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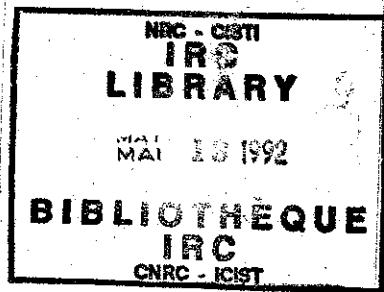
**Experimental Studies on the Fire
Resistance of Hollow Steel Columns
Filled with Bar-Reinforced Concrete**

M. Chabot and T.T. Lie

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EXPERIMENTAL STUDIES ON THE FIRE RESISTANCE OF HOLLOW STEEL COLUMNS FILLED WITH BAR-REINFORCED CONCRETE

by

M. Chabot and T. T. Lie

ABSTRACT

Experimental studies were carried out to determine the fire resistance of circular and square hollow structural steel columns filled with bar-reinforced concrete. The results of eight full-scale fire resistance tests are described. The main study variables were the column dimensions and the load intensity. These studies were conducted as part of a research program aimed at developing methods capable of predicting the fire resistance of concrete-filled hollow steel columns.

1. INTRODUCTION

Steel Hollow Structural Sections (HSS) are very efficient sections in resisting compression loads, since, by filling these sections with concrete, a substantial increase in load-bearing capacity can be achieved. Also, fire resistance can be obtained without the necessity of external fire protection for the steel section. The elimination of such external surface protection increases usable space in the building and allows the steel outer surface to be left exposed. Furthermore, the tubular sections eliminate the need for formwork during erection.

These perceived benefits have resulted in research into the structural and fire performance of concrete-filled hollow steel columns by several organizations around the world [1-8]. For a number of years, the National Fire Laboratory of the Institute for Research in Construction, National Research Council of Canada, has also been engaged in studies to develop methods for predicting the fire resistance of these composite columns. A multi-phase research program, which involves both theoretical and experimental studies, has been set up, with the support of the Canadian Steel Construction Council and the American Iron and Steel Institute.

In the first phase of this research program, hollow steel columns filled with plain concrete were considered. Mathematical models for predicting the fire resistance of hollow steel columns filled with plain concrete were developed [9] and full-scale fire tests were carried out [10].

This report deals with the second phase of this program which focussed on hollow steel columns filled with bar-reinforced concrete. The results of eight fire resistance tests on full-size circular and square columns are described in detail, including the column temperatures, axial deformation and fire resistance.

2. DESCRIPTION OF TEST SPECIMENS

2.1. Dimensions

All eight columns were 3810 mm long from end plate to end plate. Two columns had a circular cross-section and six columns had a square cross-section. The outside width of the square columns ranged from 203.2 mm to 304.8 mm, while the outer diameter of the circular columns was 273.1 mm. The wall thickness of all eight sections was 6.35 mm.

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The specific dimensions of each column are listed in Table 1. In this table, the columns whose number starts with "C" are circular, and those with a number starting with "SQ" are square.

2.2. Materials

2.2.1. Steel

Hollow structural sections (HSS) meeting the requirements of CSA Standard G40.20-M81 [11], Class H, were used. The sections were made with grade 350W steel (CSA Standard G40.21-M81 [12]) with minimum yield strength of 350 MPa. The sections were supplied by Stelco Inc.

Deformed bars, meeting the requirements of Ref. [13] with a minimum yield strength of 400 MPa, were used for the main reinforcing and tie bars. The diameter of the main reinforcing bars varied from 16 mm to 25.2 mm. The diameters of the ties were 6.4 mm and 9.5 mm.

2.2.2. Concrete

The concrete mixes were supplied by Dufferin Concrete from Ottawa. The mixes were made with general purpose Type 10 Portland cement, carbonate stone and silica based sand. Superplasticizer, Mighty 150, and retarding admixtures, Master Builders 100 XR, were added to the mix to improve workability. Batch quantities are given in Table 2. Two pours were made and the 28-day cylinder compressive strengths were 41.3 and 42.3 MPa, respectively.

2.3. Fabrication

2.3.1. Steel column and reinforcing bars

The columns were fabricated by cutting the supplied hollow structural sections to 3797 mm in length. Steel end plates measuring 508 mm wide by 610 mm long by 25 mm thick, were then welded to both section extremities (Figure 1). The total column length was thus 3810 mm including the end plates. The hollow structural sections and end plates were first joined by a groove weld. Secondly, a fillet weld was added around the outside diameter of the hollow structural section. AWS 5.18 Type E705-6 welding rods were used for both welds. Accurate centering and perpendicularity of the end plates were given special attention. Figure 1 shows the details and dimensions of a typical circular column specimen. Except for geometry, square column specimens are essentially similar.

Before assembly, a hole with a diameter 25.4 mm less than the inner diameter of the hollow structural section was cut in each end plate. As shown in Figures 2 and 3, this created a lip of 13 mm between the inner surface of the section and the edges of the opening in the end plate.

Five small holes were drilled in the wall of each hollow structural section. Two pairs, 13 mm in diameter, located 457 mm from each end of the column, were provided as vent holes for the water vapour produced during the experiment. The fifth hole, located near the top end plate, was used for entry of the thermocouple wires.

The main reinforcing bars and ties were tied together to complete the steel cage. The main bars were cut 10 mm shorter than the column length. The steel cage was then placed into the column with special care to ensure appropriate centering. The steel cage in

all but one column consisted of four bars. Column No. SQ-22 had eight bars. All but one column had 16.5 mm cover to the tie bars and 23 mm cover to the main bars. Column No. SQ-23 had a 26 mm cover to the main bars. The details of the steel cage of each column are shown in Figures 4 to 8.

2.3.2. Concrete placement

The concrete was mixed in a truck mixer. A concrete placement bucket and a funnel were used to deposit the concrete in the steel column. An internal vibrator was carefully applied to consolidate the concrete. The top surface of the column was finished with a small trowel. To avoid possible moisture leaks during curing, the section was sealed at both ends with plastic sheet and tape. The columns were left upright for 28 days, then stored horizontally at room temperature, with no particular curing measures being taken, until the test date. Approximately two years elapsed between the time the columns were poured and the time the first column was tested.

Before each test, the moisture condition in the concrete core of the column was measured by inserting a resistance moisture sensor in a hole drilled in the concrete through one of the vent holes. In general, a high moisture content, corresponding to approximately 85 to 95% relative humidity, was measured.

2.4. Instrumentation

Type K chromel-alumel thermocouples, with a thickness of 0.91 mm, were used for measuring concrete and reinforcing bar temperatures at several locations across the mid-height section of the columns. The thermocouples in the concrete were tied to a steel rod which was secured to the main reinforcing cage and to the main reinforcing steel. A thermocouple was also attached to the outer face of the steel wall of each column at mid-height. The thermocouple locations are shown in Figures 9 to 11.

3. 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 was designed to produce the conditions to which a member might be exposed during a fire; i.e., temperatures, structural loads, and heat transfer. It consisted of a steel framework supported by four steel columns, with the furnace chamber inside the framework (Figure 12). The characteristics and instrumentation of the furnace are described in detail in Reference [14]. Only a brief description of the furnace and the main components is given here.

3.1 Loading device

A hydraulic jack with a capacity of 9778 kN produced the load along the axis of the test column. The jack was located at the bottom of the furnace chamber.

3.2. Furnace chamber

The furnace chamber had a floor area of 2642 × 2642 mm and was 3048 mm high. The interior faces of the chamber were lined with ceramic fibre materials that efficiently transfer heat to the specimen. There were 32 propane gas burners in the furnace chamber, arranged in eight columns containing four burners each. The total capacity of the burners was 4700 kW. Each burner can be adjusted individually to give a high degree of

temperature uniformity in the furnace chamber. The pressure in the furnace chamber was also adjustable and was set somewhat lower than atmospheric pressure.

3.3 Instrumentation

The furnace temperature was measured with the aid of eight chromel-alumel thermocouples. The junction of each thermocouple was located 305 mm (1 ft) from the test specimen and thermocouples were located at various heights. Two thermocouples were placed opposite each other at intervals of 610 mm (2 ft) along the height of the furnace chamber. The location of their junctions and their numbering are shown in Figure 13. 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 and measured using pressure transducers. The accuracy of controlling and measuring loads was approximately 10 kN.

The axial deformation of the test specimen was determined by measuring the displacement of the jack that supports the column. The displacement was measured using transducers with an accuracy of 0.002 mm.

4. TEST CONDITIONS AND PROCEDURES

4.1 End conditions

All tests were carried out with both ends of the columns fixed, i.e., restrained against rotation and horizontal translation. For this purpose, eight 19 mm bolts spaced regularly around the column were used at each end to bolt the end plates to the loading head at the top and the hydraulic jack at the bottom.

4.2. Loading

All columns were tested under a concentric load. The applied load ranged from 22 to 82% of the factored compressive resistance of the columns (C_{rc}) or 70 to 192% of the factored compressive resistance of the concrete core (C'_r), determined according to CSA Standard CSA/CAN-S16.1-M89 [15]. The factored compressive resistances of each column, as well as the applied loads, are given in Table 1. The effective length factors, K, used in the calculation of the factored compressive resistances were those recommended in CSA/CAN-S16.1-M89 for the given end condition, i.e., 0.65. The effective length of the columns, KL , was thus assumed to be 2.48 m.

The load was applied approximately 45 min before the start of the test, until a condition was reached at which no further increase of the axial deformation could be measured. This condition was selected as the initial condition for the column axial deformation. The load was maintained constant throughout the test.

4.3. Fire exposure

The ambient temperature at the start of each test was approximately 20°C. During the test, the column was exposed to heating controlled in such a way that the average temperature in the furnace followed as closely as possible the ASTM-E119 [16] or CAN/ULC-S101 [17] standard temperature-time curve.

4.4. Failure criterion

The columns were considered to have failed, and the tests were terminated, when the hydraulic jack, which has a maximum speed of 76 mm/min (3 in./min), could no longer maintain the load.

The failure mode, which varied from buckling to compression, was determined by visual observation. A column was considered to have failed by buckling when bending of the column was apparent.

4.5. Recording of results

The furnace, concrete and steel temperatures, as well as the axial deformation of the columns were recorded at 2 min intervals.

5. RESULTS

The results of the eight tests are summarized in Table 1, in which column characteristics, test conditions, fire resistances and failure modes are given for each column.

The furnace, concrete and steel temperatures recorded during the tests, as well as the axial deformations of the column specimens, are given in Tables A1 to A8 and plotted in Figures A1 to A8, in Appendix A. Positive axial deformation values indicate expansion of the column. Finally, Figures B1 to B8 in Appendix B show the column specimens after the fire tests.

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Table 1. Summary of test parameters and results

Column No.	Test Date	HSS Dimensions (mm)	Reinforcement # bars	Concrete Strength 28 days (MPa)	Factored Resistance C'_r (kN)	Test Load C (kN)	Load Intensity C/C'_r C/Crc	Fail. Mode	Fire Resistance (hr:min)				
C-48	89/01/18	273.1 dia x 6.35	4 @ 19.5 mm	2.3	42.3	46.7	1110	2851	1050	0.95	0.37	B	3:08
C-49	91/03/20	273.1 dia x 6.35	4 @ 19.5 mm	2.3	42.3	47.0	1110	2851	1900	1.71	0.67	B	1:36
SQ-12	91/01/14	203.2 x 203.2 x 6.35	4 @ 16.0 mm	2.2	41.3	47.0	717	2258	500	0.70	0.22	B	2:30
SQ-13	91/05/01	203.2 x 203.2 x 6.35	4 @ 16.0 mm	2.2	41.3	47.0	717	2258	930	1.30	0.41	B	1:45
SQ-18	90/10/24	254.0 x 254.0 x 6.35	4 @ 19.5 mm	2.1	42.3	48.1	1223	3186	1440	1.18	0.45	C	1:53
SQ-19	91/03/05	254.0 x 254.0 x 6.35	4 @ 19.5 mm	2.1	42.3	48.1	1223	3186	2200	1.80	0.69	C	1:10
SQ-22	91/03/13	304.8 x 304.8 x 6.35	4 @ 16.0 mm & 4 @ 19.5 mm	2.3	41.3	47.0	1775	4154	3400	1.92	0.82	C	0:39
SQ-23	91/02/25	304.8 x 304.8 x 6.35	4 @ 25.2 mm	2.3	41.3	47.0	1775	4154	2000	1.13	0.48	C	3:32

Factored Resistance:

 C'_r = Factored compressive resistance of concrete core of column according to CAN3-S16.1-M89

Crc = Factored compressive resistance of concrete-filled HSS column according to CAN3-S16.1-M89

Failure Mode:

B = Buckling

C = Compression

Table 2. Concrete batch quantities

Component	Quantity (kg/cu. m)
Cement (Portland Type 10)	439
Coarse aggregate (Carbonate stone)	
19.0 mm (3/4 in.)	788
9.5 mm (3/8 in.)	340
Total	1128
Fine aggregate (Silica based sand)	621
Water	161
Water/Cement ratio	0.37

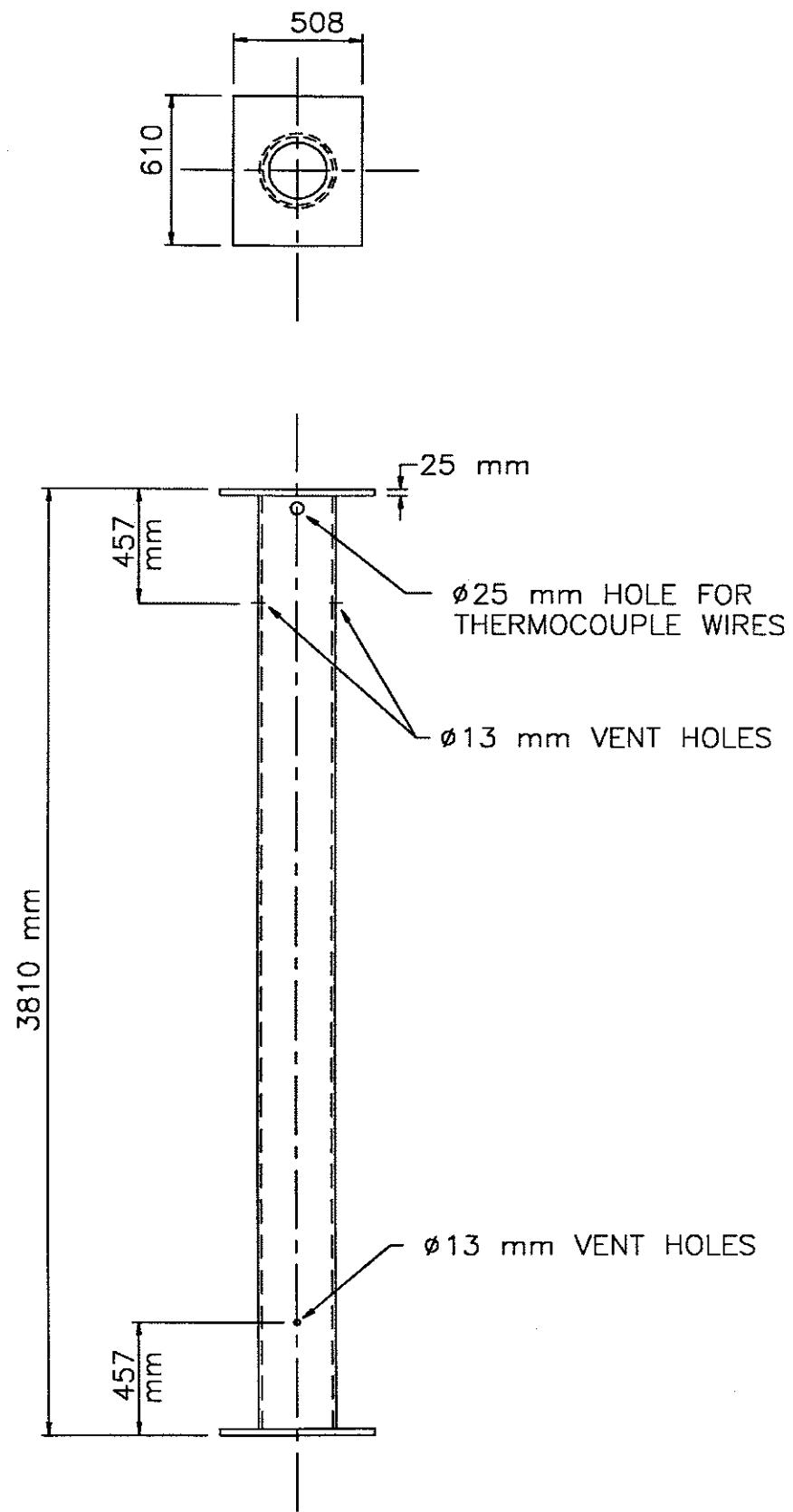


Figure 1. Column specimen details and dimensions

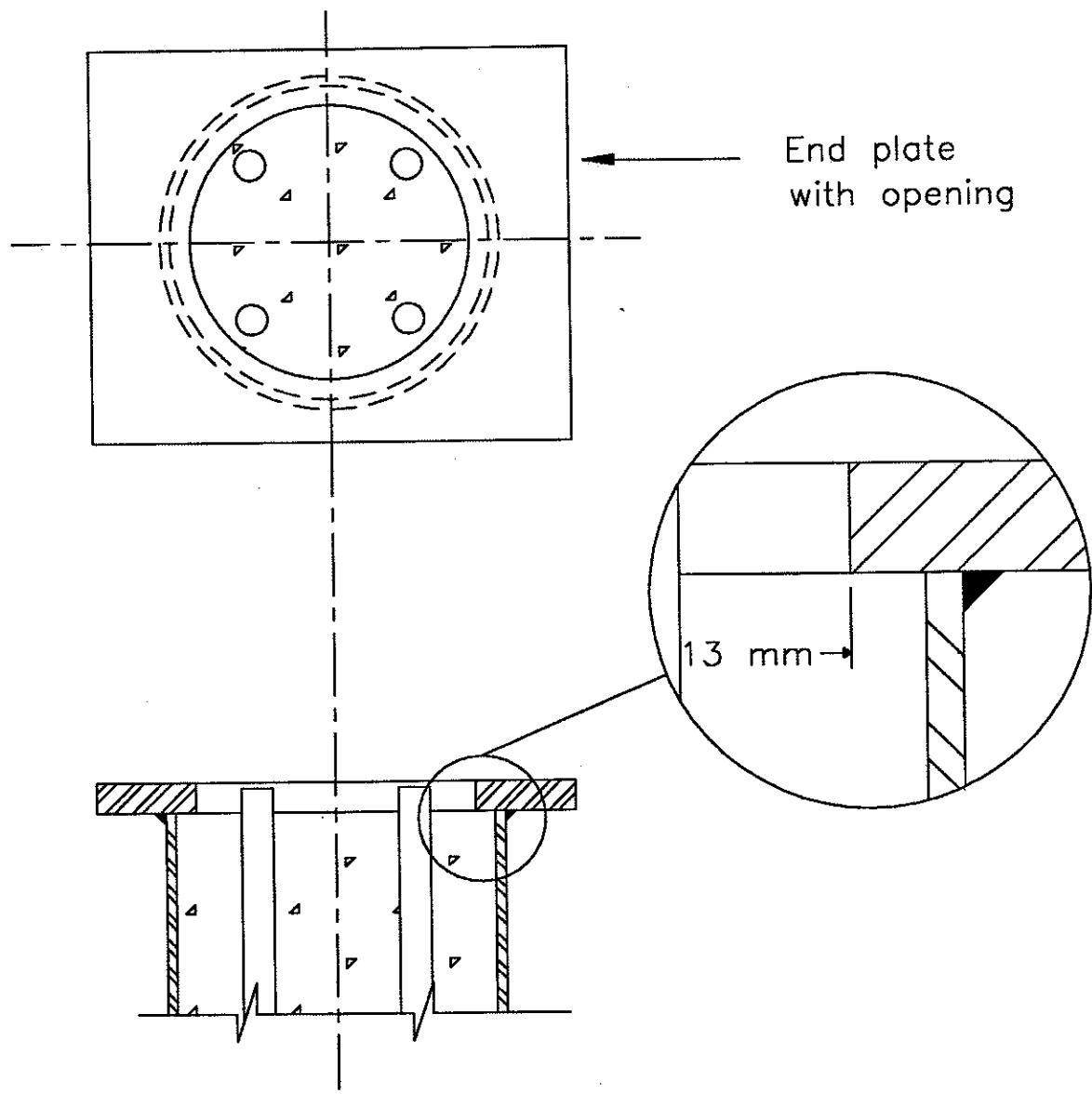


Figure 2. End plate connection details for circular columns

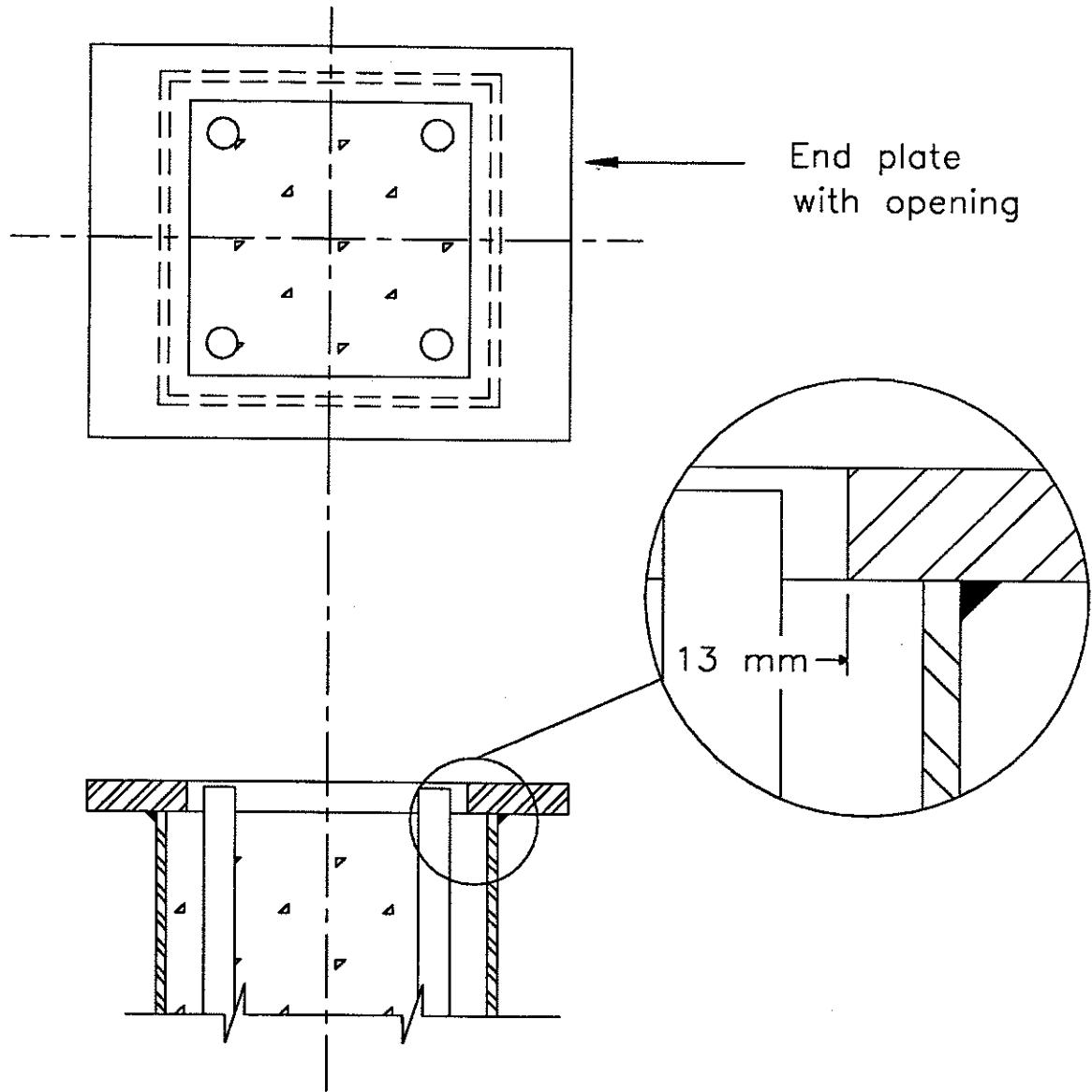


Figure 3. End plate connection details for square columns

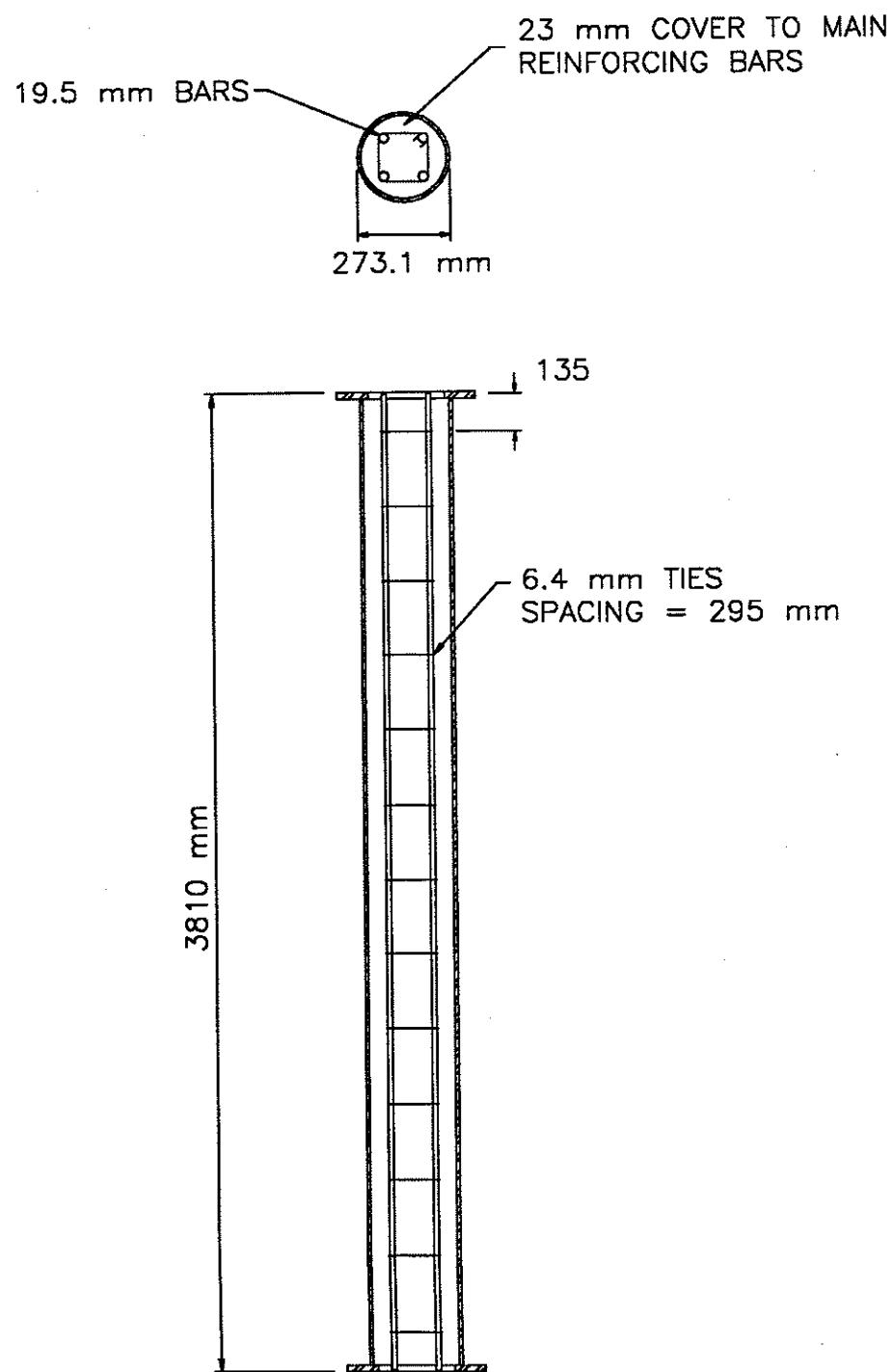


Figure 4. Elevation and cross-section of Column Nos. C-48 and C-49

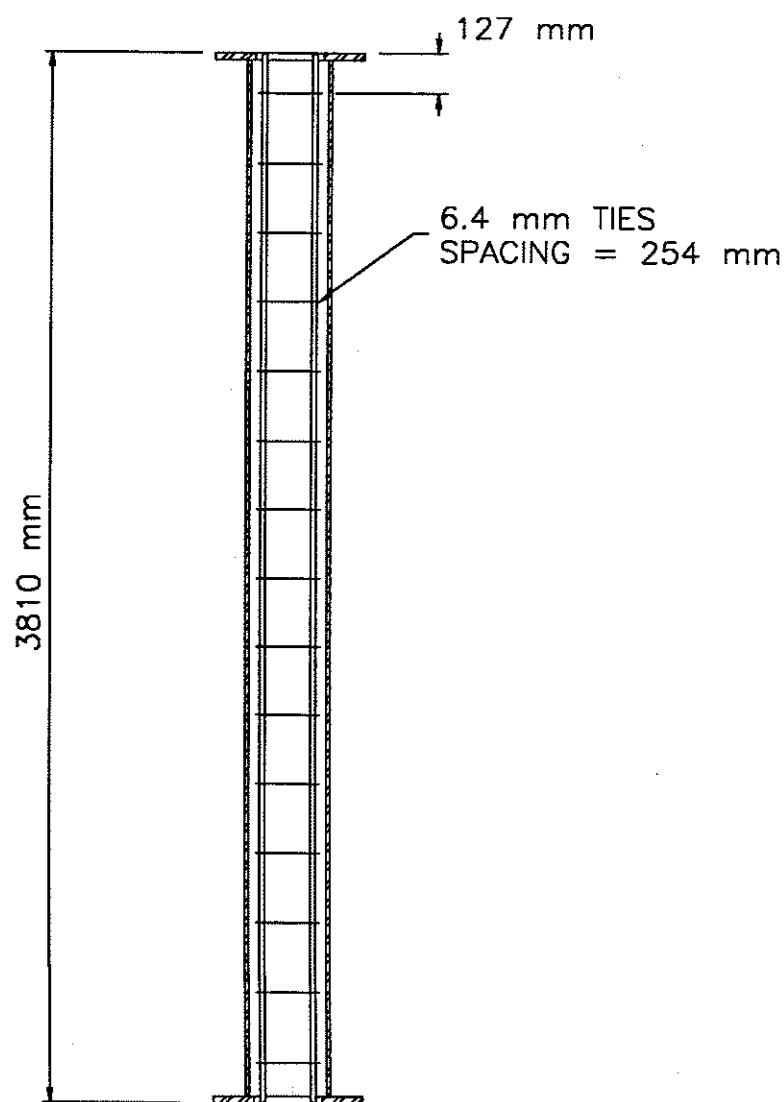
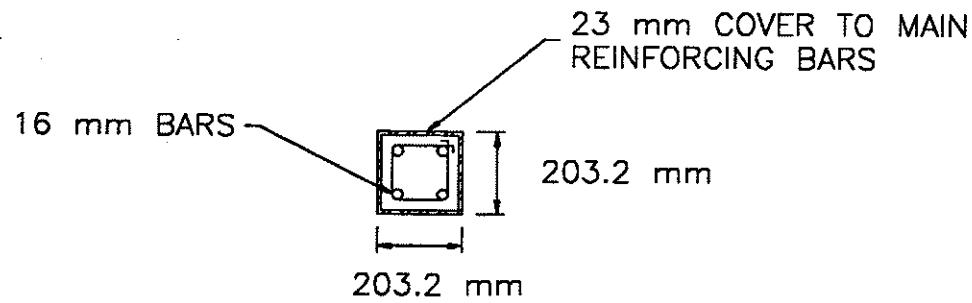


Figure 5. Elevation and cross-section of Column Nos. SQ-12 and SQ-13

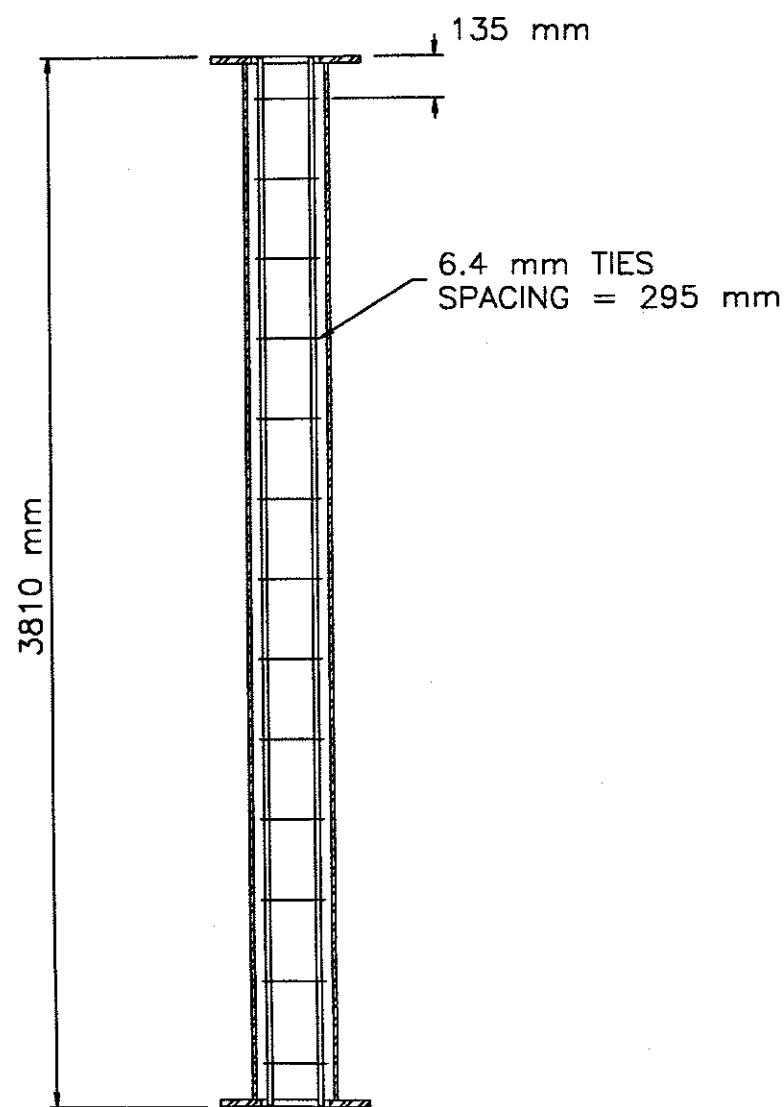
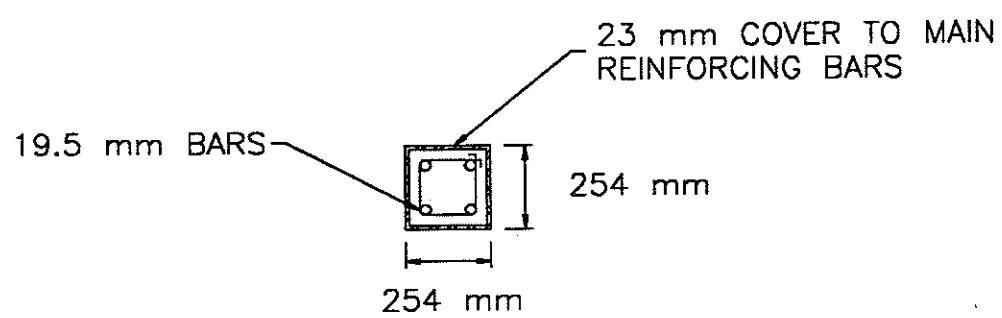


Figure 6. Elevation and cross-section of Column Nos. SQ-18 and SQ-19

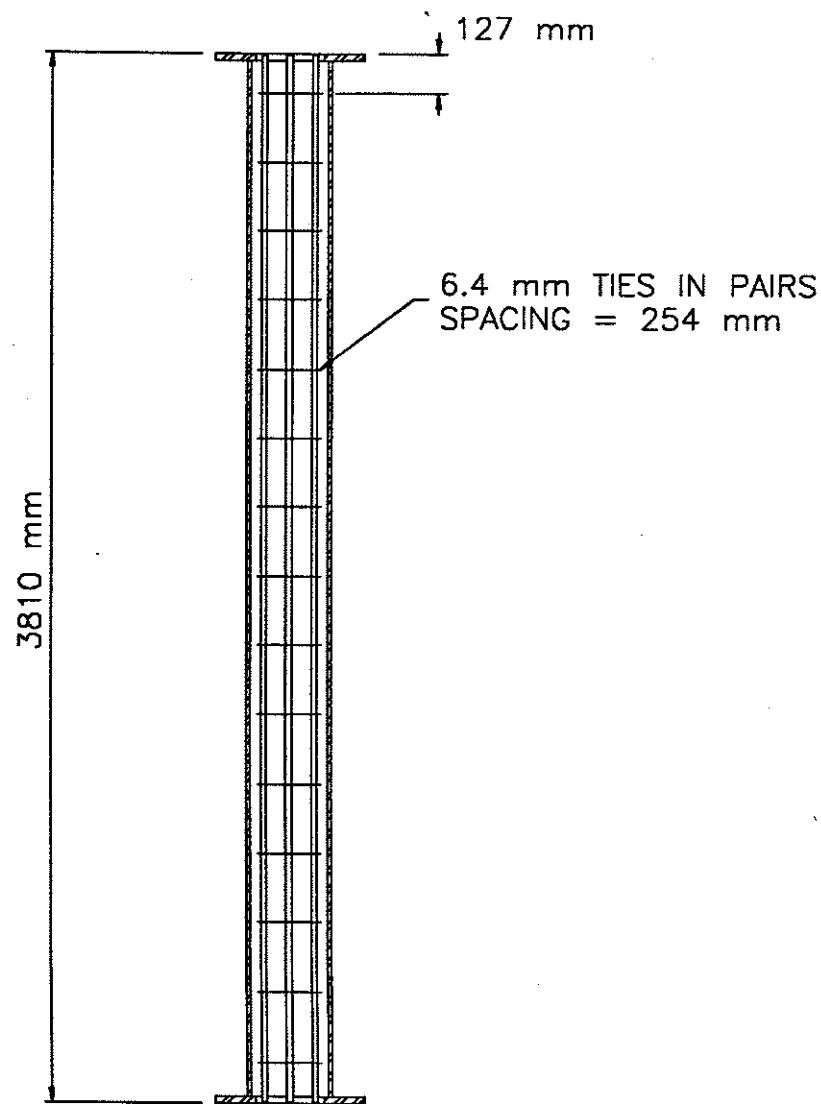
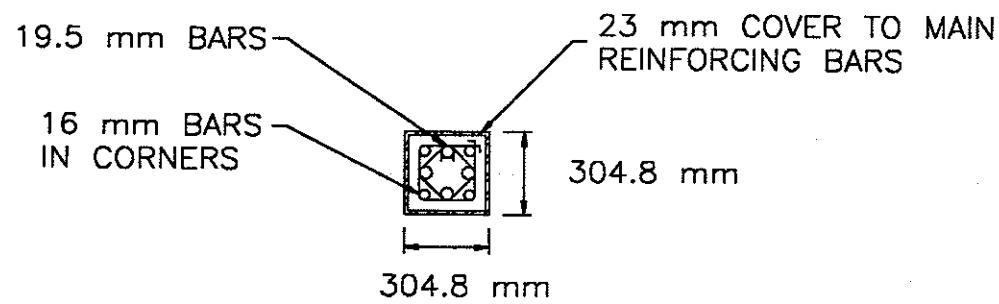


Figure 7. Elevation and cross-section of Column No. SQ-22

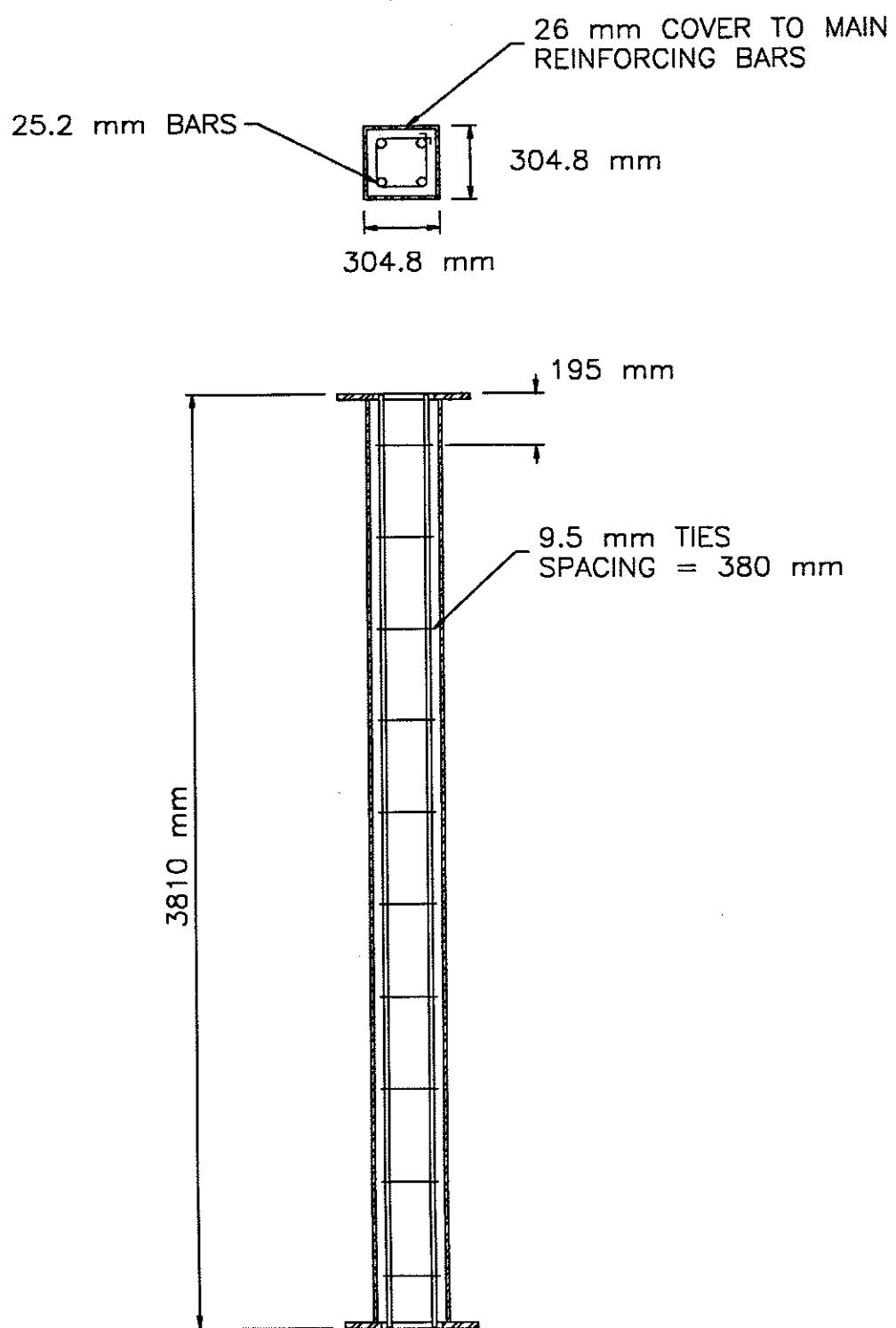


Figure 8. Elevation and cross-section of Column No. SQ-23

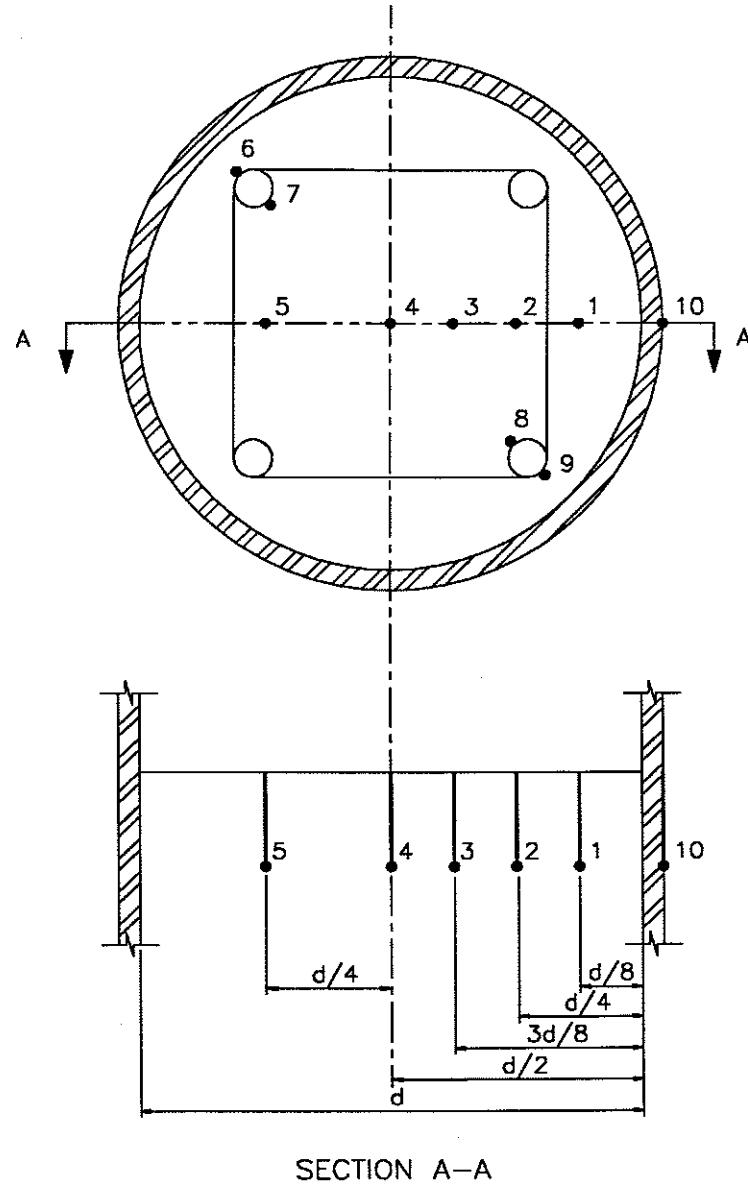
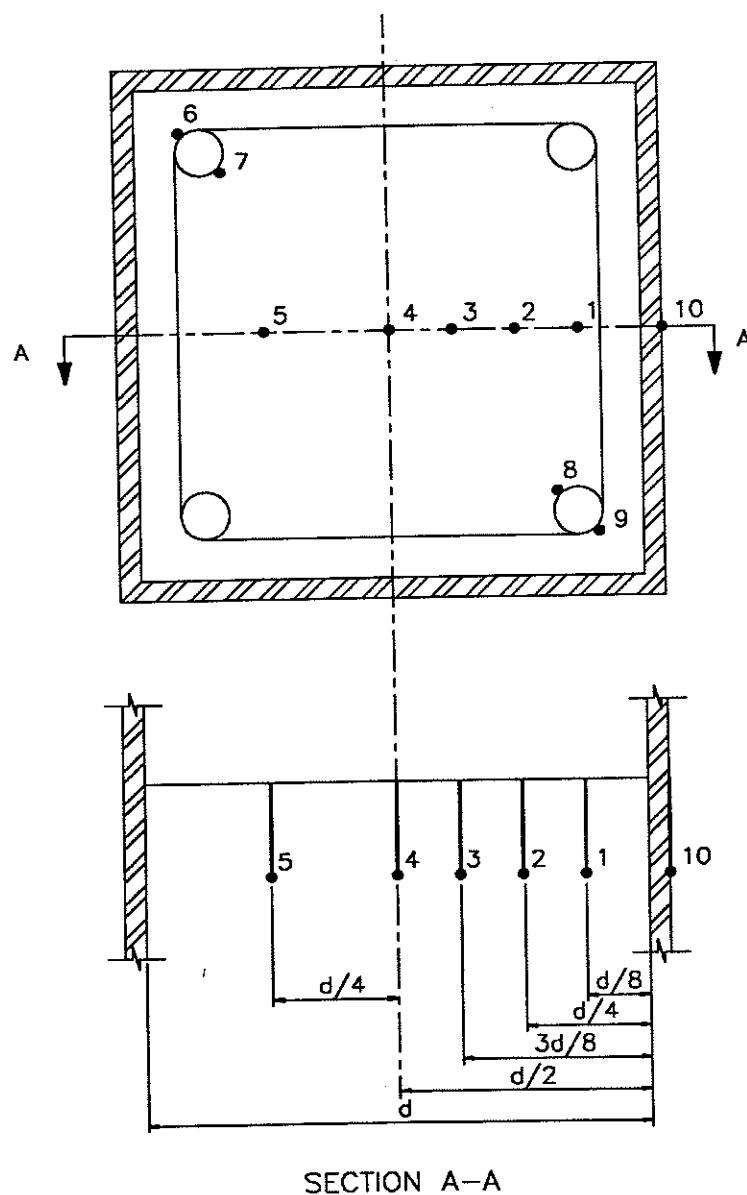
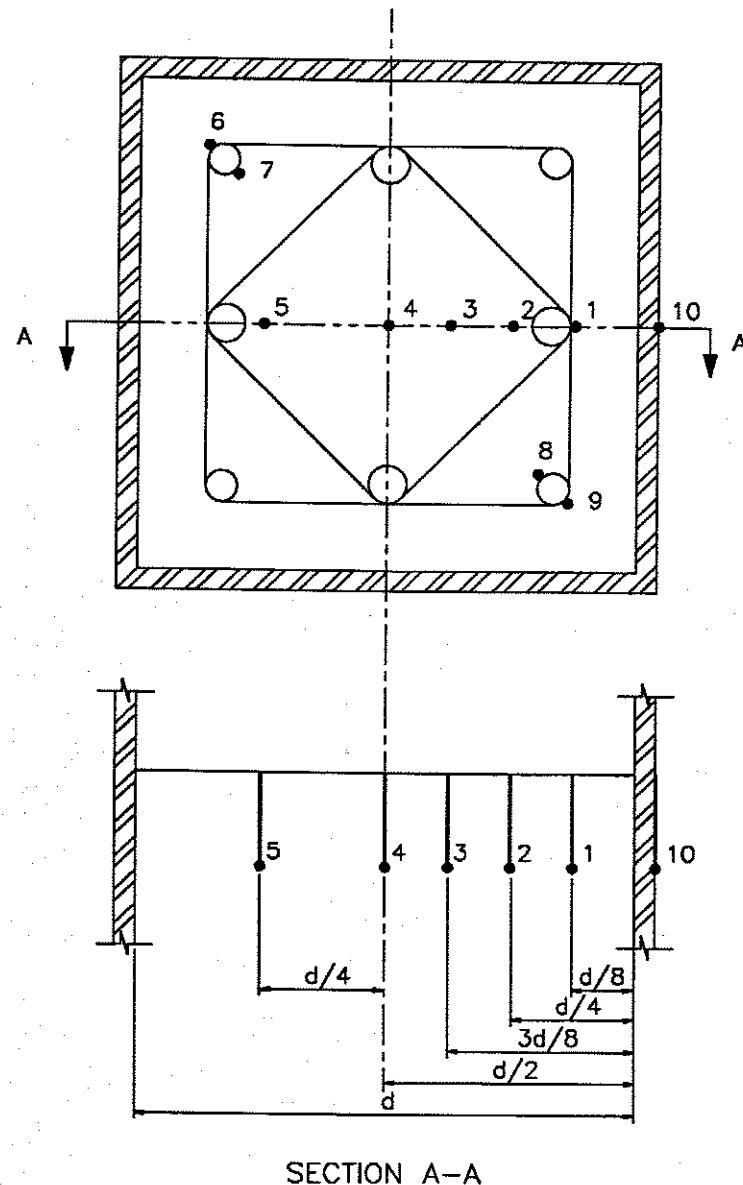


Figure 9. Locations of thermocouples in Column Nos. C-48 and C-49



SECTION A-A

Figure 10. Locations of thermocouples in Column Nos. SQ-12, SQ-13, SQ-18, SQ-19 and SQ-23



SECTION A-A

Figure 11. Locations of thermocouples in Column No. SQ-22

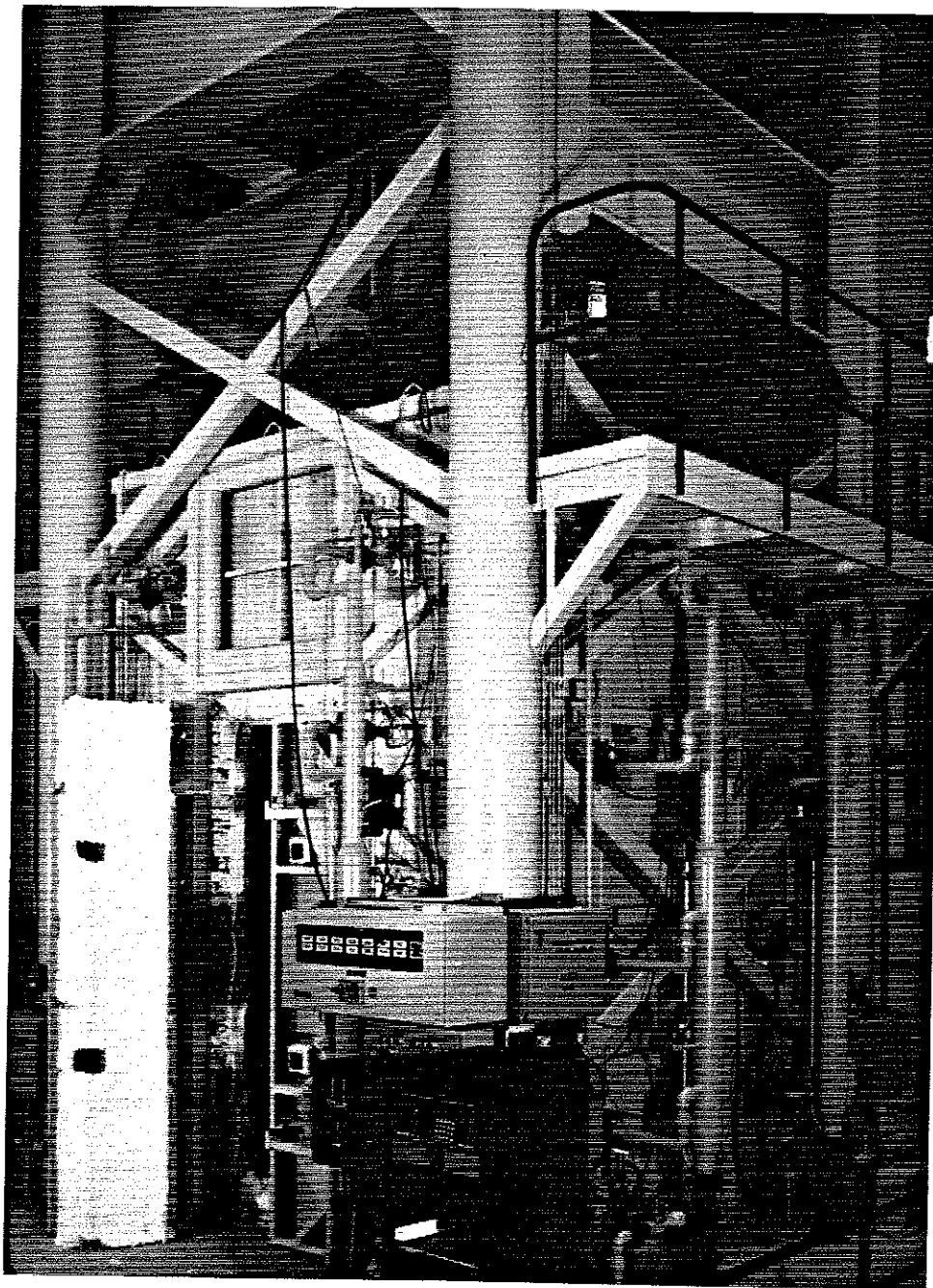
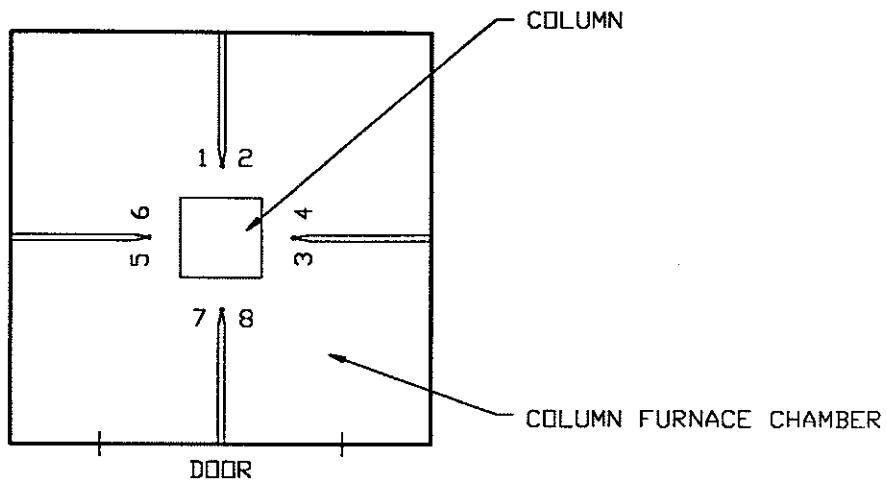


Figure 12. Column test furnace

TOP VIEW



FRONT VIEW

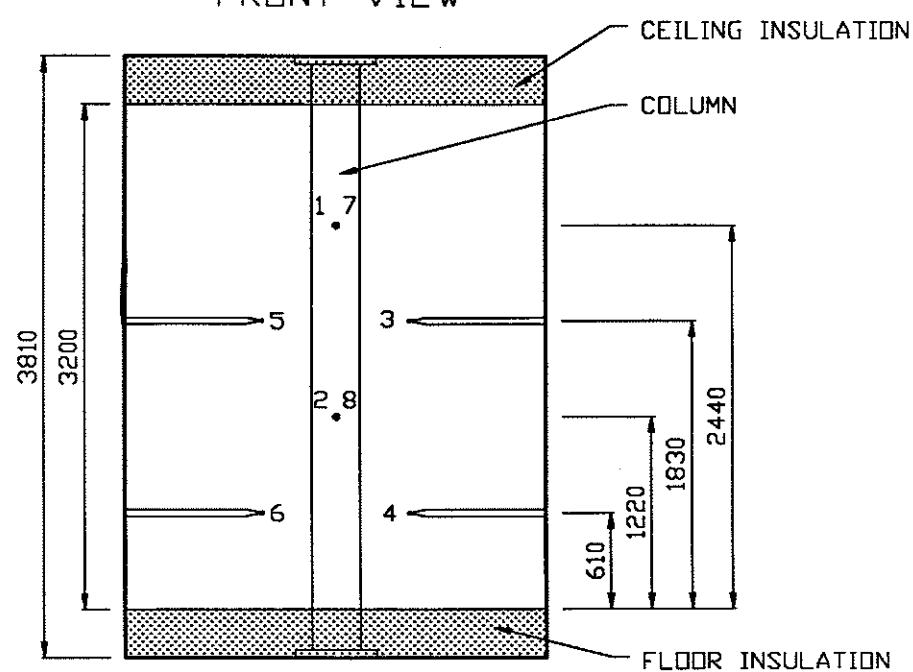


Figure 13. Locations of thermocouples in furnace chamber

APPENDIX A

TEMPERATURES AND AXIAL DEFORMATIONS OF COLUMN SPECIMENS

Table A1. Temperatures and axial deformation of Column No. C48

Time (min)	Std. furn. temp. (°C)	Avg. furn. temp. (°C)	Column temperature (°C) measured at Thermocouple No.										Axial Def. (mm)
			1	2	3	4	5	6	7	8	9	10	
0	20	47	21	21	21	21	22	21	21	22	22	26	0.00
2		443	21	21	21	21	22	22	21	22	22	123	0.55
4		554	22	21	21	21	22	25	22	22	23	187	1.77
6		612	23	21	21	21	23	30	25	23	25	268	4.78
8		646	26	22	21	21	26	38	29	24	29	338	7.62
10		677	29	22	21	21	30	45	34	27	34	396	10.07
12		699	34	24	22	22	36	55	41	30	40	444	11.90
14		724	39	25	22	22	43	67	48	35	48	484	12.70
16		749	46	28	23	22	51	79	58	41	57	515	12.68
18		765	56	31	24	23	62	93	68	49	70	554	4.57
20	795	780	78	35	25	24	71	108	79	58	84	585	3.28
22		796	106	40	27	25	80	115	91	71	95	610	2.70
24		807	108	50	30	27	88	130	103	86	108	629	2.28
26		816	110	59	33	30	95	145	112	105	116	649	2.11
28		830	114	67	38	33	104	156	119	110	123	670	1.95
30		838	118	74	42	37	113	166	123	113	131	690	1.78
40		878	144	101	69	64	143	232	155	131	171	752	0.87
50		905	900	187	117	92	85	171	297	207	159	222	813
60	927	925	240	136	113	101	213	356	260	201	274	858	0.20
70	946	940	290	155	126	116	261	408	308	244	322	887	-0.12
80	963	957	335	182	140	131	307	454	350	286	365	911	-0.65
90	978	974	377	215	155	147	349	495	388	325	403	930	-1.37
100	991	984	415	251	176	162	386	531	423	360	438	945	-2.26
110	1001	996	449	287	206	178	418	563	455	392	469	958	-3.22
120	1010	1007	481	319	237	198	448	593	485	420	497	974	-4.48
130	1017	1016	509	350	268	229	476	620	515	448	523	987	-5.90
140	1024	1026	536	380	300	268	504	645	542	476	550	999	-7.66
150	1031	1038	563	410	331	303	531	668	570	504	577	***	-10.07
160	1038	1048	590	440	362	334	559	690	596	532	602	***	-13.44
170	1045	1056	617	470	392	365	588	710	622	559	626	***	-18.17
180	1052	1062	640	498	421	394	615	728	641	585	647	***	-25.01
188		1068	658	520	445	417	634	739	659	603	663	***	-39.88

*** Measurements not reliable

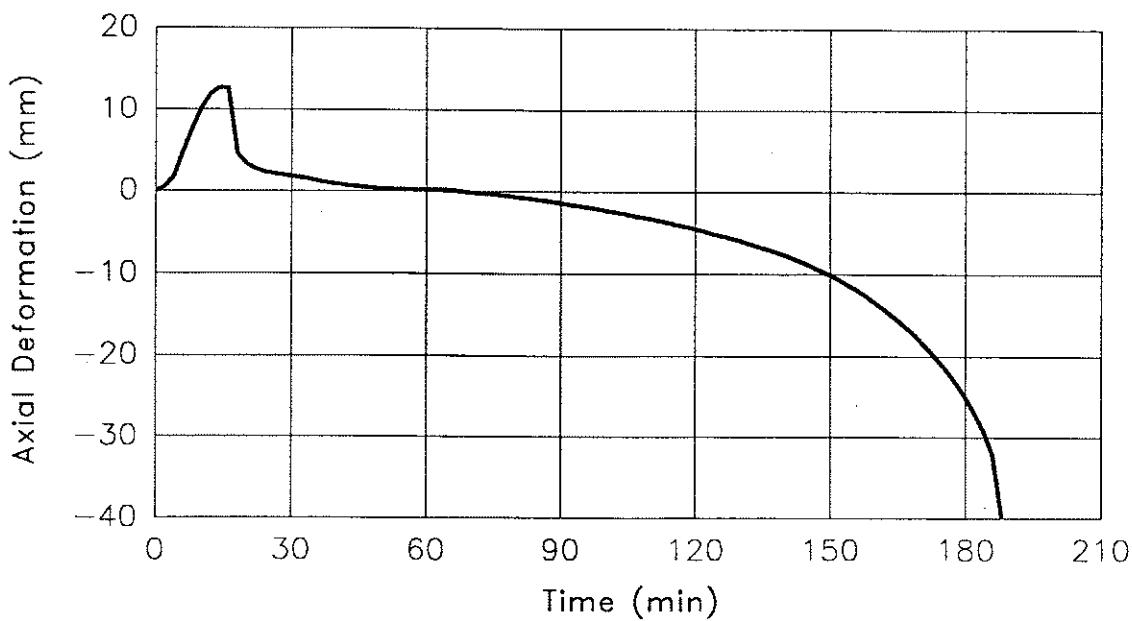
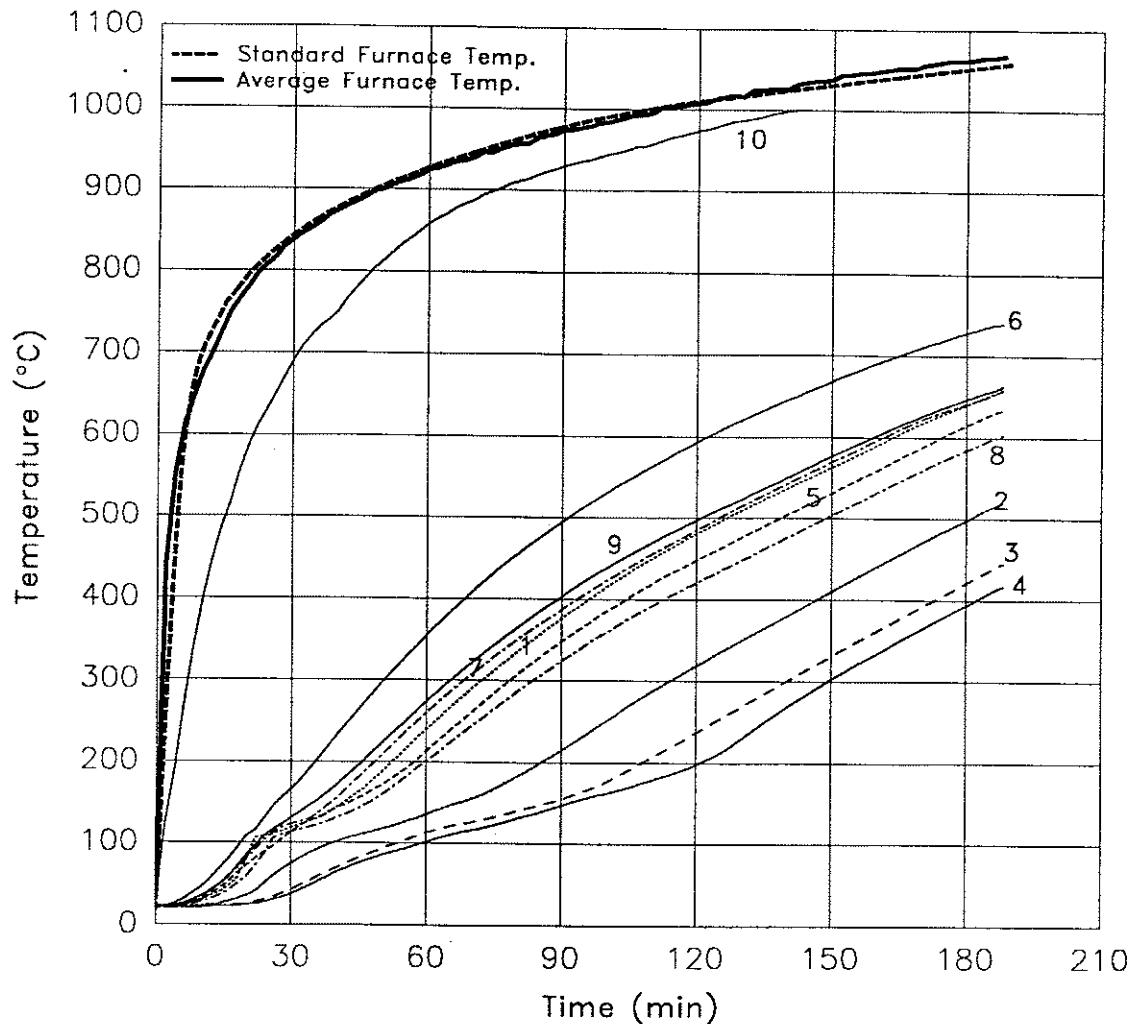


Figure A1. Temperatures and axial deformation of Column No. C-48

Table A2. Temperatures and axial deformation of Column No. C49

Time (min)	Std. furn. temp. (°C)	Avg. furn. temp. (°C)	Column temperature (°C) measured at Thermocouple No.										Axial Def. (mm)
			1	2	3	4	5	6	7	8	9	10	
0	20	48	20	20	20	20	20	20	20	20	20	26	0.00
2		150	20	20	20	20	20	20	20	20	20	49	0.00
4		582	21	20	20	20	20	20	20	21	21	179	0.82
6		628	23	21	20	20	20	21	21	22	22	244	1.24
8		638	28	23	20	20	20	24	22	25	26	301	1.36
10		677	37	27	21	20	21	28	25	30	32	372	1.36
12		697	46	33	22	20	22	34	29	37	39	431	1.36
14		722	54	39	24	21	23	40	34	46	49	475	1.16
16		748	62	46	26	21	26	46	40	55	59	514	0.64
18		767	70	53	29	22	29	53	46	65	70	546	0.29
20	795	779	79	59	32	24	32	60	51	76	82	568	-0.02
22		794	88	65	37	26	36	68	58	88	96	576	-0.27
24		803	97	72	42	29	41	76	67	102	110	610	-0.49
26		815	107	80	46	31	46	85	76	118	123	635	-0.69
28		826	116	87	51	35	52	94	84	126	130	657	-0.88
30		835	125	95	56	38	60	104	93	132	137	677	-1.09
32		843	133	102	60	42	68	119	114	137	144	694	-1.29
34		852	141	109	64	48	77	125	120	145	153	710	-1.53
36		859	143	116	68	55	86	126	119	152	162	726	-1.81
38		870	150	126	76	62	98	132	119	160	172	740	-2.12
40	878	878	156	129	84	71	107	138	121	169	181	754	-2.46
42		884	162	131	90	80	113	143	126	178	191	765	-2.85
44		887	168	132	94	87	117	149	130	188	202	775	-3.24
46		888	175	132	102	94	120	156	135	199	213	784	-3.63
48		893	182	134	109	100	121	163	141	210	225	794	-4.02
50		895	189	136	111	106	120	171	146	220	237	802	-4.42
52		905	197	139	113	110	120	180	153	231	249	812	-4.82
54		912	205	143	114	114	122	189	162	242	260	823	-5.25
56		914	214	150	114	116	125	199	171	253	271	832	-5.69
58		917	223	157	114	120	129	209	180	264	283	839	-6.14
60	927	920	233	164	114	123	132	219	189	274	294	846	-6.62
62		923	243	171	116	121	137	229	198	285	305	852	-7.11
64		925	254	179	118	118	141	239	207	295	315	857	-7.61
66		932	265	187	120	117	146	249	216	305	326	864	-8.12
68		937	276	195	122	115	151	259	224	315	336	872	-8.67
70		939	287	204	124	114	156	269	233	325	346	877	-9.22
72		942	298	213	126	113	162	278	242	334	356	882	-9.78
74		945	309	222	128	114	167	288	250	343	365	888	-10.38
76		949	320	232	131	115	173	296	258	352	375	893	-11.01
78		952	331	242	134	117	179	305	266	361	384	899	-11.72
80	963	952	342	252	138	118	185	313	274	370	393	902	-12.53
82		956	353	262	142	120	191	322	281	378	402	906	-13.36
84		959	364	272	147	122	197	330	289	387	410	911	-14.31
86		962	375	281	152	125	203	338	296	395	419	915	-15.35
88		966	386	291	157	128	209	345	303	403	428	918	-16.49
90		968	396	300	163	131	215	353	310	411	436	922	-17.77
92		970	407	309	170	135	221	360	317	419	444	924	-19.25
94		971	418	318	177	139	228	368	324	427	452	926	-21.09
96		974	428	326	184	144	234	375	331	434	459	929	-26.08

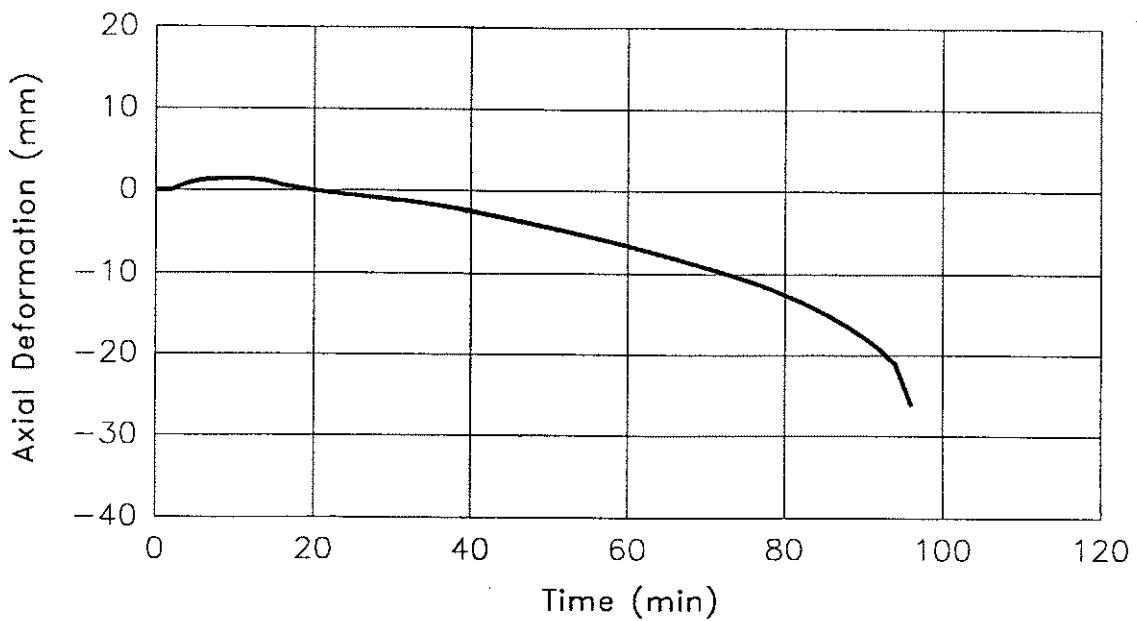
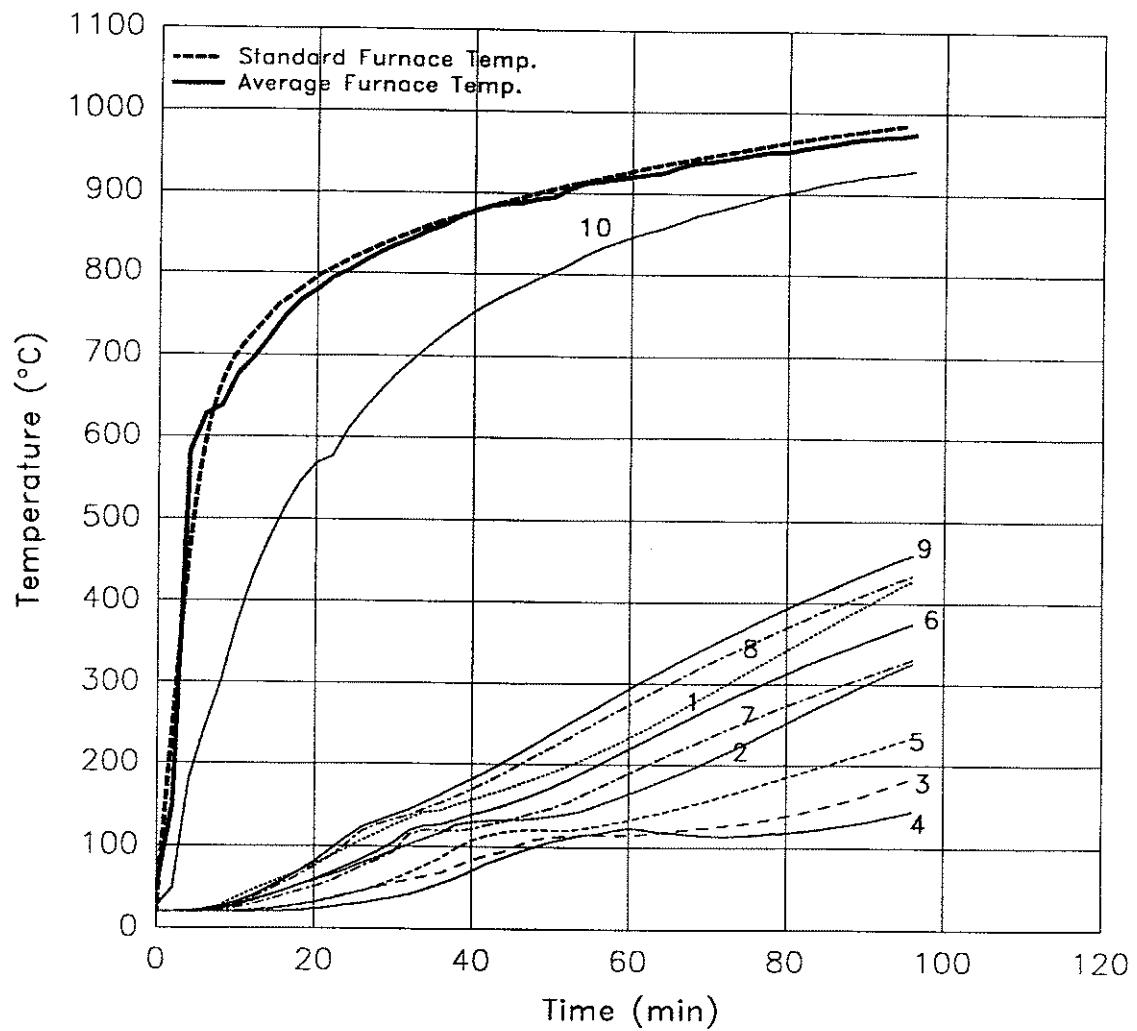


Figure A2. Temperatures and axial deformation of Column No. C-49

Table A3. Temperatures and axial deformation of Column No. SQ12

Time (min)	Std. furn. temp. (°C)	Avg. furn. temp. (°C)	Column temperature (°C) measured at Thermocouple No.										Axial Def. (mm)	
			1	2	3	4	5	6	7	8	9	10		
0	20	48	***	***	18	18	***	17	17	***	***	25	0.00	
2		451	***	***	18	18	***	18	17	***	***	172	0.92	
4		533	***	***	18	18	***	24	19	***	***	190	3.63	
6		640	***	***	18	18	***	33	22	***	***	279	6.76	
8		681	***	***	18	18	***	44	27	***	***	319	9.79	
10		704	***	***	19	18	***	60	25	***	***	358	12.37	
12		707	***	***	20	19	***	79	26	***	***	394	14.46	
14		721	***	***	23	21	***	100	57	***	***	427	16.22	
16		736	***	***	41	25	***	119	76	***	***	467	17.64	
18		754	***	***	59	29	***	139	106	***	***	510	18.60	
20	795	787	***	***	65	38	***	151	114	***	***	565	19.00	
22		782	***	***	70	52	***	162	121	***	***	597	19.08	
24		809	***	***	64	67	***	175	128	***	***	627	19.08	
26		802	***	***	74	75	***	190	134	***	***	638	19.08	
28		830	***	***	92	80	***	209	140	***	***	669	18.19	
30	843	824	***	***	94	86	***	228	147	***	***	683	14.14	
32		837	***	***	96	92	***	246	157	***	***	701	8.15	
34		858	***	***	103	97	***	263	170	***	***	728	7.15	
36		849	***	***	109	103	***	281	183	***	***	741	6.43	
38		869	***	***	115	109	***	298	196	***	***	756	5.93	
40		878	854	***	***	122	117	***	314	210	***	***	754	5.46
50		905	888	***	***	148	143	***	389	274	***	***	816	4.61
60		927	909	***	***	162	151	***	456	336	***	***	852	4.34
70		946	941	***	***	188	172	***	512	391	***	***	885	3.77
80		963	949	***	***	227	207	***	559	440	***	***	904	2.67
90		978	969	***	***	277	255	***	602	485	***	***	923	1.24
100		991	987	***	***	325	304	***	639	524	***	***	944	-0.80
110		1001	990	***	***	370	349	***	671	561	***	***	954	-3.48
120		1010	993	***	***	412	391	***	701	598	***	***	969	-7.20
130		1017	1014	***	***	451	431	***	726	633	***	***	982	-12.18
140		1024	1027	***	***	488	468	***	747	665	***	***	998	-19.46
150		1031	1029	***	***	521	515	***	***	692	***	***	1007	-35.71

*** Measurements not reliable

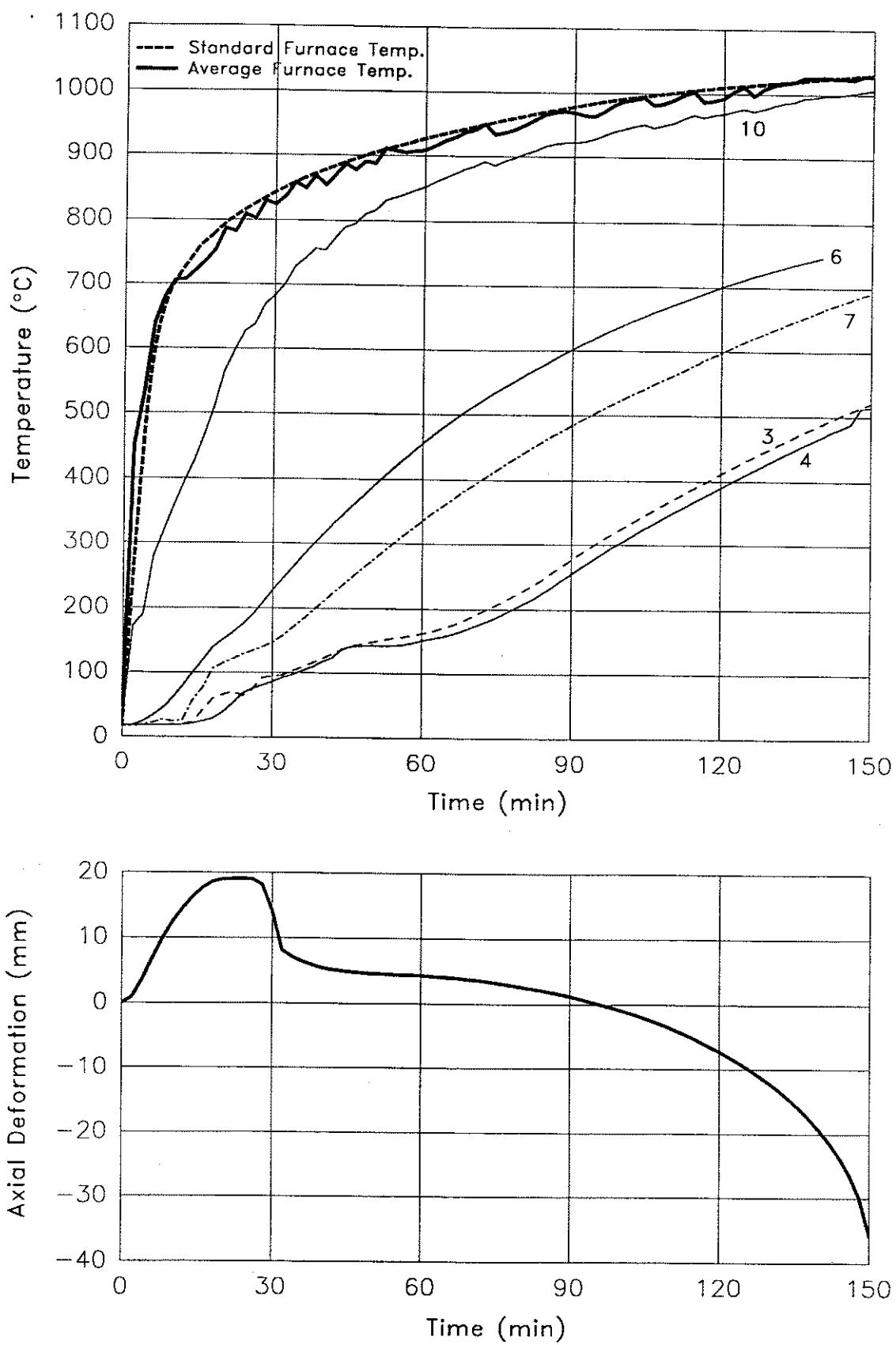


Figure A3. Temperatures and axial deformation of Column No. SQ-12

Table A4. Temperatures and axial deformation of Column No. SQ13

Time (min)	Std. furn. temp. (°C)	Avg. furn. temp. (°C)	Column temperature (°C) measured at Thermocouple No.										Axial Def. (mm)
			1	2	3	4	5	6	7	8	9	10	
0	20	72	27	***	23	23	27	29	27	26	29	37	0.00
2		251	28	***	23	23	28	30	28	28	30	57	0.05
4		607	29	***	23	23	29	33	30	29	33	138	2.78
6		521	34	***	24	23	34	42	35	31	41	178	5.30
8		680	42	***	24	24	42	55	43	37	***	285	8.89
10		704	688	30	***	25	28	51	68	53	45	***	362
12		689	34	***	27	32	62	81	63	54	***	420	13.42
14		737	37	***	28	35	76	98	76	68	***	473	14.73
16		748	39	***	31	37	90	116	90	85	***	515	14.98
18		771	42	***	34	31	104	134	107	112	***	556	14.58
20	795	780	43	***	42	35	115	149	125	130	***	589	8.20
22		798	140	***	48	39	128	163	140	139	165	623	4.47
24		806	154	***	57	45	139	171	154	148	174	646	3.52
26		815	164	***	67	52	149	185	163	155	183	664	2.98
28		825	172	***	77	60	156	202	169	160	199	681	2.61
30		834	170	***	89	68	161	224	177	163	216	697	2.29
32		839	176	***	99	77	166	245	190	166	233	710	1.94
34		827	185	***	105	86	171	265	202	176	251	717	1.53
36	843	848	201	***	111	97	179	285	216	191	271	727	1.18
38		860	217	***	116	112	187	304	232	208	289	739	0.68
40		873	230	***	129	122	196	322	247	225	307	747	0.10
42		885	242	***	134	128	207	339	262	242	324	760	-0.45
44		886	254	***	135	131	219	356	277	257	340	775	-0.91
46		889	267	***	134	133	232	372	292	272	356	786	-1.31
48		894	281	***	134	134	245	388	306	286	371	797	-1.69
50	905	900	294	***	134	135	259	404	319	299	386	807	-2.04
52		904	307	***	136	136	272	419	333	312	401	817	-2.38
54		909	320	***	139	139	284	434	346	325	415	826	-2.71
56		913	333	***	142	142	297	448	358	337	429	835	-3.03
58		916	346	***	145	145	309	462	371	349	442	843	-3.36
60		921	359	***	149	148	320	476	383	360	455	849	-3.71
62	927	926	371	***	153	151	331	489	395	372	468	857	-4.07
64		930	383	***	157	153	342	501	406	382	480	864	-4.47
66		931	394	***	161	156	352	513	417	393	491	869	-4.92
68		936	406	***	166	159	363	524	429	403	502	875	-5.39
70		939	417	***	170	162	373	535	439	414	513	881	-5.90
72		944	428	***	174	165	383	545	450	423	523	887	-6.43
74		943	439	***	179	169	393	555	460	433	532	891	-7.02
76		950	449	***	183	173	403	566	470	442	542	896	-7.62
78	946	952	459	***	190	177	413	576	479	451	551	901	-8.27
80		954	469	***	196	181	423	586	489	460	560	905	-8.95
82		957	478	***	204	187	433	595	498	469	570	909	-9.68
84		960	487	***	212	194	443	604	507	478	579	913	-10.43
86		963	496	***	221	202	452	613	516	486	588	918	-11.22
88		963	505	***	231	211	461	622	524	494	597	923	-12.07
90	978	971	513	***	242	222	470	630	532	502	605	927	-12.99
92		973	521	***	252	234	479	638	541	510	613	930	-14.00
94		968	529	***	263	245	488	646	549	518	621	934	-15.07
96		976	537	***	273	256	497	654	557	526	629	938	-16.23
98		980	545	***	283	267	505	662	566	533	637	940	-17.54
100		991	982	552	***	292	277	514	670	574	541	644	942
102	981	981	560	***	302	287	522	677	583	549	651	944	-20.53
104		981	568	***	311	296	530	683	591	556	658	944	-22.47

*** Measurements not reliable

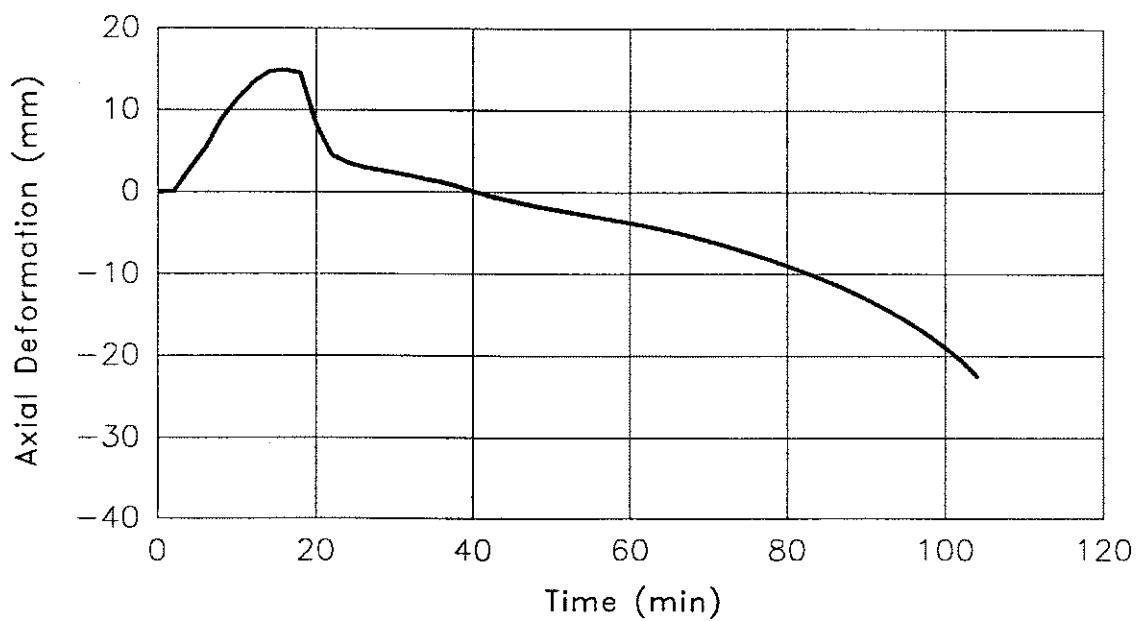
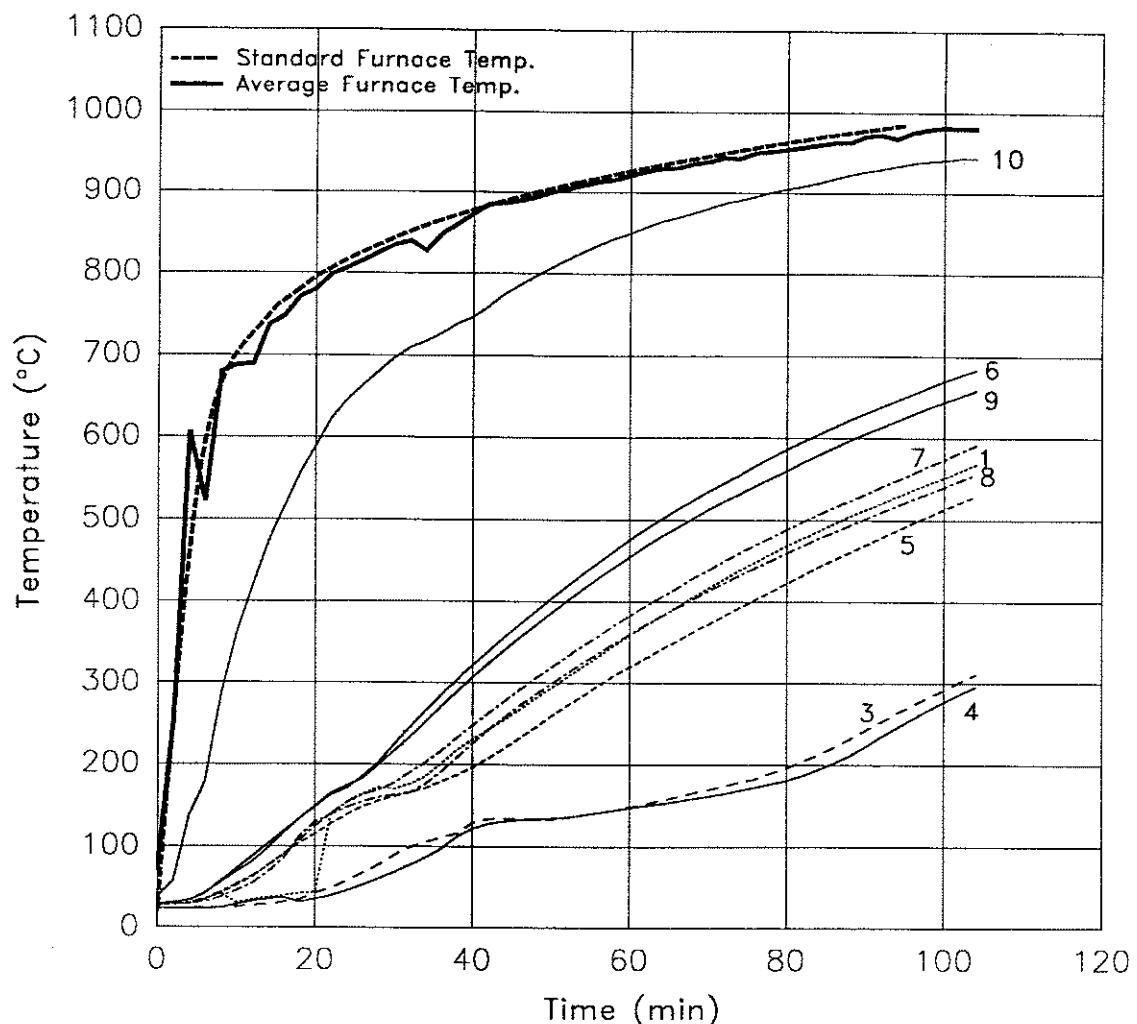


Figure A4. Temperatures and axial deformation of Column No. SQ-13

Table A5. Temperatures and axial deformation of Column No. SQ18

Time (min)	Std. furn. temp. (°C)	Avg. furn. temp. (°C)	Column temperature (°C) measured at Thermocouple No.										Axial Def. (mm)
			1	2	3	4	5	6	7	8	9	10	
0	20	44	***	16	15	15	***	16	16	16	16	18	0.00
2		459	***	16	15	15	***	17	16	16	16	84	0.70
4		572	***	16	15	15	***	21	17	16	18	144	2.69
6		634	***	16	15	15	***	31	20	18	24	210	5.72
8		669	***	17	15	15	***	45	26	20	31	274	8.67
10		704	***	18	16	15	***	60	33	24	38	335	11.31
12		745	***	21	16	16	***	75	44	28	47	396	12.67
14		749	***	24	16	16	***	95	57	34	57	458	12.82
16		788	***	27	17	16	***	113	72	41	69	465	2.92
18		806	***	32	19	16	***	129	86	51	83	495	1.94
20	795	821	***	37	20	17	***	146	100	62	99	539	1.47
22		823	***	43	22	18	***	147	109	83	118	578	1.14
24		843	***	48	25	20	***	153	110	120	147	615	0.92
26		856	***	54	28	22	***	171	120	131	158	648	0.80
28		866	***	61	31	24	***	189	132	136	164	673	0.59
30		843	***	68	35	27	***	202	143	136	172	695	0.38
32		873	***	73	40	30	***	215	151	134	180	714	0.17
34		856	***	78	44	34	***	237	157	132	190	723	-0.04
36		885	***	84	48	38	***	257	162	133	202	737	-0.15
38		901	***	90	53	42	***	273	166	137	224	743	-0.35
40	878	911	***	97	58	46	***	288	171	142	240	761	-0.52
42		921	***	103	63	51	***	301	175	148	256	783	-0.67
44		928	***	110	69	56	***	315	181	154	271	801	-0.80
46		934	***	116	80	61	***	330	191	162	286	817	-0.93
48		937	***	123	93	68	***	346	203	170	300	830	-1.05
50		905	***	130	105	76	***	362	216	178	314	841	-1.14
52		948	***	135	111	83	***	379	229	186	328	852	-1.25
54		951	***	140	115	90	***	395	242	195	341	860	-1.39
56		957	***	144	118	97	***	411	255	204	354	868	-1.51
58		963	***	148	120	102	***	426	269	213	367	878	-1.67
60	927	968	***	152	120	108	***	441	282	223	379	887	-1.84
62		970	***	155	121	112	***	455	295	233	391	894	-2.00
64		972	***	158	122	114	***	468	308	243	403	898	-2.20
66		978	***	161	123	116	***	481	320	253	414	905	-2.41
68		981	***	164	125	118	***	493	332	264	425	910	-2.62
70		946	***	167	126	119	***	505	343	274	436	915	-2.83
72		989	***	169	127	121	***	516	355	285	446	920	-3.05
74		990	***	171	129	122	***	526	366	295	456	924	-3.31
76		994	***	173	131	123	***	536	377	305	466	928	-3.57
78		997	***	177	133	124	***	545	388	314	475	931	-3.87
80	963	1001	***	183	135	125	***	554	398	324	484	934	-4.19
82		1005	***	190	137	125	***	564	408	333	493	937	-4.48
84		1008	***	197	139	123	***	573	418	343	501	941	-4.81
86		1008	***	204	141	124	***	582	428	352	509	944	-5.17
88		1013	***	211	143	125	***	592	438	361	517	948	-5.54
90		978	***	219	146	127	***	600	447	369	525	953	-5.92
92		1017	***	227	149	128	***	609	456	378	533	955	-6.34
94		1021	***	235	153	130	***	616	465	386	540	960	-6.74
96		1026	***	243	156	131	***	624	473	395	548	964	-7.20
98		1026	***	250	160	133	***	630	482	403	555	967	-7.67
100	991	1028	***	258	165	135	***	637	490	411	563	970	-8.24
102		1030	***	265	169	138	***	644	498	419	570	974	-8.76
104		1033	***	272	174	141	***	650	505	427	578	978	-9.34
106		1035	***	279	179	144	***	655	512	435	585	981	-9.97
108		1038	***	286	184	148	***	660	519	442	591	985	-10.71
110		1001	***	293	190	152	***	665	525	450	598	988	-11.54
112		1042	***	299	196	157	***	669	532	457	605	990	-12.81

*** Measurements not reliable

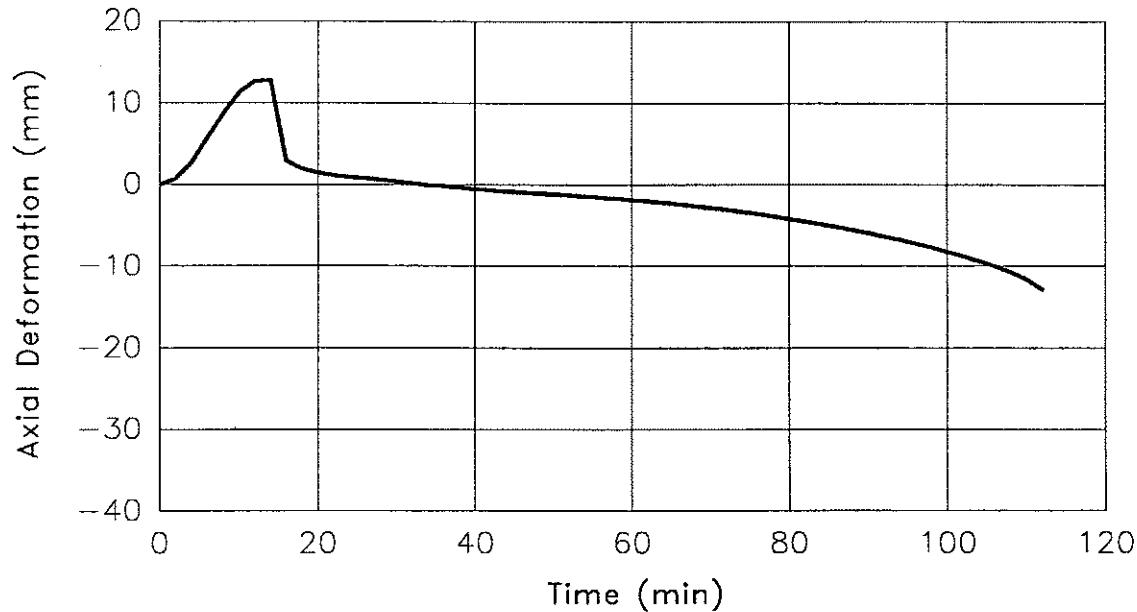
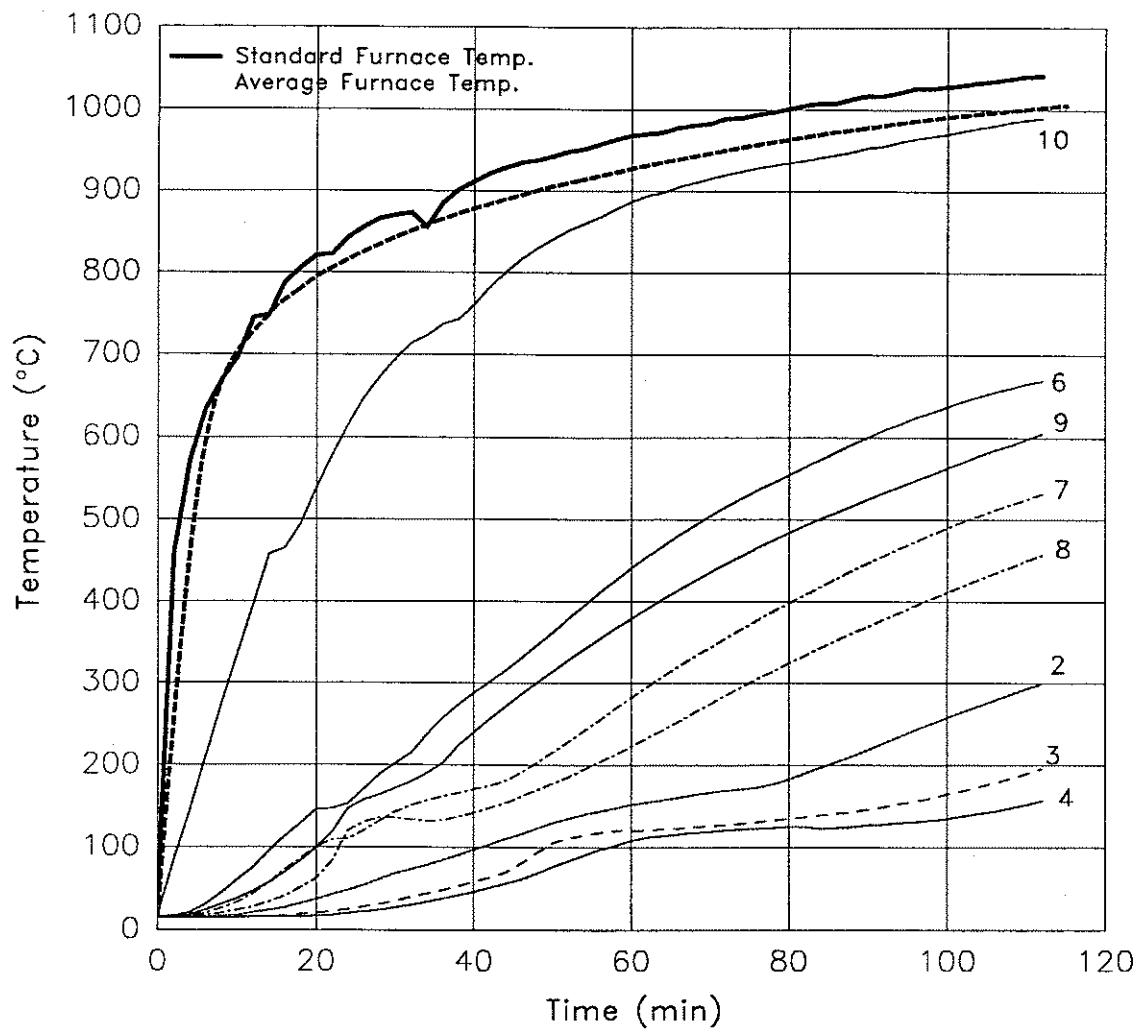


Figure A5. Temperatures and axial deformation of Column No. SQ-18

Table A6. Temperatures and axial deformation of Column No. SQ19

Time (min)	Std. furn. temp. (°C)	Avg. furn. temp. (°C)	Column temperature (°C) measured at Thermocouple No.										Axial Def. (mm)
			1	2	3	4	5	6	7	8	9	10	
0	20	48	11	11	11	10	11	11	11	***	11	15	0.00
2		454	11	11	10	10	11	11	11	***	11	87	0.59
4		536	13	11	11	10	12	12	11	***	15	141	1.49
6		587	17	11	11	10	15	17	12	***	22	196	2.19
8		651	24	11	11	10	20	24	15	***	31	232	2.90
10		691	32	12	11	11	25	32	18	***	43	283	2.97
12		684	42	13	11	11	31	42	23	***	59	332	2.88
14		730	53	14	11	11	38	47	30	***	77	392	2.28
16		744	66	16	12	11	47	60	38	***	103	441	1.60
18		761	80	18	13	12	57	72	48	***	111	485	1.06
20	795	760	90	22	15	13	69	91	64	***	104	520	0.64
22		776	96	25	17	14	81	109	82	***	113	546	0.42
24		797	104	30	19	16	90	110	91	***	122	581	0.15
26		824	113	35	22	18	98	114	94	***	132	617	-0.17
28		832	123	40	26	21	107	128	97	***	143	645	-0.49
30		837	133	47	31	24	116	145	100	***	154	667	-0.80
32		843	143	57	42	27	125	159	106	***	166	685	-1.15
34		850	153	69	63	31	133	171	113	***	180	702	-1.57
36		861	163	85	100	38	143	183	118	***	195	720	-2.08
38		866	173	103	110	49	150	197	122	***	210	736	-2.64
40	878	870	181	111	110	81	156	213	128	***	224	740	-3.16
42		879	189	111	110	107	163	228	134	***	238	753	-3.68
44		885	200	111	110	109	173	242	142	***	251	772	-4.20
46		890	214	111	110	109	184	255	150	***	265	789	-4.70
48		895	227	112	111	110	194	268	158	***	279	802	-5.19
50		899	242	111	111	110	205	280	167	***	294	813	-5.68
52		902	255	111	111	110	214	292	176	***	308	823	-6.17
54		909	268	111	110	109	224	304	185	***	322	833	-6.66
56		912	280	113	110	109	233	315	195	***	336	840	-7.17
58		918	292	115	109	108	243	327	204	***	350	847	-7.70
60	927	920	304	118	109	108	252	338	214	***	363	854	-8.26
62		926	316	121	110	107	261	350	223	***	377	860	-8.84
64		930	328	124	110	107	270	361	233	***	390	867	-9.46
66		932	339	128	112	107	279	372	242	***	402	872	-10.13
68		935	350	132	113	107	288	383	252	***	415	877	-10.87
70		946	939	***	137	***	108	297	394	261	***	882	-12.88

*** Measurements not reliable

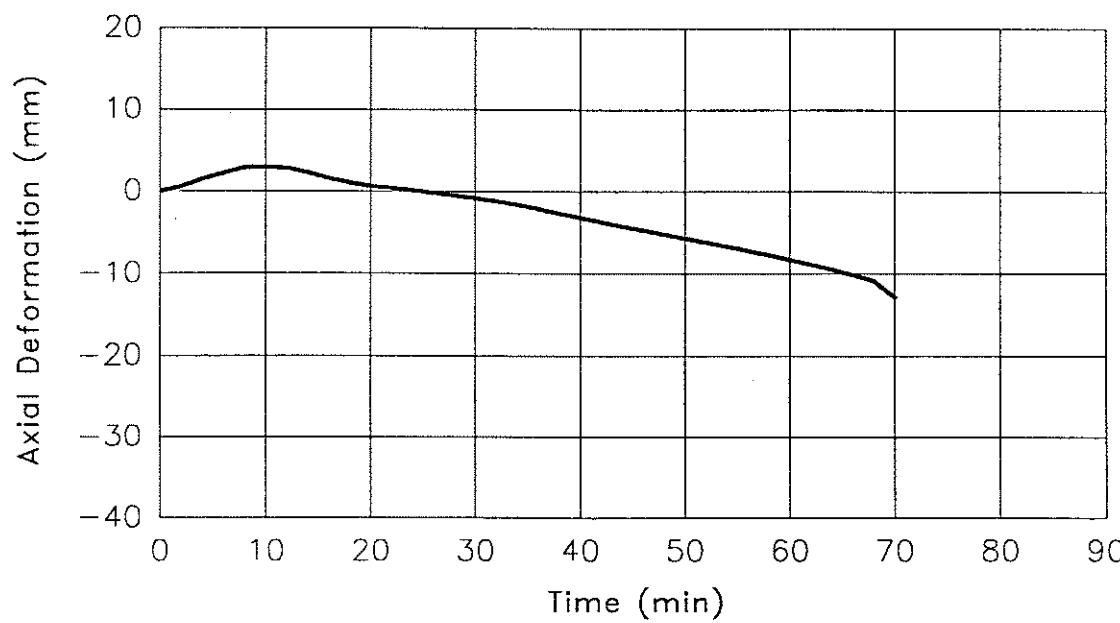
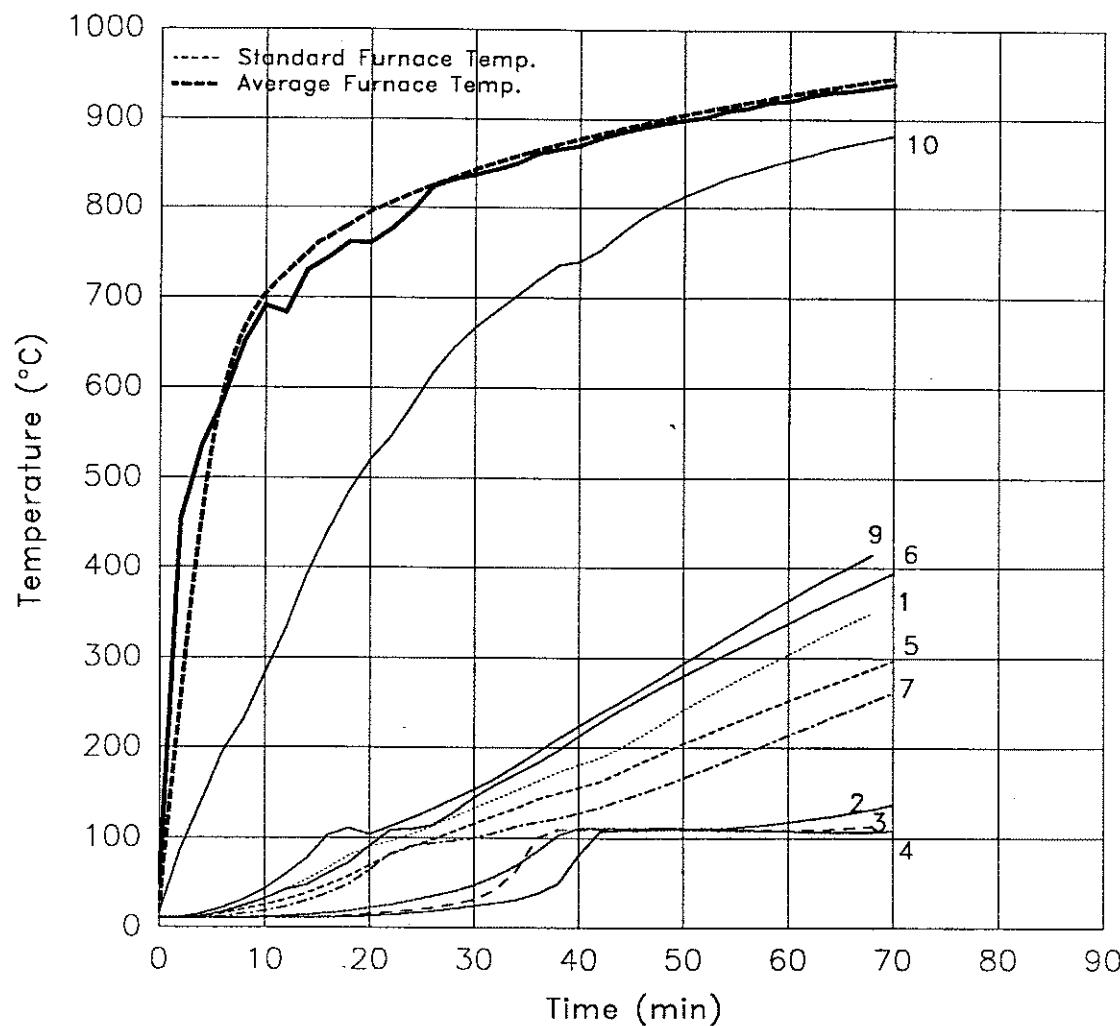


Figure A6. Temperatures and axial deformation of Column No. SQ-19

Table A7. Temperatures and axial deformation of Column No. SQ22

Time (min)	Std. furn. temp. (°C)	Avg. furn. temp. (°C)	Column temperature (°C) measured at Thermocouple No.										Axial Def. (mm)
			1	2	3	4	5	6	7	8	9	10	
0	20	48	15	15	15	15	15	15	15	15	15	19	0.00
2		224	15	15	15	15	15	15	15	15	15	44	0.00
4		532	16	15	15	15	15	16	15	17	19	116	0.50
6		649	18	15	15	15	15	19	16	21	25	221	0.90
8		666	22	16	15	15	15	15	25	18	27	36	290
10		704	27	17	15	15	16	33	22	38	50	356	0.74
12		700	33	19	15	15	17	43	27	50	66	407	0.34
14		717	39	21	15	15	18	54	36	65	83	450	-0.09
16		718	48	24	16	15	19	67	46	81	101	480	-0.41
18		748	58	28	16	15	21	82	57	100	119	516	-0.65
20	795	760	71	32	17	15	24	108	94	127	139	543	-0.92
22		783	90	37	17	15	27	124	100	141	156	575	-1.16
24		795	101	44	18	16	30	133	103	140	166	602	-1.42
26		805	111	51	20	16	34	141	104	146	176	625	-1.68
28		822	118	59	21	17	38	158	105	156	192	651	-1.94
30		863	122	66	23	17	42	176	105	163	248	688	-2.30
32		863	125	72	25	19	45	176	110	179	292	707	-2.73
34		871	130	77	28	20	47	174	115	198	315	726	-3.16
36	843	860	135	82	31	21	50	189	121	216	350	736	-3.67
38		860	141	86	34	23	52	204	127	233	364	739	-4.38

*** Measurements not reliable

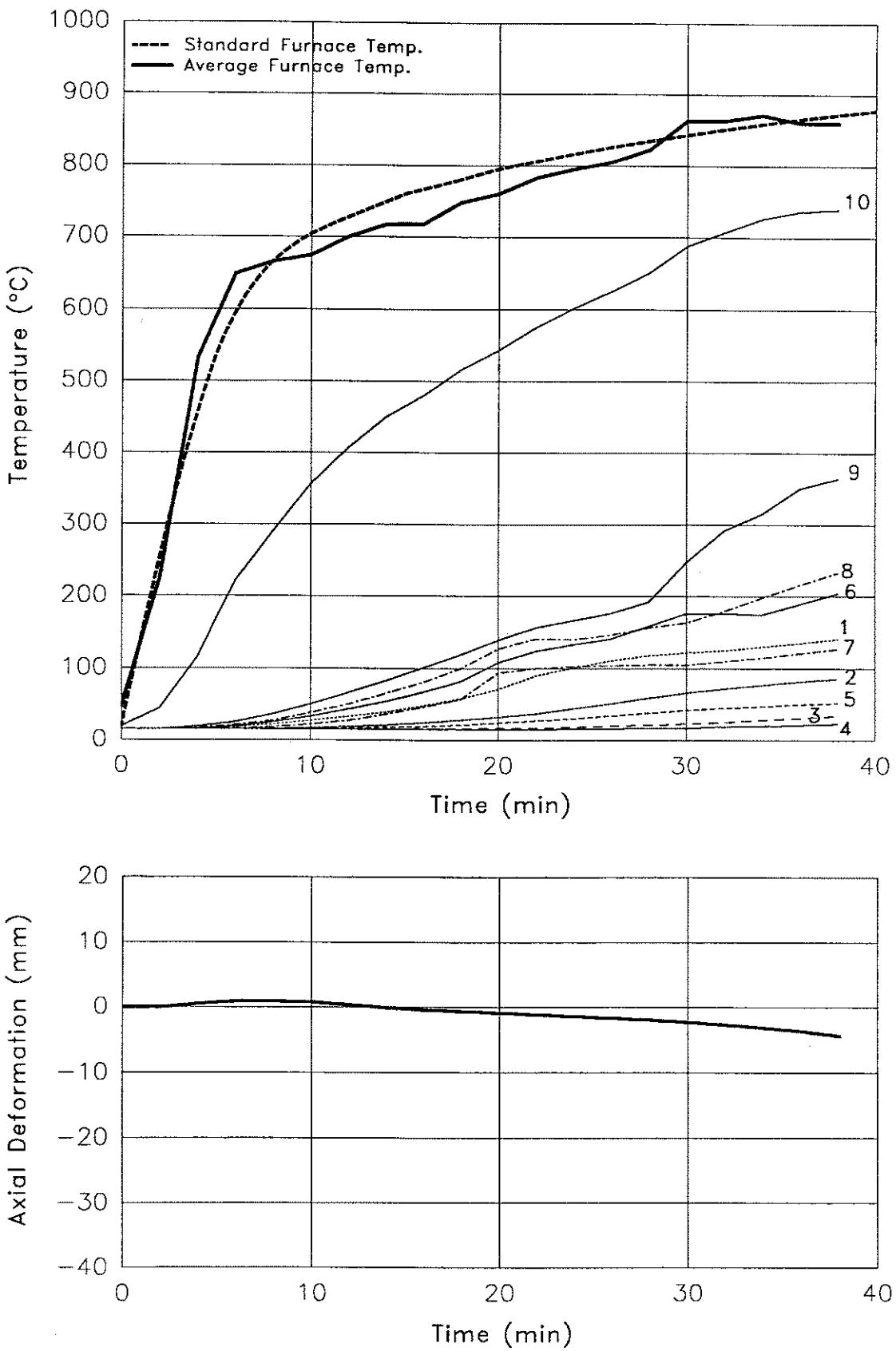


Figure A7. Temperatures and axial deformation of Column No. SQ-22

Table A8. Temperatures and axial deformation of Column No. SQ23

Time (min)	Std. furn. temp. (°C)	Avg. furn. temp. (°C)	Column temperature (°C) measured at Thermocouple No.										Axial Def. (mm)	
			1	2	3	4	5	6	7	8	9	10		
0	20	48	19	19	19	19	***	***	***	20	19	24	0.00	
2		212	19	19	19	19	***	***	***	20	20	58	0.00	
4		587	20	20	19	19	***	***	***	21	22	170	0.98	
6		613	21	22	20	20	***	***	***	25	28	235	2.76	
8		640	24	28	21	22	***	***	***	33	38	294	4.43	
10		677	29	34	24	25	***	***	***	40	46	353	4.75	
12		700	36	39	27	28	***	***	***	48	54	399	4.41	
14		725	44	45	32	32	***	***	***	57	64	445	2.62	
16		744	53	53	39	36	***	***	***	70	76	485	1.89	
18		760	62	61	46	41	***	***	***	83	89	532	1.43	
20	704	778	73	70	54	46	***	***	***	94	102	572	1.09	
22		788	85	79	62	52	***	***	***	106	116	601	0.83	
24		801	96	89	73	59	***	***	***	118	131	626	0.69	
26		809	106	100	83	65	***	***	***	131	146	646	0.59	
28		818	118	110	93	73	***	***	***	142	159	664	0.52	
30		831	134	119	111	80	***	***	***	153	171	682	0.46	
32		849	152	127	133	91	***	***	***	164	181	701	0.39	
34		857	160	137	138	107	***	***	***	175	189	720	0.26	
36		864	162	149	139	113	***	***	***	185	198	736	0.10	
38		871	165	155	139	117	***	***	***	194	213	748	-0.06	
40*	843	701	169	160	141	118	***	***	***	207	232	706	***	
42		505	176	165	143	120	***	***	***	222	249	622	***	
44		419	188	171	146	124	***	***	***	233	261	549	***	
46		357	201	179	149	128	***	***	***	240	266	492	***	
48		601	212	188	153	132	***	***	***	243	267	500	***	
50		797	221	195	159	135	***	***	***	243	264	594	-0.61	
52		837	228	200	166	138	***	***	***	244	265	658	-0.69	
54		867	235	205	173	141	***	***	***	248	270	707	-0.77	
56		886	242	212	179	144	***	***	***	255	280	741	-0.85	
58		899	249	219	185	148	***	***	***	264	292	758	-0.93	
60	878	912	257	228	191	153	***	***	***	275	304	785	-1.01	
62		923	266	236	197	158	***	***	***	285	317	810	-1.09	
64		935	275	246	203	163	***	***	***	296	329	833	-1.17	
66		943	285	255	209	168	***	***	***	307	342	853	-1.25	
68		952	294	264	216	174	***	***	***	318	354	870	-1.33	
70		946	956	304	274	223	180	***	***	***	328	366	881	-1.45
80		963	961	354	321	260	212	***	***	***	377	420	897	-1.94
90		978	967	400	361	297	245	***	***	***	417	462	910	-2.51
100		991	982	440	396	334	277	***	***	***	450	496	926	-3.16
110		1001	992	475	428	368	307	***	***	***	480	526	940	-3.92
120	905	1010	1002	506	456	399	336	***	***	***	505	551	950	-4.79
130		1017	1009	533	482	429	362	***	***	***	527	574	965	-5.77
140		1024	1039	557	505	455	388	***	***	***	548	595	991	-6.85
150		1031	1035	580	526	479	411	***	***	***	567	613	983	-8.11
160		1038	1040	601	545	501	434	***	***	***	584	628	991	-9.50
170		1045	1047	621	563	521	455	***	***	***	601	645	1001	-11.01
180		1052	1059	641	582	541	475	***	***	***	619	661	1014	-12.69
190		1059	1071	659	601	561	495	***	***	***	636	676	1024	-14.62
200		1066	1074	675	619	585	514	***	***	***	652	691	1031	-16.94
210		1072	1086	691	636	607	533	***	***	***	668	705	1042	-19.99
212		1087	694	640	613	537	***	***	***	671	707	1044	-21.04	

* The burners were automatically shut off at 40 min due to a power failure; the test resumed at 47 min

*** Measurements not reliable

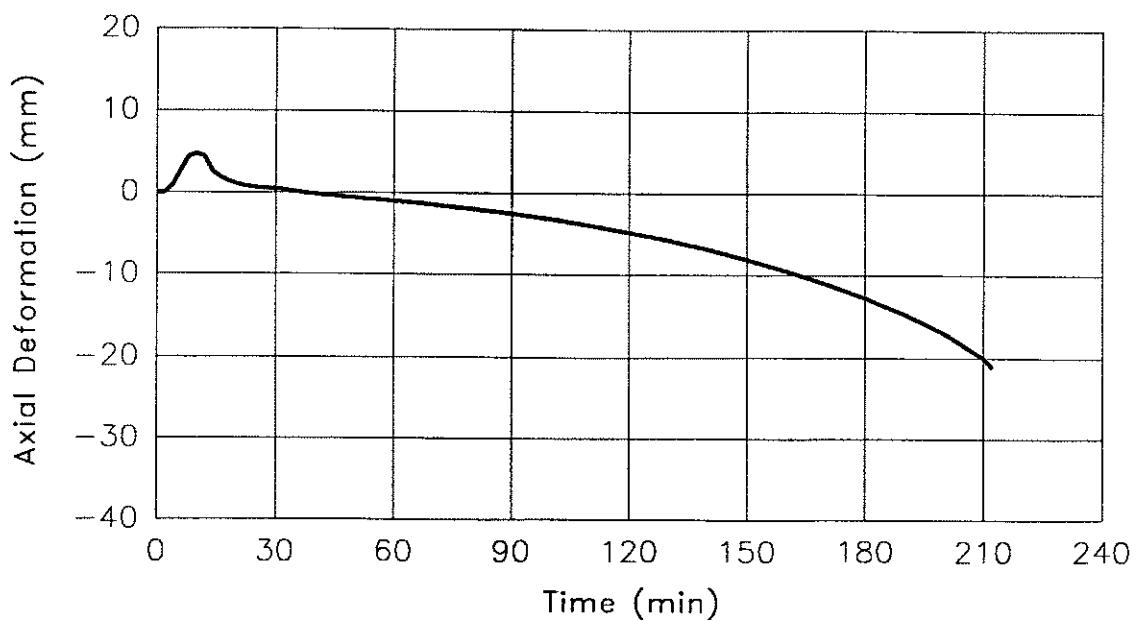
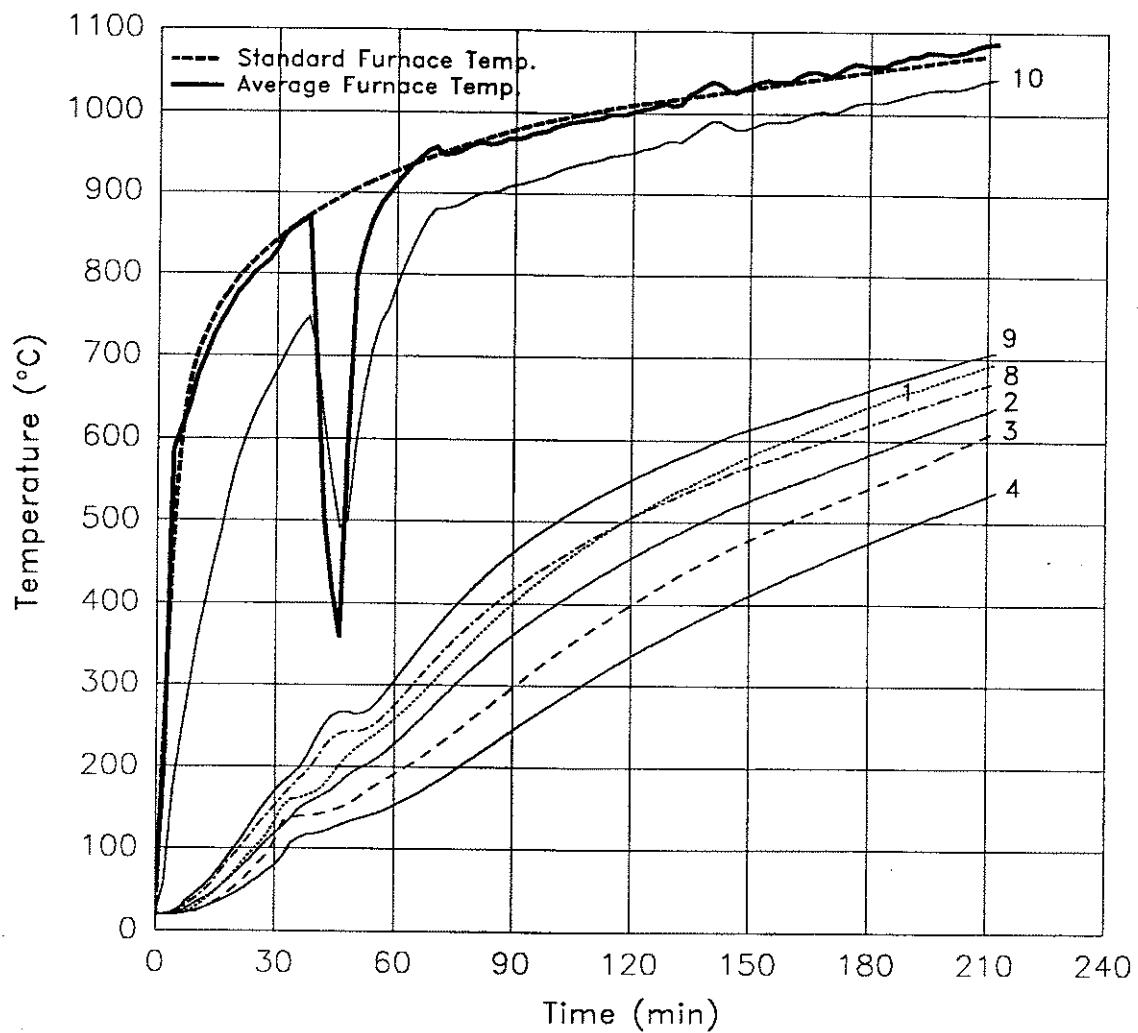


Figure A8. Temperatures and axial deformation of Column No. SQ-23

APPENDIX B

VIEW OF COLUMN SPECIMENS AFTER TESTS



Figure B1. Column No. C-48 after test



Figure B2. Column No. C-49 after test

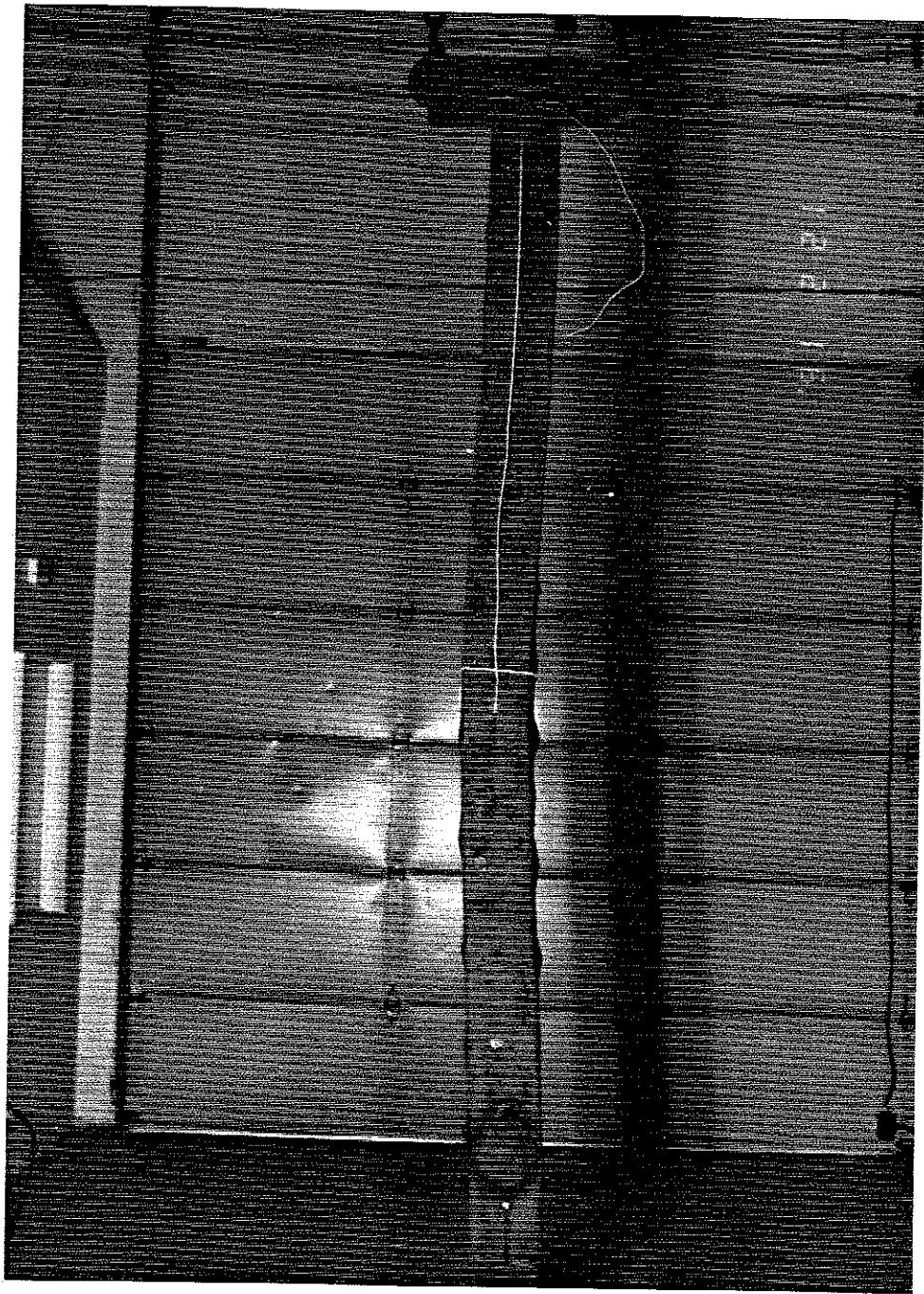


Figure B3. Column No. SQ-12 after test

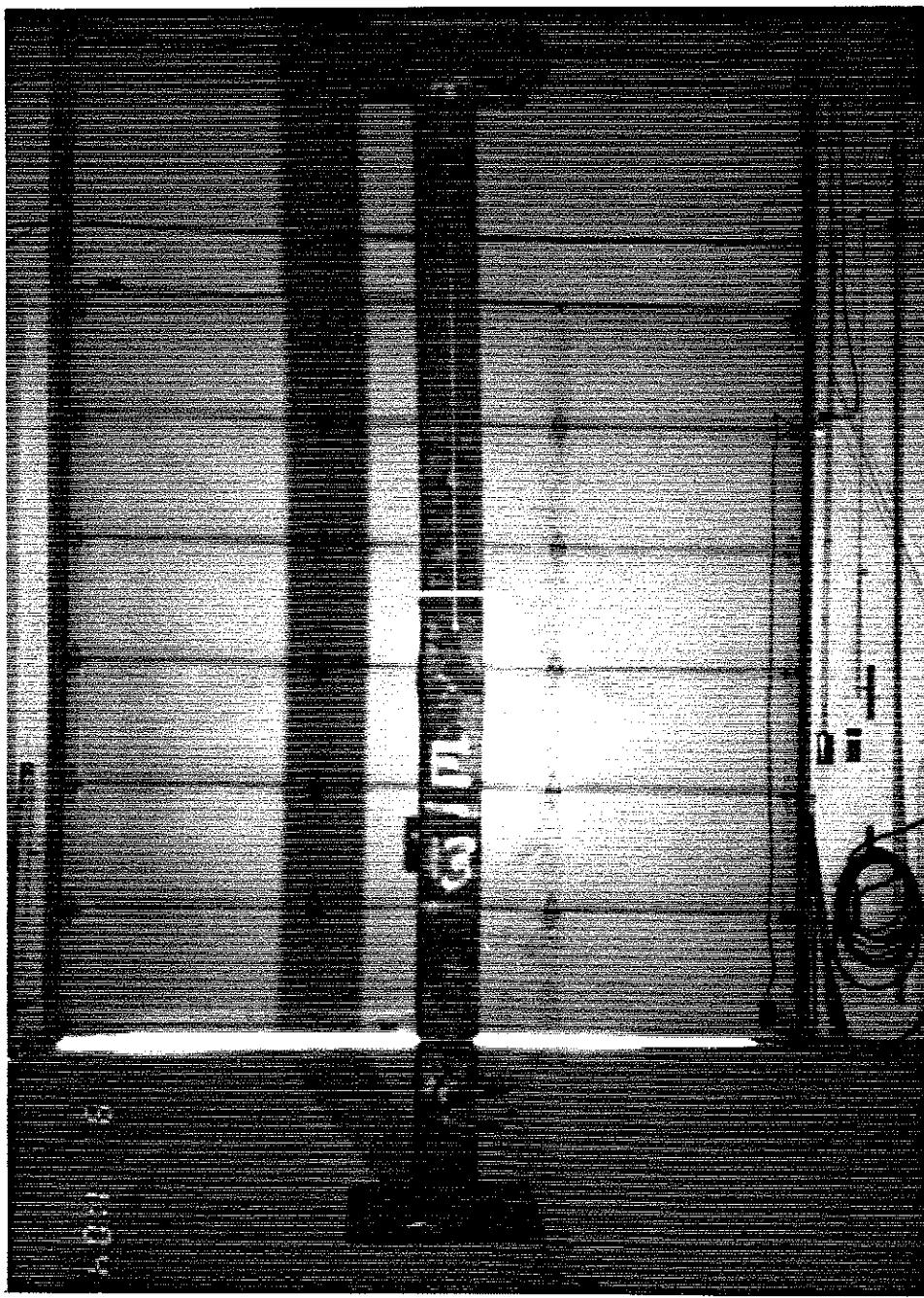


Figure B4. Column No. SQ-13 after test

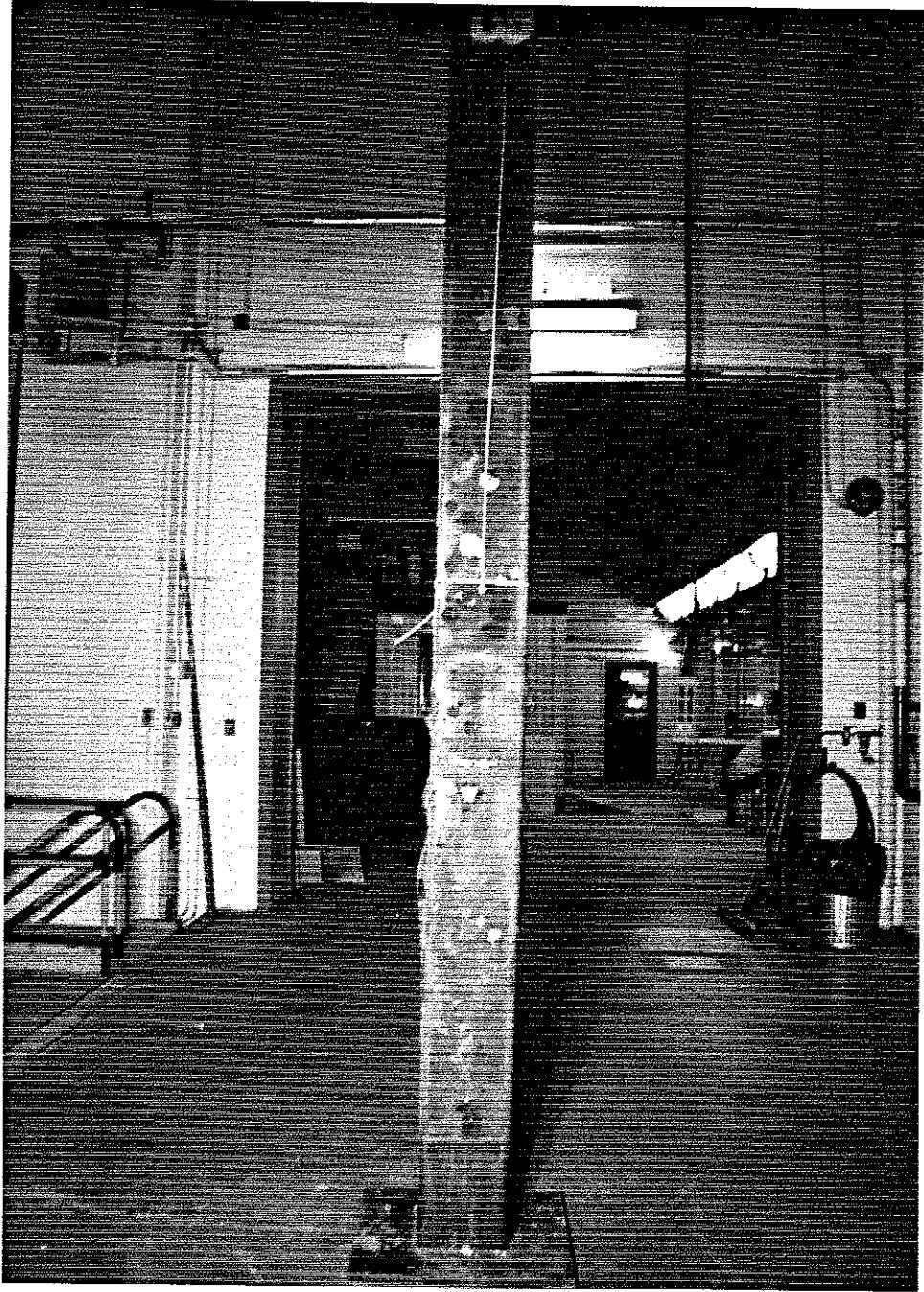


Figure B5. Column No. SQ-18 after test

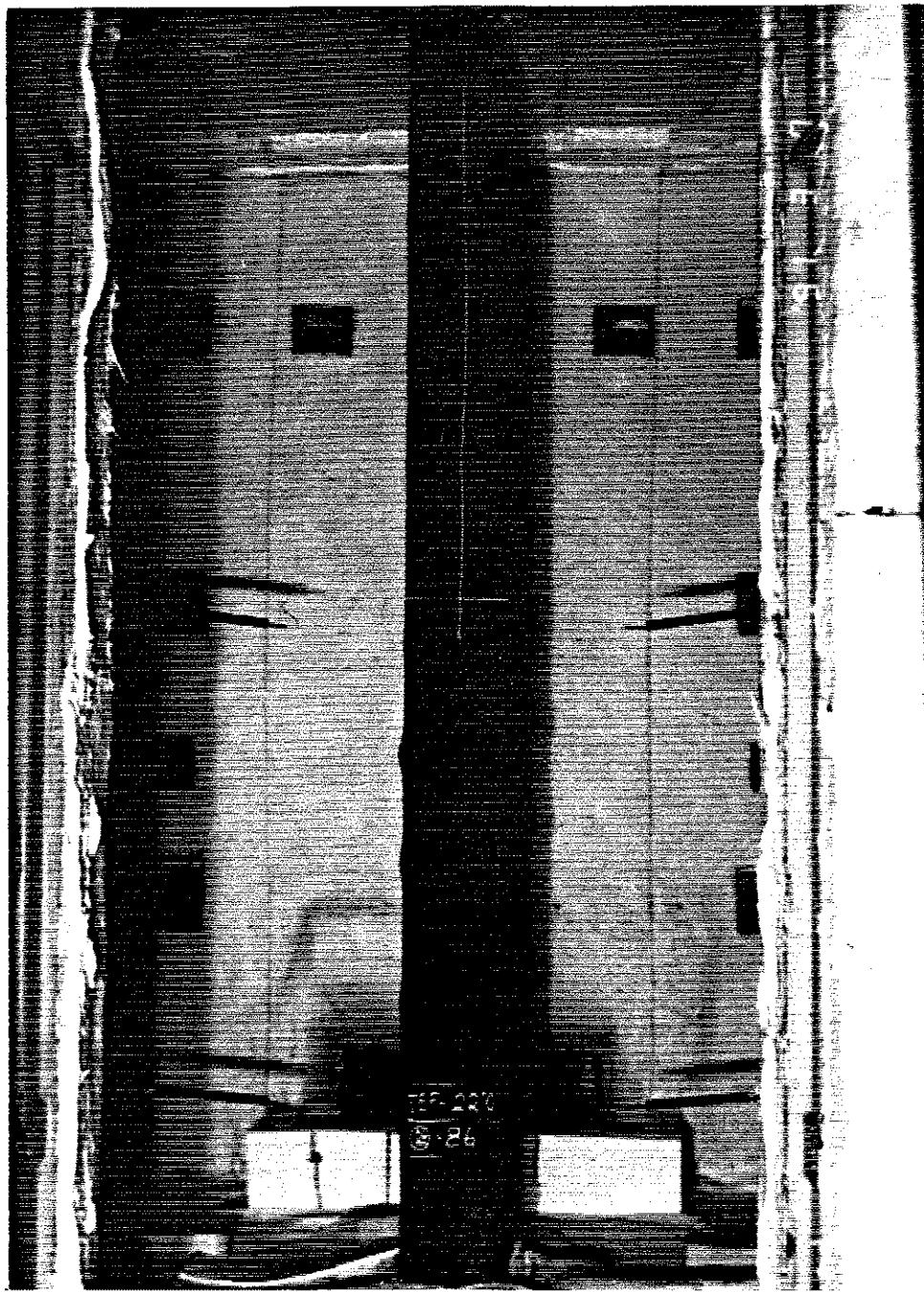


Figure B6. Column No. SQ-19 after test

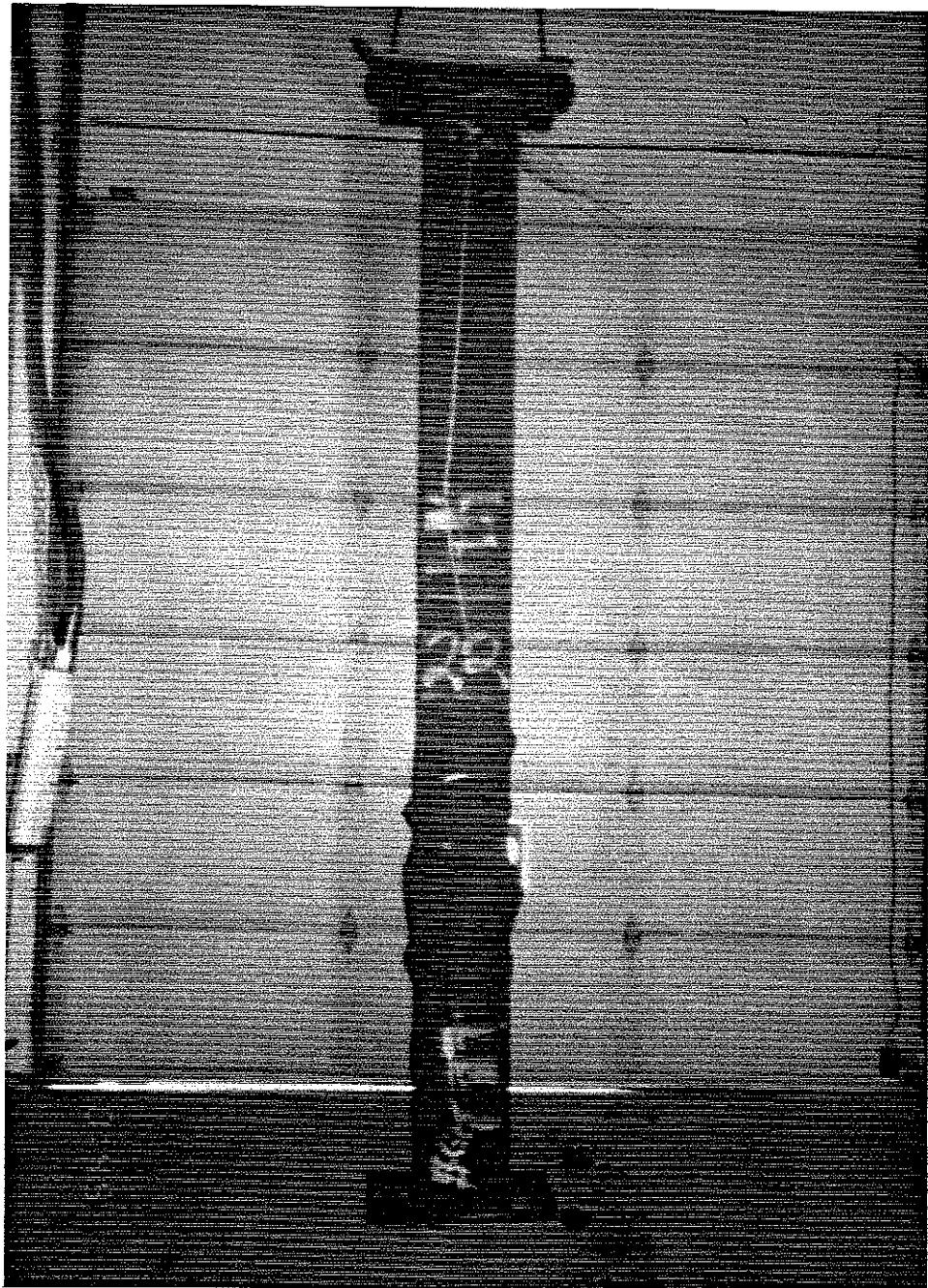


Figure B7. Column No. SQ-22 after test

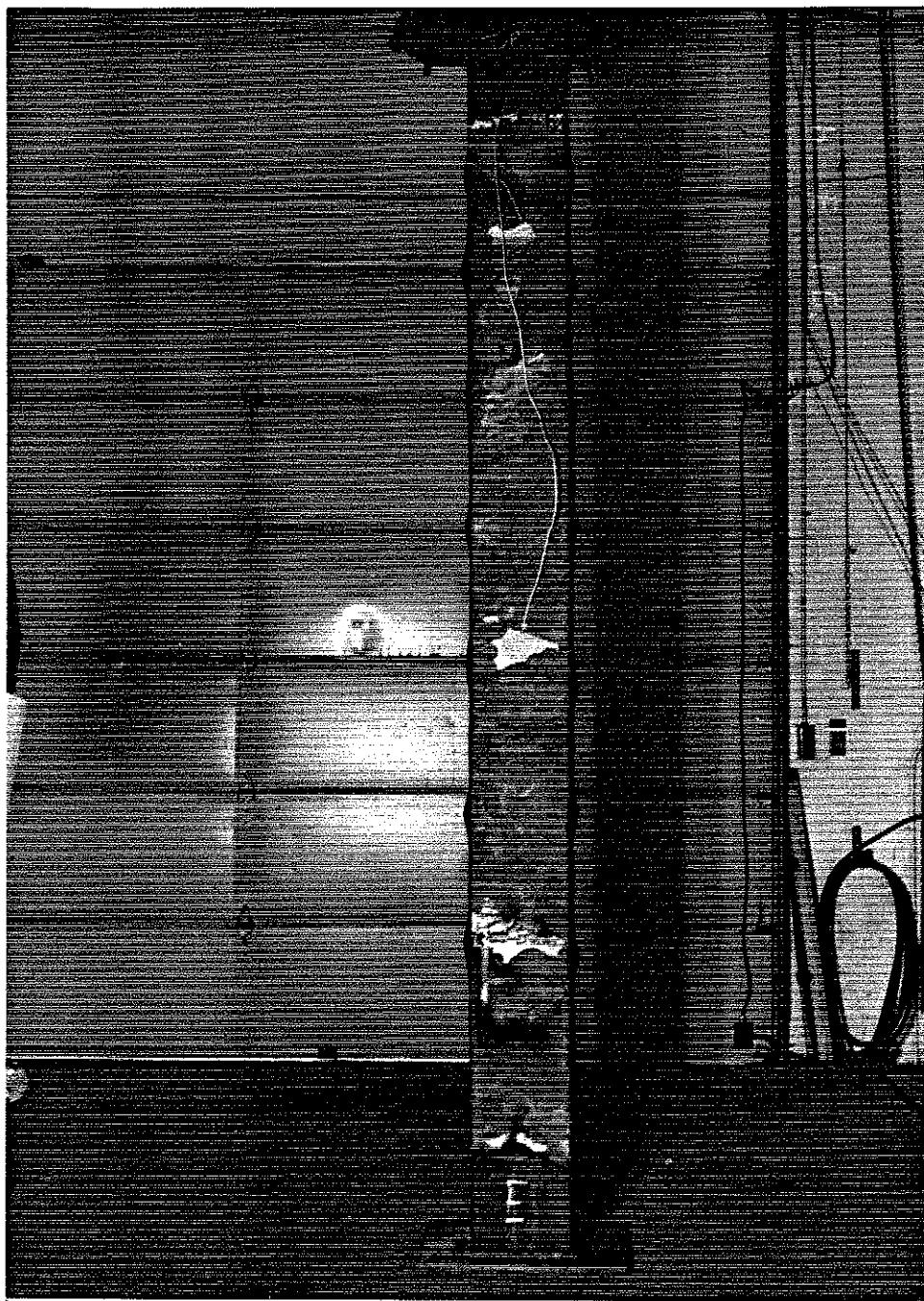


Figure B8. Column No. SQ-23 after test