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Wu, H. J.; Lie, T. T.

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Fire Resistance of Reinforced Concrete Columns — Experimental Studies

by H.J. Wu and T.T. Lie

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FIRE RESISTANCE OF REINFORCED CONCRETE COLUMNS – EXPERIMENTAL STUDIES

ABSTRACT

The results of fire tests on seven columns, constructed at the Tianjin Fire Research Institute and tested at the National Fire Laboratory of the Institute for Research in Construction, National Research Council of Canada are described. The tests were carried out mainly for the purpose of providing data for the verification of methods for the calculation of the fire resistance of reinforced concrete columns, made with materials commonly used in China. The columns were made with siliceous and carbonate aggregates. The study variables included column length, dimensions of cross sections and load eccentricity.

FIRE RESISTANCE OF REINFORCED CONCRETE COLUMNS – EXPERIMENTAL STUDIES

1 INTRODUCTION

As a part of a joint research project on the "Fire Resistance Evaluation for Housing (China)" between the Tianjin Fire Research Institute (TFRI) of the Fire Bureau of the Public Security Ministry of China, and the Institute for Research in Construction (IRC), National Research Council of Canada, seven tests were carried out on reinforced concrete columns.

The main purpose of the tests was to provide data for the verification of methods, now being developed, for the calculation of the fire resistance of reinforced concrete columns, made with materials commonly used in China.

In this report, the results of tests on seven siliceous and carbonate aggregate, reinforced concrete columns with various dimensions are described. The columns were designed jointly by TFRI and the National Fire Laboratory (NFL) of IRC and were tested at the NFL.

2 TEST SPECIMENS

In this joint project, ten reinforced concrete columns, having different dimensions, aggregates and bearing capacities, were fabricated at TFRI. Seven of them were tested at the NFL; the others will be tested at TFRI. This report describes the test results at the NFL.

In order to determine the performance during fire of concrete columns that are widely used in China, design methods and construction techniques, generally adopted in China, as well as building materials commonly used in China, were selected in the design and fabrication of these test columns [1, 2, 3].

The seven columns, which had cross sections similar to those tested previously at the NFL [4, 5], are described in Table 1. Details of the specimens are given below.

2.1 Dimensions

Five columns were 3810 mm long from end plate to end plate, the others were 3500 mm. Five of the columns had square sections of 305 mm. In order to be able to apply an eccentric load, one of the columns had brackets at the ends, consisting of a horizontal steel plate overhang with reinforced concrete underneath. One column had a rectangular cross section measuring 305 × 457 mm, and one measured 203 × 914 mm.

2.2 Materials

2.2.1 Steel

The reinforcing steel consisted of deformed bars, usually used in the construction of reinforced concrete structures in China. The longitudinal bars were Type II deformed bars, with diameters of 20 and 22 mm. The yield strength of the steel (σ_s) was 340 MPa and the ultimate strength (σ_b) was 500 MPa. The tie bars were Type I deformed bars with a diameter of 8 mm ($\sigma_s = 240$ MPa, $\sigma_b = 380$ MPa).

2.2.2 Concrete

Details of the concrete mixes are given below:

Cement: 425 portland cement, a general purpose cement for the construction of reinforced structures, was used.

Aggregates: Two types of coarse aggregates were used. One was siliceous, the other carbonate. The sizes were from 10 mm to 40 mm. The fine aggregate was siliceous sand.

Concrete Mixes: The concrete mixes were designed to produce a 25 MP strength concrete. Approximate batch quantities were:

Siliceous Concrete Mix:
Cement: 304 kg/m^3
Aggregate: 1265 kg/m^3
Sand: 626 kg/m^3
Water: 170 kg/m^3
Cement : Water = 1 : 0.56
Cement : Sand : Aggregate = 1 : 2.06 : 4.16

Carbonate Concrete Mix:
Cement: 314 kg/m^3
Aggregate: 1306 kg/m^3
Sand: 647 kg/m^3
Water: 176 kg/m^3
Cement : Water = 1 : 0.56
Cement : Sand : Aggregate = 1 : 2.06 : 4.16

2.2.3 Thermocouples

Type K chromel-alumel thermocouples were used to measure the temperatures of the concrete and steel reinforcing bars of the columns. The diameter of the thermocouple wire was 0.8 mm. The exact locations and numbering of the thermocouples are shown in Figures 4, 5, 12, 13, 16 and 17.

2.3 Fabrication

The columns were cast in forms, made of steel plate and were of the type widely used in the construction of reinforced concrete structures in China. The reinforcement cages were assembled by welding the longitudinal bars to steel end plates. A T-42 welding rod was used. The thermocouples were secured to the reinforcing steel at specified locations after the cage was properly positioned in the form.

The concrete was mixed in a general drum mixer. A small internal vibrator was carefully applied to consolidate the concrete. The concrete was cured under damp burlap for 7 days at about 20°C. The forms were then stripped and the columns conditioned in the laboratory.

A hole with a diameter of 14 mm was drilled near one end of the column before testing for measuring the relative humidity at mid-depth of the column.

3. TEST APPARATUS

The tests were carried out by exposing the columns to heat in a furnace specially built for testing loaded columns. 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. A photograph of the furnace is shown in Figure 1. The characteristics and the instrumentation of the furnace are described in detail in Ref. 6.

3.1 Furnace Chamber

The furnace chamber has a floor area of 2642 × 2642 mm and is 3048 mm high. The interior faces of the chamber are lined with a ceramic fibre material that efficiently transfers 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 is set somewhat lower than atmospheric pressure.

3.2 Loading Device

A hydraulic jack with a capacity of 9778 KN and located at the bottom of the furnace chamber, produced the concentric load along the axis of the test column. The jack was . Eccentric loads were applied by means of other hydraulic jacks, 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 was 587 KN and that of the bottom jack 489 KN.

3.3 Instrumentation

The furnace temperatures were measured with the aid of eight chromel-alumel thermocouples. The junction of each thermocouple was located 305 mm from the test specimen, at various heights of the furnace chamber. The location of the junctions and their numbering are shown in Figure 2. The temperatures measured by eight thermocouples were averaged automatically and the average temperature was used as the criterion for controlling the furnace temperature.

The loads were measured and controlled using hydraulic pressure transducers. The accuracy of measuring and controlling loads was about 4 KN at lower load levels and relatively better at higher loads.

The axial deformation of the test column was determined by measuring the displacement of the concentric loading jack. The rotation of the end plates of the columns with brackets was determined by measuring the displacement of the plates at a distance of 711 mm from the centre of the hinge at the top and at a distance of 1295 mm from the centre of the hinge at the bottom. The displacement was measured using transducers with an accuracy of 0.002 mm.

4. TEST CONDITIONS AND PROCEDURES

4.1 Restraint Conditions

Six of the seven columns were tested 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 fasten the end plates to the loading head at the top and to the hydraulic jack at the bottom. The seventh column was tested under hinged conditions, i.e., with restraint against horizontal translation only. In this case, the column end plates were bolted to the receiving plates with a roller bearing at each end.

4.2 Loading

Six of the seven columns were tested under a concentric load. The seventh column was tested under a concentric main load and a smaller eccentric load at 508 mm from the centre of the column. The applied loads were calculated and determined according to Refs. 1 and 2 and are given in Table 1.

The load was applied approximately 45 minutes before the start of each 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 column axial deformation. The load was maintained constant throughout the test.

4.3 Fire Exposure

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 ISO 834 [7] standard temperature-time curve. This curve can be given by the following equation:

$$T_f = 345 \log_{10}(8t + 1) + T_0$$

where:

T_f = furnace temperature (°C)
T_0 = ambient temperature (°C)
t = time (minutes)

The ambient temperature T_0 at the start of the seven tests was approximately 20°C.

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, could no longer maintain the load.

4.5 Recording of Results

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

The results of the seven tests are summarized in Table 2, in which column concrete strengths, 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 3 to 23. Positive axial deformation values indicate expansion of the column. The photographs of the columns after the tests are given in Figures 6, 7, 9, 10, 14, 18 and 20.

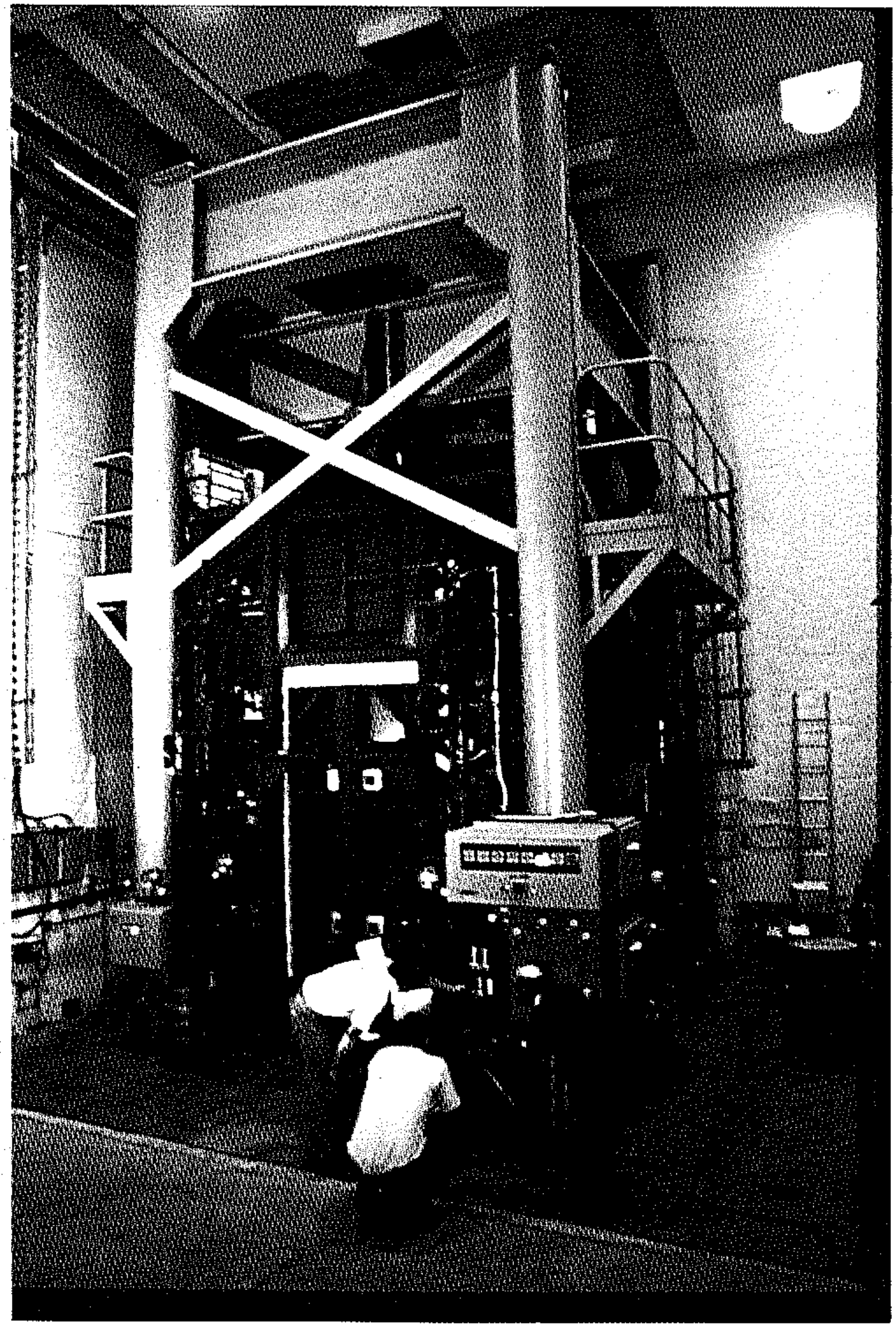

Figure 1. Column Furnace at NFL

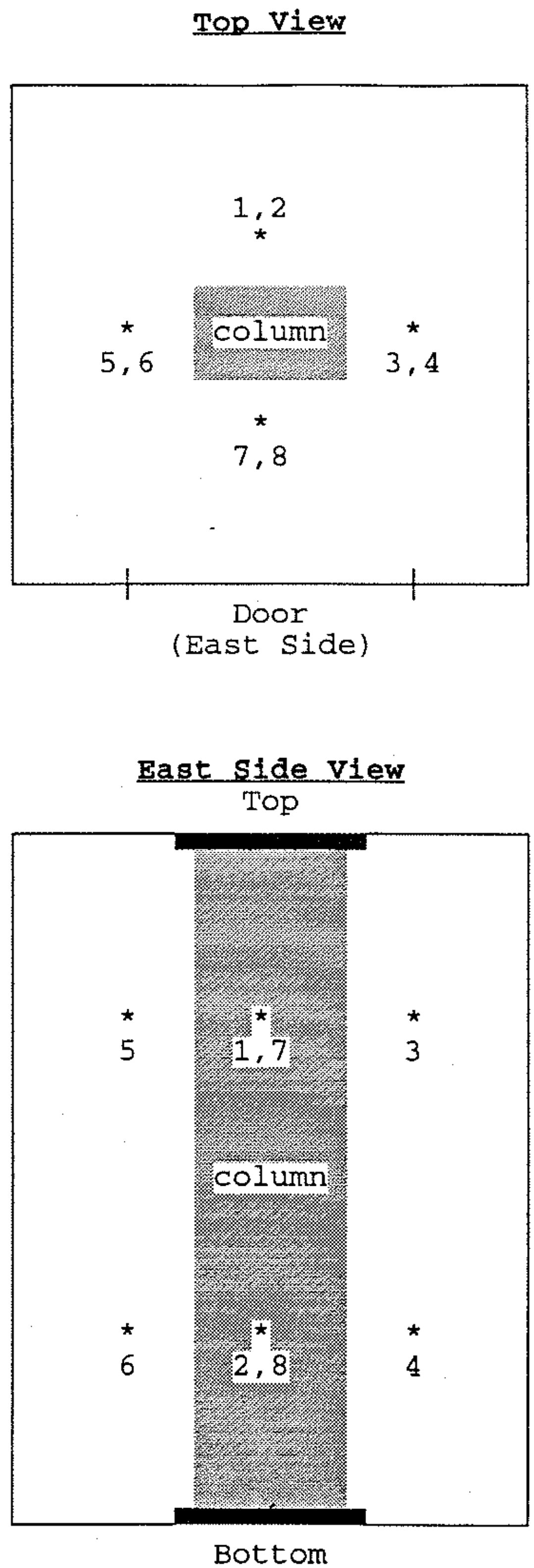

Figure 2. T/C Locations for Furnace Temperatures

Table 1. Summary of Design Parameters of the Columns

Column No.	Dimensions (mm)	Aggregate	Steel (%)	Concrete Design Strength (MPa)*	Design Load (KN)
1	305 x 305 x 3810	Siliceous	1.689	25	1180
2	305 x 305 x 3810	Carbonate	1.689	25	1180
3	305 x 305 x 3500	Siliceous	1.689	25	1180
4	305 x 305 x 3500	Carbonate	1.689	25	1180
5	305 x 457 x 3810	Carbonate	1.862	25	1585
6	203 x 914 x 3810	carbonate	1.392	25	2218
7	305 x 305 x 3810 (with brackets)	Siliceous	2.533	25	910(axial) 49 (eccen)

* The concrete strength is determined using 100 x 100 x 100 mm concrete cubes according to the Construction Codes of China, and this strength can be converted to the concrete cylinder strength by the equation $f_{cyl.}=0.83f_{cube}$

Table 2. Summary of Test Parameters of the Columns

Column No.	Concrete Tested Strength (MPa)*	Relative Humidity(%)	Actual Load (KN)	Failure Mode	Failure Time (hrs)
1	36.37	63.2	1180	Compression	1:37
2	28.77	91.8	1180	Compression	2:44
3	28.16	98.0	1180	Compression	1:49
4	31.75	80.0	1180	Compression	2:55
5	32.25	69.3	1585	Compression	3:52
6	26.38	66.7	2218	Compression	2:55
7	32.90	95.1	910 (axial) 49(eccentric)	Buckling	0:41

* 100 x 100 x 100 mm concrete cube strength on test date

5 TEST DESCRIPTIONS AND RESULTS

5.1 Column 1

Specimen Properties

Cross-Section: 305 × 305 mm
Length: 3810 mm
Aggregate: Siliceous
Reinforcement: 1.689% as 4 ϕ22 mm bars
Elevation, Cross-Section and Finishing Detail: Figure 3
Locations of T/C's on Steel Bars: Figure 4
Locations of T/C's at Mid-Height Section: Figure 5

Measured Properties

Concrete Cube Strength: 36.37 MP on test date
Relative Humidity: 63.2%
Actual Loading: 1180 KN, Concentric

Test Results

Test Duration: 1 hour 37 minutes
Axial Deformation: Table 3
Steel Bar Temperatures: Table 4
Concrete Temperatures: Table 5

Observations

0:40 Small cracks developed on the east face.
1:04 The column began to contract.
1:06 Some concrete fell off and a reinforcing bar was visible on the east face.
1:30 Reinforcing bars, about 1 m in length, were visible on the east face at mid-height.
1:37 The column failed in compression (Figure 6).

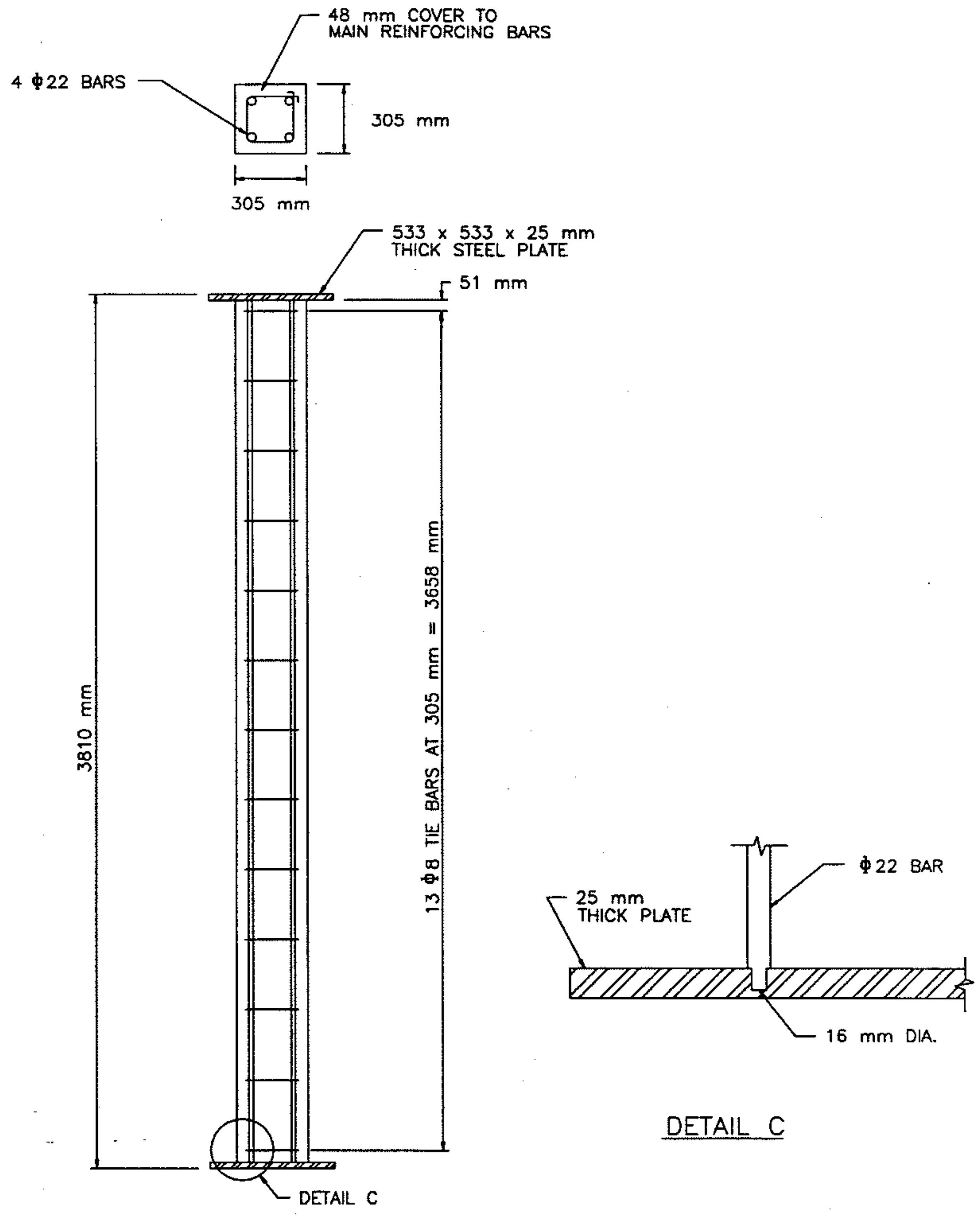

Figure 3. Elevation, Cross-Section and Finishing Detail: Column 1 and Column 2

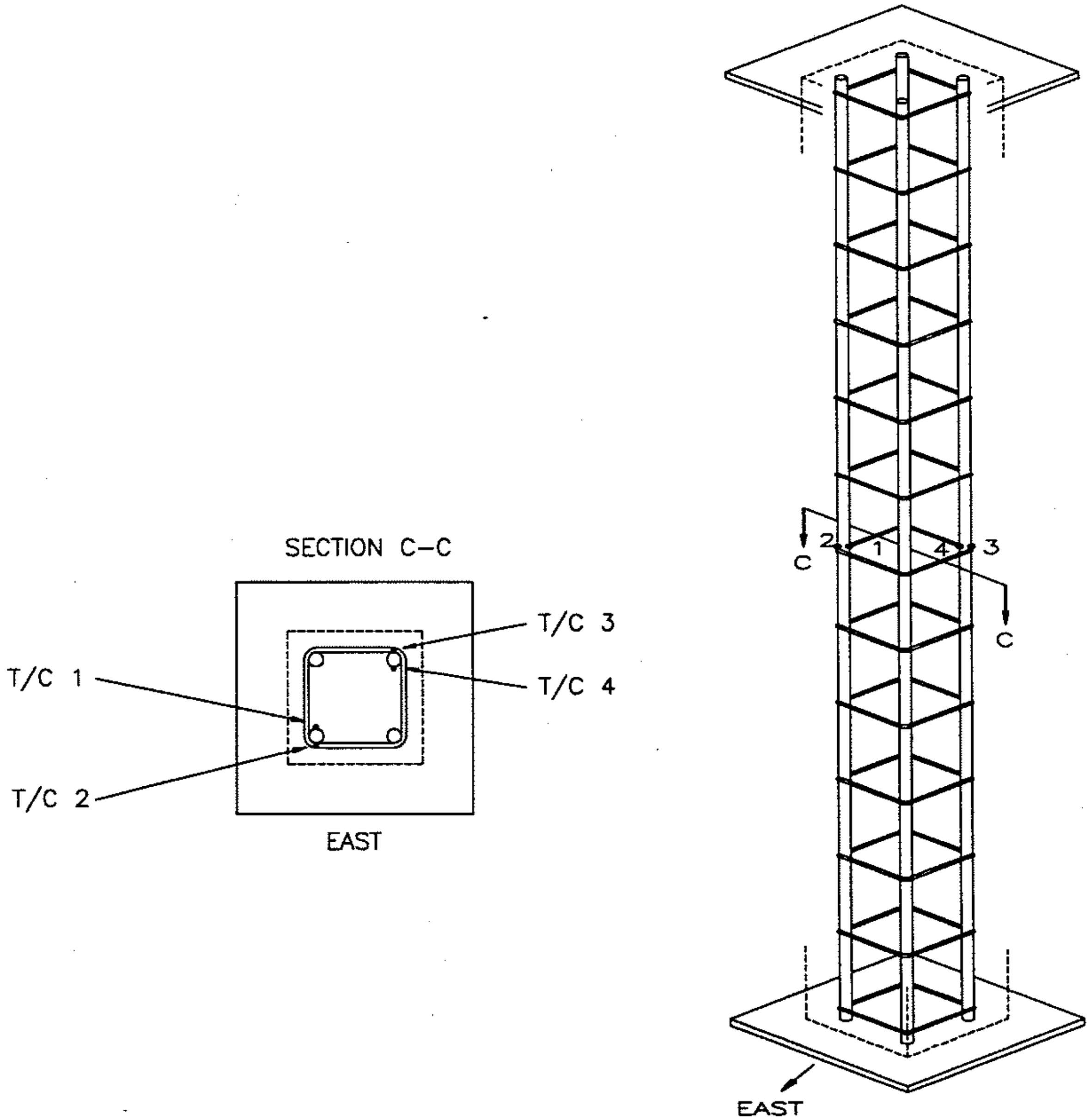

Figure 4. Locations of T/C's on Steel Bars: 305 x 305 mm Section Columns

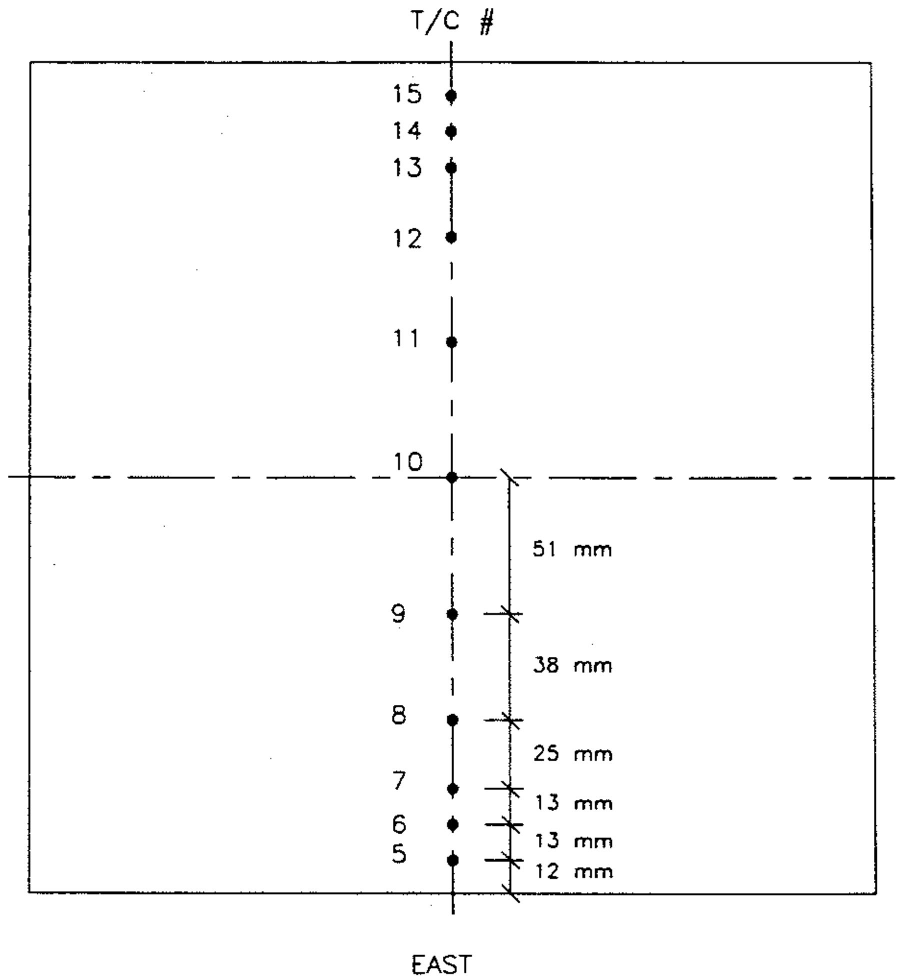

Figure 5. Locations of T/C's at Mid-Height Section: 305 x 305 mm Columns

Figure 6. Column 1 After Test

Table 3. Axial Deformation, Column 1

Time (min)	Expansion (mm)
0	0.0
10	0.1
20	0.9
30	0.9
40	0.9
50	0.9
60	0.4
70	-0.4
80	-1.1
90	-2.4
98	-6.4

Table 4. Steel Bar Temperatures, Column 1

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	Furnace Temperature (°C)
0	23	--	23	23	20
10	72	--	61	63	704
20	109	---	115	113	812
30	129	---	138	153	875
40	170	---	174	192	909
50	222	---	225	231	948
60	276	---	281	288	973
70	329	---	331	339	993
80	382	---	379	385	1001
90	430	---	425	431	1031
98	469	---	465	499	1006

Table 5. Concrete Temperatures, Column 1

Time (min)	Temperatures (°C) Measured at Thermocouple #: 5	6	7	8	9	10	11	12	13	14	15	Furnace Temperature (°C)
0	24	23	23	23	23	23	23	23	23	23	24	20
10	188	108	80	38	24	23	24	36	67	103	148	704
20	321	190	114	81	41	28	37	83	111	173	273	812
30	408	265	154	101	66	48	59	95	134	232	343	875
40	467	319	198	110	86	70	78	107	178	281	394	909
50	516	362	237	137	102	88	94	124	214	324	441	948
60	558	401	274	165	105	98	104	149	250	368	490	973
70	593	435	310	193	110	102	106	175	284	407	527	993
80	627	471	346	222	123	103	111	204	319	449	571	1001
90	668	510	383	254	148	102	119	233	360	516	648	1031
98	700	543	416	279	167	102	132	259	400	571	706	1006

5.2 Column 2

Specimen Properties

Cross-Section: 305 × 305 mm
Length: 3810 mm
Aggregate: Carbonate
Reinforcement: 1.689% as 4 ϕ22 mm bars
Elevation, Cross-Section and Finishing Detail: Figure 3
Locations of T/C's on Steel Bars: Figure 4
Locations of T/C's at Mid-Height Section: Figure 5

Measured Properties

Concrete Cube Strength: 28.77 MP on test date
Relative Humidity: 91.8%
Actual Loading: 1180 KN, Concentric

Test Results

Test Duration: 2 hours 44 minutes
Axial Deformation: Table 6
Steel Bar Temperatures: Table 7
Concrete Temperatures: Table 8

Observations

1:00	Small cracks developed on the column faces.
1:50	The column began to contract.
2:40	Cracks on the left of the east face extended.
2:44	The column sheared at about one third of the height and failed (Figure 7).

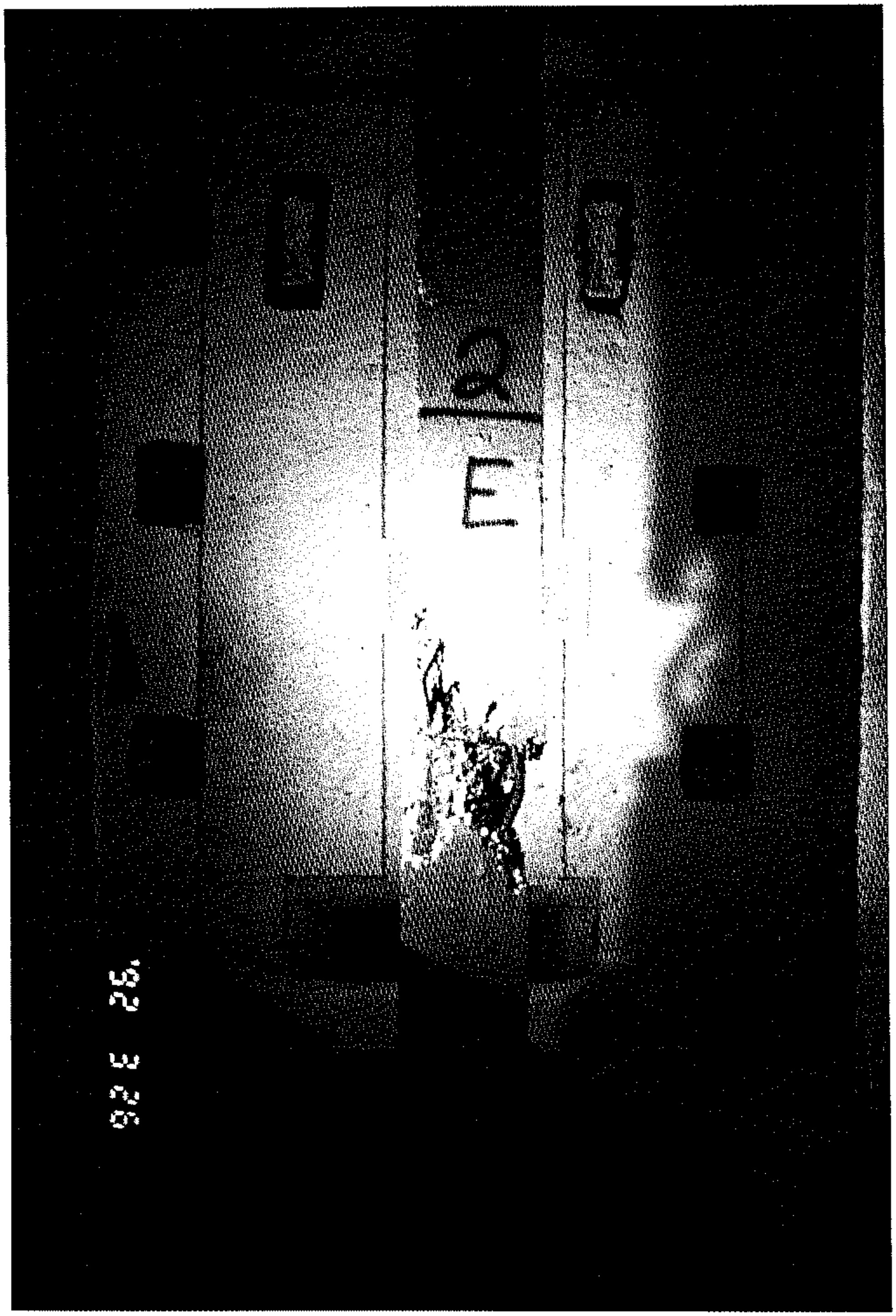

Figure 7. Column 2 After Test

Table 6. Axial Deformation, Column 2

Time (min)	Expansion (mm)
0	0.0
10	0.1
20	0.9
30	1.2
40	1.4
50	1.4
60	1.4
70	1.3
80	1.0
90	0.7
100	0.4
110	0.0
120	-0.6
130	-1.2
140	-2.0
150	-3.1
160	-4.6
164	-20.3

Table 7. Steel Bar Temperatures, Column 2

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	Furnace Temperature (°C)
0	18	18	18	18	20
10	40	42	53	56	690
20	105	107	121	121	778
30	104	105	164	170	829
40	125	128	240	248	870
50	172	174	299	309	895
60	220	222	339	361	918
70	265	268	377	404	932
80	306	309	413	440	950
90	342	346	445	471	965
100	376	379	473	499	980
110	406	410	499	524	991
120	434	438	523	546	1003
130	460	464	547	566	1013
140	484	488	574	585	1027
150	506	510	595	603	1035
160	527	530	611	619	1043
164	534	538	618	625	1032

Table 8. Concrete Temperatures, Column 2

Time (min)	Temperatures (°C) Measured at Thermocouple #: 5	6	7	8	9	10	11	12	13	14	15	Furnace Temperature (°C)
0	19	19	19	19	19	19	18	18	19	19	21	20
10	137	82	53	23	19	19	20	31	74	112	217	690
20	253	129	111	51	27	21	36	83	118	213	366	778
30	338	199	121	77	46	34	59	103	170	295	461	829
40	405	256	163	91	64	51	77	111	226	361	530	870
50	455	303	205	103	79	68	93	133	269	411	581	895
60	495	341	241	107	94	88	105	153	304	449	616	918
70	527	373	274	125	104	101	109	182	340	485	648	932
80	555	404	307	150	105	106	117	213	374	515	672	950
90	578	433	338	178	121	105	130	243	404	542	694	965
100	600	460	368	205	138	105	151	271	433	567	714	980
110	620	485	396	232	161	105	173	299	460	588	734	991
120	640	509	422	258	187	113	195	325	489	608	752	1003
130	659	532	448	285	213	128	219	351	508	626	768	1013
140	677	553	472	311	240	163	245	377	530	643	786	1027
150	694	573	495	336	266	194	270	401	550	658	801	1035
160	709	592	517	361	276	220	296	424	569	674	816	1043
164	714	599	525	370	311	230	306	433	576	680	823	1032

5.3 Column 3

Specimen Properties

Cross-Section: 305 × 305 mm
Length: 3500 mm
Aggregate: Siliceous
Reinforcement: 1.689% as 4 ϕ22 mm bars
Elevation, Cross-Section and Finishing Detail: Figure 8
Locations of T/C's on Steel Bars: Figure 4
Locations of T/C's at Mid-Height Section: Figure 5

Measured Properties

Concrete Cube Strength: 28.16 MP on test date
Relative Humidity: 98%
Actual Loading: 1180 KN, Concentric

Test Results

Test Duration: 1 hour 49 minutes
Axial Deformation: Table 9
Steel Bar Temperatures: Table 10
Concrete Temperatures: Table 11

Observations

0:34 Small cracks developed on the east face.
0:46 Small cracks extended on the east face.
1:15 Some concrete crushed on the east face.
1:23 Concrete near the lower quarter point on the east face protruded.
1:40 Maximum cracks on the east face reached 3 cm.
1:49 The column failed in compression (Figure 9).

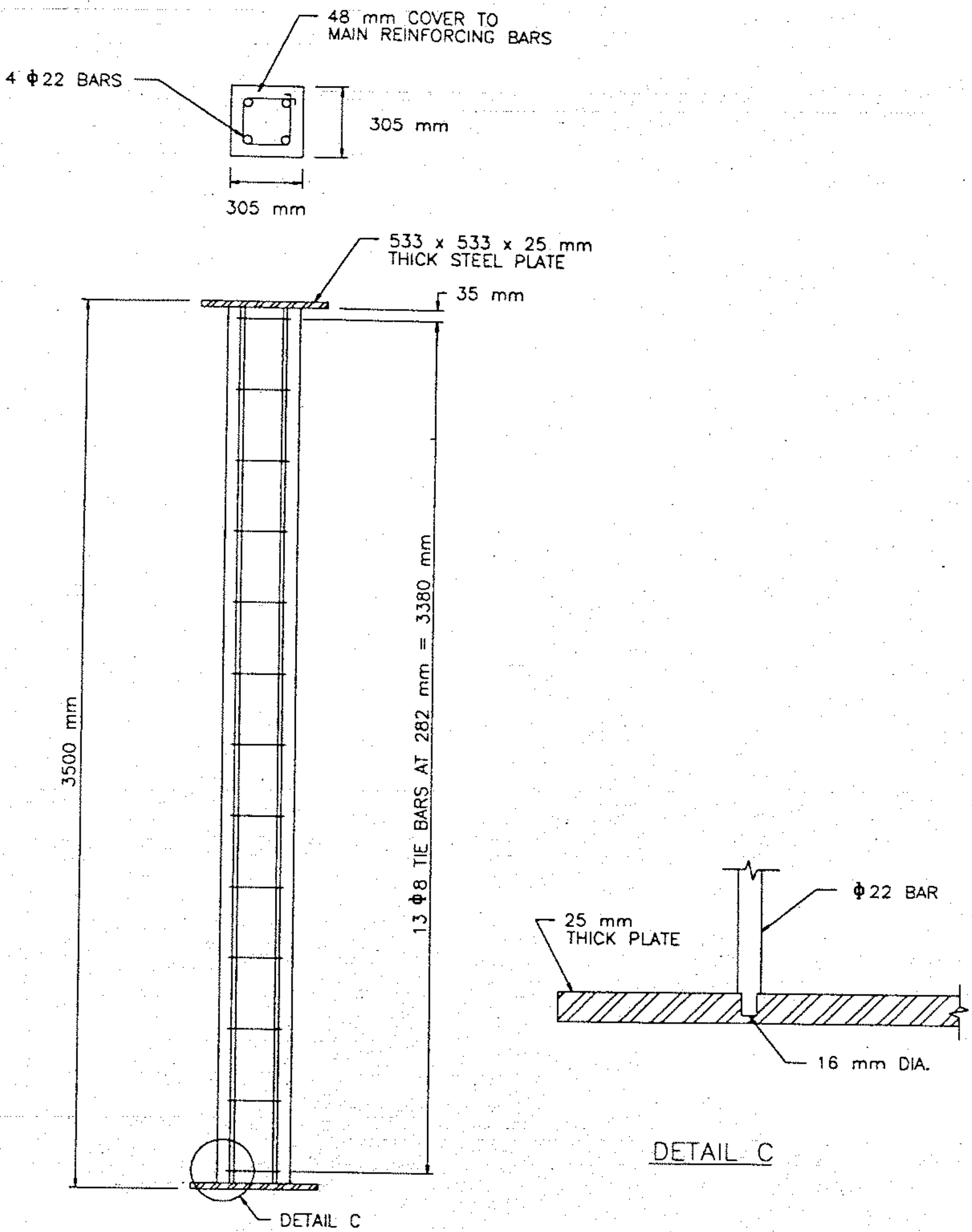

Figure 8. Elevation, Cross-Section and Finishing Detail: Column 3 and Column 4

Figure 9. Column 3 After Test

Table 9. Axial Deformation, Column 3

Time (min)	Expansion (mm)
0	0.0
10	0.7
20	1.6
30	1.8
40	1.8
50	1.8
60	1.7
70	1.3
80	0.7
90	-0.1
100	-1.5
109	-5.4

Table 10. Steel Bar Temperatures, Column 3

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	Furnace Temperature (°C)
0	23	22	24	--	20
10	72	68	88	--	706
20	108	109	122	---	823
30	120	120	178	---	879
40	163	158	238	---	926
50	218	214	291	---	955
60	266	263	342	---	967
70	330	323	388	---	995
80	435	420	432	---	1015
90	541	517	474	---	1032
100	620	564	515	---	1043
109	666	597	546	---	1065

Table 11. Concrete Temperatures, Column 3

Time (min)	Temperatures (°C) Measured at Thermocouple #: 5	6	7	8	9	10	11	12	13	14	15	Furnace Temperature (°C)
0	29	26	23	20	19	19	19	20	23	26	29	20
10	199	109	78	36	21	19	20	35	88	107	162	706
20	343	183	119	79	38	25	35	85	117	163	285	823
30	444	259	148	102	59	44	60	99	144	232	365	879
40	514	319	198	109	79	64	79	104	185	281	420	926
50	565	367	242	133	97	82	91	105	216	318	460	955
60	609	409	282	164	111	97	98	106	237	348	494	967
70	649	448	318	192	113	110	105	135	268	379	526	995
80	686	486	353	221	116	108	105	167	301	412	552	1015
90	720	524	389	251	124	106	105	197	334	443	580	1032
100	752	560	426	282	143	103	111	228	370	483	634	1043
109	775	589	454	308	160	103	118	255	403	523	681	1065

5.4 Column 4

Specimen Properties

Cross-Section: 305 × 305 mm
Length: 3500 mm
Aggregate: Carbonate
Reinforcement: 1.689% as 4 ϕ22 mm bars
Elevation, Cross-Section and Finishing Detail: Figure 8
Locations of T/C's on Steel Bars: Figure 4
Locations of T/C's at Mid-Height Section: Figure 5

Measured Properties

Concrete Cube Strength: 31.75 MP on test date
Relative Humidity: 80%
Actual Loading: 1180 KN, Concentric

Test Results

Test Duration: 2 hours 55 minutes
Axial Deformation: Table 12
Steel Bar Temperatures: Table 13
Concrete Temperatures: Table 14

Observations

0:50 Small cracks were visible on the east face.
1:34 Small cracks extended.
1:50 The column began to contract.
2:55 Large cracks developed on the east face and the column failed in compression (Figure 10).

Figure 10. Column 4 After Test

Table 12. Axial Deformation, Column 4

Time (min)	Expansion (mm)
0	0.0
10	0.2
20	1.0
30	1.2
40	1.4
50	1.5
60	1.5
70	1.5
80	1.4
90	1.0
100	0.6
110	0.2
120	-0.3
130	-1.0
140	-1.8
150	-2.6
160	-3.8
170	-5.5
174	-6.5

Table 13. Steel Bar Temperatures, Column 4

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	Furnace Temperature (°C)
0	--	16	16	16	20
10	--	89	28	33	705
20	---	118	102	109	812
30	---	169	103	105	882
40	---	232	104	108	918
50	---	288	123	130	938
60	---	338	152	161	965
70	---	382	188	198	989
80	---	420	224	234	1026
90	---	454	257	269	1040
100	---	485	290	302	1060
110	---	514	323	335	1054
120	---	539	353	365	1068
130	---	563	381	394	1081
140	---	584	408	421	1101
150	---	605	434	446	1099
160	---	623	458	470	1112
170	---	641	481	493	1128
174	---	647	490	502	1133

Table 14. Concrete Temperatures, Column 4

Time (min)	Temperatures (°C) Measured at Thermocouple #:											Furnace Temperature (°C)
	5	6	7	8	9	10	11	12	13	14	15	
0	21	17	16	16	15	15	16	16	16	16	17	20
10	224	107	74	30	16	16	16	21	38	85	114	705
20	384	191	115	69	30	19	25	54	108	125	201	812
30	490	275	149	108	70	32	49	85	110	187	291	882
40	567	355	207	110	106	52	66	97	130	252	363	918
50	621	413	258	140	105	71	81	107	164	304	419	938
60	659	457	302	171	105	90	96	119	192	344	463	965
70	692	494	339	202	108	100	107	136	221	377	496	989
80	723	528	373	231	117	105	109	157	252	408	526	1026
90	749	559	404	260	129	105	116	180	282	437	553	1040
100	772	586	434	288	147	106	122	205	311	464	577	1060
110	792	610	461	316	168	112	136	231	338	489	598	1054
120	811	632	487	344	191	119	157	258	365	514	619	1068
130	831	654	512	369	214	129	182	285	392	537	639	1081
140	849	675	536	394	237	148	205	311	417	559	658	1101
150	866	695	559	419	261	174	230	336	442	581	676	1099
160	882	713	580	442	286	203	255	360	466	600	694	1112
170	897	731	601	465	311	232	281	384	489	619	710	1128
174	902	738	609	473	322	242	291	393	497	627	717	1133

5.5 Column 5

Specimen Properties

Cross-Section: 305 × 457 mm
Length: 3810 mm
Aggregate: Carbonate
Reinforcement: 1.862% as 8 ϕ20 mm bars
Elevation, Cross-Section and Finishing Detail: Figure 11
Locations of T/C's on Steel Bars: Figure 12
Locations of T/C's at Mid-Height Section: Figure 13

Measured Properties

Concrete Cube Strength: 32.25 MP on test date
Relative Humidity: 69.3%
Actual Loading: 1585 KN, Concentric

Test Results

Test Duration: 3 hours 52 minutes
Axial Deformation: Table 15
Steel Bar Temperatures: Table 16
Concrete Temperatures: Table 17

Observations

1:00 Small cracks developed on the column faces.
2:40 The column began to contract.
3:10 Small cracks extended.
3:52 The column failed in compression (Figure 14).

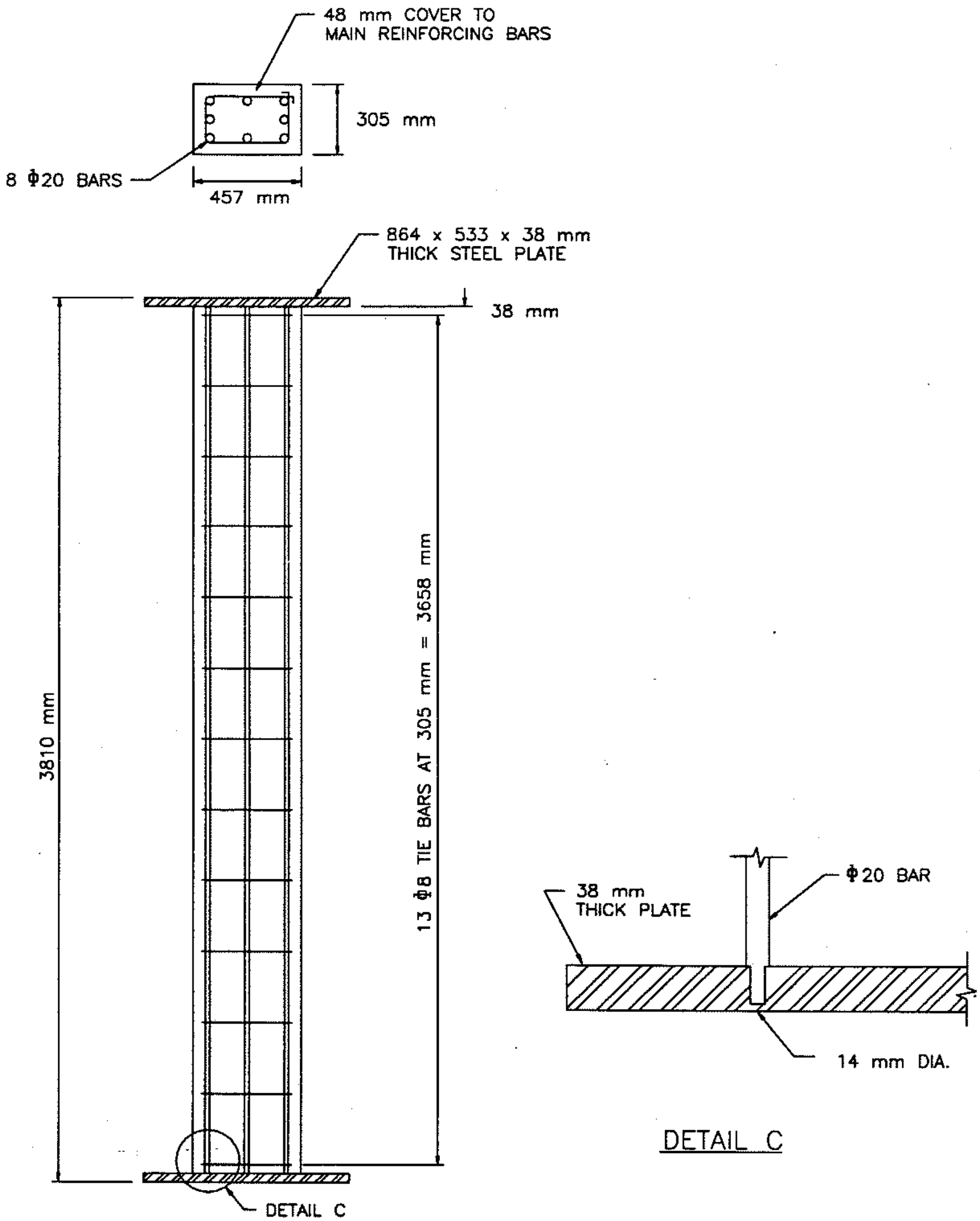

Figure 11. Elevation, Cross-Section and Finishing Detail: Column 5

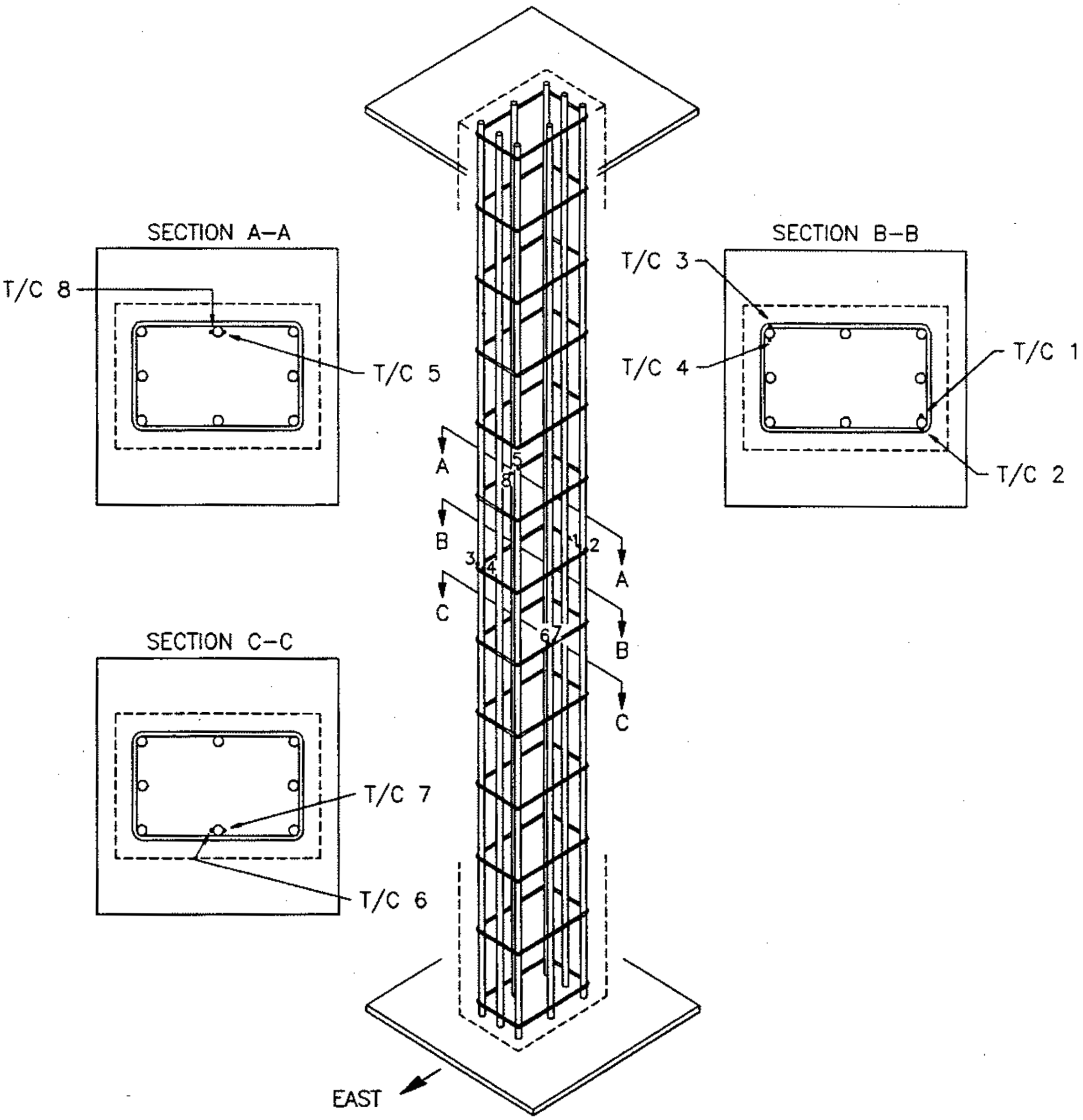

Figure 12. Locations of T/C's on Steel Bars: Column 5

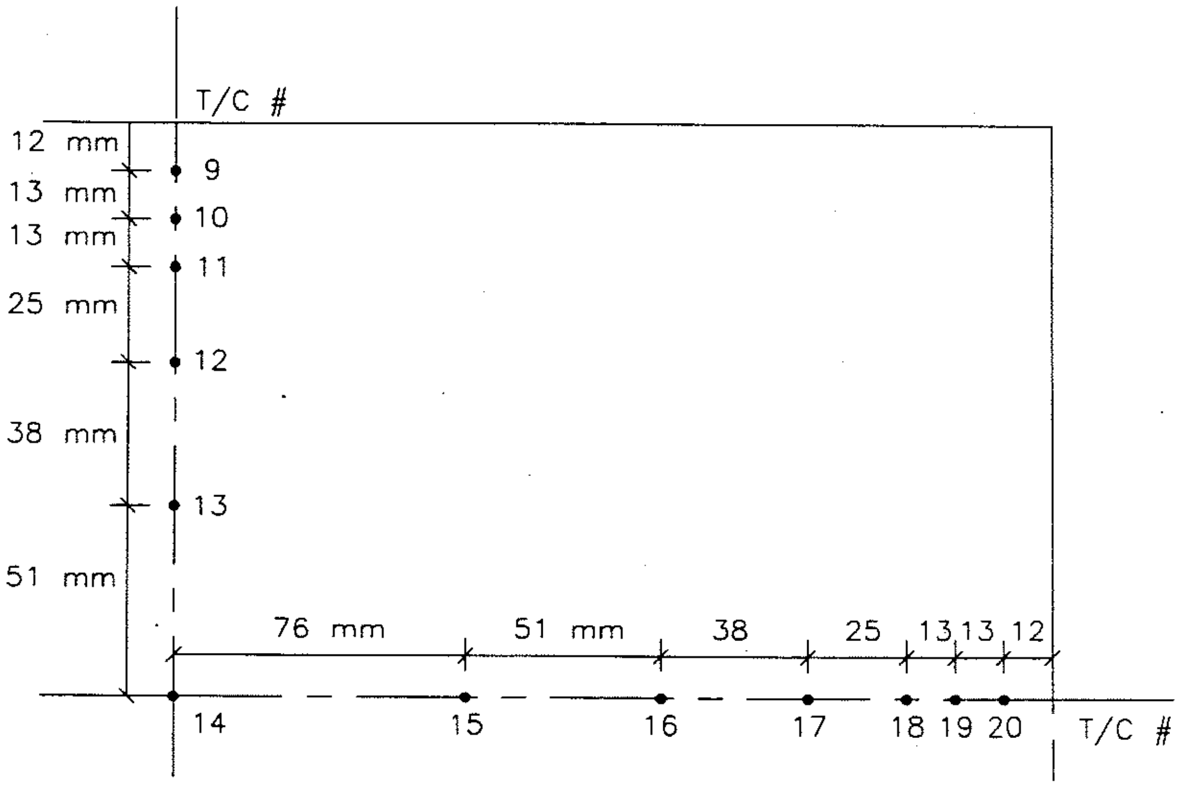

Figure 13. Locations of T/C's at Mid-Height Section: Column 5

Figure 14.   Column 5 After Test

Table 15. Axial Deformation, Column 5

Time (min)	Expansion (mm)
0	0.0
10	-0.2
20	0.7
30	1.1
40	1.5
50	1.9
60	1.9
70	1.9
80	1.9
90	1.9
100	1.9
110	1.8
120	1.5
130	1.2
140	0.9
150	0.4
160	-0.0
170	-0.5
180	-1.2
190	-2.1
200	-3.1
210	-4.2
220	-5.7
230	-7.8
232	-10.1

Table 16. Steel Bar Temperatures, Column 5

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	5	6	7	8	Furnace Temperature (°C)
0	21	21	21	21	21	20	20	21	20
10	46	52	51	49	41	41	41	41	712
20	114	118	121	120	120	112	113	113	803
30	119	128	151	145	123	129	129	121	867
40	164	179	202	195	157	166	167	155	909
50	220	237	266	254	199	203	203	199	937
60	271	289	325	311	236	237	237	236	964
70	318	334	372	358	269	271	272	269	997
80	359	375	412	398	299	306	306	299	1020
90	396	412	448	433	326	336	336	327	1029
100	429	445	479	465	352	364	364	353	1044
110	459	475	508	494	375	389	389	377	1058
120	489	502	533	520	397	413	412	398	1077
130	511	527	556	543	416	434	434	418	1087
140	534	548	577	565	435	454	454	437	1097
150	554	565	596	585	453	473	473	455	1108
160	574	584	615	604	470	492	491	472	1118
170	593	602	633	623	488	509	509	489	1127
180	610	620	650	640	504	526	526	505	1134
190	627	637	666	656	520	542	542	521	1144
200	644	653	681	672	535	558	558	537	1151
210	659	668	696	687	550	573	573	552	1159
220	674	682	711	701	565	588	588	566	1165
230	688	695	725	715	579	602	602	581	1173
232	---	---	---	718	582	604	604	584	1174

Table 17. Concrete Temperatures, Column 5

Time (min)	Temperatures (°C) Measured at Thermocouple #: 9	10	11	12	13	14	15	16	17	18	19	20	Furnace Temperature (°C)
0	22	21	21	21	21	21	32	21	21	21	21	22	20
10	151	109	66	27	21	21	34	21	26	65	100	195	712
20	318	177	119	99	41	23	33	37	64	119	154	347	803
30	431	270	164	107	81	78	--	59	93	146	230	448	867
40	510	344	231	111	104	97	--	76	105	208	303	524	909
50	562	397	279	121	105	103	--	90	111	256	359	581	937
60	598	438	320	151	106	104	--	104	133	298	404	625	964
70	626	471	354	186	106	105	87	109	161	336	443	661	997
80	650	500	384	216	108	105	90	122	191	371	478	693	1020
90	673	525	410	240	114	104	93	140	221	401	509	720	1029
100	693	547	434	262	124	104	95	160	247	429	536	744	1044
110	712	567	455	283	140	104	96	182	274	455	561	766	1058
120	730	584	475	302	155	105	99	203	300	479	583	786	1077
130	748	601	493	320	170	109	105	224	325	503	604	806	1087
140	765	617	510	337	184	115	117	246	349	524	624	824	1097
150	781	632	527	355	200	130	132	269	373	545	644	840	1108
160	797	647	543	372	218	154	154	291	396	565	662	857	1118
170	811	661	558	390	238	180	175	314	417	584	680	873	1127
180	825	675	573	407	258	202	194	336	441	602	698	889	1134
190	838	687	587	424	278	222	212	357	463	619	714	904	1144
200	849	699	600	441	297	242	230	377	483	635	729	917	1151
210	861	711	614	458	316	261	247	398	503	651	744	931	1159
220	872	723	626	474	334	281	263	417	520	665	759	944	1165
230	883	736	639	490	352	300	278	436	536	679	773	957	1173
232	886	738	642	493	354	304	930	744	---	98	775	---	1174

5.6 Column 6

Specimen Properties

Cross-Section: 203 × 914 mm
Length: 3810 mm
Aggregate: Carbonate
Reinforcement: 1.392% as 8 ϕ20 mm bars
Elevation, Cross-Section and Finishing Detail: Figure 15
Locations of T/C's on Steel Bars: Figure 16
Locations of T/C's at Mid-Height Section: Figure 17

Measured Properties

Concrete Cube Strength: 26.38 MP on test date
Relative Humidity: 66.7%
Actual Loading: 2218 KN, Concentric

Test Results

Test Duration: 2 hours 55 minutes
Axial Deformation: Table 18
Steel Bar Temperatures: Table 19
Concrete Temperatures: Table 20

Observations

1:20 Small cracks were visible to the right of the east face.
2:00 More small cracks developed.
2:20 A crack about 20 cm in length was visible on the east face at mid-height.
2:35 Small cracks were also visible on the north face.
2:38 A large crack 30 cm in length and 1 cm in width was visible on the south face.
2:55 The column failed in compression (Figure 18).

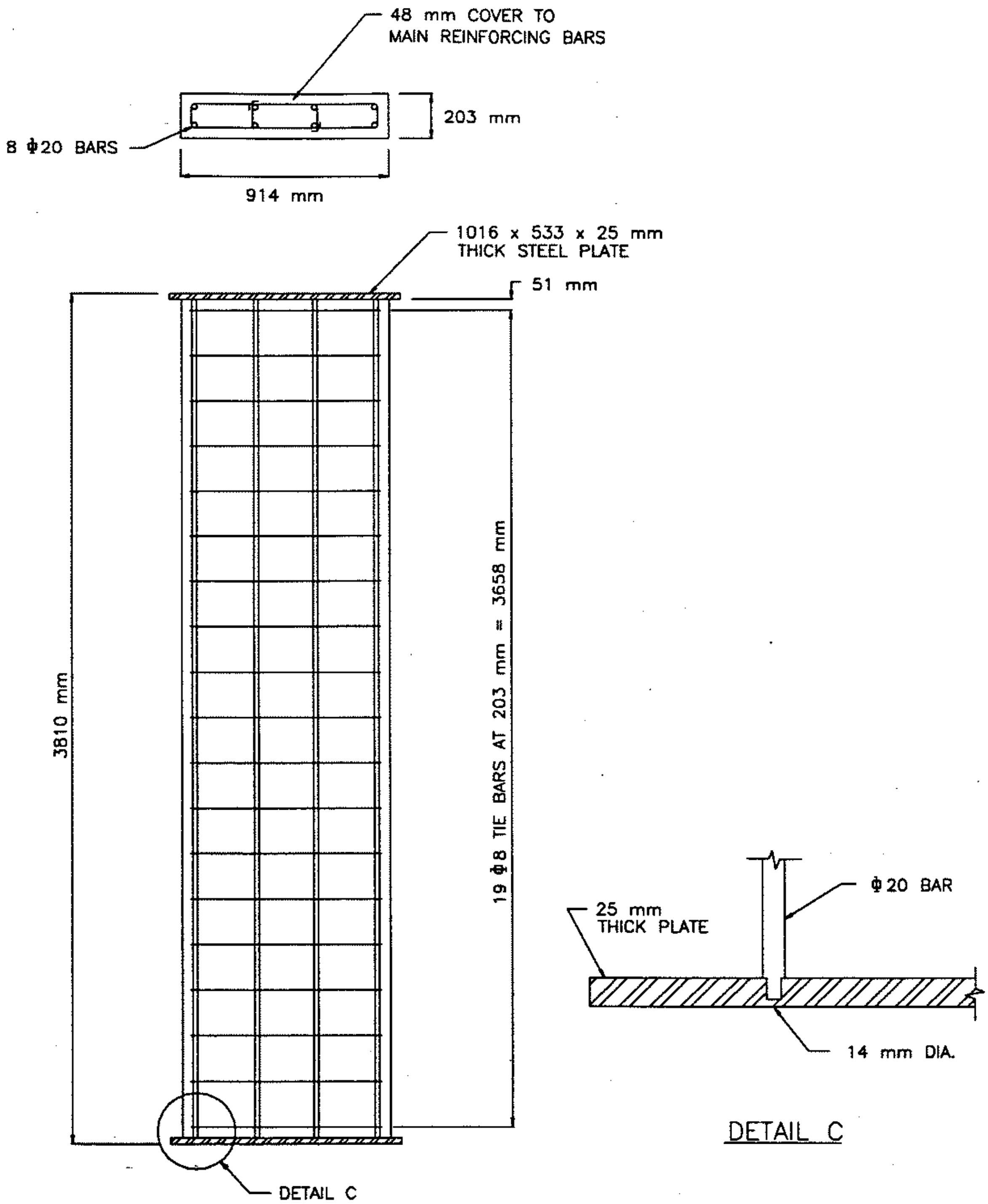

Figure 15. Elevation, Cross-Section and Finishing Detail: Column 6

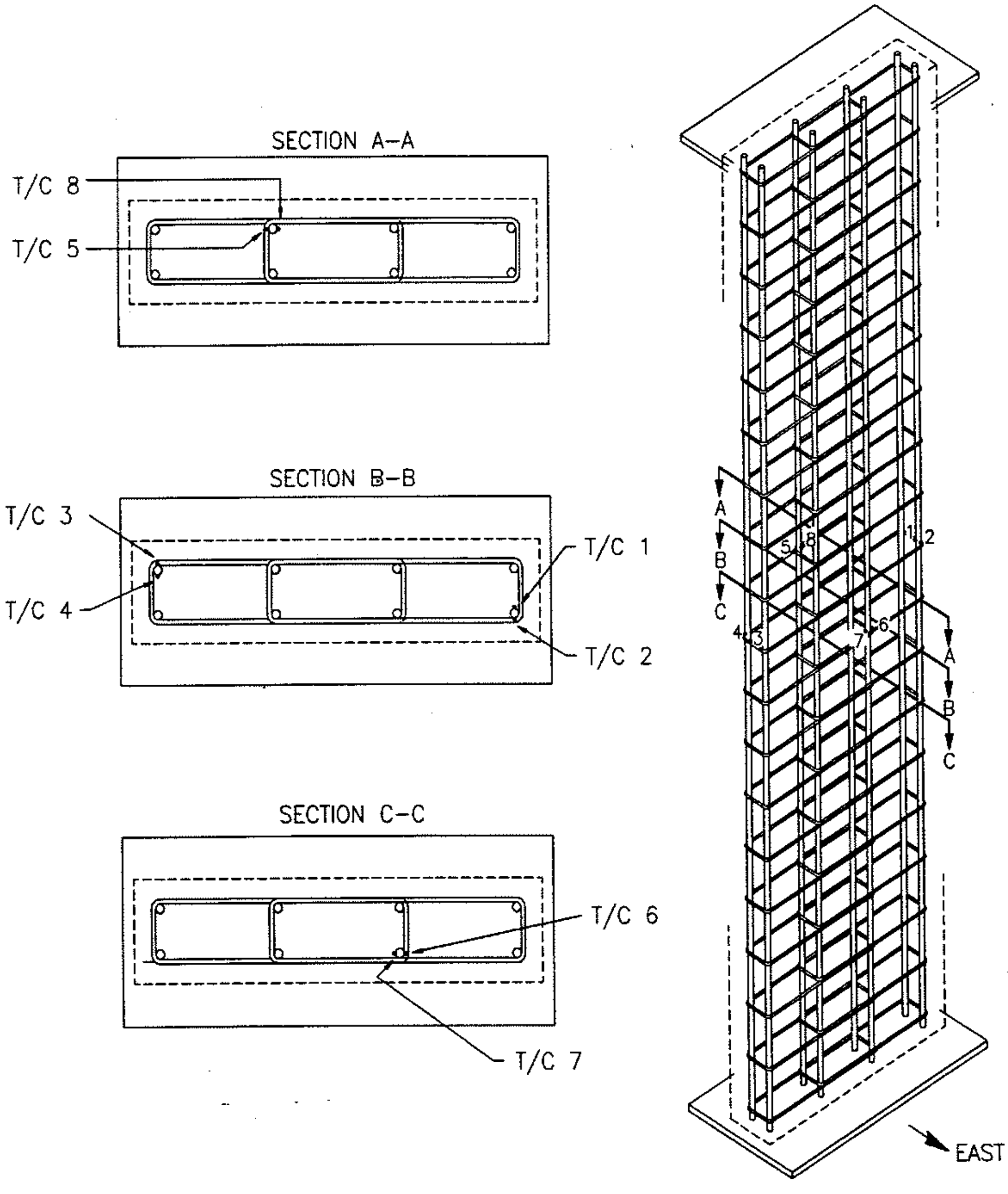

Figure 16. Locations of T/C's on Steel Bars: Column 6

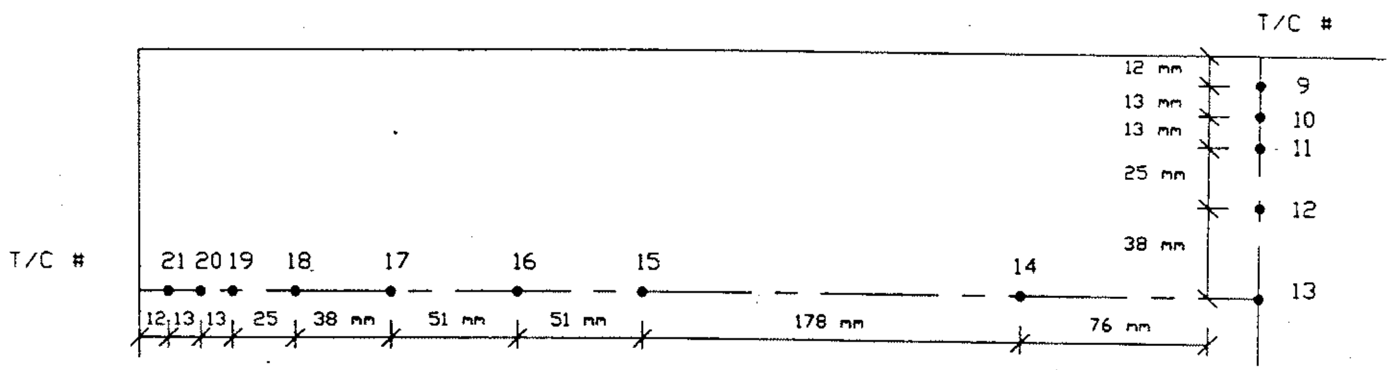

Figure 17. Locations of T/C's at Mid-Height Section: Column 6

Figure 18. Column 6 After Test

Table 18. Axial Deformation, Column 6

Time (min)	Expansion (mm)
0	0.0
10	0.0
20	0.9
30	1.4
40	1.6
50	1.7
60	1.7
70	1.7
80	1.7
90	1.7
100	1.6
110	1.3
120	0.7
130	-0.1
140	-1.3
150	-2.9
160	-5.0
170	-7.8
176	-9.8

Table 19. Steel Bar Temperatures, Column 6

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	5	6	7	8	Furnace Temperature (°C)
0	18	18	18	18	18	17	17	18	20
10	50	51	46	44	33	39	39	33	703
20	117	123	121	118	99	93	94	92	801
30	123	126	122	118	128	123	125	125	873
40	153	156	166	161	146	134	135	142	911
50	199	204	222	215	181	160	162	175	944
60	246	254	275	267	217	194	197	211	968
70	292	302	324	315	249	227	230	243	994
80	338	348	370	361	280	259	262	274	1016
90	382	393	413	404	311	295	298	304	1032
100	424	435	454	445	341	331	334	335	1048
110	463	474	492	483	372	365	368	366	1068
120	498	509	526	517	402	396	399	396	1072
130	529	540	556	548	430	426	428	425	1088
140	558	567	584	576	458	454	455	452	1093
150	586	592	606	601	484	479	480	478	1108
160	606	614	630	624	508	503	504	503	1117
170	626	633	650	644	531	525	526	529	1127
176	636	644	201	---	543	538	540	539	1129

Table 20. Concrete Temperatures, Column 6

Time (min)	Temperatures (°C) Measured at Thermocouple #: 9	10	11	12	13	14	15	16	17	18	19	20	21	Furnace Temperature (°C)
0	23	20	18	17	17	17	17	17	17	17	18	18	19	20
10	218	121	86	34	19	19	18	19	20	25	44	79	106	703
20	379	237	132	90	39	40	42	41	47	73	105	122	198	801
30	485	334	191	116	77	77	81	79	79	97	117	125	280	873
40	556	401	244	129	121	112	125	120	106	111	113	143	317	911
50	602	451	291	139	126	128	125	125	122	122	146	208	387	944
60	642	495	336	178	122	125	120	123	125	141	196	274	447	968
70	672	529	374	214	123	131	121	129	131	170	252	330	494	994
80	707	564	409	245	132	152	129	143	150	215	304	383	536	1016
90	739	593	445	280	183	192	158	171	191	263	354	432	573	1032
100	762	622	479	316	221	229	195	207	237	309	401	478	605	1048
110	795	649	510	350	256	263	231	245	279	353	444	518	634	1068
120	814	674	539	383	291	296	266	282	319	392	483	553	660	1072
130	837	697	565	414	324	327	301	318	356	429	517	583	685	1088
140	853	718	589	443	355	357	334	351	391	463	547	610	708	1093
150	875	741	611	470	384	385	364	382	422	493	574	633	728	1108
160	887	761	632	496	411	411	393	411	452	521	598	654	746	1117
170	904	779	652	520	435	435	419	437	482	545	618	673	762	1127
176	908	790	665	534	451	444	428	454	495	605	625	680	767	1129

5.7 Column 7

Specimen Properties

Cross-Section: 305 × 305 mm
Length: 3810 mm
Aggregate: Siliceous
Reinforcement: 2.533% as 6 ϕ22 mm bars
Elevation, Cross-Section and Finishing Detail: Figure 19
Locations of T/C's on Steel Bars: Figure 4
Locations of T/C's at Mid-Height Section: Figure 5

Measured Properties

Concrete Cube Strength: 32.90 MP on test date
Relative Humidity: 95.1%
Actual Loading: 910 KN, Concentric; 49 KN, Eccentric

Test Results

Test Duration: 41 minutes
Axial Deformation: Table 21
Steel Bar Temperatures: Table 22
Concrete Temperatures: Table 23

Observations

0:30 Small cracks developed on the north face.
0:38 Two cracks about 5 cm in length and 0.3 cm in width were visible on the north face.
0:41 The column buckled and failed (Figure 20).

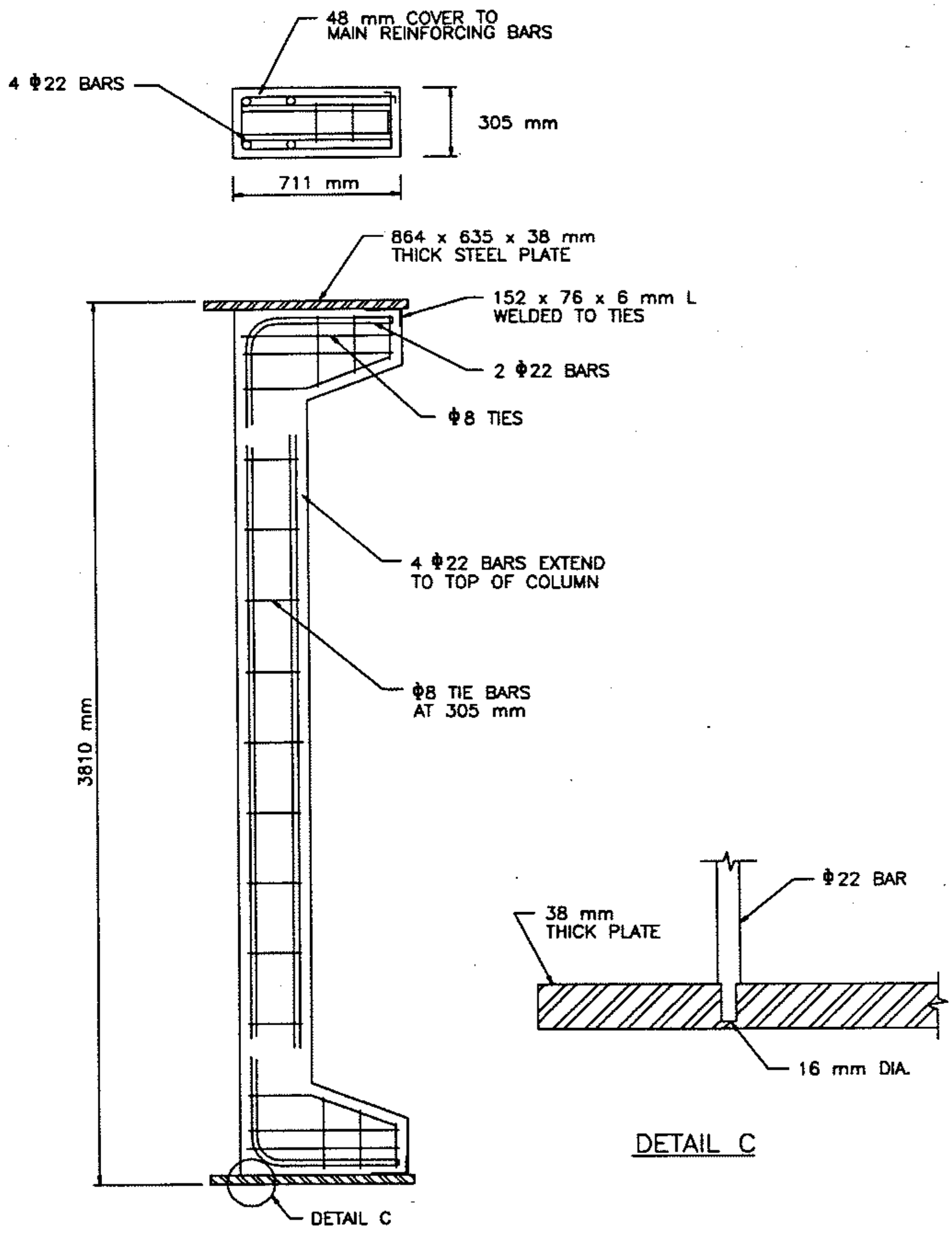

Figure 19. Elevation, Cross-Section and Finishing Detail: Column 7

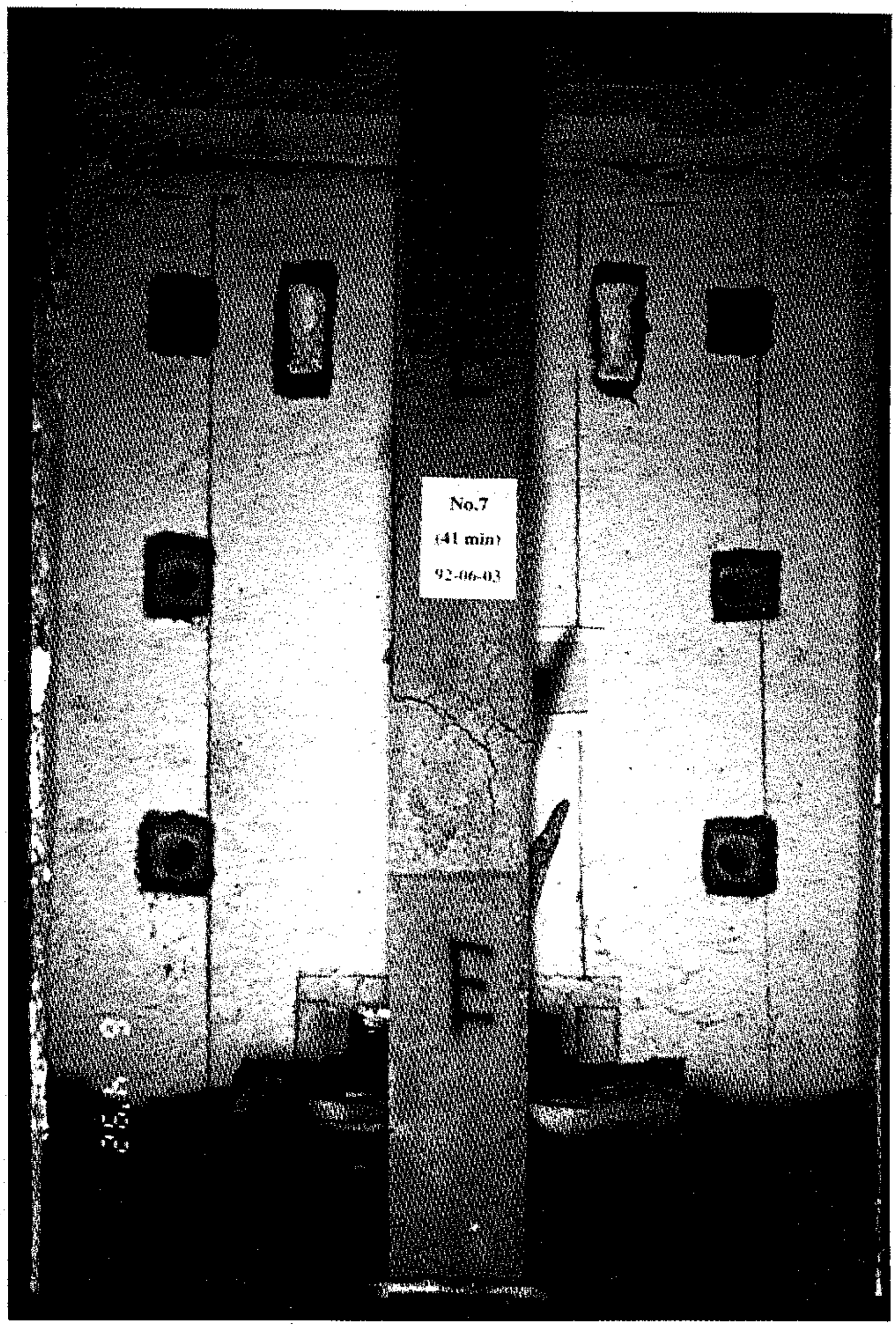

Figure 20. Column 7 After Test

Table 21. Deformation, Column 7

Time (min)	Expansion (mm)	Rotation of Top (°)	Rotation of Bottom (°)
0	0.0	0.00	0.00
4	0.0	0.01	0.00
8	0.0	0.08	0.02
10	0.3	0.11	0.03
14	0.9	0.19	0.08
18	1.3	0.30	0.13
20	1.4	0.33	0.15
24	1.4	0.38	0.18
28	1.4	0.44	0.21
30	1.4	0.50	0.24
34	1.4	0.59	0.30
38	1.0	0.76	0.40
40	0.0	0.99	0.55
41	-16.6	----	----

Table 22. Steel Bar Temperatures, Column 7

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	Furnace Temperature (°C)
0	19	19	19	19	20
4	21	21	21	20	611
8	36	37	34	32	690
10	50	52	48	44	717
14	104	104	84	79	760
18	111	111	99	96	797
20	111	110	104	101	808
24	111	112	105	105	840
28	120	123	108	106	870
30	128	130	112	109	881
34	144	146	124	119	891
38	160	163	139	133	901
40	168	171	147	141	908

Table 23. Concrete Temperatures, Column 7

Time (min)	Temperatures (°C) Measured at Thermocouple #: 5	6	7	8	9	10	11	12	13	14	15	Furnace Temperature (°C)
0	21	19	19	19	19	19	19	19	19	19	19	20
4	115	42	28	20	19	19	19	19	23	42	84	611
8	196	87	57	27	19	19	19	25	43	90	113	690
10	236	102	73	33	20	19	20	30	57	101	142	717
14	309	123	97	47	24	19	23	48	87	123	199	760
18	367	157	115	65	30	21	29	65	101	153	248	797
20	390	172	118	76	35	23	33	70	101	169	267	808
24	431	202	131	89	46	29	41	78	104	189	291	840
28	468	233	155	94	58	37	50	84	102	210	316	870
30	487	249	169	98	62	42	54	87	102	222	331	881
34	519	278	193	99	70	50	62	91	108	246	359	891
38	547	305	215	101	76	59	70	98	127	271	386	901
40	559	318	227	101	79	63	73	100	137	283	399	908

REFERENCES

1. Reinforced Concrete Structures Design Code (TJ10-74), The China Construction Industry Publishing House, 1974.
2. Reinforced Concrete Structures, Tianjin University, Tongji University, The China Construction Industry Publishing House, 1987.
3. Building Materials, Hunan University, The China Construction Industry Publishing House, 1987.
4. Lie, T. T. and Woollerton, J. L., Fire Resistance of Reinforced Concrete Columns-Test Results, National Research Council Canada, Institute for Research in Construction, Internal Report No.569, Ottawa, Ontario, 1988.
5. Lie, T. T. and Irwin, R. J., Evaluation of the Fire Resistance of Reinforced Concrete Columns with Rectangular Cross-Section, National Research Council Canada, Institute for Research in Construction, Internal Report No.601, Ottawa, Ontario, 1990.
6. Lie, T. T., New Facility to Determine Fire Resistance of Columns, Canadian Journal of Civil Engineering, Vol. 7, 1980.
7. Fire Resistance Tests-Elements of Building Construction, ISO-834, International Organization for Standardization, 1975.