERE BUILT. WEB INFILLED WITH BLOCKWORK BRICK

BSC Test No. 58, Data Sheet 33, FIRTO No. TE4413, Test Date 15.2.83

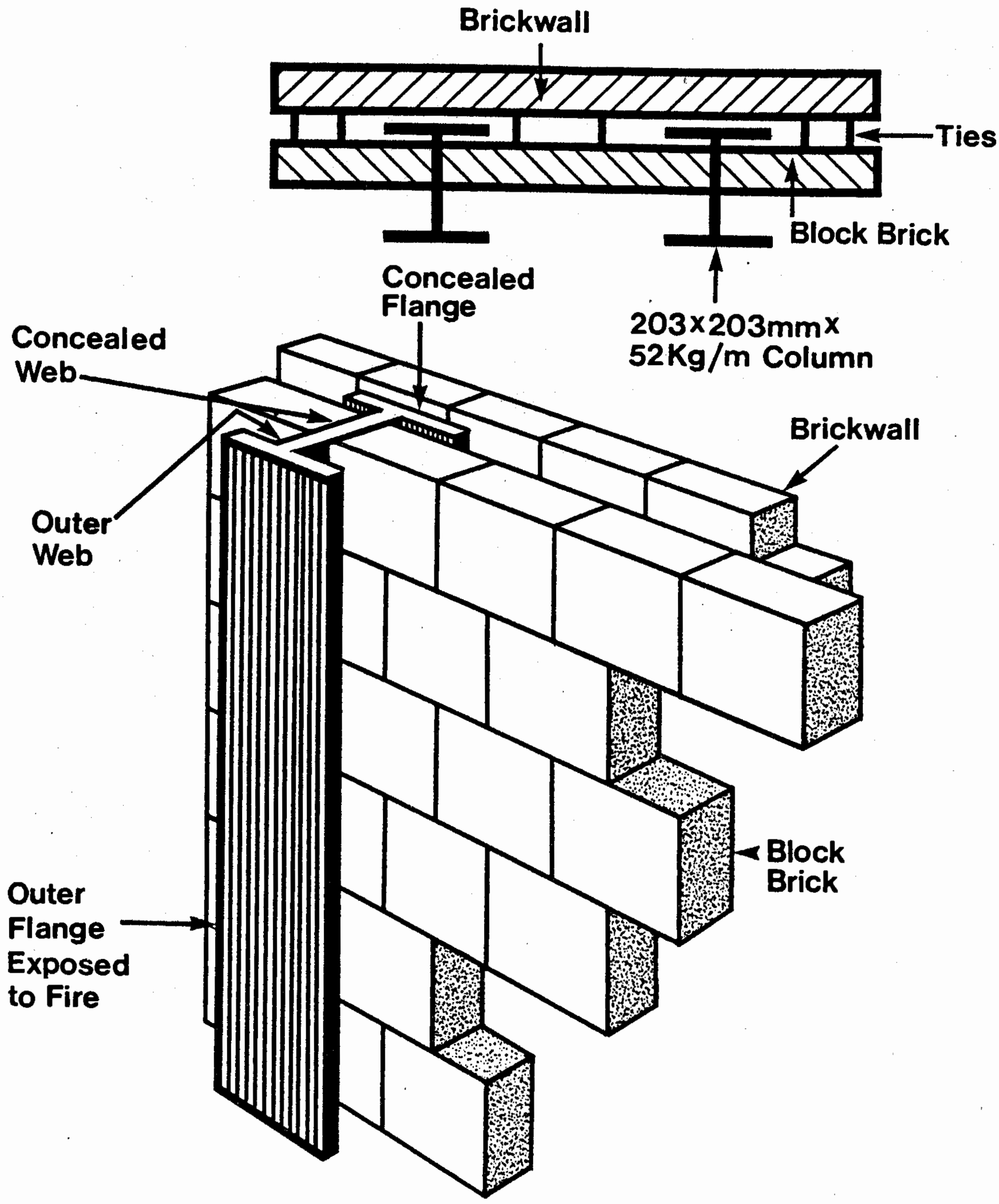
Flange

Yield Stress, N/mm^2
Tensile strength, N/mm^2
Elongation (200 mm GL), %

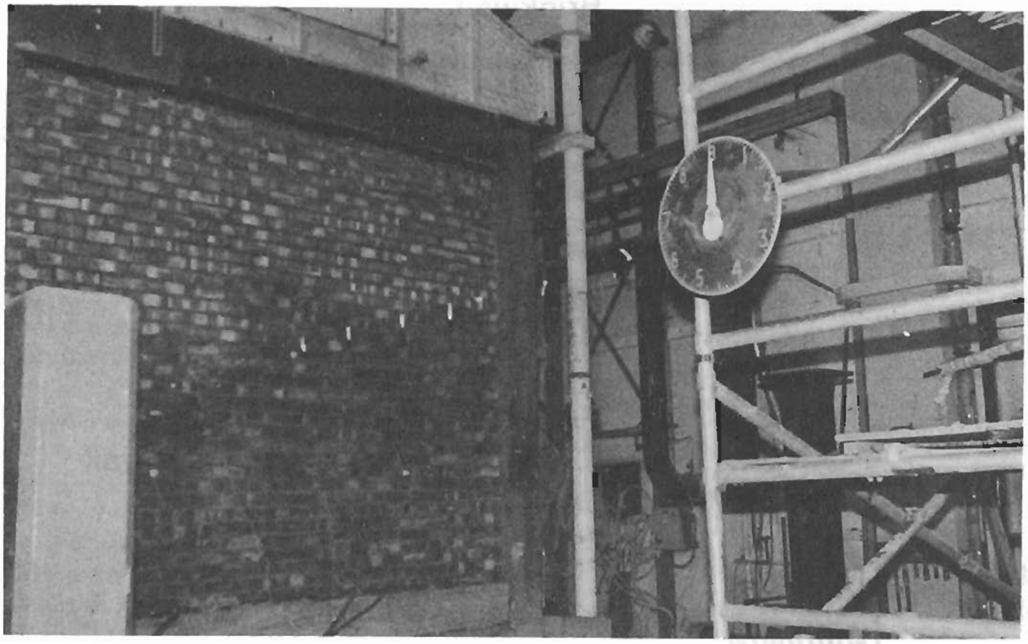
Code No.	Composition, %														
	C	Si	Mn	P	S	Cr	Mo	Ni	V	Ti	Cu	Sn	Nb	Cr	Tot. Al	N_2
RS392	0.17	<0.02	1.24	0.011	0.018	0.01	<0.005	0.02	0.075	<0.005	0.04	<0.005	<0.005	<0.005	0.008	0.006

Failure time: 180 min

Thermocouple Location		Temperature, °C, At Various Times, min																							
		5	10	15	20	25	30	35	40	45	50	55	60	70	80	90	100	110	120	130	140	150	160	170	180
Unexposed flange	21	10	13	15	18	22	27	34	44	55	65	74	79	87	97	106	112	120	128	138	152	169	189	205	225
	22	9	8	9	9	12	15	21	29	41	52	63	72	83	94	100	105	110	114	119	126	135	146	159	177
	23	8	8	8	8	10	12	16	21	28	39	53	71	94	99	101	103	107	110	113	117	122	128	135	143
	24	8	8	8	8	10	14	18	25	37	54	70	80	90	97	101	105	108	111	115	120	126	133	143	156
	25	7	7	7	8	9	10	13	16	24	40	64	83	90	93	96	98	99	100	100	101	102	103	105	107
Mean		8	9	9	10	13	16	20	27	37	50	65	77	89	96	101	105	109	113	117	123	131	140	149	162
Exposed flange	36	111	198	289	384	473	552	619	677	725	758	788	820	884	930	948	972	996	1014	1029	1038	1044	1068	1072	1064
	37	91	205	319	437	543	628	696	745	779	816	852	886	936	972	979	1001	1024	1040	1053	1060	1066	1093	1097	1087
	38	83	194	321	445	533	640	709	754	796	829	868	903	951	984	980	1002	1026	1042	1051	1052	1055	1092	1090	1075
	39	88	206	327	449	552	636	701	748	784	818	855	890	940	974	976	995	1016	1030	1039	1042	1046	1079	1069	1054
	40	105	222	323	412	493	563	622	665	692	709	729	751	798	844	869	899	924	942	952	949	959	1008	984	960
Mean		96	205	316	425	519	604	669	718	755	786	818	850	902	941	950	974	997	1014	1025	1028	1034	1068	1062	1048
Unexposed web	26	9	10	12	17	24	35	47	59	73	90	97	100	107	116	127	138	148	159	171	186	205	225	249	277
	27	8	8	10	18	31	43	57	80	92	97	99	101	110	118	131	144	156	166	177	191	208	230	257	291
	28	8	8	9	14	21	29	37	51	72	97	101	103	113	120	127	135	142	149	156	164	175	187	202	219
	29	7	8	9	13	19	27	37	55	75	91	100	101	102	110	122	129	137	144	152	162	174	189	209	234
	30	7	8	9	13	19	26	36	51	85	97	101	102	104	108	113	117	121	125	128	132	137	142	147	152
Mean		8	8	10	15	23	32	43	59	79	94	97	101	107	114	124	133	141	149	157	167	180	195	213	235
Exposed web	31	24	58	106	157	204	249	288	325	358	388	413	434	476	517	552	582	614	648	685	725	764	800	843	874
	32	23	61	117	172	226	280	327	365	393	417	440	462	506	546	577	604	638	675	716	760	813	872	937	979
	33	24	63	115	187	250	307	354	392	422	447	470	495	543	581	606	627	657	686	713	739	764	802	835	855
	34	24	67	135	198	256	308	353	393	424	449	471	494	540	578	605	627	652	679	710	743	778	810	833	854
	35	21	62	112	163	210	254	294	329	358	378	396	414	446	479	507	532	557	582	603	620	636	662	685	690
Mean		23	62	117	175	229	280	323	361	391	416	438	460	502	540	569	594	622	654	685	717	751	789	827	850
Furnace atmosphere	1	481	616	675	722	762	807	831	857	880	896	919	937	964	989	983	1011	1026	1037	1047	1052	1056	1092	1085	1075
	2	479	662	726	796	831	863	886	909	926	933	957	971	997	1019	1005	1034	1046	1058	1064	1061	1058	1102	1082	1062
	3	577	665	739	766	805	846	865	890	905	910	936	952	977	995	985	1011	1020	1027	1024	1013	1004	1062	1018	1000
	4	568	683	734	796	826	860	879	901	920	929	945	962	988	1008	997	1025	1042	1056	1070	1071	1072	1113	1102	1084
	5	491	641	715	737	775	813	835	860	868	858	894	913	949	975	928	961	981	1039	1045	1036	1042	1104	1072	1031
	6	555	673	731	753	794	834	859	886	905	913	940	956	986	1009	1003	1027	1042	1061	1065	1060	1061	1106	1081	1056
Mean		525	657	720	762	799	837	859	884	901	906	932	948	977	999	983	1011	1026	1046	1052	1049	1049	1087	1073	1051
ISO curve RT 13°C		569	671	731	774	808	835	858	878	895	911	925	938	961	981	999	1015	1029	1042	1054	1065	1075	1085	1094	1103

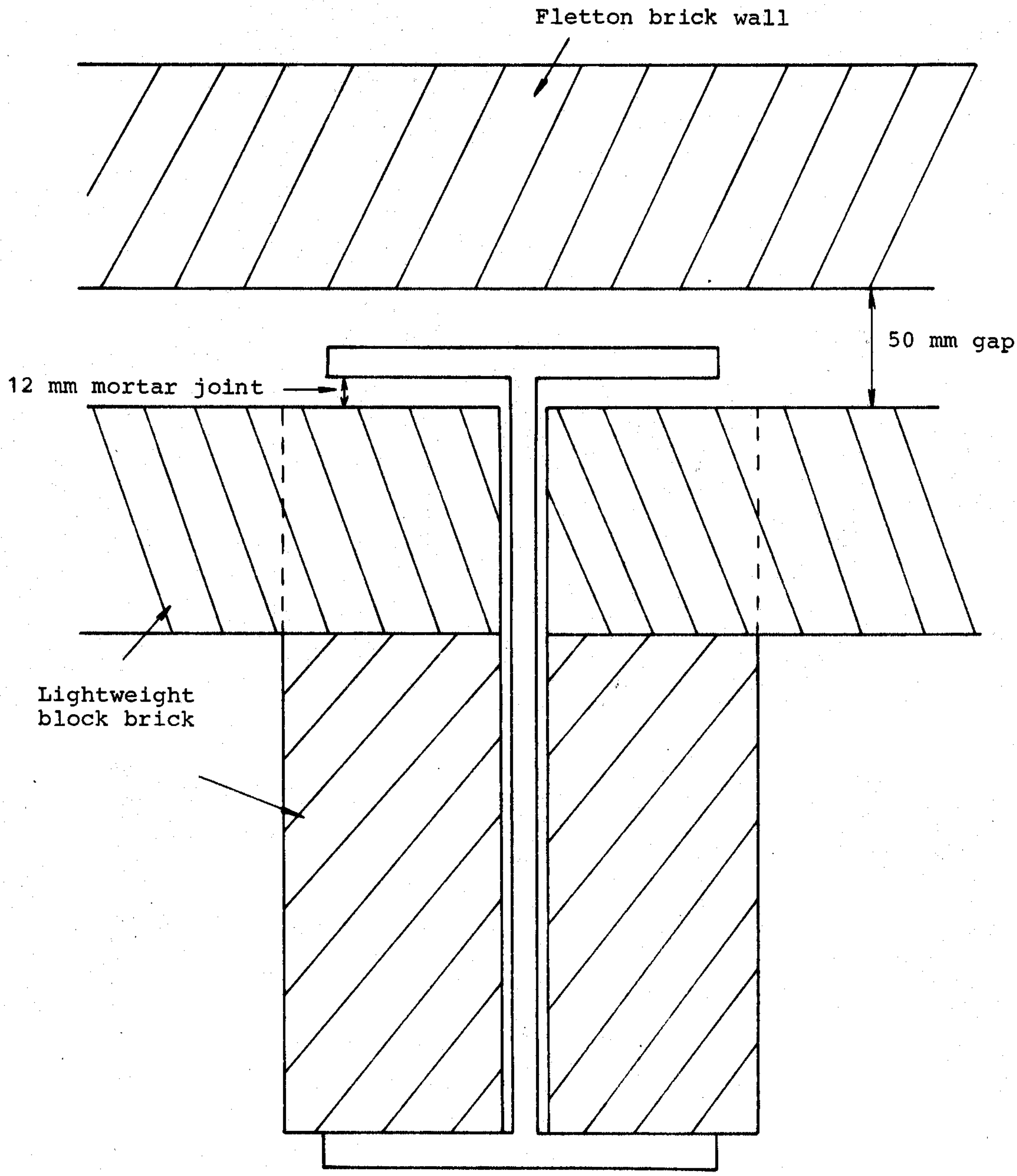


CONFIGURATION OF STEEL COLUMN BUILT INTO WALL FIG. 1



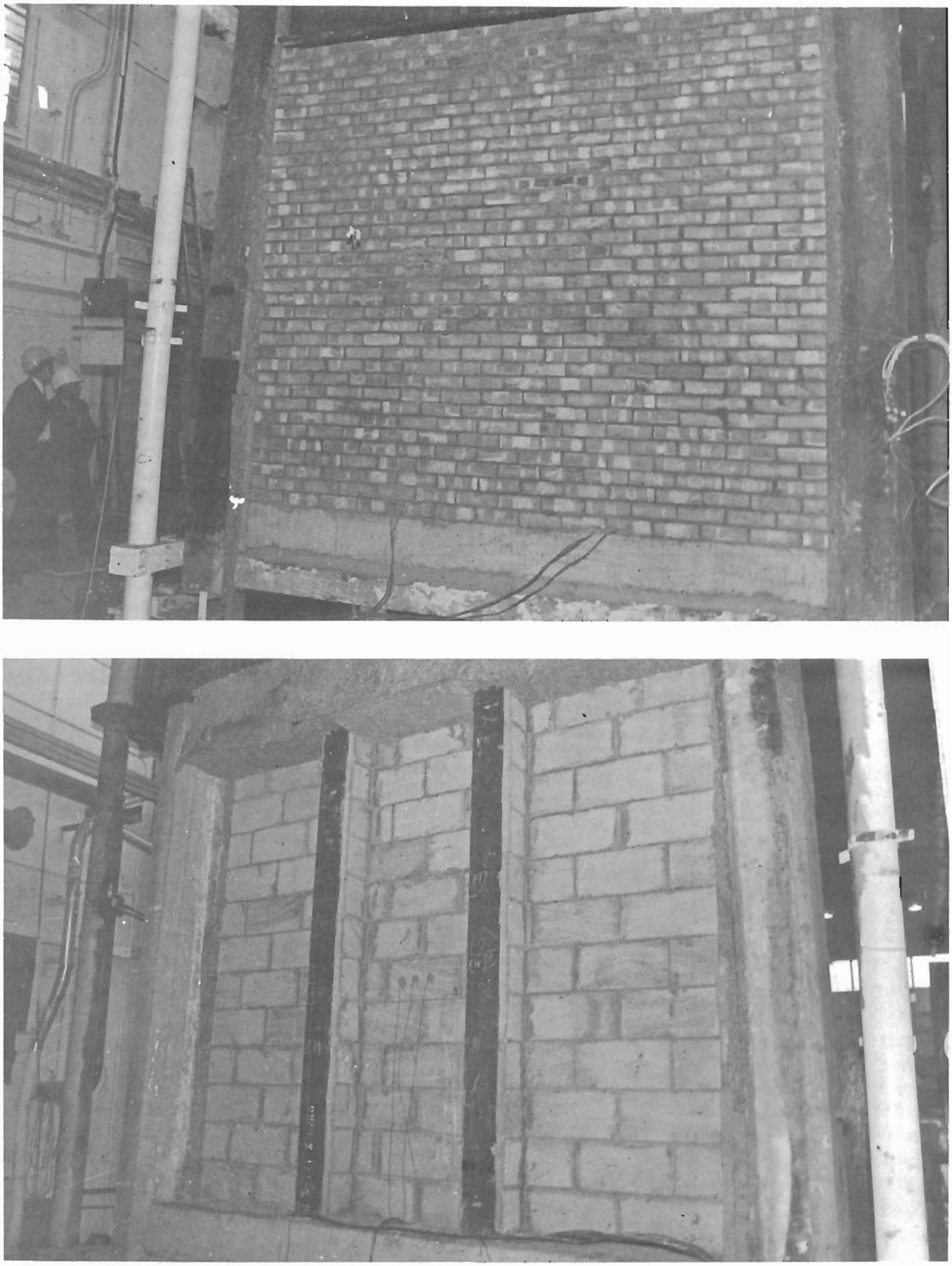
203 x 203 mm x 52 kg/m COLUMNS IN WALLS
CONSTRUCTION PRIOR TO TESTING

FIG. 2



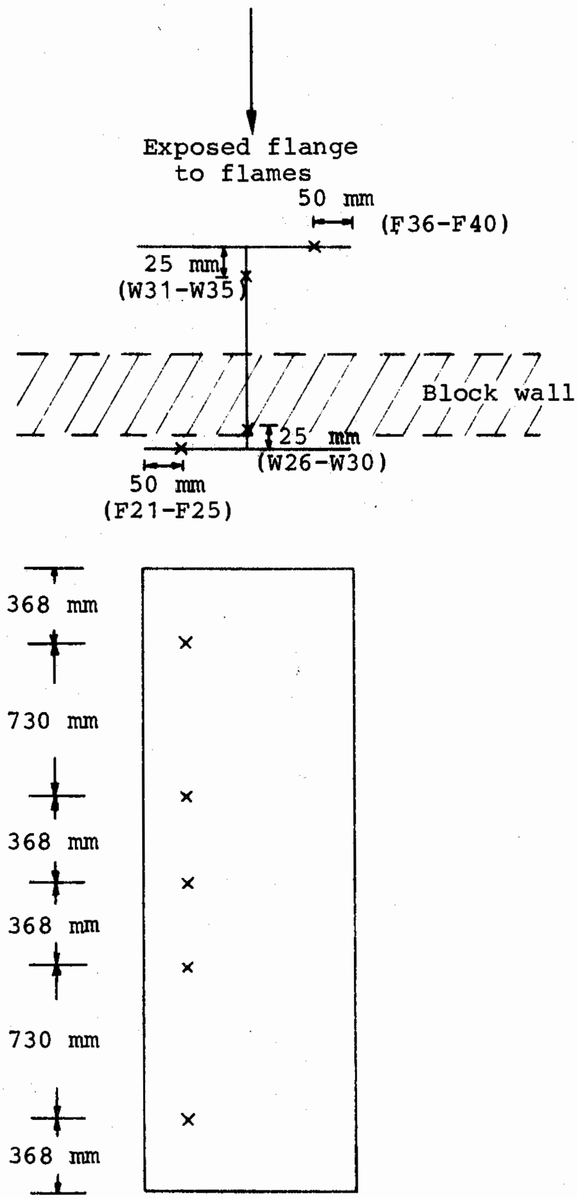
356 x 171 mm x 67 kg/m BEAMS IN WALLS ARRANGEMENT

FIG. 3
(R1/9188)



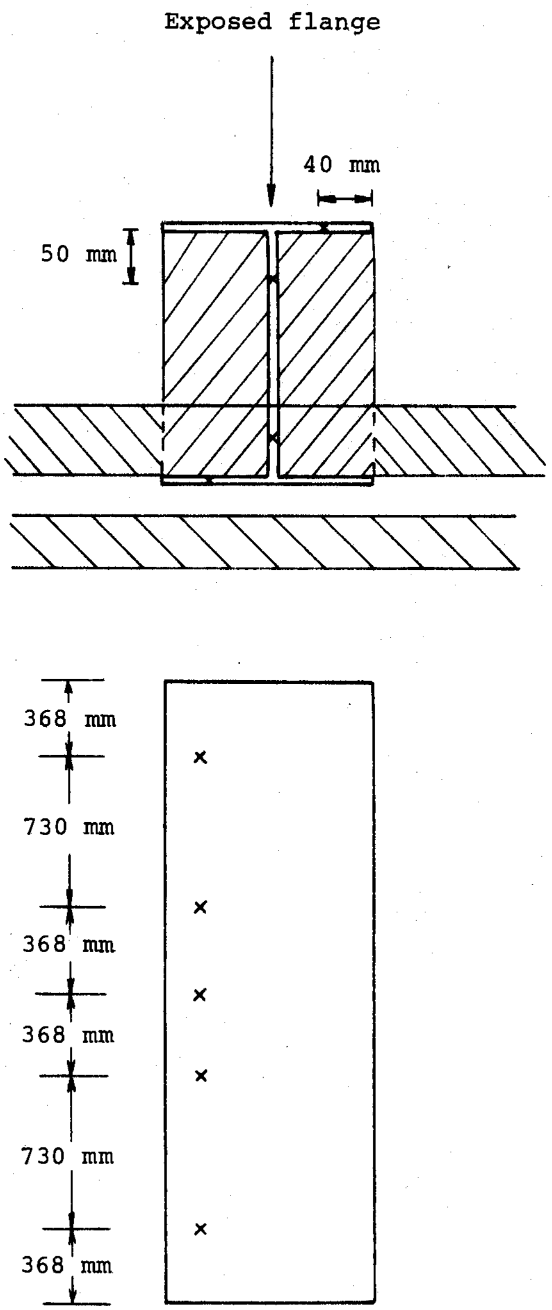
356 x 171 mm x 67 kg/m BEAMS IN WALLS
CONSTRUCTION PRIOR TO TESTING

FIG. 4



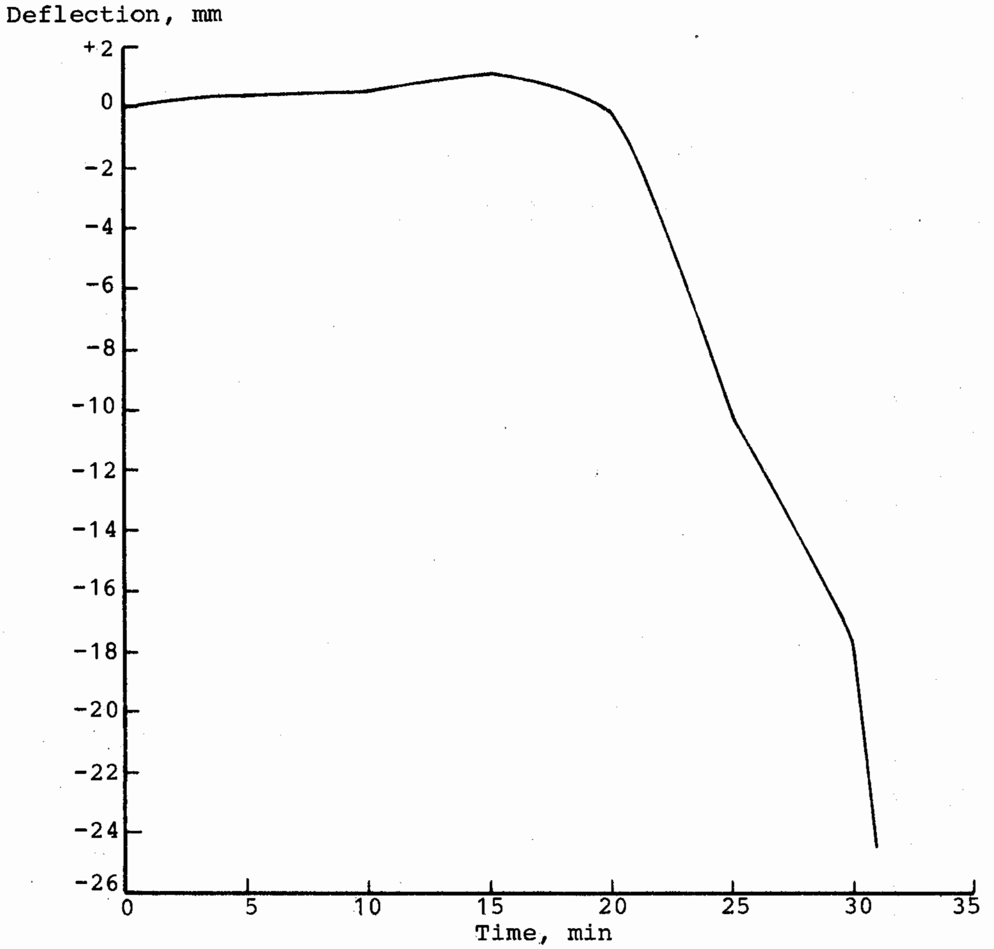
THERMOCOUPLE POSITIONS
203 x 203 mm x 52 kg/m COLUMNS IN WALLS TEST

FIG. 5
(R1/9189)



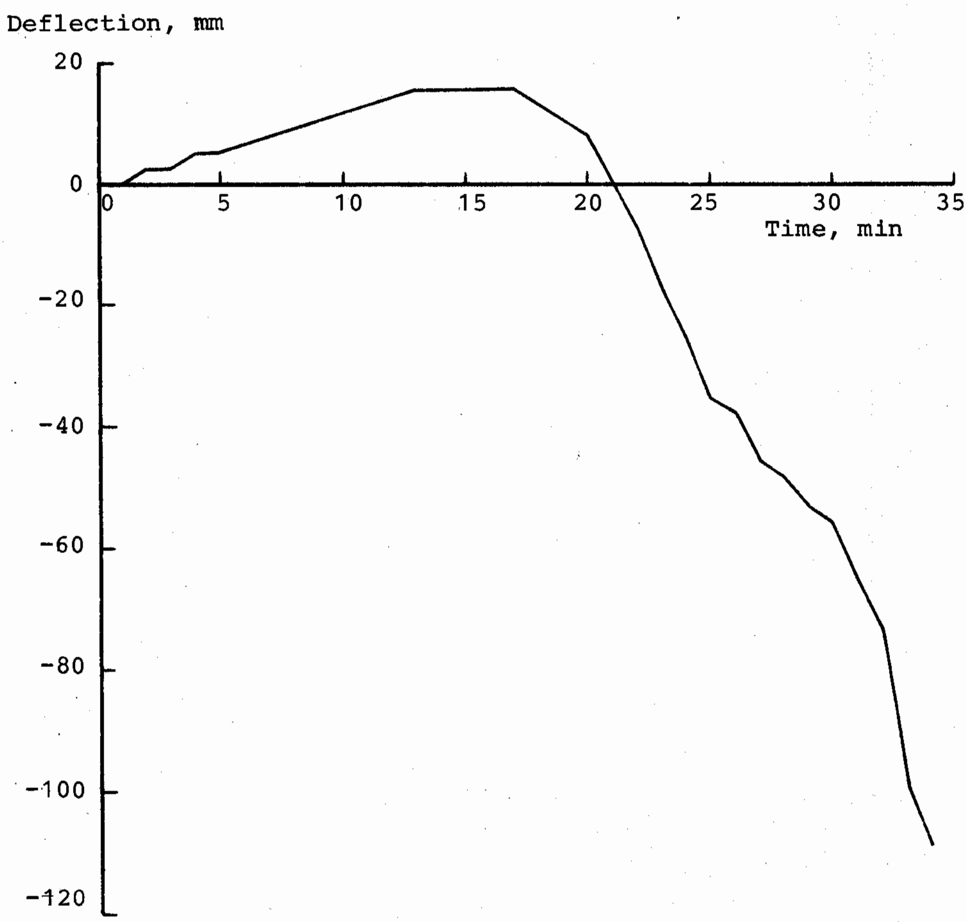
THERMOCOUPLE POSITIONS
356 x 171 mm x 67 kg/m BEAMS IN WALLS TEST

FIG. 6
(R1/9190)



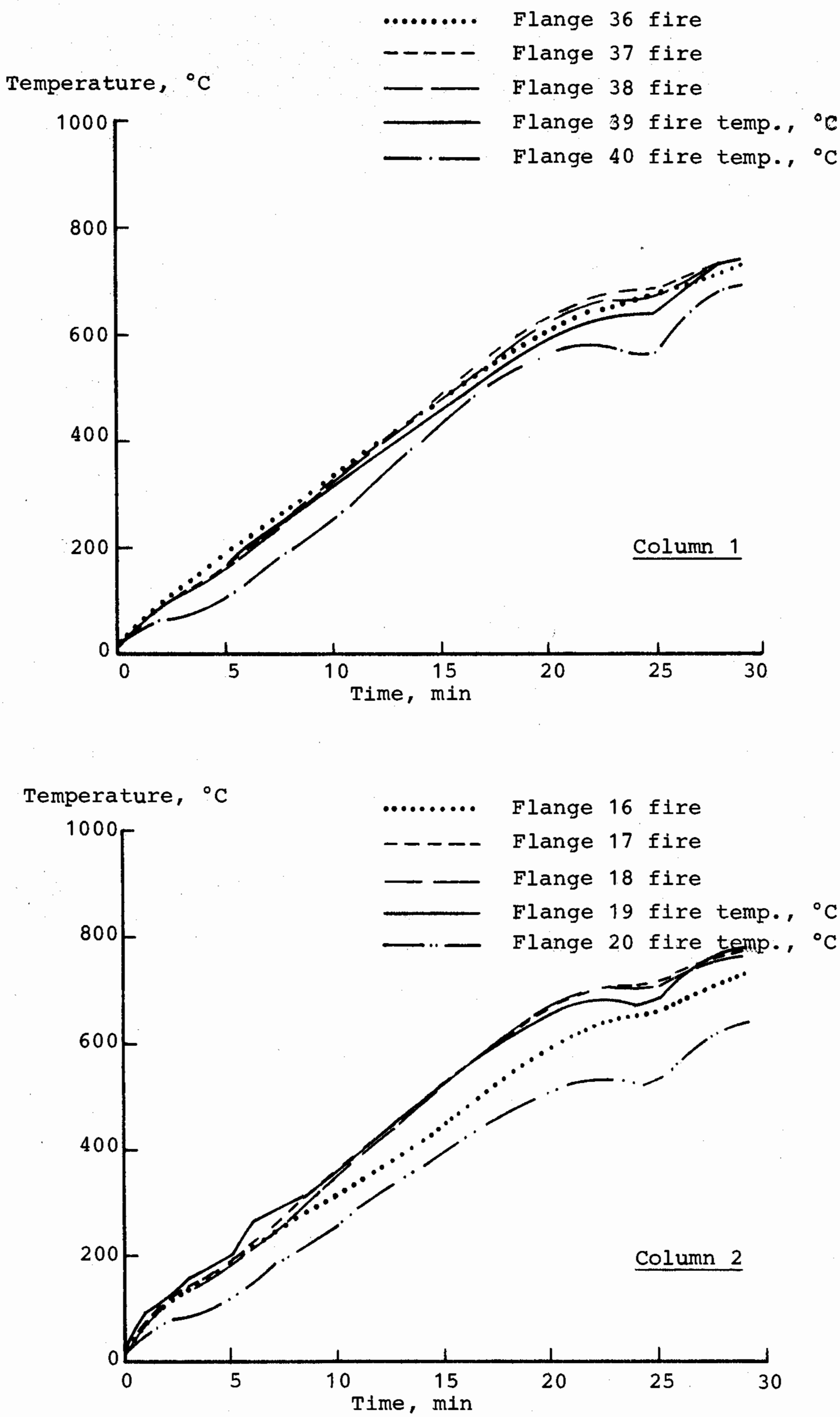
MEAN LONGITUDINAL EXTENSION MEASURED ON THE 203 x 203 mm x 52 kg/m COLUMNS THROUGHOUT THE TEST

FIG. 7 (R1/9191)



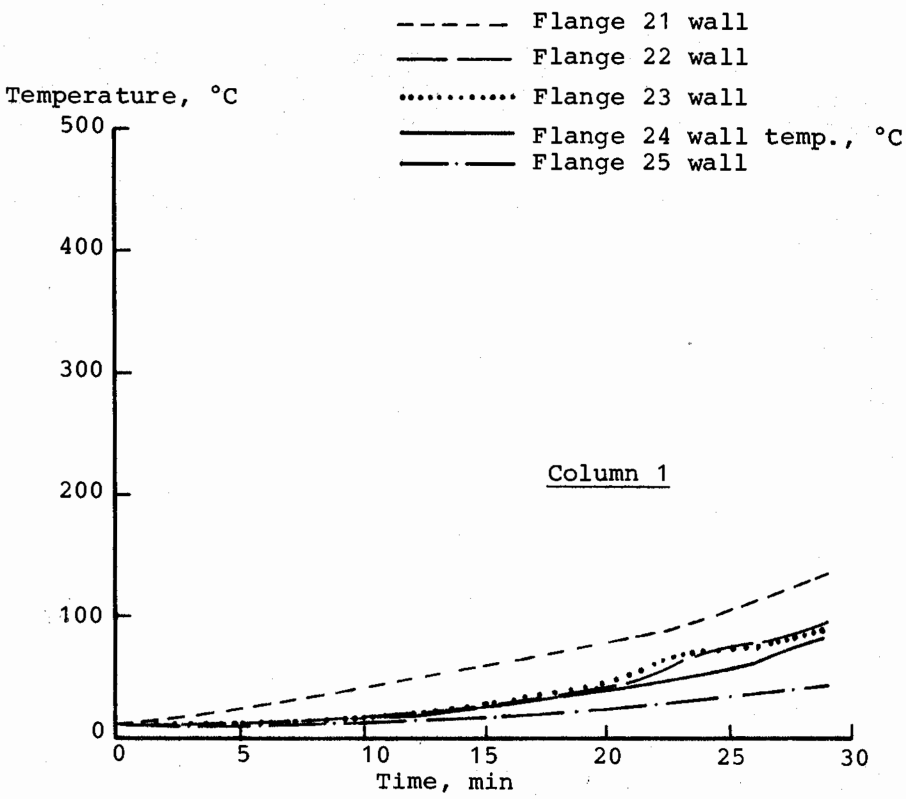
LATERAL DEFLECTION MEASURED ON COLUMN DURING THE 203 x 203 mm x 52 kg/m COLUMNS TEST

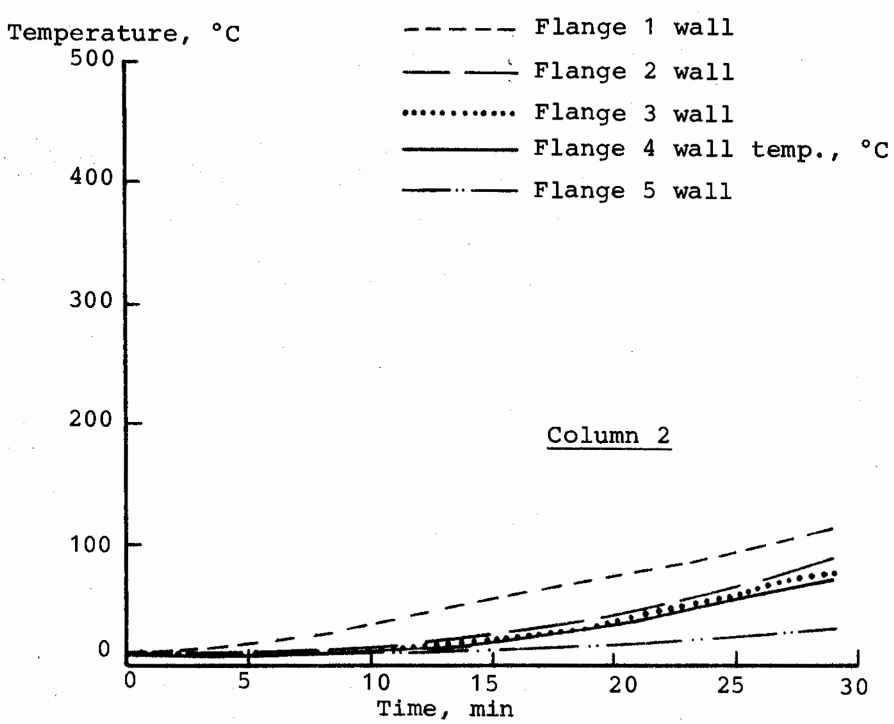
FIG. 8
(R1/9192)



<u>TEMPERATURES RECORDED ON THE EXPOSED FLANGE OF BOTH COLUMNS</u>

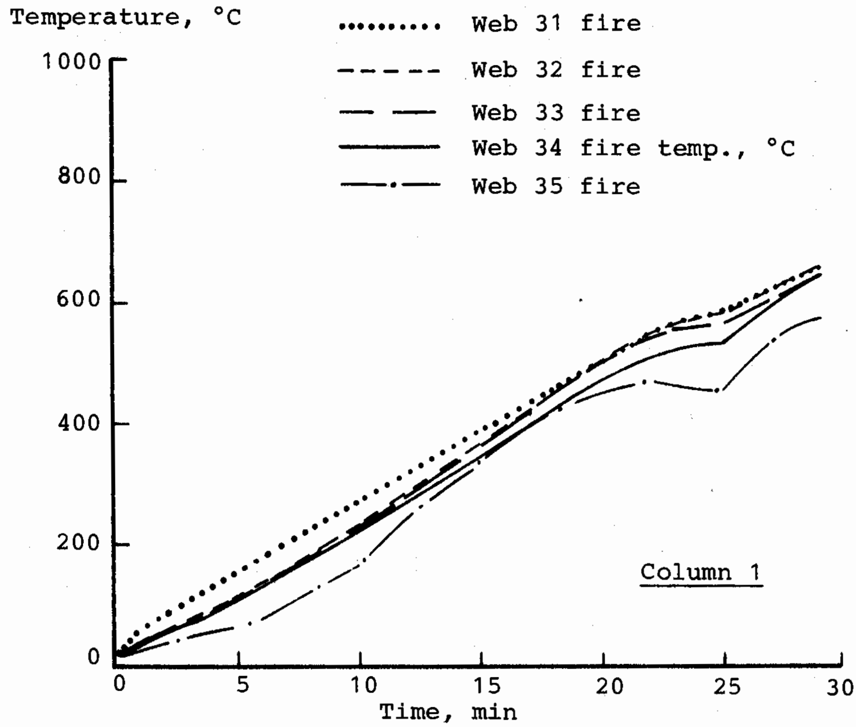
FIG. 9
(R1/9193)

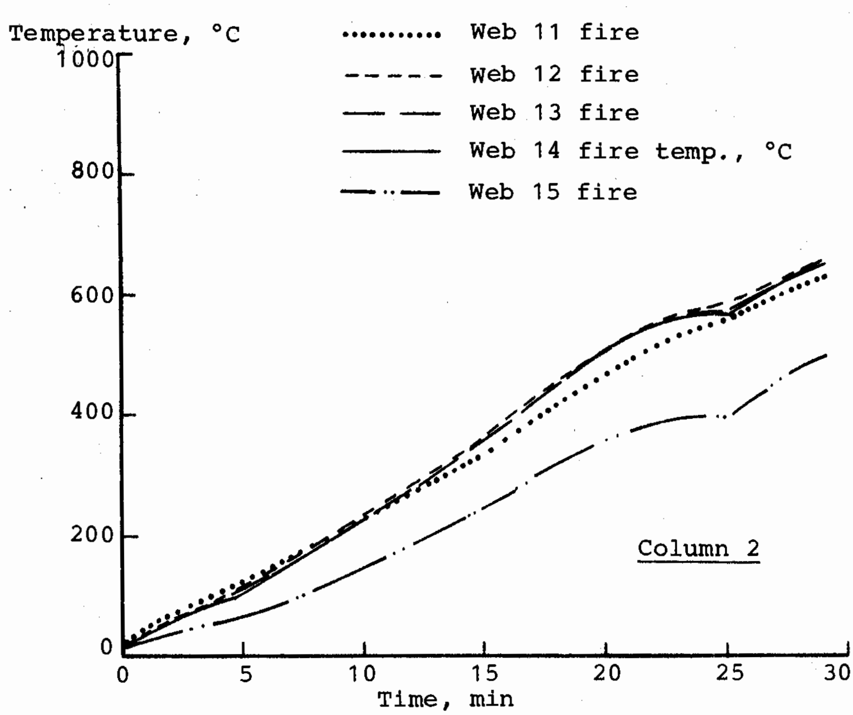




TEMPERATURES RECORDED ON THE UNEXPOSED FLANGE OF BOTH COLUMNS

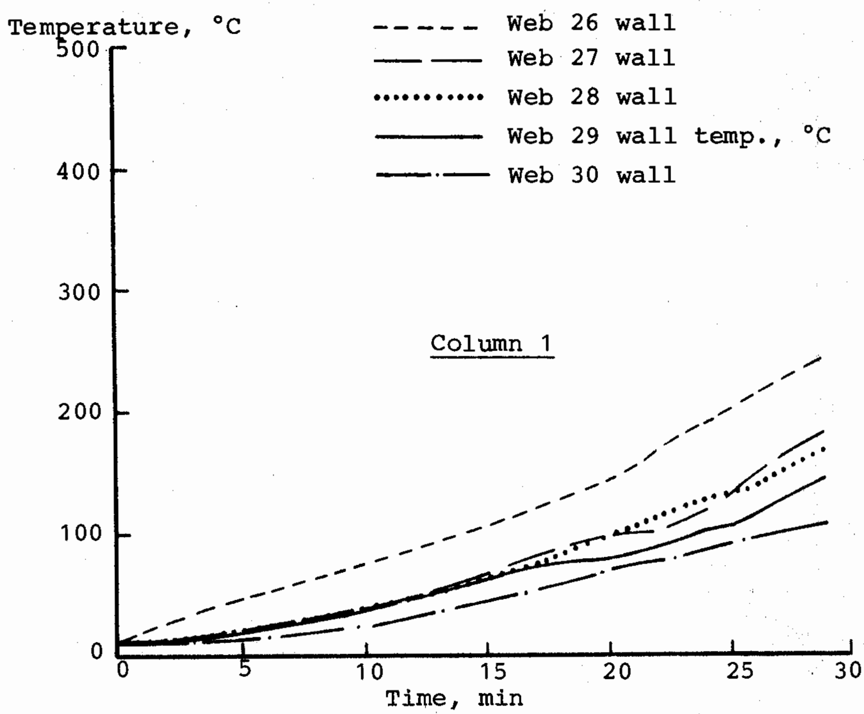
FIG. 10
(R1/9194)

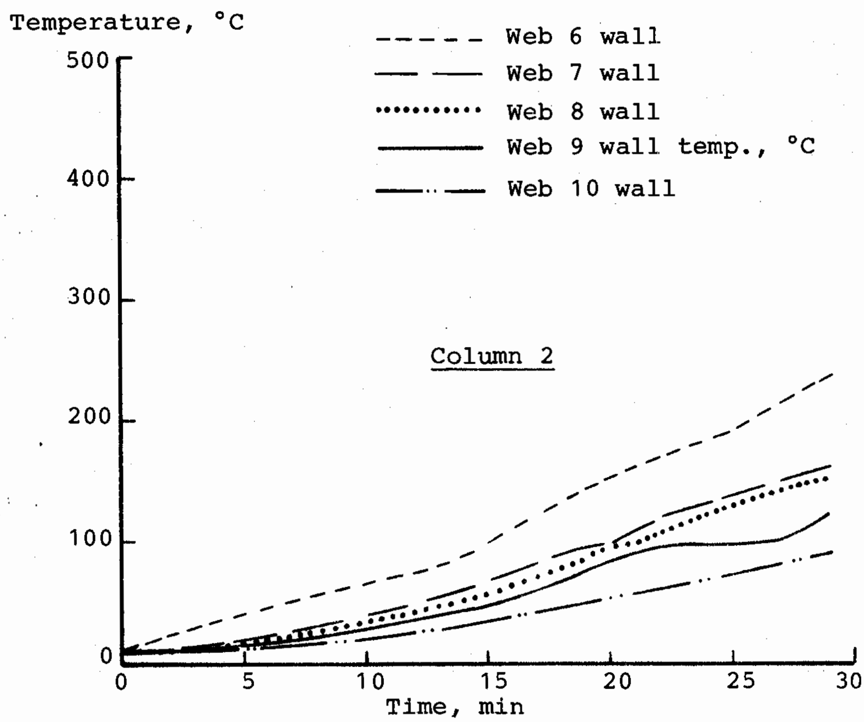




TEMPERATURES RECORDED ON THE EXPOSED WEB OF BOTH COLUMNS

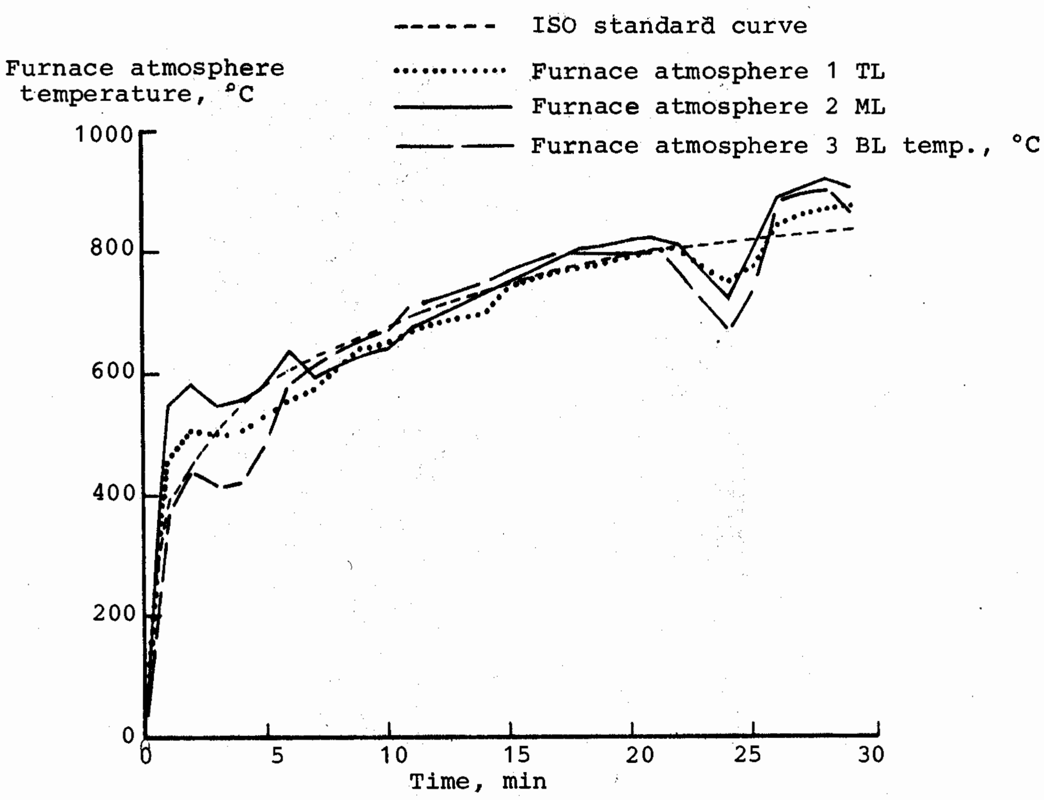
FIG. 11
(R1/9195)

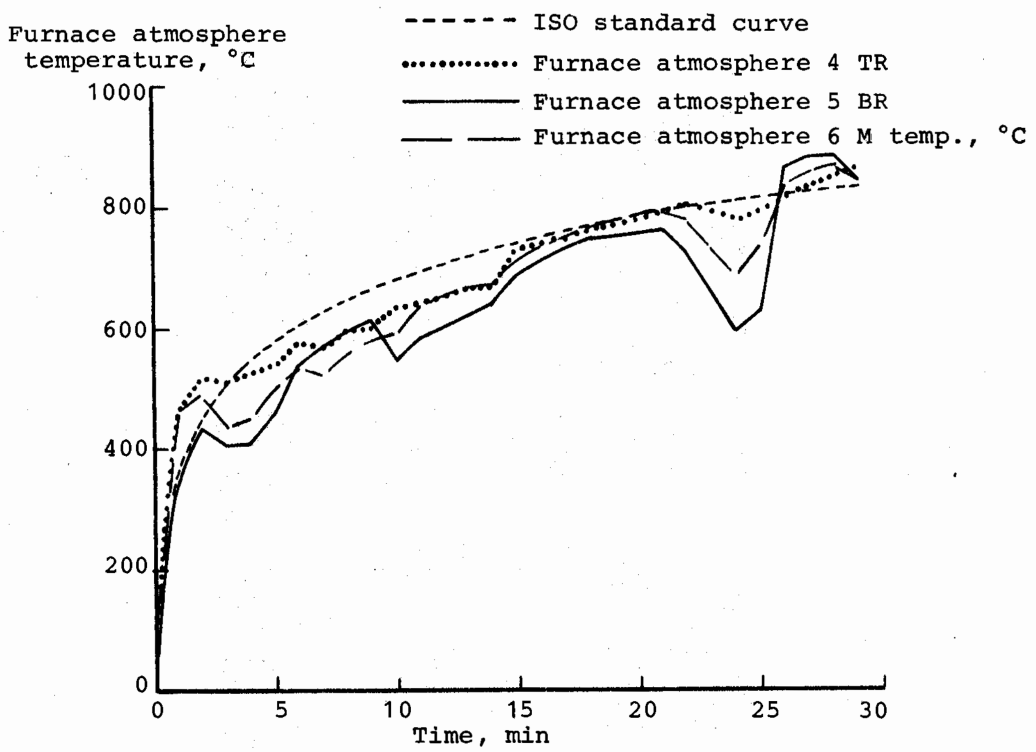




TEMPERATURES RECORDED ON THE CONCEALED PART OF THE WEB FROM BOTH COLUMNS

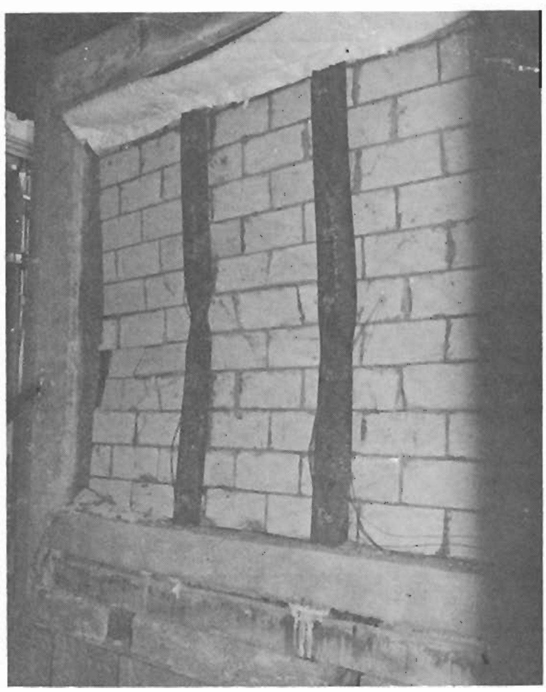
FIG. 12
(R1/9196)





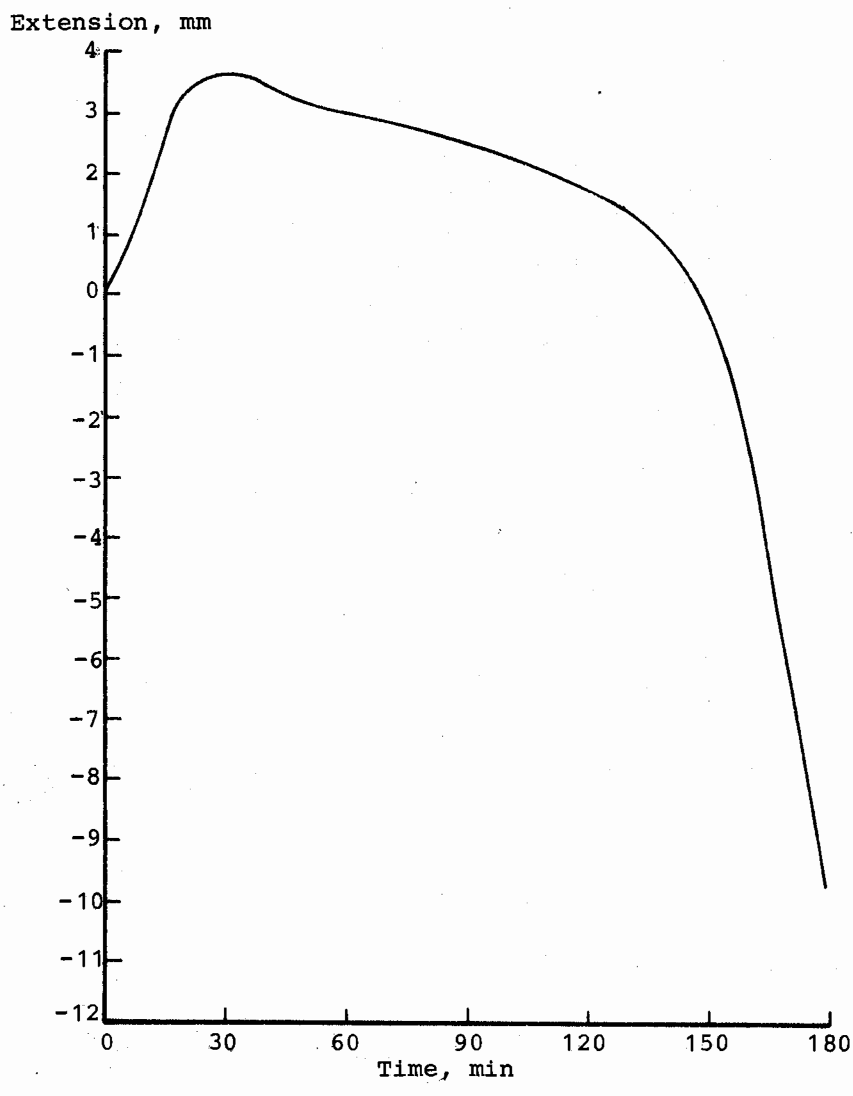
FURNACE HEATING RATE COMPARED WITH THE ISO STANDARD CURVE

FIG. 13
(R1/9197)



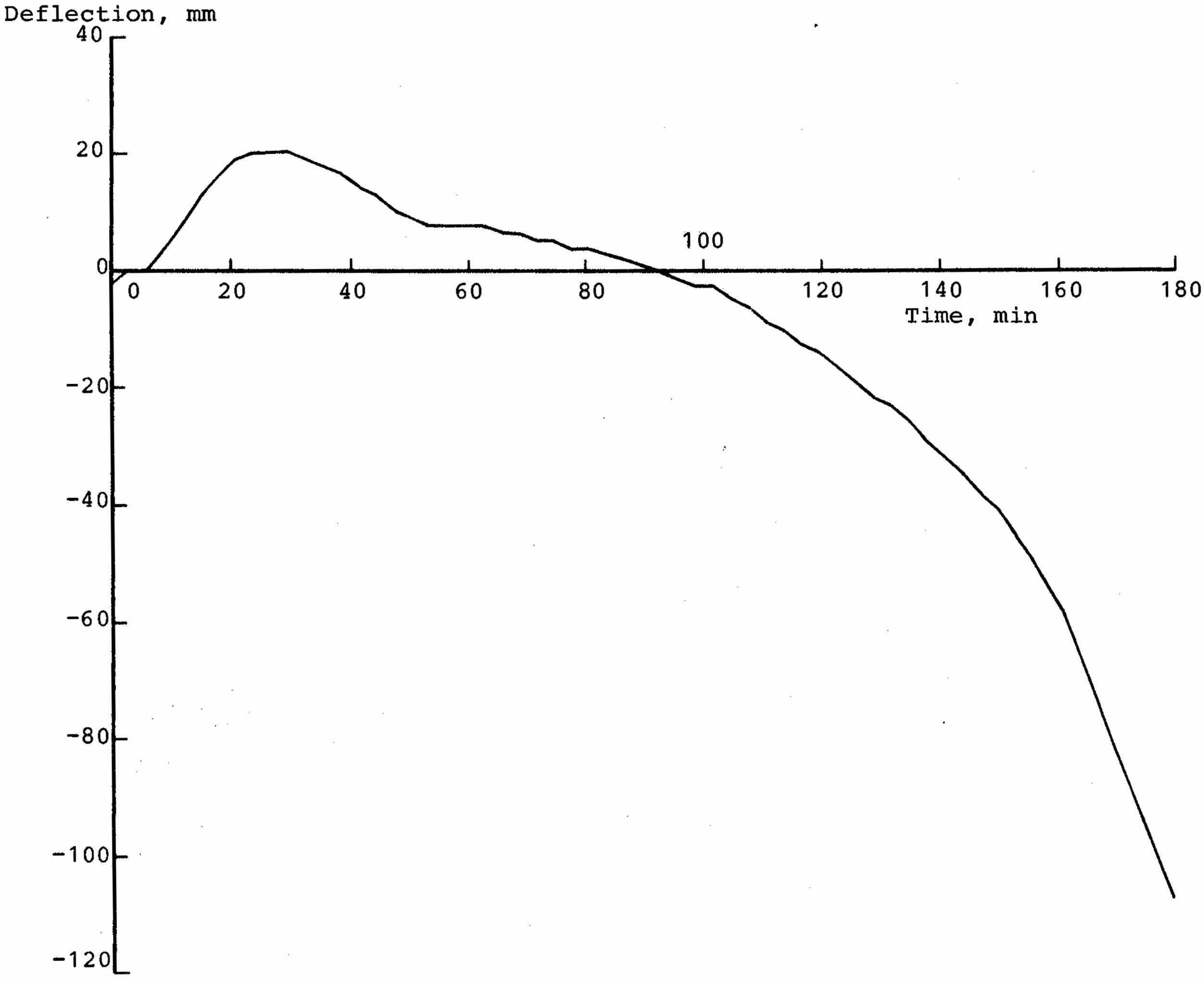
THE 203 x 203 mm x 52 kg/m COLUMNS IN WALL CONSTRUCTION AFTER TESTING

FIG. 14



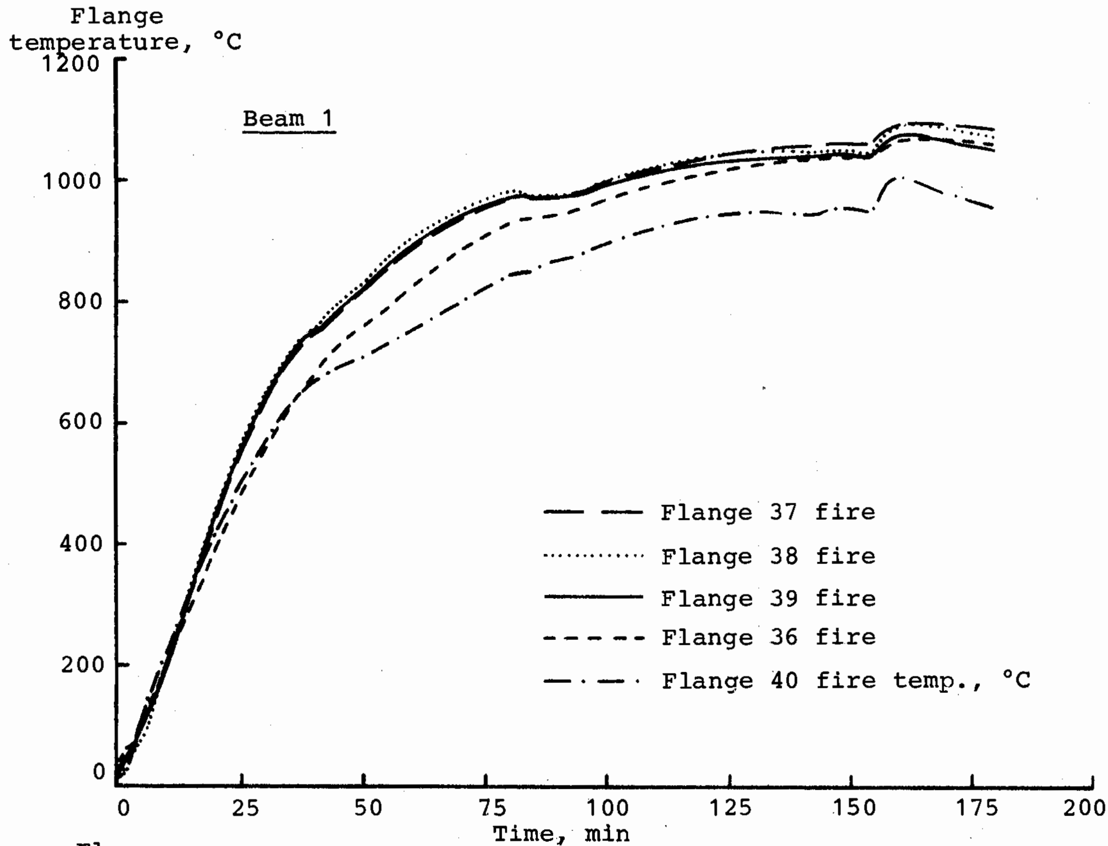
<u>MEAN LONGITUDINAL EXTENSION MEASURED ON THE 356 x 171 mm x 67 kg/m BEAMS DURING THE TEST</u>

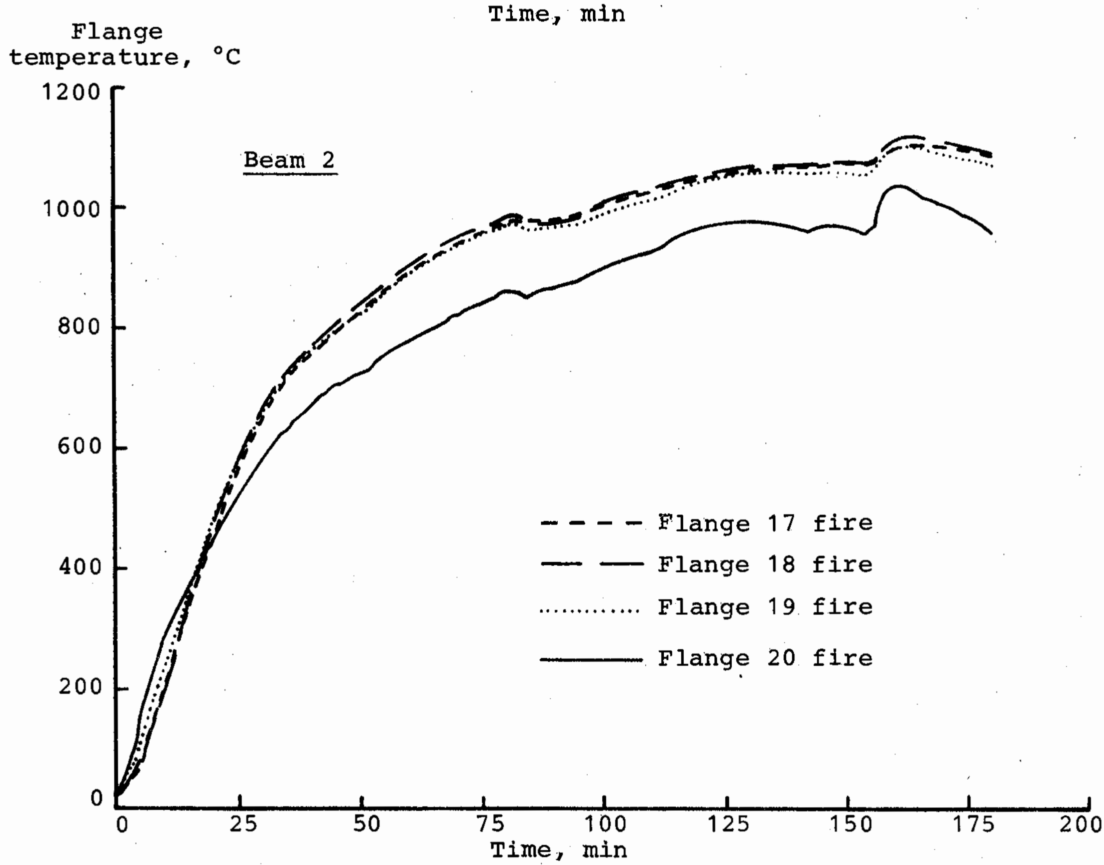
FIG. 15
(R1/9198)



LATERAL DEFLECTION MEASURED ON THE
356 x 171 mm x 67 kg/m BEAMS IN WALLS CONSTRUCTION

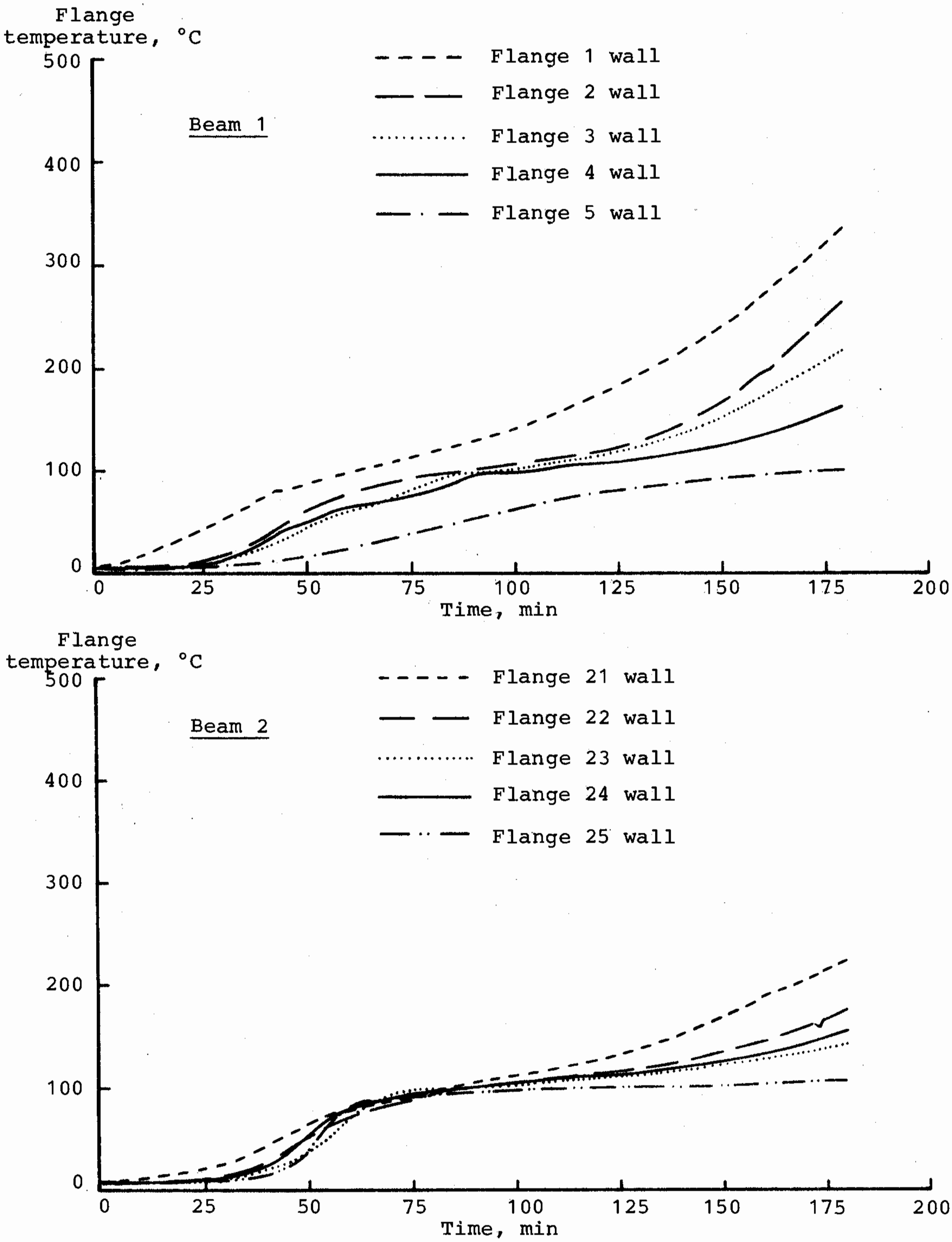
FIG. 16
(R1/9199)





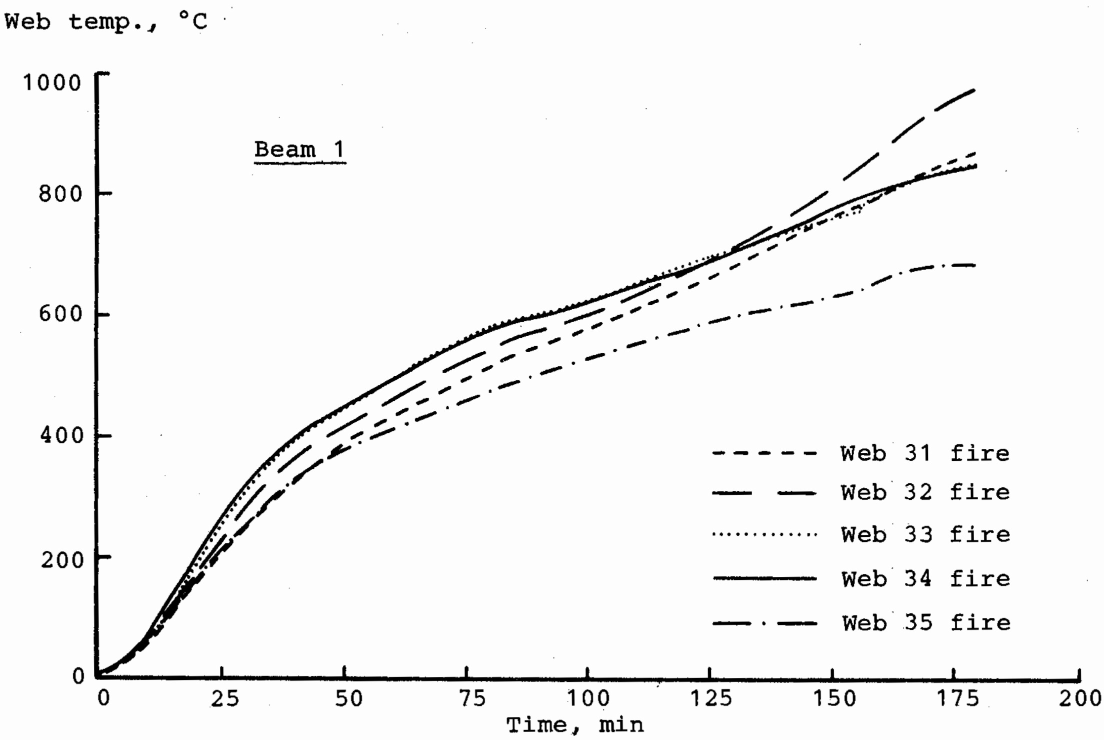
TEMPERATURES RECORDED ON THE EXPOSED FLANGE OF THE 356 x 171 mm x 67 kg/m BEAMS DURING THE TEST

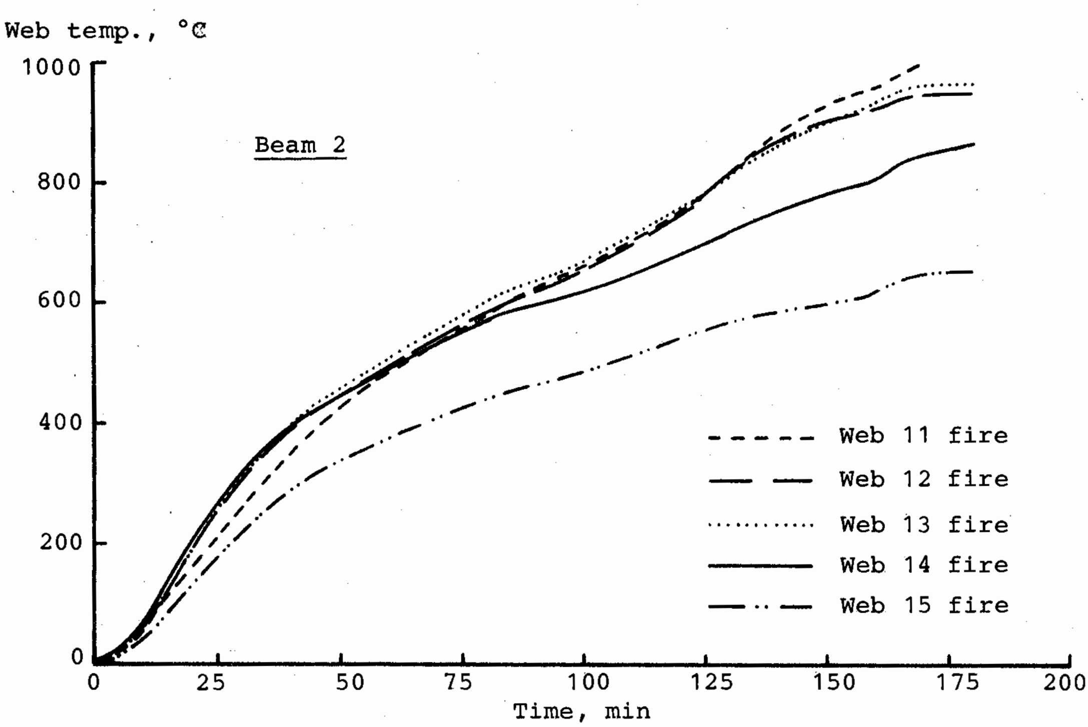
FIG. 17
(R1/9200)



TEMPERATURES RECORDED ON THE CONCEALED FLANGE OF THE 356 x 171 mm x 67 kg/m BEAMS DURING THE TEST

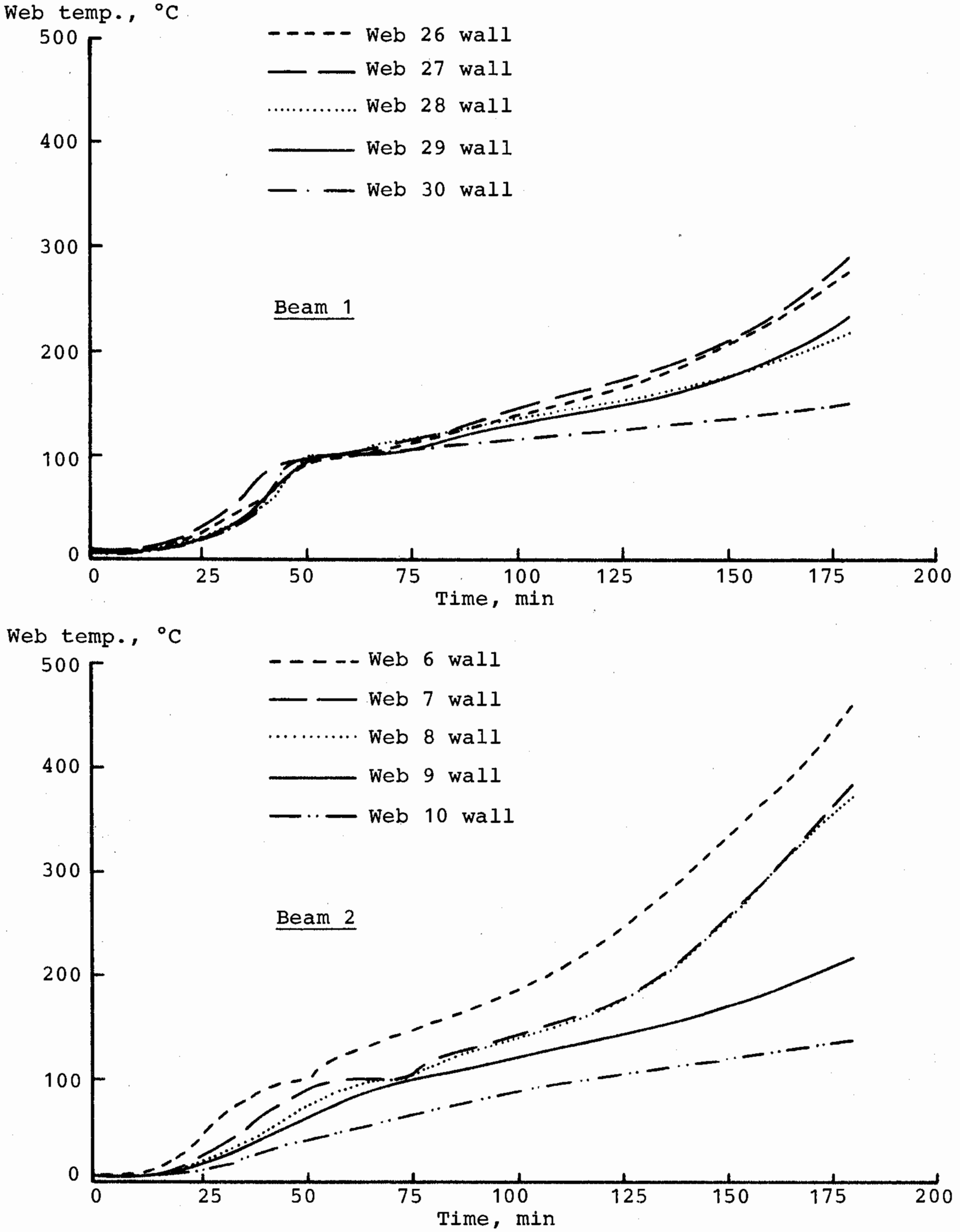
FIG. 18
(R1/9201)





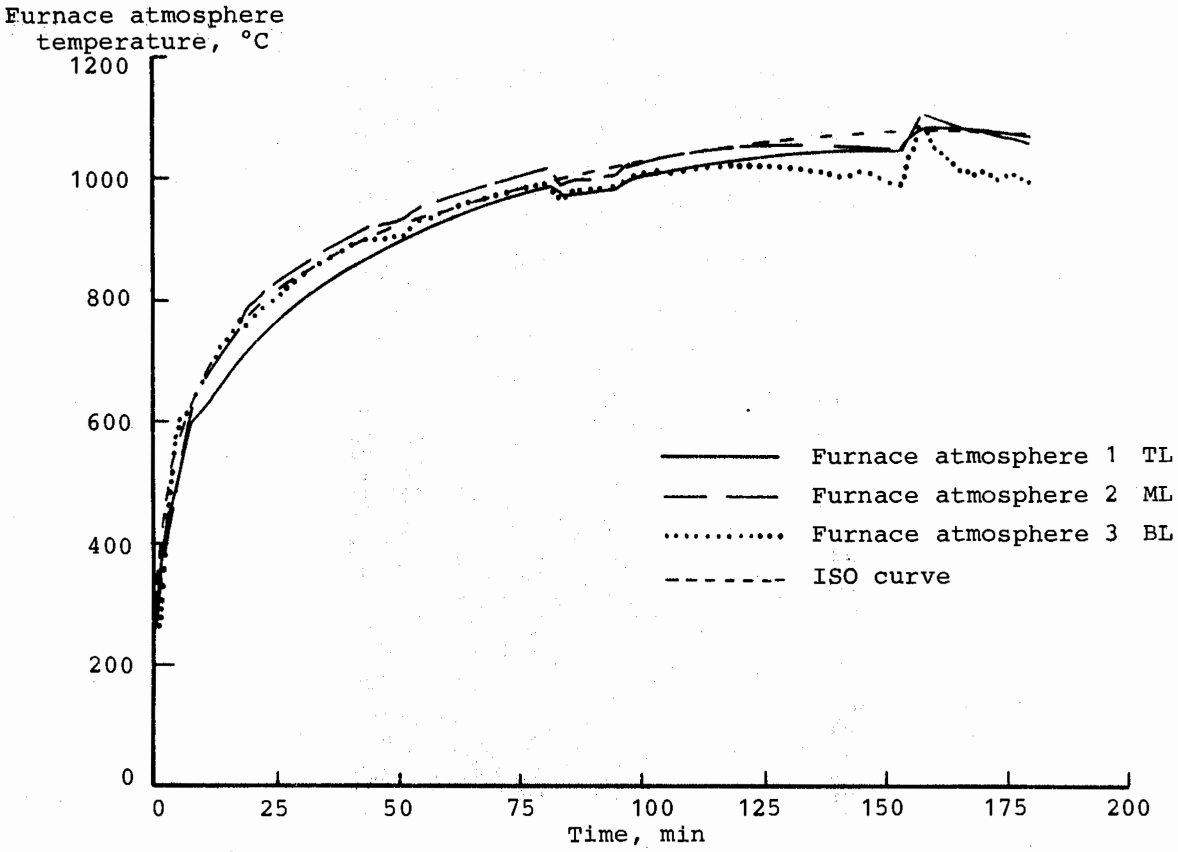
TEMPERATURES RECORDED ON THE PROTECTED WEB OF THE 356 x 171 mm x 67 kg/m BEAMS WHICH PROTRUDED INTO THE FURNACE

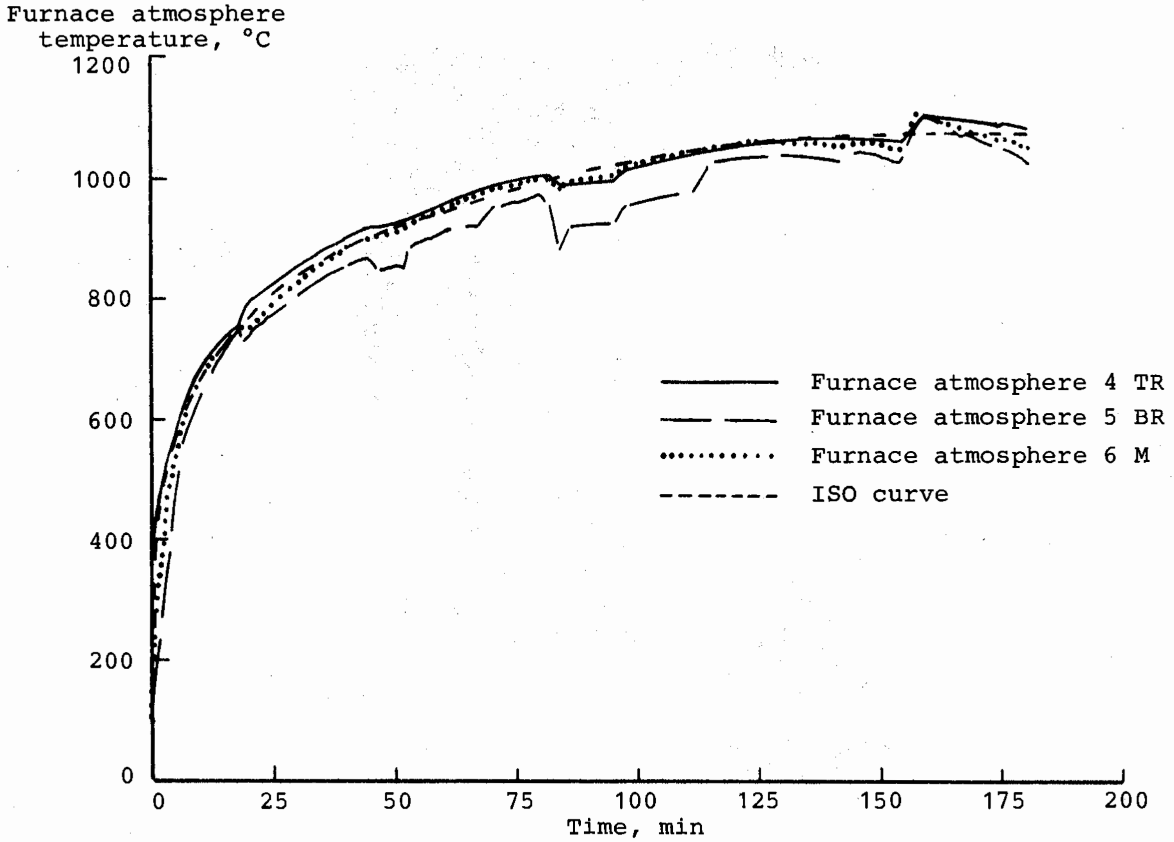
FIG. 19
(R1/9202)



TEMPERATURES RECORDED ON THE WEB OF THE 356 x 171 mm x 67 kg/m BEAMS CONCEALED IN THE CAVITY BETWEEN THE WALLS

FIG. 20
(R1/9203)



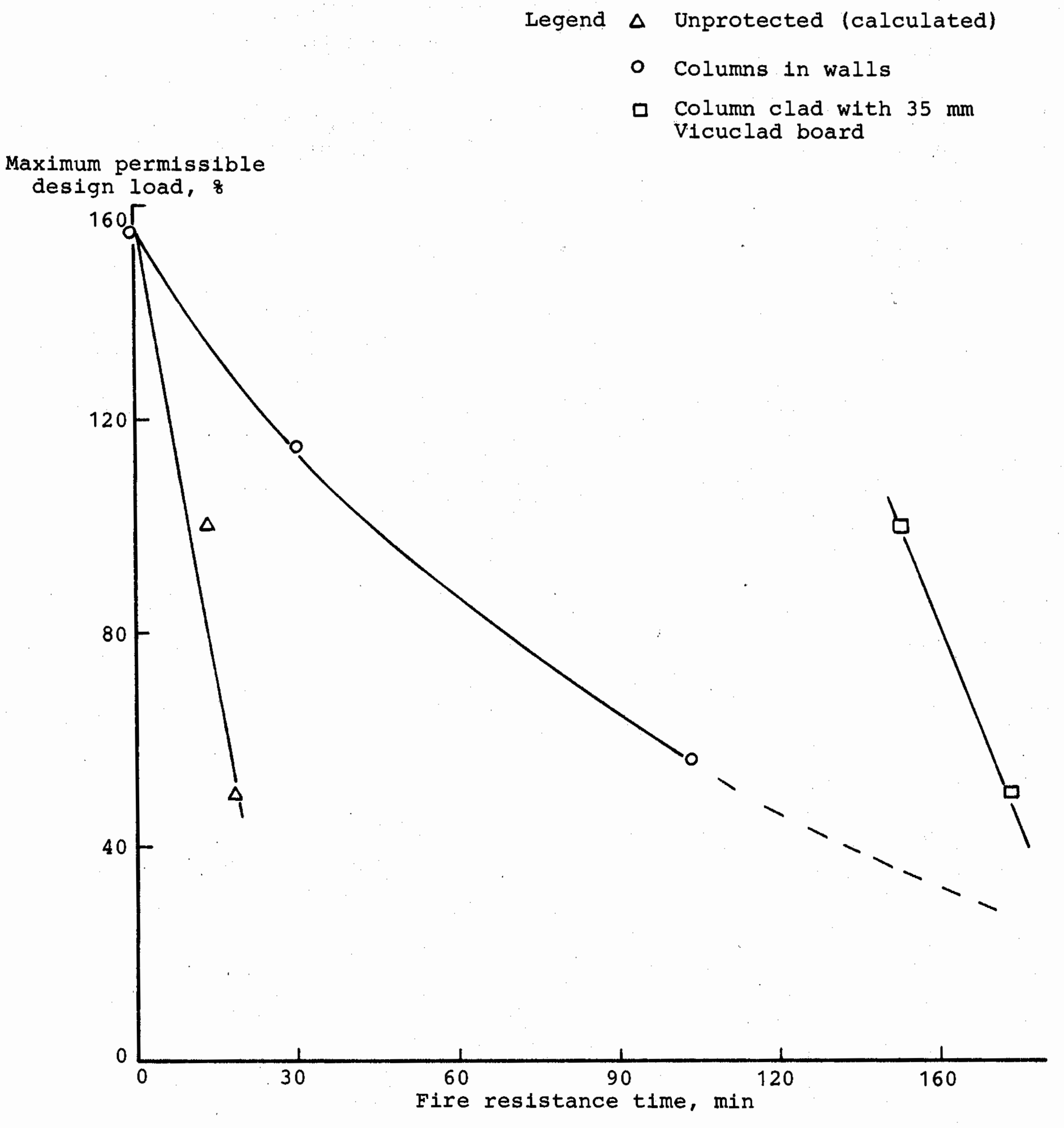


<u>FURNACE HEATING RATES COMPARED WITH ISO STANDARD HEATING CURVE</u>

FIG. 21
(R1/9204)

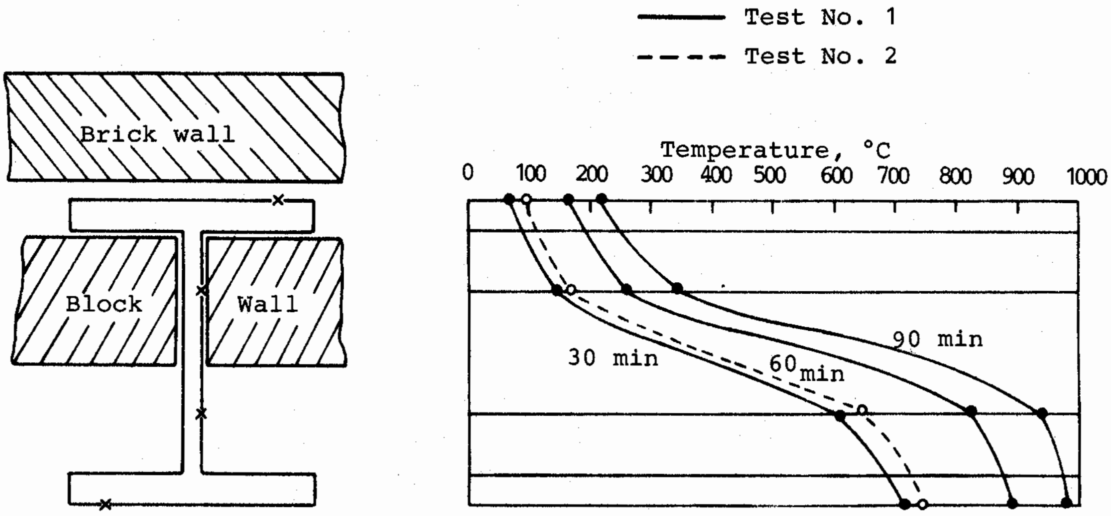
<u>356 x 171 mm x 67 kg/m BEAMS IN WALLS CONSTRUCTION AFTER TESTING</u>

FIG. 22

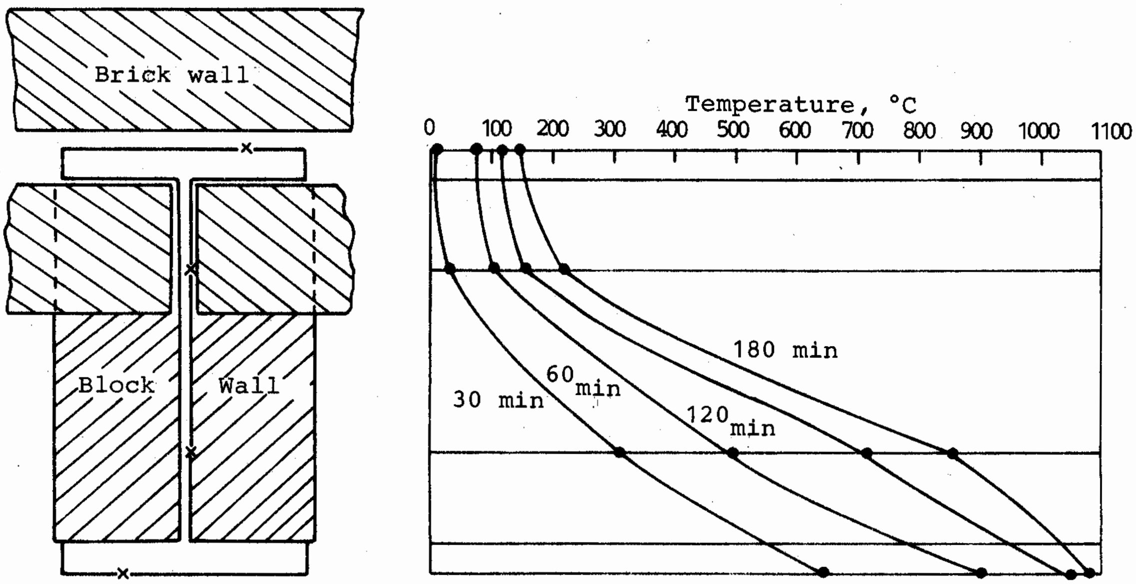


THE EFFECT OF THE MAGNITUDE OF AXIAL LOAD ON THE FIRE RESISTANCE OF 203 x 203 mm x 52 kg/m COLUMNS TO BS4360:GRADE 43A

FIG. 23 (R1/9205)



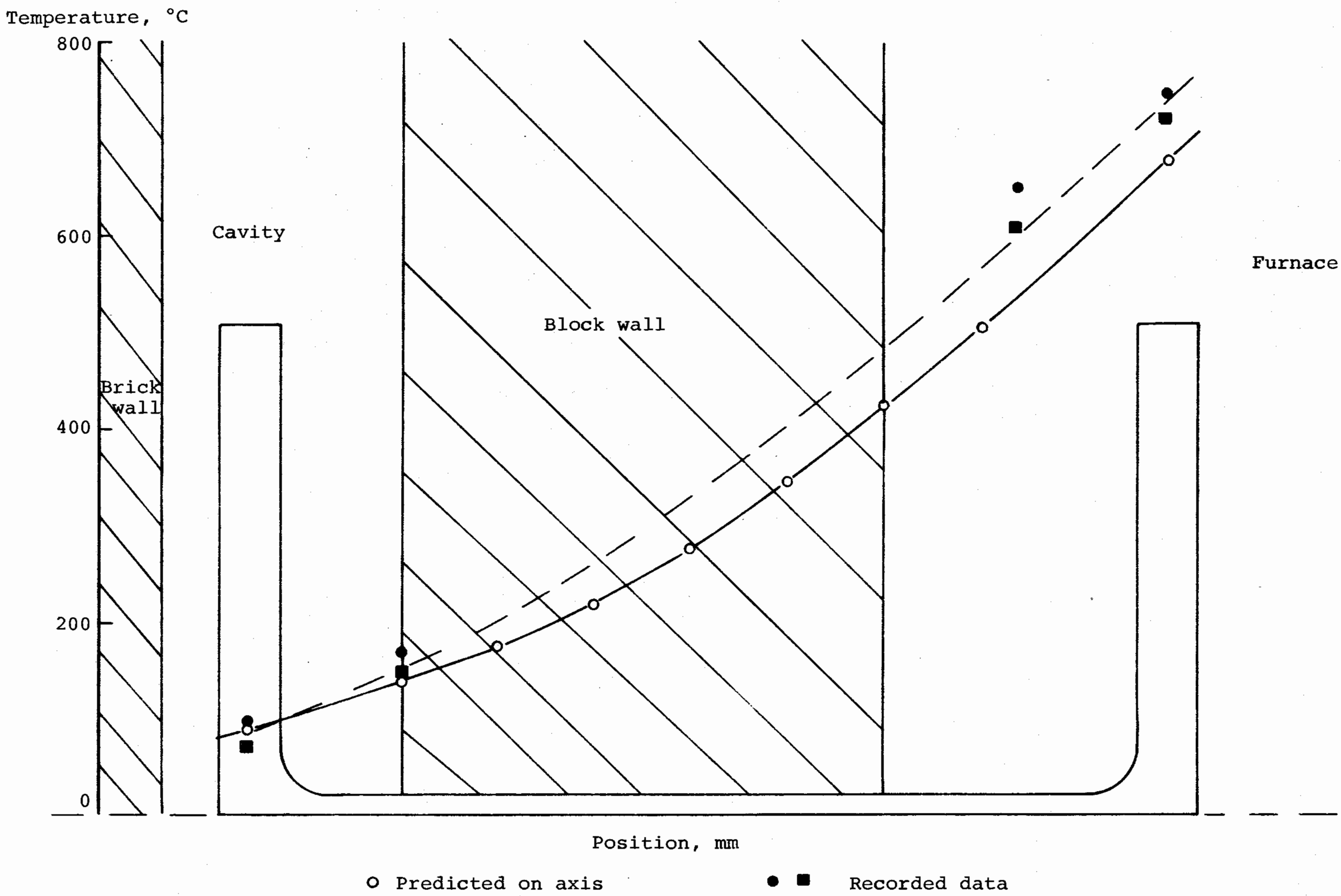
(a) 203 x 203 mm x 52 kg/m Column



(b) 356 x 171 mm x 67 kg/m Beam

TEMPERATURE PROFILES ACROSS STEEL SECTIONS EMBEDDED IN WALLS RECORDED AT MID-HEIGHT

FIG. 24 (R1/9206)



PREDICTED AND OBSERVED TEMPERATURES IN 203 x 203 mm x 52 kg/m COLUMN

FIG. 25
(R1/9207)

APPENDIX AXIAL LOAD CALCULATIONS FOR COLUMNS IN WALLS AND BEAMS IN WALLS TESTS

A.1 203 x 203 mm x 52 kg/m Universal Column, BS4360:Grade 43A

Actual length (L) = 3 m (ignoring concrete cover at base)

Area = 66.4 cm^2

r_{xx} = 8.9 cm

r_{yy} = 5.16 cm

Z_{xx} = 510 cm^3

Examination of test behaviour suggests that for the:-

x-x axis the effective length factor = 1.0 to 1.2 (estimate)

Hence: $\frac{\ell}{r_{xx}} = \frac{1.2 \times 300 \times 1.0}{8.9} = 40.44$

y-y axis the effective length factor = 1.0

Hence: $\frac{\ell}{r_{yy}} = \frac{1.0 \times 300 \times 1.0}{5.16} = 58.14$

∴ y-y axis governs collapse and the allowable stress P_c on gross section for axial compression (Table 17(a) BS449) = 127 N/mm^2 (N.B. if L = 2.75, P_c = 130.5 N/mm^2).

Maximum design load to BS449 = 127 x 66.4 x 10^2 x 10^{-3} = 843.3 kN

The total load used in the first test was 476.5 kN (for 1 column).

The total load used in the second test was 970 kN (for 1 column).

∴ % of maximum load for first test = $\frac{476.5 \times 100}{843.3}$ = <u>56.5%</u>

% of maximum load for second test = $\frac{970 \times 100}{843.3}$ = <u>115.0%</u>

A.2 356 x 171 mm x 67 kg/m Universal Beam, BS4360:Grade 50

Actual length (L) = 3 m

Area = 85.4 cm^2

r_{xx} = 15.12 cm

r_{yy} = 3.99 cm

Z_{xx} = 1073 cm^3

The y-y axis governs behaviour and effective length factor = 1.0

Hence: $\frac{\ell}{r_{yy}} = \frac{1.0 \times 300 \times 1.0}{3.99} = 75.2$

Allowable stress on gross section, P_c = 110 N/mm^2 (Grade 43A steel)

= 140 N/mm^2 (Grade 50 steel)

Maximum design load to BS449 $= 110 \times 85.4 \times 10^2 \times 10^{-3}$
$= 939.4$ kN (Grade 43A)

or $= 140 \times 85.4 \times 10^2 \times 10^{-3}$
$= 1195.6$ kN (Grade 50)

The total load used in the beam test was 470 kN (1 beam)

$\therefore$ % of maximum load as based on Grade 43A $= \dfrac{470 \times 100}{939.4} = \underline{50.0\%}$

% of maximum load as based on Grade 50 $= \dfrac{470 \times 100}{1195.6} = \underline{39.3\%}$

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