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Fire Resistance Tests of Square Hollow Steel Columns Filled with Reinforced Concrete

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FIRE RESISTANCE TESTS OF SQUARE HOLLOW STEEL COLUMNS FILLED WITH REINFORCED CONCRETE

ABSTRACT

The results of fire resistance tests conducted at the National Research Council of Canada, on three square bar-reinforced concrete filled steel columns, made by the Technical Research Centre of Finland are described. They were constructed with Finnish siliceous aggregate concrete. One of the columns was tested under a concentric load. The other two columns, which were similar, were tested under two different eccentric loads for the purpose of obtaining information on the influence of eccentric loads on the fire resistance of the columns.

FIRE RESISTANCE OF TESTS OF SQUARE HOLLOW STEEL COLUMNS FILLED WITH REINFORCED CONCRETE

1 INTRODUCTION

By filling hollow steel columns with concrete, the load-carrying capacity of these columns can be increased substantially. In addition, a high fire resistance can be obtained without the necessity of additional surface fire protection for the steel. The elimination of such surface protection in turn increases space in the building and improves architectural aesthetics.

These benefits have stimulated research into the structural and fire resistance performance of concrete-filled hollow steel sections in several laboratories around the world. For a number of years, the National Fire Laboratory of the Institute for Research in Construction, National Research Council of Canada (NRC), and the Fire Technology Laboratory of the Technical Research Centre of Finland (VTT) have been engaged in studies to predict the fire resistance of concrete-filled steel columns.

The mutual interest in these studies led to an agreement between NRC and VTT to conduct joint studies on the fire resistance of concrete-filled steel columns. These studies include theoretical as well as experimental work.

In this report, results are described of tests on three concrete-filled steel columns. The columns were fabricated by the Building Materials Laboratory of VTT in Finland and tested at the National Fire Laboratory in Canada.

2 TEST SPECIMENS

Three square hollow steel columns filled with bar-reinforced concrete were tested. Two of the columns were tested under an eccentric load. The third column was tested under a concentric load. Details concerning the test specimens are given in Table 1. They are illustrated in Figs. 1-4. Further details of the test specimens and their fabrication are given below.

2.1 Dimensions

All columns were 3810 mm long from end plate to end plate. The cross section of all columns was square. The outside dimensions of the cross section of Column Nos. 1 and 2 were 300 x 300 mm and those of Column No. 3 were 150 x 150 mm. The steel wall thickness of Column Nos. 1 and 2 was 8 mm and that of Column No. 3 was 5 mm.

2.2 Materials

Steel:

The hollow structural sections (HSS) and end plates consisted of steel meeting the requirements of Finnish Standard SFS 200 grade Fe 52 C [1]. A tensile test was performed for each section size to determine yield and ultimate strength. The test results are listed in Table 1.

Weldable ribbed bars meeting the requirements of Standard SFS 1215 grade A 500 HW [2] were used for the main and tie bars. The diameter of the longitudinal steel bars in Column Nos. 1 and 2 was 32 mm and that of Column 3 was 12 mm. The diameters of the ties were 6 and 8 mm. A tensile test was performed for each bar size to determine yield and ultimate strength. The test results are listed in Table 2.

Cement:

Two concrete mixes were poured in the Building Materials Laboratory of VTT in Finland. In both pours, general purpose Portland cement for construction of concrete structures was used. The cement was manufactured by Oy Partek Ab.

Aggregate:

The aggregates used were Finnish siliceous sand and gravel, both from Lohja Oy Rudus. A sieve analysis was conducted. The results of the sieve analysis are given in Table 3.

Concrete Mix:

Batch quantities for each mix are given in Table 3. The mixes contained a super plasticizer called SP 62.

2.3 Fabrication

Steel Column and Reinforcing Bars (see Figs. 1-4):

The hollow steel sections were fabricated by cutting the sections to appropriate lengths. The bottom end plates were then welded to one end of the sections. The end plates of Column Nos. 1 and 2 were reinforced with web plates, which were welded to the end plates and to the steel column (Fig. 2). Centering and perpendicularity of the end plates were given special attention. The components of the columns were dimensioned so that their length was 3810 mm, including the plate thickness.

The dimensions of the end plates of the 300 mm square hollow section (Column Nos. 1 and 2) were 630 x 850 x 40 mm and those of the 150 mm square hollow section (Column No. 3) were 508 x 610 x 40 mm. Holes with a diameter 4 mm larger than the diameter of the longitudinal reinforced bars were drilled through the plates.

The longitudinal reinforcement bars were cut to 3774 mm in Column Nos. 1 and 2 and to 3790 mm in Column No. 3. The main bars and ties were joined together to complete the steel cage. The steel cage was placed vertically into the hollow section on a leveled end plate in such a way that the ends of the bars were positioned in the holes.

A fillet weld was made around the bars on the outer face of the top and bottom plates. The welding of the top steel plate was performed two days after the casting of the concrete. The type of welding rod used was OK Autrod 12.51, which has a tensile strength of 400 MPa. The rough surfaces of the welds on the outer face of the plate were ground to a smooth finish.

Columns 1 and 2 had to be repaired before testing to strengthen end plates since these columns were subjected to eccentric loading. This was achieved by carefully chiseling concrete at the ends of the column, and by welding small steel plates to reinforcing bars and web plates as shown in Figure 2. New concrete was filled in the chiseled portion of the column and, after the hardening of the concrete, an additional steel plate was welded to the column. It should be noted that this repair would not alter the heat flow in the columns since the repair was carried out only near the ends.

Concrete Placement:

The concrete was mixed in a paddle mixer, called Zyklos. A concrete placement bucket and a long plastic tube were used to deposit the mix in the steel column. When necessary, an internal vibrator was carefully applied to consolidate the concrete. To avoid possible moisture leaks, the section was sealed at the top end with a plastic sheet and tape before welding the top plate.

Before positioning the top plate, a layer of mortar was spread over the top of the column to ensure good contact between the steel plate and the concrete. The mortar, called Rapid Set Grout, was a non-shrinkable high strength mortar, and had a compressive strength of 84.4 MPa at 28 days.

Thermocouples:

Type K chromel-alumel thermocouples, with a thickness of 0.5 mm, were used for measuring concrete and reinforcement temperatures at several locations in different cross sections of the columns. The temperatures were measured at approximately one-quarter height, mid-height and three-quarters height. At mid-height, the temperatures were measured along the whole length of an axis and a diagonal of the section; at the other two levels, the temperatures were measured only in the middle of the section and at a number of locations in the steel. The thermocouples in the concrete were tied to steel rods that were firmly secured to the main reinforcing bars. The locations of the thermocouples are shown in Figs. 5-7.

3 MATERIAL PROPERTIES TESTS

3.1 Cube Compressive Strength

From each concrete mix, ten 150 mm cubes were made using steel forms. Compression strength tests were conducted for three specimens at 7 and 28 days and on the test date. The tests were conducted according to Finnish Standard SFS 4474 [3] (ISO 4012).

3.2 Thermal Properties

From concrete mix No. 2, ten 100 x 200 x 50 mm prisms for the measurement of the thermal properties of the concrete were made, using wooden forms. Details concerning the thermal properties measurements are given in Reference [4].

3.3 Cylinder Compressive Strength and Moisture Content

From concrete mix No. 2, two short composite columns were constructed. The size of the hollow section of one column was 300 x 300 x 8 mm and of the other column, 150 x 150 x 5 mm. Four cylinders with a diameter and height of 100 mm were cut from the concrete, using a core drill. Three cylinders were used for the measurement of the strength and one for the measurement of the moisture content of the concrete.

4 TEST APPARATUS

The tests were carried out by exposing the columns to heat in a furnace specially built for testing loaded columns and walls. The test furnace produces conditions to which a member might be exposed during a fire, i.e., temperatures, structural loads and heat transfer. It consists of a steel framework supported by four steel columns, with the furnace chamber inside the framework (Fig. 8). The characteristics and instrumentation of the furnace are described in detail in Ref. [5]. Only a brief description of the furnace and the main components is given here.

4.1 Loading Device

A hydraulic jack with a capacity of 9778 kN produces a load (N_1) along the axis of the test column (Fig. 9). The jack is located at the bottom of the furnace chamber. Eccentric loads can be applied by means of hydraulic jacks (N_2), one at the top and one at the bottom of the column, located at a distance of 508 mm from the axis of the column. The capacity of the top jack is 587 kN and that of the bottom jack 489 kN.

4.2 Furnace Chamber

The furnace chamber has a floor area of 2642 x 2642 mm and is 3048 mm high. The interior faces of the chamber are lined with insulating materials that efficiently transfer heat to the specimen. There are 32 propane gas burners in the furnace chamber, arranged in eight columns containing four burners each. The total capacity of the burners is 4700 kW. Each burner can be adjusted individually, which allows for a high degree of temperature uniformity in the furnace chamber. The pressure in the furnace chamber is also adjustable and was set somewhat lower than atmospheric pressure.

4.3 Instrumentation

The furnace temperatures were measured with the aid of eight chromel-alumel thermocouples. The thermocouple junctions were located 305 mm from the test specimen, at various heights. Two thermocouples were placed opposite each other at intervals of 610 mm along the height of the furnace chamber. The locations of their junctions and their numbering are shown in Fig. 10. Thermocouples 4 and 6 were located at a height of 610 mm from the floor, Thermocouples 2 and 8 at 1220 mm, Thermocouples 3 and 5 at 1830 mm and Thermocouples 1 and 7 at 2440 mm. The temperatures measured by the thermocouples were averaged automatically and the average temperature used as the criterion for controlling the furnace temperature.

The loads were controlled by servocontrollers and measured with pressure transducers. The accuracy of controlling and measuring loads is about 4 kN at lower load levels and relatively better at higher loads.

The lateral deflection of the columns at mid-height was measured using a theodolite. The axial deformation of the test columns was determined by measuring the displacement of the jack that supports the column. The rotation of the end plates of the columns was determined by measuring the displacement of the plates at a distance of 500 mm from the centre of the hinge at the top and bottom respectively. The displacements were measured using transducers with an accuracy of 0.002 mm.

5 TEST CONDITIONS AND PROCEDURES

The columns were installed in the furnace by securing the end plates to the plates of the bearings (Fig. 9). The bearings were bolted to a loading head at the top and to the plate of the main hydraulic jack at the bottom. In all cases, the end conditions were hinged. Column Nos. 1 and 2 were, in addition to an axial load, subjected to eccentric loads, applied by hydraulic jacks at a distance of 508 mm from the longitudinal axis of the column.

Before each test, the moisture condition in the centre of a column section was measured by inserting a Vaisala moisture sensor into a hole drilled in the concrete at a height of 410 mm above the bottom of the column. The readings are given in Section 6.

5.1 Loading

Column Nos. 1 and 2 were tested under an eccentric load. The total load on Column No. 1 was 1400 kN of which 1218 kN was applied concentrically and 182 kN eccentrically at a distance of 508 mm from the column axis. The eccentricity of the total load was 66 mm. The load on Column No. 2 was 1000 kN and the eccentricity of the load was 120 mm. Of this load, 764 kN was applied concentrically and 236 kN eccentrically at a distance of 508 mm from the column axis. Column No. 3 was subjected to a concentric load of 140 kN.

All loads were applied at least 45 minutes before the start of the test until a condition was reached at which no further increase of the axial and rotational deformations could be measured. This condition was selected as the initial condition of the column deformations.

5.2 Fire Exposure

During the test, the columns were exposed to heating controlled in such a way that the average temperature in the furnace followed, as closely as possible, the ISO 834 [6] standard temperature-time curve. This curve can be given by the following equation:

$$T_f - T_o = 345 \log_{10} (8t + 1)$$

where: t = time in minutes
T_f = temperature of furnace in °C
T_o = initial furnace temperature in °C

During the test, temperatures in the furnace and in the column were measured at the locations described earlier.

5.3 Recording of Results

Temperature readings were taken at each thermocouple location at intervals of one minute. The axial deformation of the columns, the lateral deflection of the columns at mid-height and the rotation of the end plates of the columns were measured with varying frequencies, depending on the rate of change of the measured quantities.

The columns were considered to have failed, and the tests were terminated, when the axial hydraulic jack, which has a maximum speed of 76 mm/min, could no longer maintain the load.

6 TEST RESULTS

This section contains results and observations for each of the three tests. The basic characteristics, already given in Table 1, are reiterated for each specimen.

6.1 Column 1

Date tested:	February 15, 1994
Total loading:	1400 kN
Eccentricity:	66 mm
Applied loads:	N_1 = 1218 kN
	N_2 = 182 kN

Specimen Characteristics:

Square cross section:	300 x 300 x 8 mm
Length:	3810 mm
Reinforcement	4 f 32 mm, A500 HW, ribbed bars
Steel grade:	Fe 52 C
Casting day:	January 24, 1991
Elevation, cross section and finishing detail:	Figs. 1 and 2
Layout of thermocouples:	Figs. 5 and 6

Measured Properties:

Concrete Strength

150 mm cube strengths:	32.3 MPa at 7 days
	40.7 MPa at 28 days
	43.8 MPa at June 5, 1991

Steel Strength

Strength of HSS

Upper yield strength:	398 MPa
Lower yield strength:	394 MPa
Ultimate strength:	537 MPa
Strength of longitudinal 32 mm reinforcing steel bars and 8 mm ties:	Table 2

Moisture Condition

Relative humidity in long test column measured with Vaisala moisture sensor:	97% R.H. at 11° C on test date

Results:

Test duration:	58 min
Type of failure:	Buckling
Temperatures:	Table 4
Axial deformation:	Table 4
Lateral deflection at midheight:	Not obtained due to instrumentation problems

Observations:

At 14 minutes, expansion of the paint on the north side of the deflection meter was noticed. This was followed by bulging of the steel at this location. At 20 minutes, bulging occurred about mid-height on the east side. At 58 minutes, the column failed (Figure 11) due to buckling, resulting from the eccentric load at the maximum stroke, and the test was terminated. An examination of the post-test column was carried out by cutting the steel at several locations and no spalling was noticed. Temperature readings from a few thermocouples could not be recorded due to damage caused to the thermocouples while repairing and also due to some instrumentation problems.

6.2 Column 2

Date tested:	February 18, 1994
Total loading:	1000 kN
Eccentricity:	120 mm
Applied loads:	N_1 = 764 kN
	N_2 = 236 kN

Specimen Characteristics:

Square cross section:	300 x 300 x 8 mm
Length:	3810 mm
Reinforcement:	4 f 32 mm, A500 HW, ribbed bars
Steel grade:	Fe 52 C
Casting day:	January 24, 1991
Elevation, cross section and finishing detail:	Figs. 1 and 2
Layout of thermocouples:	Figs. 5 and 6

Measured Properties:

Concrete Strength

150 mm cube strengths:	32.3 MPa at 7 days
	40.7 MPa at 28 days
	43.8 MPa at June 5, 1991

Steel Strength

Strength of HSS

Upper yield strength:	398 MPa
Lower yield strength:	394 MPa
Ultimate strength:	537 MPa
Strength of longitudinal 32 mm reinforcing steel bars and 8 mm ties:	Table 2

Moisture Condition

Relative humidity in long test column measured with Vaisala moisture sensor:	91% R.H. at 9°C on test date

Results:

Test duration:	126 min
Type of failure:	Buckling
Temperatures:	Tables 5 and 6
Axial deformation:	Table 6
Lateral deflection at midheight:	Table 6 92 mm, maximum that can be measured with the delectionometer.
Rotation of column at the ends:	Table 6

Observations:

A bang was heard at 54 minutes and the top displacement meter had to be reset. The deformation curve indicated that the connection between the eccentrically loaded arm and the column reinforcement was lost. This might have damaged thermocouple no. 20. At 126 minutes, the test was terminated once the maximum stroke of the axial load was reached. Column failure was through buckling. Figure 12 shows the view of the column after the test.

6.3 Column 3

Date tested:	June 5, 1991
Loading:	140 kN, Concentric

Specimen Characteristics:

Hollow structural section:	150 x 150 x 5 mm
Length:	3810 mm
Reinforcement:	4 f 12 mm, A500 HW, ribbed bars
Steel grade:	Fe 52 C
Casting day:	January 25, 1991
Elevation, cross section and finishing detail:	Figs. 3 and 4
Layout of thermocouples:	Figs. 5 and 7

Measured Properties:

Concrete Strength

150 mm cube strengths:	29.6 MPa at 7 days 37.5 MPa at 28 days 37.8 MPa at test date
100 mm drilled cylinder strength:	40.3 MPa on October 18, 1991

Steel Strength

Strength of HSS

Upper yield strength:	418 MPa
Lower yield strength:	416 MPa
Ultimate strength:	558 MPa
Strength of longitudinal 12 mm reinforcing steel bars and 6 mm ties:	Table 2

Moisture Condition

Relative humidity in long test column measured with Vaisala moisture sensor:	95% R.H. at 25°C on test date
Moisture content of short column concrete:	95% on test date

Results:

Test duration:	83 min
Type of failure:	Buckling
Temperatures and axial deformation:	Tables 7 and 8
Lateral deflection at midheight:	Very small; order of magnitude 0.5 mm near failure point
Rotation of column at the ends:	Rotations were very small; order of magnitude 0.02 degrees, which corresponds to approximately 0.4 mm lateral deflection at midheight, assuming a straight line curvature.

Observations:

At 9 minutes, a loud bang was heard; several thermocouples, namely nos. 2, 4, 5 and 24, broke at that time. Several other thermocouples broke somewhat later in the test. These thermocouples are not included in Tables 4 and 5. The test was terminated at 83 minutes when the load on the column could no longer be maintained.

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2. Hot Rolled Weldable Ribbed Steel Bars for the Reinforcement of Concrete, Standard SFS 1215, 1989.
3. Concrete Compressive Strength, Standard SFS 4474, 1983.
4. Myllymäki, J. and Lie, T.T., Fire Resistance Test of a Square Reinforced Concrete Column, National Research Council of Canada, Institute for Research in Construction, Internal Report No. 619, Ottawa, Canada, September 1991.
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6. Fire Resistance Tests – Elements of Building Construction, ISO 834, International Organization for Standardization, 1975.

Table 1 - Details concerning column test specimens

Specimen No.	HSS Size (mm)	Casting Date	Test Date	Moisture Content (%RH)	Compressive Strength			Yield Strength of Steel (MPa)	Ultimate Strength of Steel (MPa)
					28 day 150 mm Cube (MPa)	test day 150 mm Cube (MPa)	100 mm Cylinder (MPa)		
1	300x300x8	91-01-24	94-02-15	-	40.7	43.8	-	394	537
2	300x300x8	91-01-24	94-02-18	-	40.7	43.8	-	394	537
3	150x150x5	91-01-25	91-06-05	95	37.5	37.8	40.3	416	558

Table 2 - Average tensile strength of reinforcing bars

Bar Size (mm)	Yeild Strength (MPa)	Ultimate Strength (MPa)
6	510.0	696.3
8	532.3	706.7
12	596.0	723.7
32	544.0	652.3

Table 3 - Batch quantities and properties of concrete

Component	Pour No. 1 (kg/m³)	Pour No. 2 (kg/m³)
Cement:	372.5	371.9
Fine aggregate:		
0 - 0.6 mm	400	400
0.5 - 1.2 mm	217.4	217.2
1 - 2 mm	331.9	331.3
Coarse aggregate:		
2 - 3 mm	169.6	170.3
3 - 5 mm	118.8	118.8
5 - 10 mm	559.4	559.4
Water:	200	200
Super plasticizer:		
SP 62:	1.86	1.86
Water/cement ratio:	0.54	0.54
Average 150 mm cube strength in MPa:		
@ 7 days	32.3	29.7
@ 28 days	40.7	37.5

Table 4 - Cross-sectional temperatures and axial deformations for Column No. 1

Time (min)	Temperature (°C)							*Axial deformation (mm)
	Steel wall			Tie	Concrete		Furnace	
	1	4	6	12	13	14	(Average)	
0	15	22	36	**	**	**	49	0.00
2	132	162	173	**	19	**	421	1.77
4	213	263	269	**	54	**	574	4.06
6	263	332	335	**	81	**	609	4.78
8	317	394	402	**	105	**	637	5.11
10	391	462	475	**	124	**	689	5.31
12	458	514	535	**	143	**	715	5.31
14	514	544	574	**	157	**	733	4.87
16	552	558	606	**	173	**	754	4.20
18	580	484	629	14	189	**	765	3.63
20	603	353	649	18	208	**	779	3.26
22	622	241	665	24	229	**	790	3.02
24	636	203	677	30	256	14	807	2.93
26	659	204	691	37	283	18	820	2.89
28	677	251	708	44	308	23	833	2.88
30	690	478	720	51	330	31	831	2.84
32	704	584	737	58	350	39	852	2.75
34	715	621	747	64	369	46	854	2.56
36	724	650	756	71	388	54	864	2.25
38	735	665	769	77	404	62	870	2.02
40	750	680	784	83	422	69	875	1.74
42	***	690	797	88	439	74	869	1.47
44	***	702	815	92	454	78	889	1.15
46	***	706	827	98	469	82	891	0.72
48	***	741	***	104	483	85	901	0.03
50	***	732	***	104	491	89	906	-1.80
52	***	***	***	104	***	91	907	-9.08
54	***	***	***	105	***	92	912	-9.93
56	***	***	***	105	***	94	917	-10.12
58	***	***	***	106	***	95	922	-10.21

* - Negative deformations indicate compression
** - Data not recorded
*** - Thermocouples damaged

Table 5 - Cross-sectional temperatures for Column No. 2

Time	Temperature of steel wall						Temperature of re-bars										Temperature of ties				
(min)	1 (°C)	4 (°C)	5 (°C)	20 (°C)	21 (°C)	26 (°C)	7 (°C)	8 (°C)	9 (°C)	10 (°C)	22 (°C)	23 (°C)	28 (°C)	29 (°C)	30 (°C)	31 (°C)	11 (°C)	12 (°C)	25 (°C)	32 (°C)	33 (°C)
0	152	25	37	19	19	27	15	15	14	15	11	11	17	17	17	17	15	15	10	17	17
3	399	160	209	178	160	173	15	15	15	15	11	11	17	17	17	17	15	15	11	17	17
6	509	295	356	323	280	315	16	16	16	17	13	12	19	19	19	19	15	15	11	18	18
9	592	421	485	433	378	426	21	20	20	21	18	17	25	25	23	24	18	18	13	22	20
12	640	522	572	519	478	520	28	27	27	29	27	26	34	34	31	33	21	22	17	28	25
15	659	577	624	576	549	564	41	42	41	44	40	42	45	48	44	45	27	27	23	37	31
18	681	620	664	623	600	607	61	65	57	67	58	63	64	74	60	68	36	36	34	53	44
21	706	639	697	659	637	643	90	99	81	95	78	86	89	99	83	95	48	48	45	74	64
24	729	625	727	693	669	676	102	106	108	102	98	110	102	118	111	106	67	59	55	94	87
27	758	659	750	724	699	710	103	108	117	106	102	111	103	124	121	107	96	74	67	101	108
30	787	696	779	743	726	740	103	109	116	105	103	110	105	126	123	107	107	85	76	104	112
33	817	726	813	776	744	762	103	109	114	105	103	108	107	125	122	108	112	94	81	107	113
36	820	738	831	794	756	788	108	108	118	110	104	106	114	130	118	111	114	100	86	108	112
39	823	750	847	806	769	809	115	106	122	119	114	107	121	144	129	120	115	103	91	110	111
42	744	773	866	817	779	830	124	105	134	129	125	117	123	161	140	132	117	106	96	115	111
45	806	808	883	822	785	855	136	104	147	142	138	130	131	179	153	146	120	109	103	120	114
48	853	824	889	808	779	870	150	124	162	155	153	141	138	197	167	163	123	112	107	125	117
51	853	837	896	799	743	887	164	143	178	169	170	152	147	214	182	179	127	117	111	130	122
54	880	846	904	794	714	904	179	158	194	185	188	163	160	232	197	196	130	121	116	136	126
57	900	839	905	***	723	922	195	172	210	201	206	175	182	249	211	212	136	126	122	144	133
60	916	828	918	***	785	935	211	186	226	218	223	186	206	265	226	228	142	131	127	154	139
63	932	838	947	***	863	950	227	201	242	235	240	197	226	282	240	245	147	139	133	164	147
66	944	855	966	***	908	960	243	216	256	252	256	209	243	299	254	261	155	147	138	174	154
69	953	870	984	***	942	950	260	231	270	269	273	222	259	315	268	278	164	157	144	184	162
72	969	903	995	***	1001	890	276	246	283	285	288	234	277	331	282	296	173	167	149	193	174
75	917	938	998	***	1007	884	292	260	296	300	304	247	296	346	296	313	182	176	155	202	185
78	924	962	999	***	952	886	307	274	308	315	321	260	312	360	310	330	200	186	163	210	197
81	931	972	1005	***	903	897	323	288	321	330	337	273	328	374	324	347	217	197	170	217	206
84	968	990	1015	***	865	918	337	301	334	344	353	287	344	388	338	363	231	207	177	223	213
87	959	1004	1023	***	840	927	352	315	346	358	368	300	359	402	352	379	244	218	185	229	216
90	964	1010	1020	***	835	933	366	328	358	372	381	313	373	415	366	394	255	229	192	235	219
93	970	1008	1009	***	818	919	379	342	370	386	395	327	386	428	380	409	266	240	200	241	228
96	964	993	998	***	806	902	393	355	382	400	407	340	398	441	393	423	276	250	208	247	239
99	987	997	1003	***	787	929	406	368	394	413	420	353	411	453	405	436	286	261	216	253	245
102	989	1014	1014	***	749	966	419	380	405	426	432	367	424	465	418	449	296	271	225	259	244
105	1007	1031	1014	***	650	981	431	392	415	438	444	380	436	476	430	462	306	281	234	266	250
108	1014	1033	1029	***	607	982	444	405	425	451	455	393	448	487	441	473	315	291	243	272	257
111	1018	1037	1033	***	963	984	456	417	434	463	467	405	459	498	452	485	325	301	252	280	264
114	1023	1039	1027	***	1023	985	467	429	443	475	478	417	471	508	463	496	334	311	262	287	273
117	1028	1053	1039	***	1030	995	479	441	452	487	490	431	482	519	474	507	344	321	272	295	282
120	1029	1060	1044	***	1033	1003	491	452	460	499	501	447	492	529	485	517	353	331	281	303	292
123	1029	1042	1048	***	1037	1010	502	464	470	510	512	464	503	539	496	528	362	340	290	312	303
126	1029	1008	1043	***	1040	985	512	477	484	521	525	417	513	549	506	539	371	350	298	320	314

*** - Thermocouple damaged

Table 6 - Cross-sectional temperatures and deformations for Column No. 2

Time	Ave. furnace temparature	Concrete temperature						Axial deformation*	Lateral deformation at midheight*	Rotation of top	Rotation of bottom
		14	15	16	17	19	34				
(min)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(°C)	(mm)	(mm)	(°)	(°)
0	51	15	15	15	15	15	18	0.00	-4.9	0.0000	0.0000
3	590	15	15	15	15	15	18	2.18	-11.0	0.2908	-0.2483
6	666	15	15	15	15	15	18	4.22	-23.7	0.8876	-0.1163
9	736	15	15	15	15	15	18	5.62	-36.2	0.8876	0.1234
12	785	15	15	15	15	15	18	5.96	-50.8	0.8876	0.7095
15	783	17	16	15	15	15	18	4.89	-62.5	1.0912	1.5023
18	809	18	17	16	16	15	18	3.81	-68.1	1.2949	1.9598
21	823	22	19	18	18	16	19	3.17	-71.8	1.4403	2.2480
24	848	28	22	21	21	17	22	2.68	-75.8	1.5711	2.4815
27	889	39	32	25	25	19	26	2.03	-78.5	1.6728	2.7332
30	884	54	45	31	31	23	33	1.20	-81.2	1.7749	3.0413
33	902	64	58	37	37	29	42	0.18	-85.0	1.9493	3.1603
36	899	72	76	44	44	36	49	-0.81	-90.3	2.1677	3.2741
39	907	77	82	51	51	44	55	-1.77	-92.0	2.3702	3.3836
42	921	81	83	58	58	50	61	-2.28	-92.0	2.4434	3.4413
45	932	84	83	65	65	56	65	-2.53	-92.0	2.5006	3.4697
48	936	86	82	73	73	61	69	-2.70	-92.0	2.5304	3.4893
51	943	88	82	80	80	66	73	-2.75	-92.0	2.5601	3.4955
54	955	91	84	86	86	70	77	-2.77	-92.0	2.5887	3.4978
57	960	93	86	93	93	75	81	-2.81	-92.0	2.6032	3.5016
60	977	96	88	97	97	79	88	-2.81	-92.0	2.6312	3.5016
63	984	99	90	100	100	83	97	-2.93	-92.0	2.6607	3.5153
66	988	103	92	104	104	86	106	-2.93	-92.0	2.6757	3.5153
69	988	108	95	105	105	90	110	-2.93	-92.0	2.6903	3.5153
72	994	111	98	105	105	94	106	-2.93	-92.0	2.7049	3.5153
75	1009	114	102	105	105	100	105	-2.93	-92.0	2.7338	3.5153
78	1006	117	103	104	104	103	104	-2.93	-92.0	2.7484	3.5153
81	1019	120	103	104	104	103	103	-2.93	-92.0	2.7775	3.5153
84	1027	123	103	104	104	103	103	-2.91	-92.0	2.8062	3.5139
87	1036	126	104	106	106	103	104	-2.90	-92.0	2.8495	3.5122
90	1024	129	107	108	108	103	104	-2.90	-92.0	2.8926	3.5122
93	1017	132	110	111	111	103	106	-2.90	-92.0	2.9372	3.5122
96	1037	136	114	114	114	103	108	-2.90	-92.0	2.9952	3.5122
99	1041	139	117	117	117	103	110	-2.90	-92.0	3.0533	3.5122
102	1053	143	121	121	121	104	113	-2.90	-91.3	3.1403	3.5122
105	1055	147	125	126	126	106	116	-2.90	-91.3	3.2249	3.5129
108	1058	151	130	130	130	109	119	-3.17	-91.3	3.3140	3.5436
111	1063	155	134	135	135	113	122	-3.54	-91.3	3.4159	3.5859
114	1067	160	139	140	140	116	125	-3.94	-91.3	3.5612	3.6308
117	1067	166	144	145	145	119	128	-4.59	-91.3	3.7201	3.7056
120	1076	173	149	150	150	121	132	-5.49	-91.3	3.9526	3.8083
123	1079	181	154	156	156	124	136	-7.40	-91.3	4.5308	4.0262
126	1079	189	159	161	161	128	139	-13.59	-91.3	5.1378	4.7310

* - Maximum possible reading on deflection gauge is 92.0 mm

Table 7 - Cross-sectional temperatures for Column No. 3

Time	Temperature of steel wall							Temperature of re-bars										Temperature of ties					
min	1 (°C)	14 (°C)	16 (°C)	18 (°C)	19 (°C)	33 (°C)	34 (°C)	7 (°C)	8 (°C)	9 (°C)	10 (°C)	20 (°C)	21 (°C)	26 (°C)	27 (°C)	28 (°C)	29 (°C)	11 (°C)	12 (°C)	22 (°C)	23 (°C)	30 (°C)	31 (°C)
0	27	29	28	25	26	42	39	20	20	20	20	20	20	20	21	20	21	20	20	20	20	21	21
2	207	189	181	200	194	268	209	21	20	20	21	20	20	21	21	21	21	26	21	20	20	21	21
4	303	289	274	286	294	358	310	26	25	24	26	26	23	28	25	24	25	44	32	24	22	25	25
6	361	341	325	343	348	414	363	37	34	34	39	38	32	44	35	34	37	62	48	33	28	34	36
8	423	401	379	409	406	474	408	55	48	48	56	58	45	62	49	45	51	83	64	45	38	46	45
10	459	453	439	481	457	500	443	77	66	64	78	82	63	84	64	58	69	105	79	59	51	61	58
12	495	496	485	341	499	496	492	117	84	82	108	125	87	115	80	74	91	128	108	66	69	82	73
14	543	543	542	522	554	527	544	134	107	110	140	125	125	139	102	94	134	146	139	86	116	134	104
16	581	577	579	559	588	563	579	136	136	136	141	138	142	141	123	121	139	160	144	119	143	135	137
18	619	613	622	596	626	605	614	142	139	141	144	145	143	148	139	140	144	184	153	136	144	143	143
20	634	632	641	614	641	621	635	145	142	144	146	147	146	154	144	143	145	197	161	142	146	145	145
22	659	657	669	652	666	652	664	156	147	148	160	153	151	172	149	147	149	223	179	150	151	149	148
24	681	678	689	671	684	677	684	174	153	153	180	164	155	194	152	152	156	248	200	156	155	152	152
26	699	690	702	686	697	694	699	194	160	156	201	181	154	216	160	154	173	274	222	156	151	165	156
28	728	719	728	715	723	721	725	215	170	165	222	199	166	238	173	160	196	296	242	155	150	181	167
30	751	742	746	741	741	745	745	230	179	176	239	217	184	259	189	172	217	318	260	160	154	198	185
32	760	759	760	756	754	760	755	243	190	193	257	238	201	279	206	188	234	337	278	180	170	217	206
34	780	777	782	779	774	781	776	258	205	211	275	259	218	300	224	206	251	356	297	205	187	236	224
36	799	795	802	798	793	799	795	273	223	229	293	280	236	319	242	225	268	375	316	229	203	255	241
38	815	811	818	815	810	815	812	289	243	247	311	301	254	338	259	243	284	394	335	252	221	272	257
40	829	827	834	828	827	830	827	306	264	266	330	322	272	357	277	261	300	414	353	273	239	290	273
42	844	842	849	841	842	843	842	323	286	285	347	342	290	375	295	280	317	433	372	294	257	307	289
44	857	857	862	862	857	858	856	341	307	304	365	361	309	394	313	298	334	452	391	313	275	325	306
46	868	869	874	869	869	870	868	359	328	323	382	381	327	411	332	317	351	471	409	333	293	343	323
48	879	880	884	880	880	880	879	377	348	342	400	400	345	429	350	336	369	489	427	352	311	360	341
50	890	888	893	888	890	891	890	396	368	361	417	419	363	446	369	355	387	507	445	371	330	378	359
52	898	896	902	893	899	899	899	415	388	379	434	437	381	463	388	374	405	524	462	390	348	395	378
54	906	903	909	899	907	907	906	434	408	397	451	456	399	480	406	393	422	541	479	409	367	412	396
56	913	909	917	***	914	914	913	453	427	416	467	473	417	496	425	411	440	558	495	427	385	430	413
58	917	913	920	***	917	917	916	462	436	425	476	482	425	504	433	420	448	566	503	436	394	438	422
60	927	920	928	***	924	925	924	480	454	442	492	499	443	519	451	438	465	582	519	454	412	454	439
62	935	926	935	***	930	934	932	498	472	460	508	516	460	534	468	455	481	597	534	471	430	471	456
64	944	932	944	***	937	942	939	515	489	476	523	532	476	549	485	472	496	613	549	488	447	486	472
66	952	938	951	***	943	949	946	532	506	493	539	547	493	563	501	488	511	628	564	504	463	501	488
68	961	944	956	***	949	955	951	548	522	509	553	562	508	578	516	503	526	643	579	519	479	516	503
70	967	950	961	***	959	960	956	564	538	524	568	578	524	593	531	519	540	658	594	534	495	530	517
72	972	955	965	***	968	964	961	580	552	539	583	593	539	607	546	534	553	672	608	548	510	544	531
74	974	960	966	***	969	967	964	596	567	554	598	608	553	621	560	548	567	686	623	560	525	558	544
76	982	972	973	***	976	973	973	612	582	568	613	623	568	635	574	562	582	699	637	576	539	571	556
78	988	988	979	***	983	978	981	628	597	583	628	637	582	648	589	576	597	712	650	593	552	585	570
80	1010	1014	998	81	934	993	1005	642	612	598	642	651	597	661	603	591	611	724	664	608	566	599	586
82	1023	1024	1009	611	909	1006	1050	657	626	612	655	664	612	673	617	605	625	737	677	622	581	613	601

*** - Thermocouple damaged

Table 8 - Cross-sectional temperature and axial deformation for Column No. 3

Time (min)	Average Furnace temperature (°C)	Concrete temprtature (°C) 13	15	17	32	*Axial deformation (mm)
0	48	21	20	20	21	0.00
2	535	36	23	20	21	2.98
4	610	71	40	20	21	7.33
6	640	105	64	22	22	9.97
8	689	136	95	27	27	12.83
10	720	168	119	35	34	16.32
12	740	203	141	47	45	18.50
14	768	255	153	77	63	20.53
16	779	300	157	134	133	21.71
18	799	340	170	142	141	22.82
20	805	359	182	144	144	23.07
22	818	394	208	147	148	23.18
24	824	426	234	153	151	23.18
26	830	454	258	157	153	22.62
28	857	478	282	159	153	20.54
30	870	499	305	152	151	13.94
32	880	520	327	147	148	11.64
34	888	540	350	142	145	11.11
36	897	560	372	140	143	11.07
38	906	579	395	149	147	11.07
40	914	600	416	168	156	11.08
42	922	620	438	188	170	11.47
44	930	639	459	208	189	11.98
46	936	657	479	227	210	12.48
48	943	674	499	246	231	12.97
50	949	691	517	266	253	13.43
52	954	706	535	285	273	13.82
54	958	721	552	304	293	14.13
56	963	735	569	322	312	14.35
58	965	742	577	331	321	14.42
60	971	755	594	348	339	14.49
62	976	768	611	365	356	14.49
64	982	781	626	382	372	14.49
66	987	793	642	399	389	14.49
68	990	805	657	416	406	14.49
70	994	816	671	432	422	14.13
72	995	827	685	449	439	13.52
74	995	836	699	465	455	12.70
76	1004	845	711	480	470	11.77
78	1011	854	724	495	485	10.55
80	1032	865	736	509	500	9.12
82	1053	877	748	522	514	5.03

* - Negative deformations indicate compression

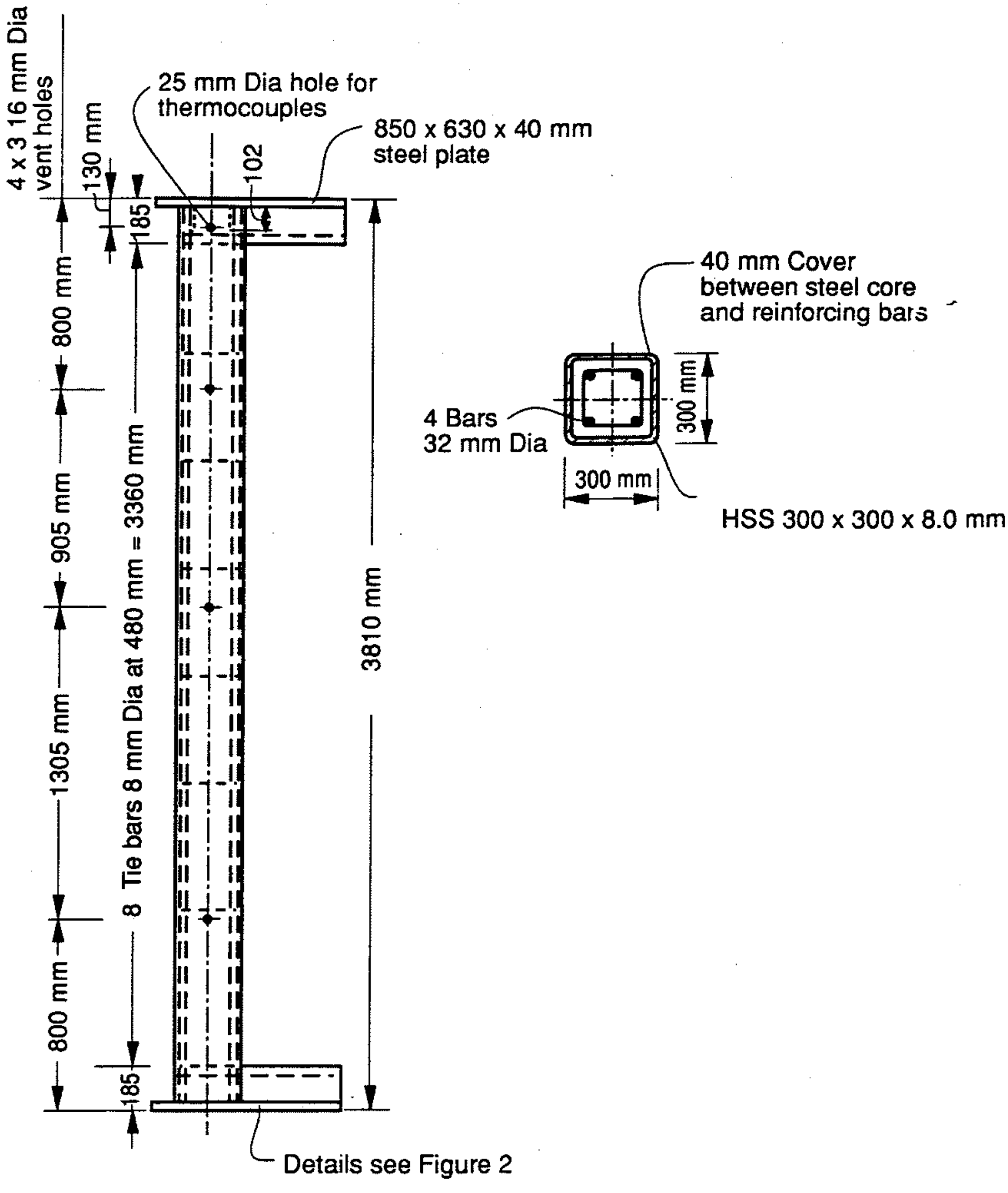


Figure 1

Elevation and cross section of Column Nos. 1 and 2

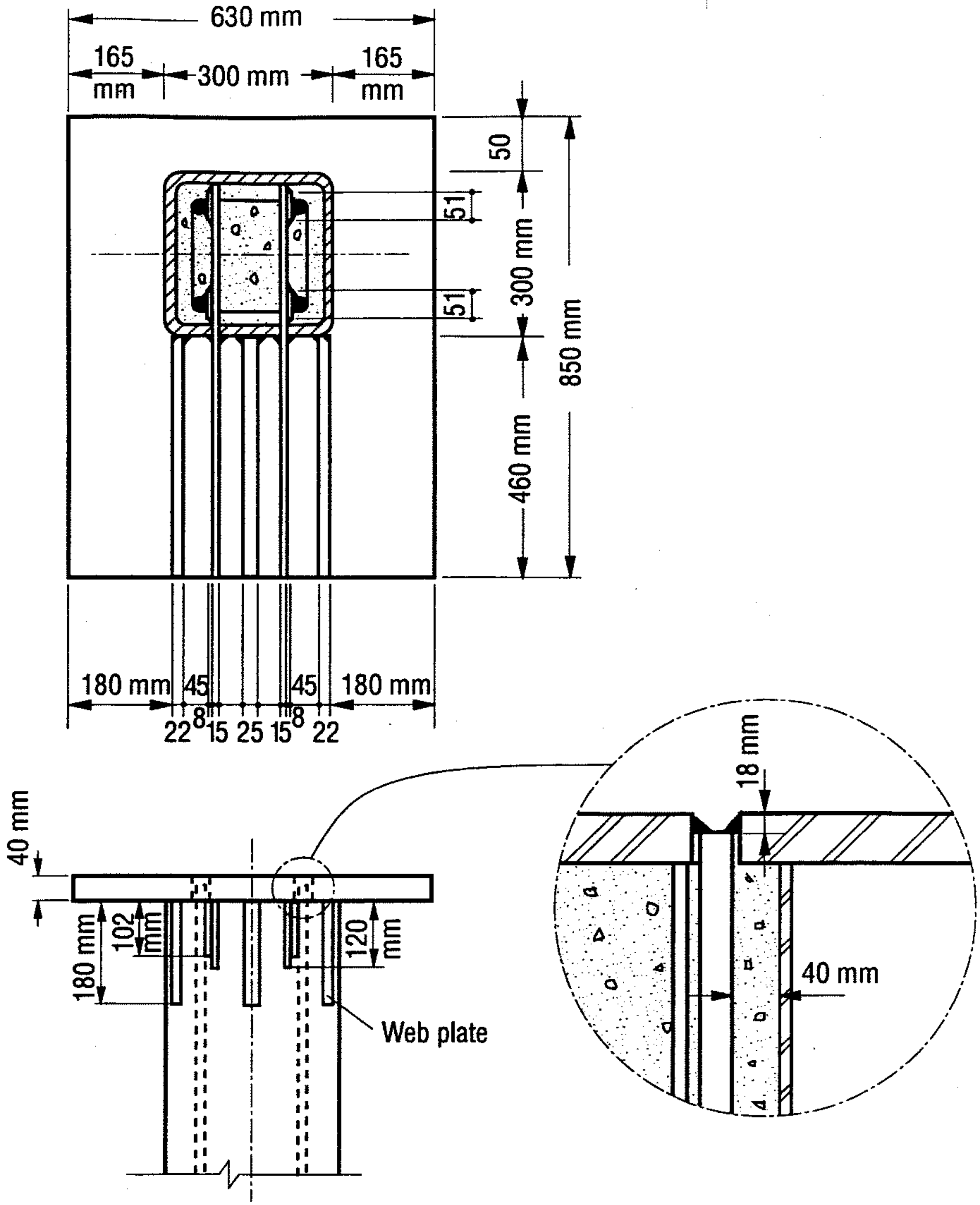


Figure 2

Details of end plates, web plates and bar connections of Column Nos. 1 and 2

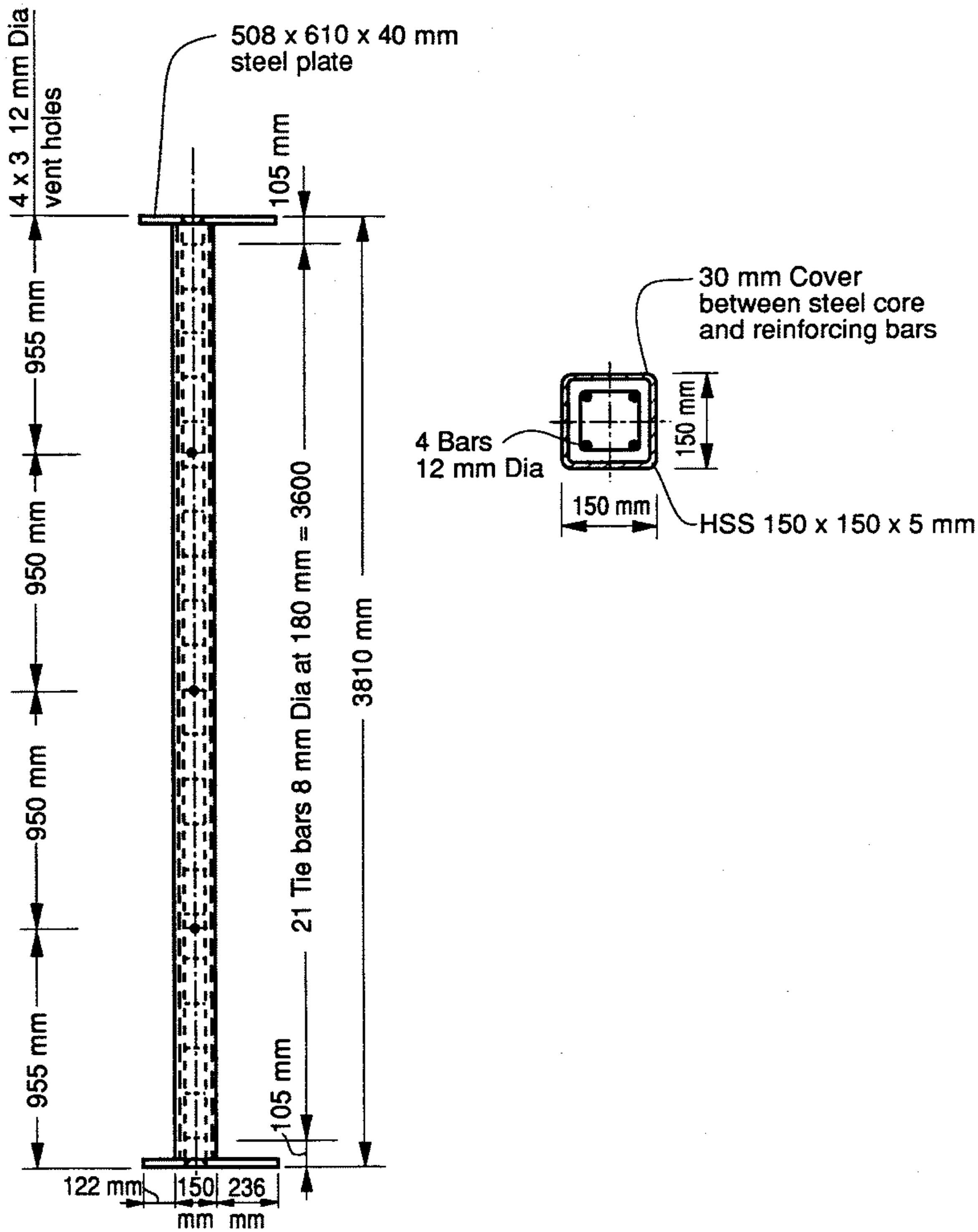


Figure 3

Elevation and cross section of Column No. 3

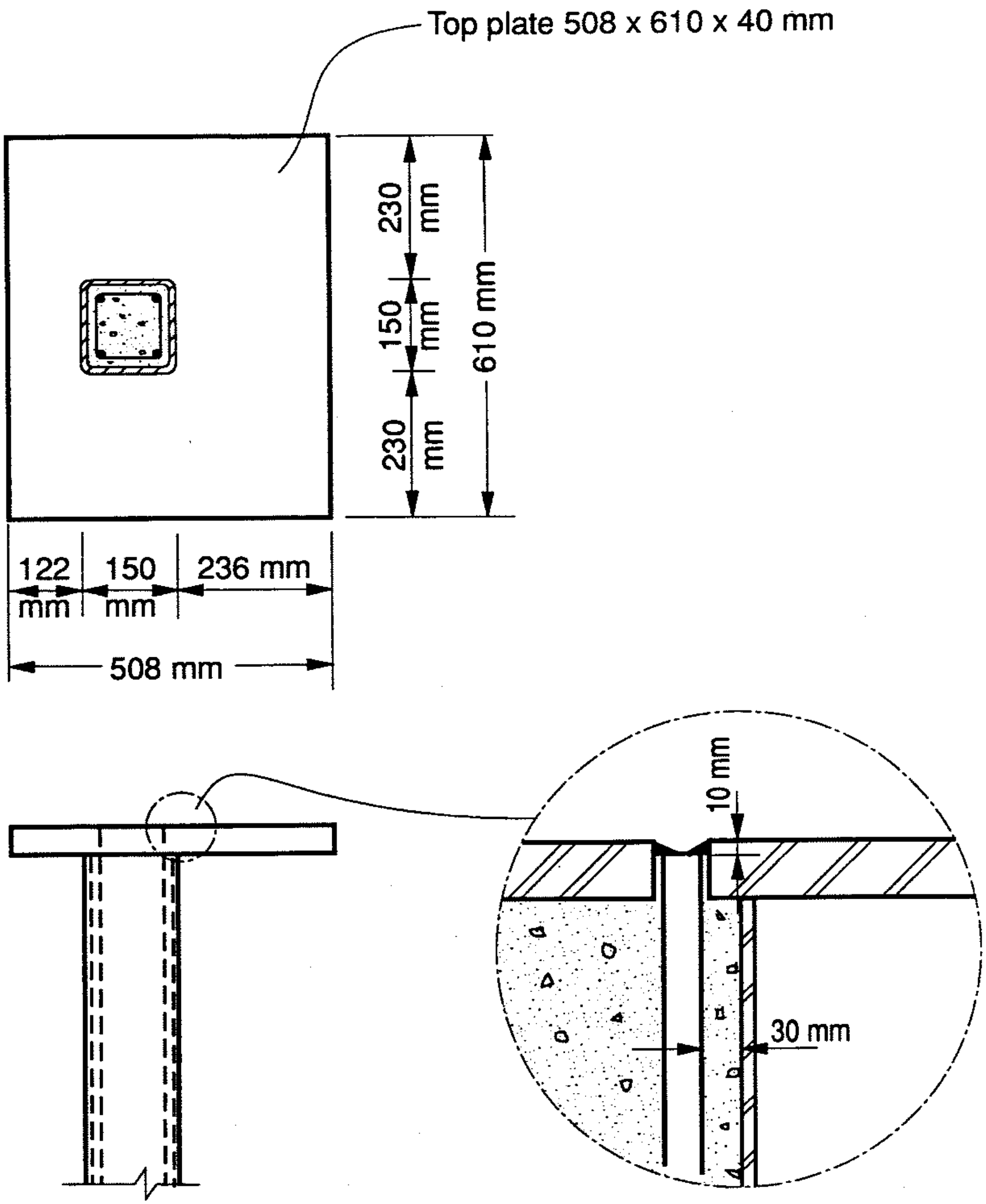


Figure 4

Details of end plates, web plates and bar connections of Column No. 3

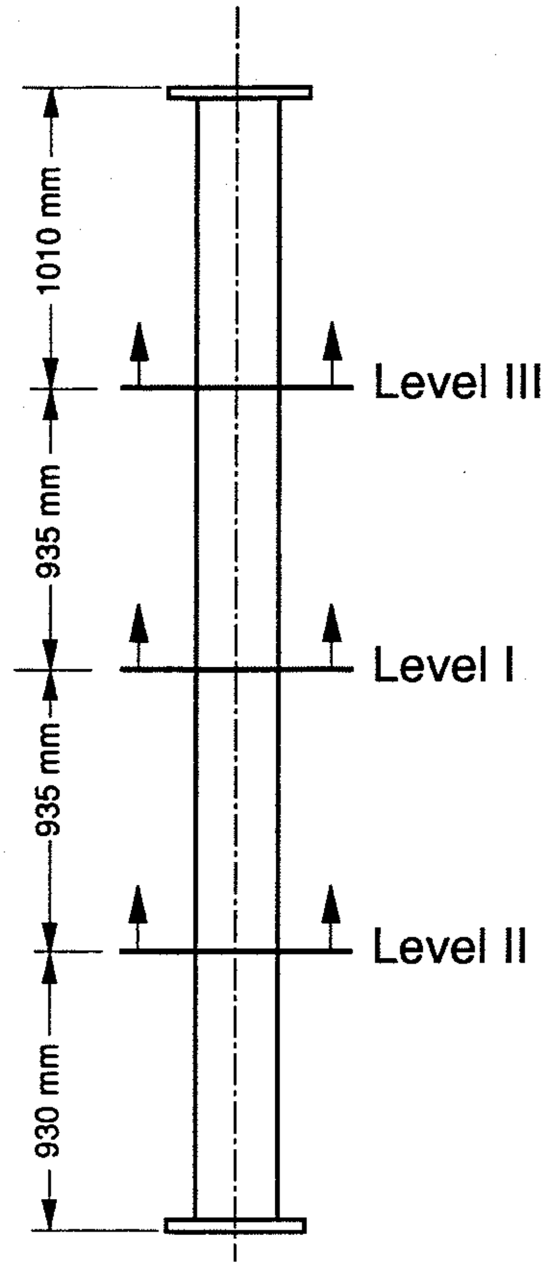
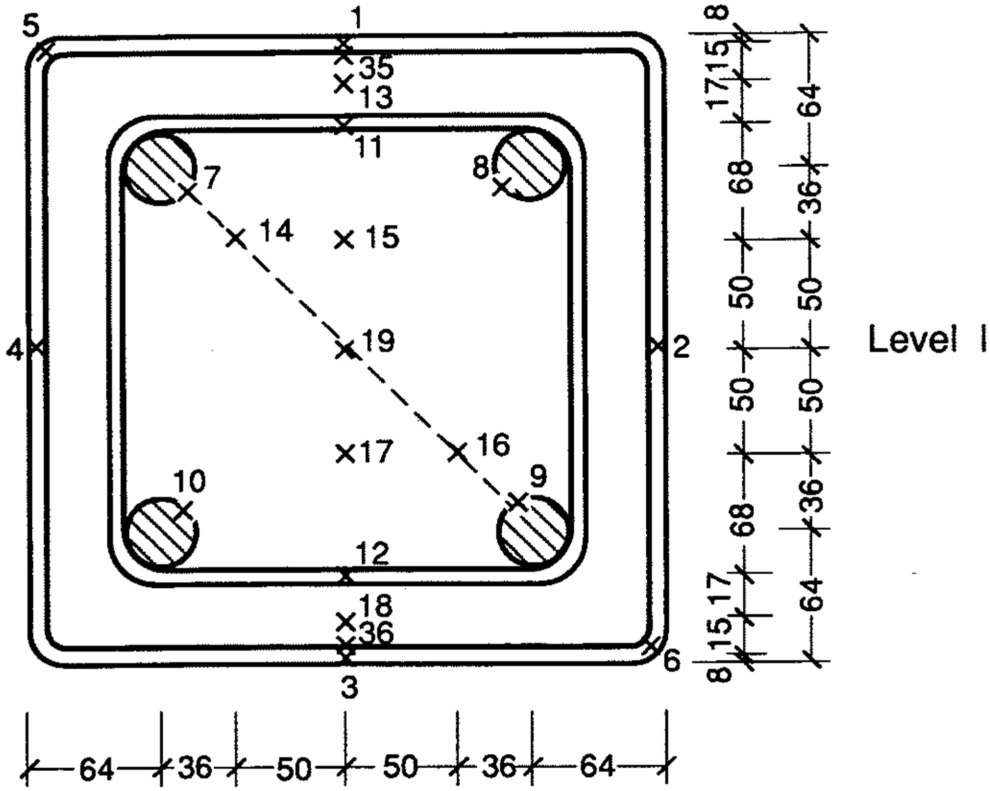


Figure 5

Levels at which thermocouples in the columns were installed



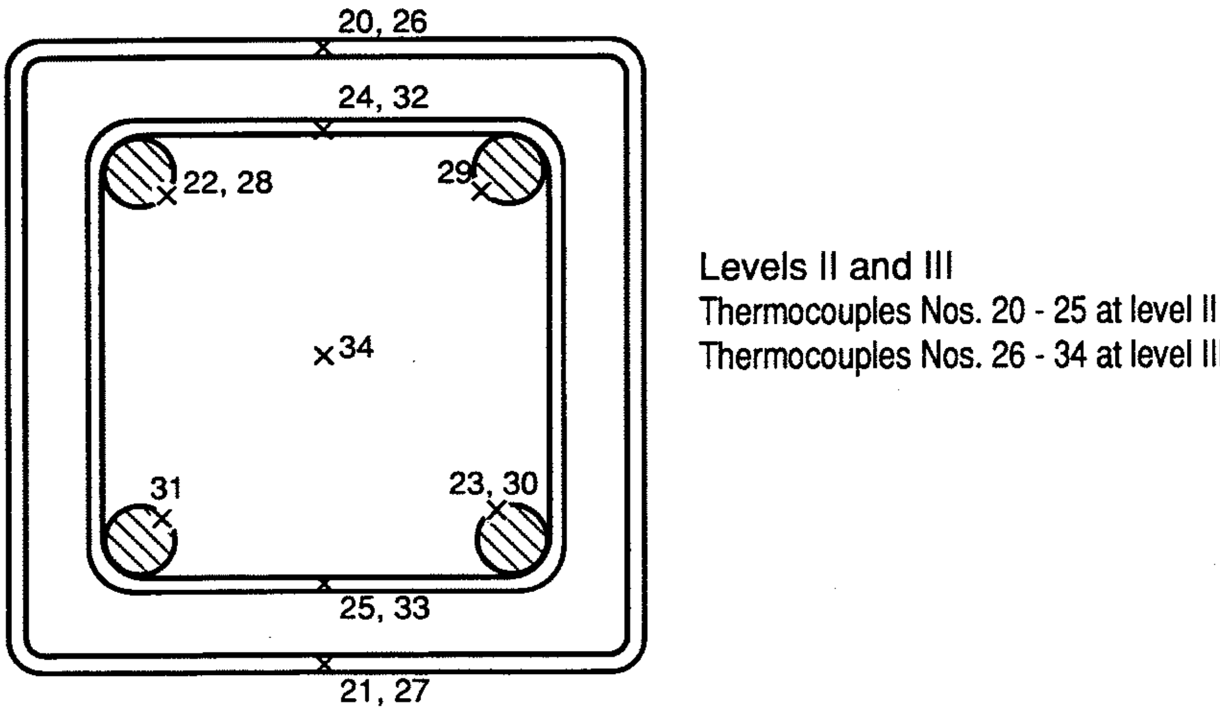
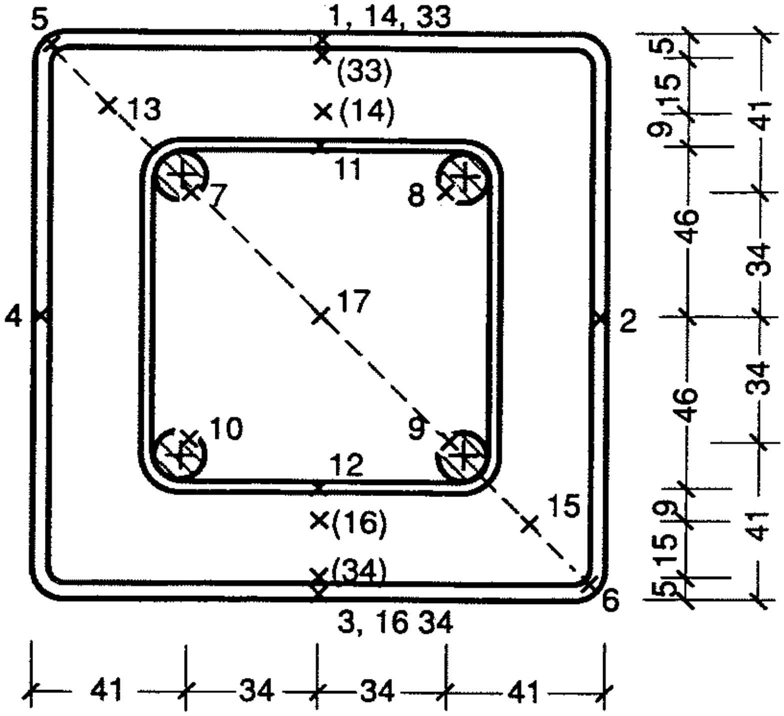


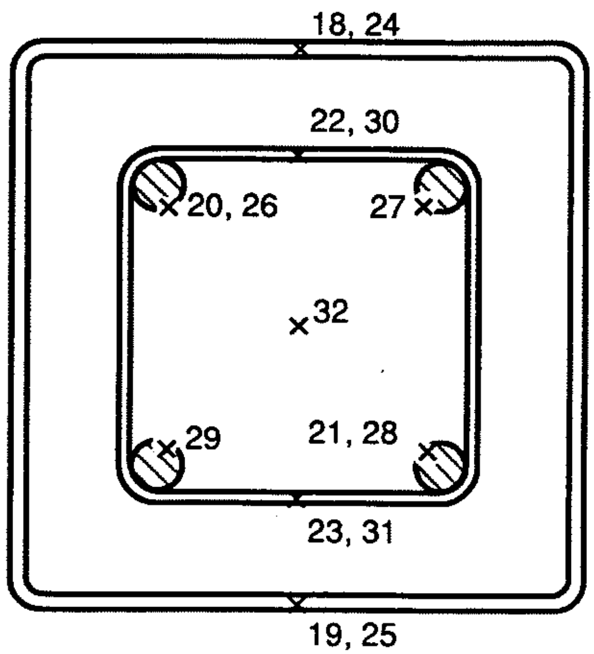
Figure 6

Location of thermocouples at various levels in Column Nos. 1 and 2



Level I

Thermocouples Nos. 14, 16, 33, and 34 (Numbers between parentheses) were not in the planned places, they were fixed to the steel walls (numbers without parentheses)



Levels II and III

Thermocouples Nos. 18 - 23 at level II

Thermocouples Nos. 24 - 32 at level III

Figure 7

Location of thermocouples at various levels in Column No. 3

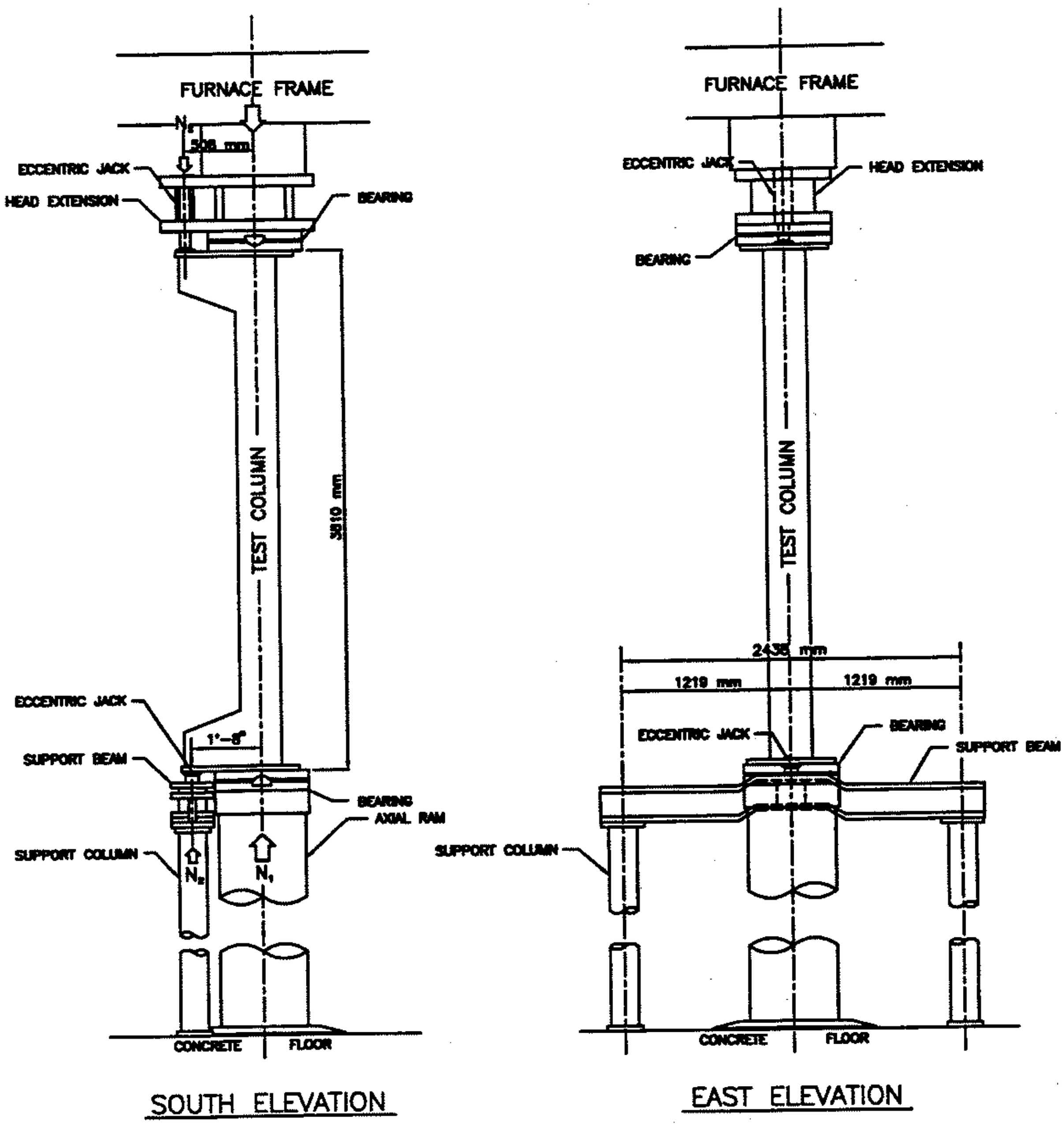


Figure 8

Test Furnace

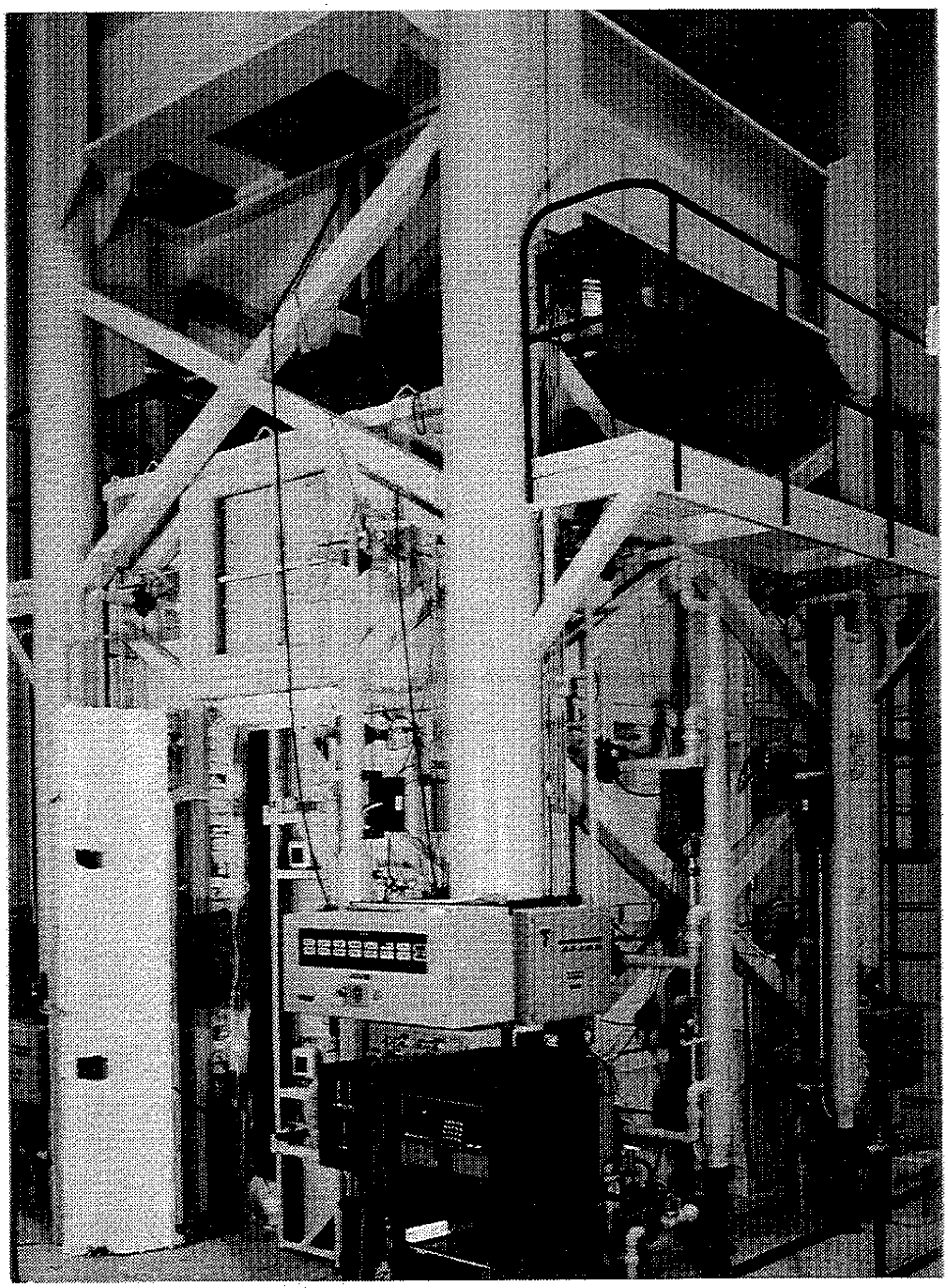


Figure 9

Loading device of column test facility

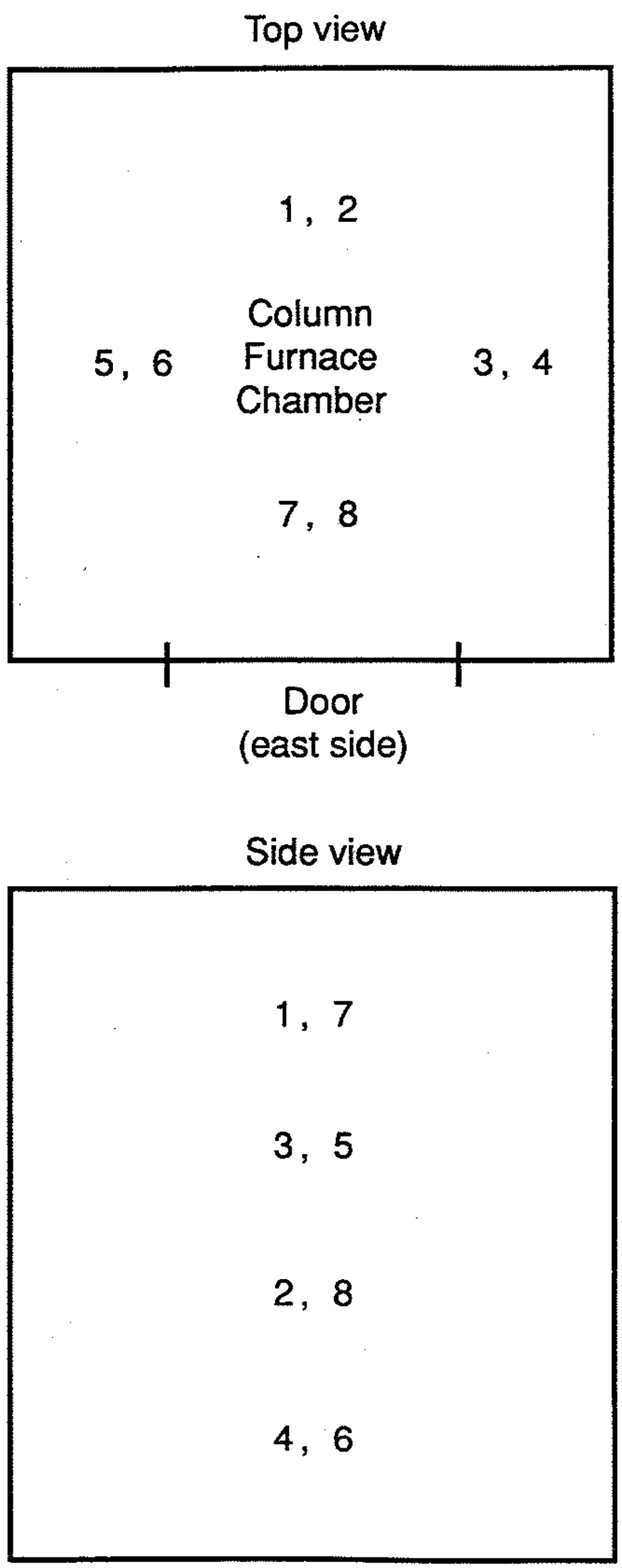


Figure 10

Location and numbers of thermocouples in column furnace chamber

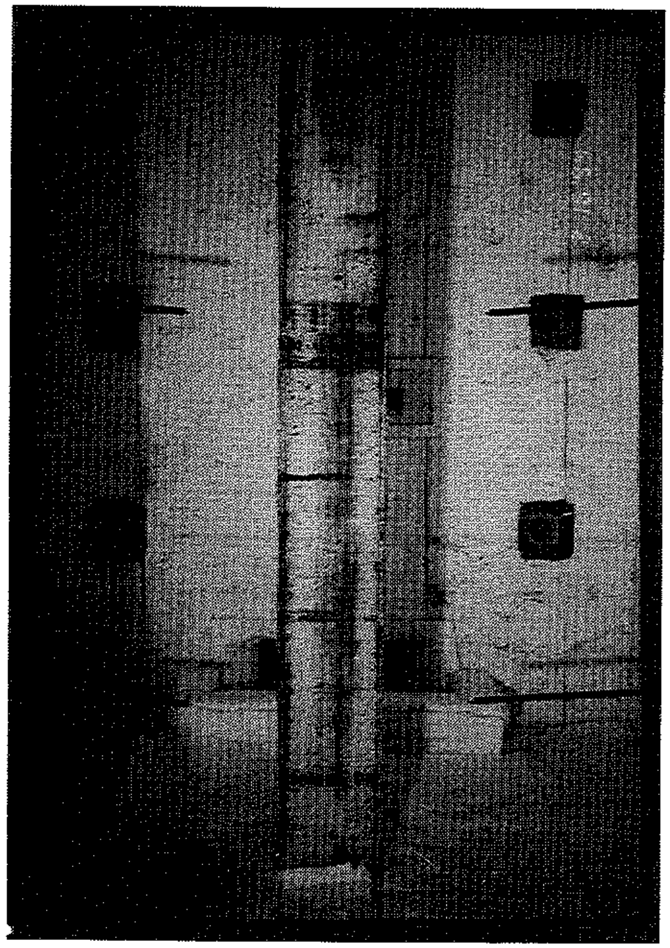


Figure 11

Column No. 1 after test

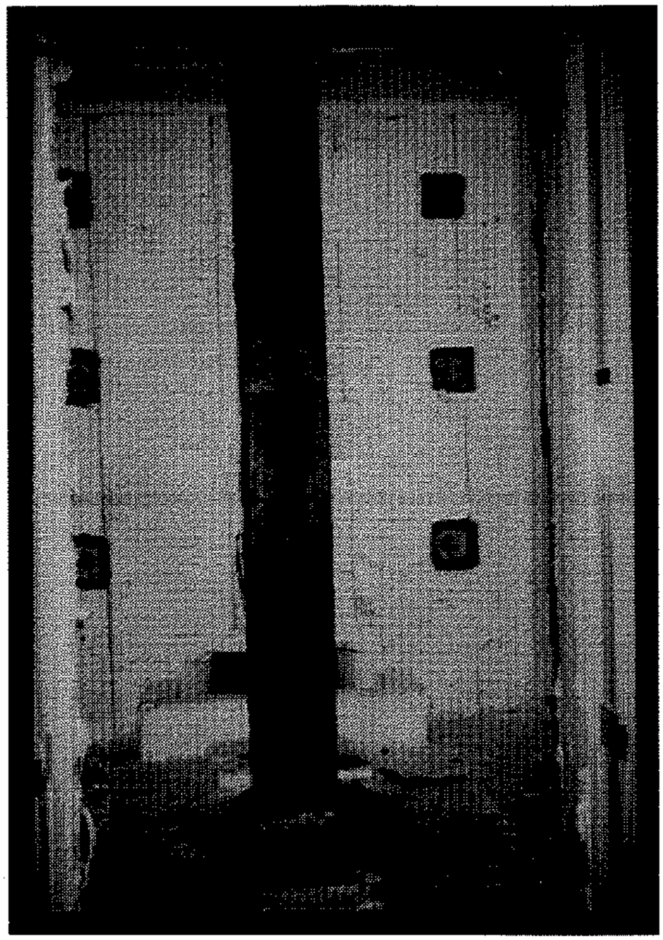


Figure 12

Column No. 2 after test