Fire resistance of reinforced concrete columns: experimental studies (conducted at TFRI)

Wu, H. J.; Lie, T. T.; Han, Q. F.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20359155
Internal Report (National Research Council of Canada. Institute for Research in Construction), 1993-03

National Research Council Canada
Conseil national de recherches Canada

Institute for Research in Construction
Institut de recherche en construction

NRC·CNRC

Fire Resistance of Reinforced Concrete Columns — Experimental Studies (Conducted at TFRI)

by H.J. Wu, T.T. Lie and Q.F. Han

Internal Report No. 638

Date of issue: March 1993

Canada

FIRE RESISTANCE OF REINFORCED CONCRETE COLUMNS - EXPERIMENTAL STUDIES (CONDUCTED AT TFRI)

1 INTRODUCTION

As 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, two tests were carried out on reinforced concrete columns at TFRI.

The main purpose of these tests was to verify the characteristics of the newly built column furnace at TFRI and to provide data for the evaluation 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 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 TFRI.

2 TEST SPECIMENS

In this joint project, nine reinforced concrete columns, which had different dimensions, aggregates and bearing capacities, were fabricated at TFRI. Seven of them were tested at the NFL in the Spring of 1992. This report describes two tests conducted at TFRI.

In order to determine the fire performance of concrete columns that are widely used in China, the design methods and construction technologies 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 two columns, which were respectively similar to Column Nos. 5 and 7 tested at the NFL [4], are illustrated in Table 1 and Figures 3 and 7. Details of the specimens are given below.

2.1 Dimensions

The columns were 3810 mm long from end plate to end plate. Column No. 1 had a rectangular cross-section of 305 × 457 mm; Column No. 2 had a square cross-section of 305 × 305 mm. In order to be able to apply an eccentric load, Column No. 2 had brackets at the ends consisting of a horizontal overhang of steel plate with reinforced concrete underneath.

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 (σ_s = 240 MPa, σ_b = 380 MPa).

2.2.2 Concrete

The details of the concrete mixes used 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 vary from 10 mm to 40 mm. The fine aggregate was siliceous sand.
- Concrete Mixes: The concrete mixes were designed to produce a 25 MPa 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. The diameter of the thermocouple wire was 0.8 mm. The exact locations and numbering of the thermocouples are shown in Figures 4, 5, 8 and 9.

2.3 Fabrication

The columns were cast in forms which were made of steel plate and were of a 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 using a T-42 welding rod. 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 in order to measure the column's mid-depth relative humidity.

3. TEST APPARATUS

The test was carried out by exposing the column to heat in a furnace built for testing loaded columns. The test furnace was designed to produce the conditions to which a member might be exposed to 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 1 is a photograph of the furnace. The characteristics and the instrumentation of the furnace are described below.

3.1 Furnace Chamber

The furnace chamber has a floor area of 2588 × 2588 mm. The height of the chamber can be changed from 3000 mm to 4200 mm. The interior faces of the chamber are lined with a ceramic fibre material that efficiently transfers heat to the specimen. There are 16 diesel oil burners in the furnace chamber. Each burner can be adjusted individually, which allows for a high degree of temperature uniformity in the furnace chamber.

3.2 Loading Device

A hydraulic jack with a capacity of 4900 kN produces the concentric load along the axis of a test column. The jack is located at the bottom of the furnace chamber. Eccentric loads are applied by means of other hydraulic jacks, one at the top and one at the bottom of the column, located at a distance of 510 mm from the axis of the column. The capacity of the jacks is 294 kN.

3.3 Instrumentation

The furnace temperatures were measured with the aid of seven chromel-alumel thermocouples. The junction of each thermocouple was located 100 mm from the test column, at various heights in the furnace chamber. The locations of the junctions and their numbering are shown in Figure 2. The temperatures measured by the seven thermocouples are averaged automatically and the average temperature used as the criterion for controlling the furnace temperature.

The loads are measured and controlled using hydraulic pressure transducers. The accuracy of measuring and controlling loads is about ±4.5 kN.

The axial deformation of a test column is determined by measuring the displacement of the concentric loading jack. The displacement is measured using a transducer with an accuracy of 0.002 mm.

4 TEST CONDITIONS AND PROCEDURES

4.1 Restraint Conditions

One of the columns was tested with both ends of the column 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 other 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

One of the columns was tested under a concentric load. The other column was tested under a concentric main load and a smaller eccentric load at 510 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 30 minutes before the start of each test, until a condition was reached at which no further increase in 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 [5] 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 two tests was approximately 20°C.

4.4 Failure Criterion

The columns were considered to have failed, and the tests were terminated, when the axial hydraulic jack, which has a maximum speed of 20 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 1 min intervals.

The results of the two tests are summarized in Table 2, in which column concrete strengths, test conditions, fire resistances and failure modes are given for each column. In this Table, the fire resistances of similar columns tested at NRC are also given.

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 8. A positive axial deformation value indicates expansion of the column. Photographs of the columns after the tests are given in Figures 6 and 10.

5 TEST DESCRIPTIONS AND RESULTS

5.1 Comparison of TFRI and NRC Test Results

The results show that there is a substantial difference in the fire resistances of the eccentrically-loaded columns between the columns tested at TFRI and NRC. The fire resistance of the column tested at TFRI was 2 hours whereas that of the column tested at NRC was 41 minutes. An examination of the test results, reported in Ref. 4, shows that the column tested at NRC failed prematurely, due to the sudden formation of large cracks in the specimen followed by failure during the test. This behaviour was not observed during the test at TFRI. Therefore, the results of the two tests on eccentrically-loaded columns cannot be compared.

The results of the tests on the columns with a cross-section of 305×457 mm showed that the fire resistance of the column measured at TFRI is somewhat higher than that measured on a similar column at NRC. The difference is about 10%, which may be regarded as small and indicates that the performance of the TFRI column furnace is comparable to that of the NRC column furnace.

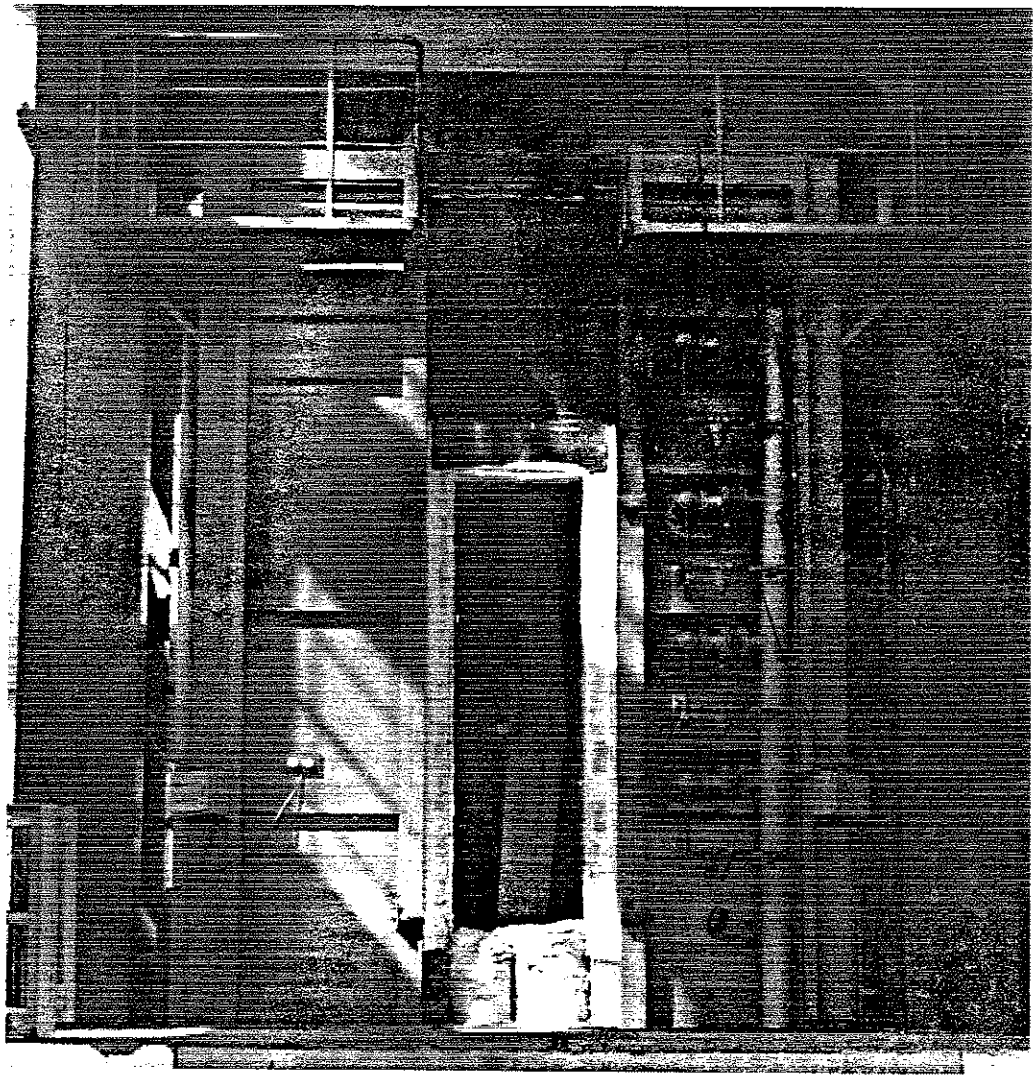
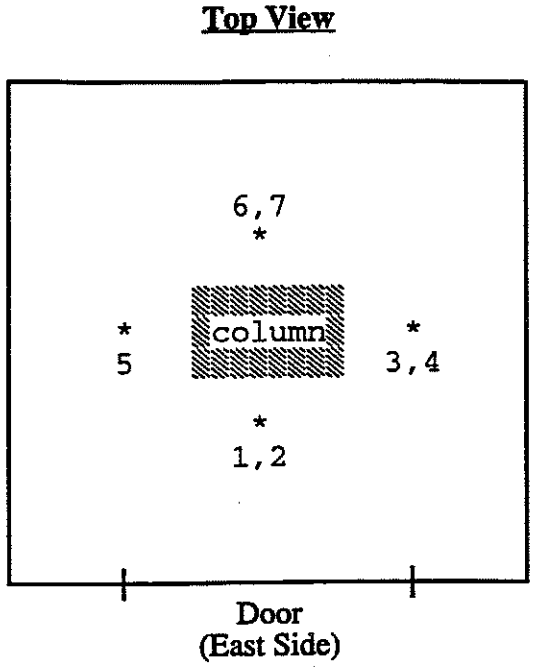


Figure 1. Column Furnace at TFRI



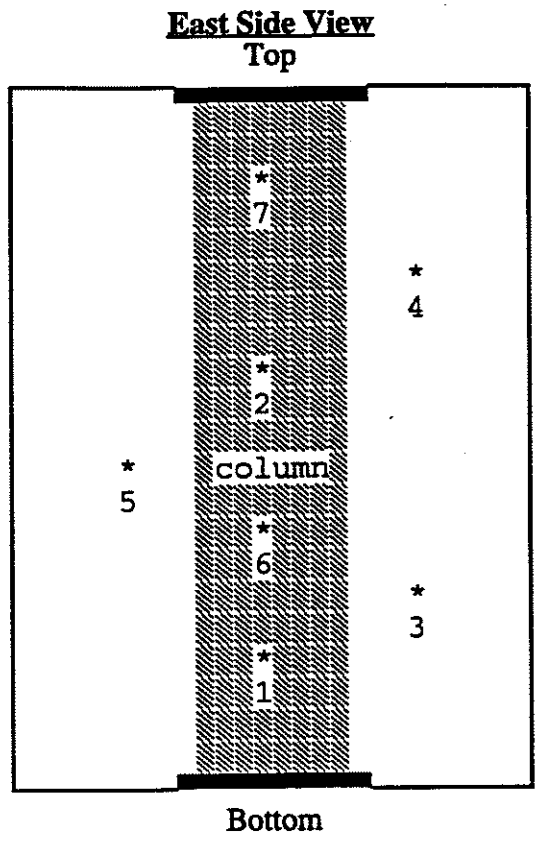


Figure 2. Thermocouple Locations for Furnace Temperatures (TFRI)

Table 1. Summary of Design Parameters of the Columns (TFRI)

Column No.	Dimensions (mm)	Aggregate	Steel (%)	Concrete Design Strength (MPa)*	Design Load (kN)
1	305 x 457 x 3810	Carbonate	1.862	25	1585
2	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 (TFRI)

Column No.	Concrete Tested Strength (MPa)*	Relative Humidity(%)	Actual Load (kN)	Failure Mode	Failure Time(hr:min)
1	31.30	86.7	1585	Compression	4:16 3:52**
2	29.50	92.4	910 (axial) 49(eccentric)	Buckling	2:00 0:41**

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

** Failure time of similar columns, tested at NRC

5.2 Column 1

Specimen Properties

Cross-Section: 305 × 457 mm
Length: 3810 mm
Aggregate: Carbonate
Reinforcement: 1.862% as 8ϕ20 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: 31.32 MPa on test date
Relative Humidity: 86.7%
Actual Loading: 1585 kN, Concentric

Test Results

Test Duration: 4 hours 16 minutes
Axial Deformation: Table 3
Steel Bar Temperatures: Table 4
Concrete Temperatures: Table 5

Observations

1:30 Small cracks developed on the column faces.
3:00 Some concrete crushed at the mid-height section.
3:12 More small cracks developed.
4:16 The column broke and the main steel bars buckled at the mid-height section.
4:17 The column failed in compression (Figure 6).

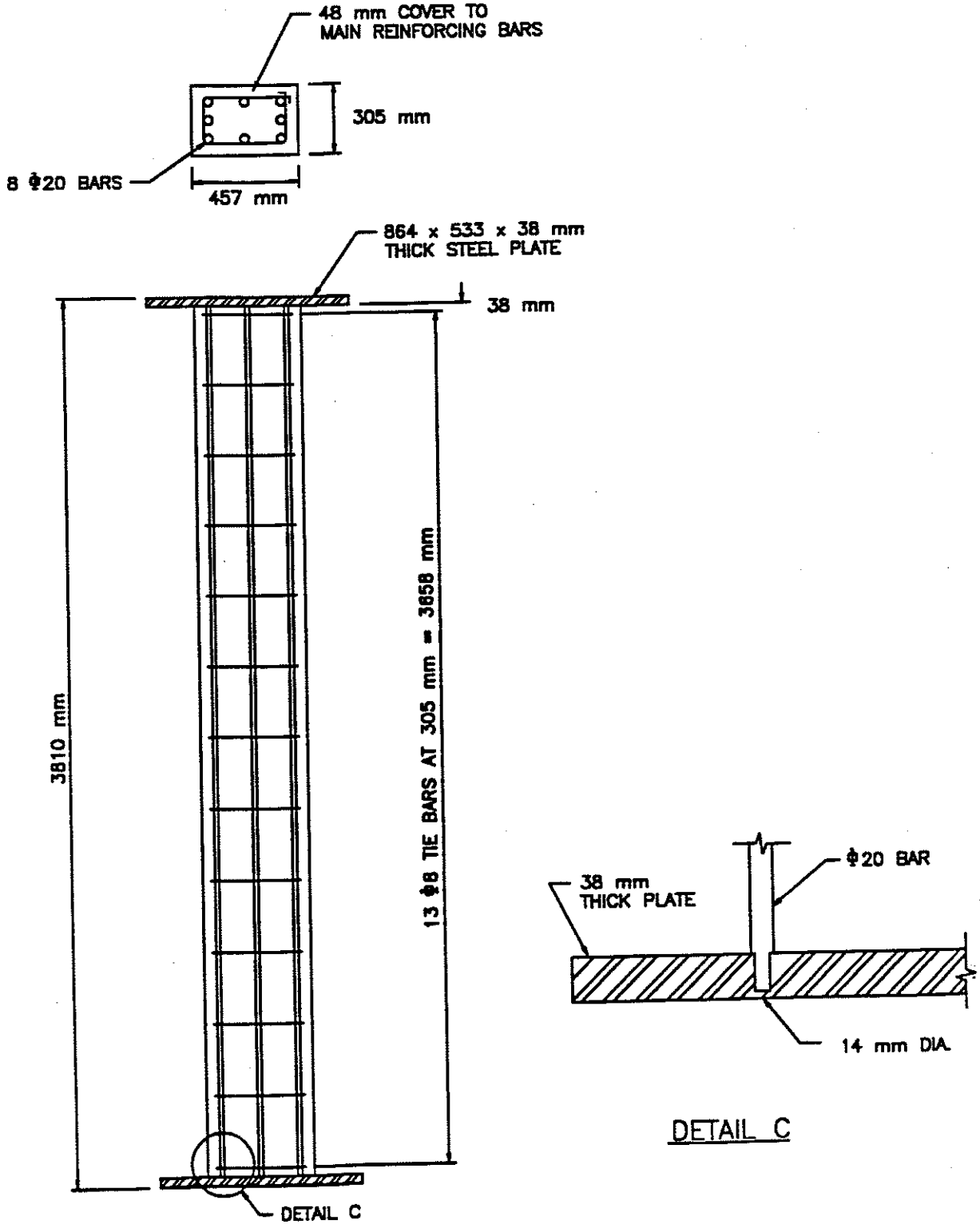


Figure 3. Elevation, Cross-Section and Finishing Detail: Column 1 (TFRI)

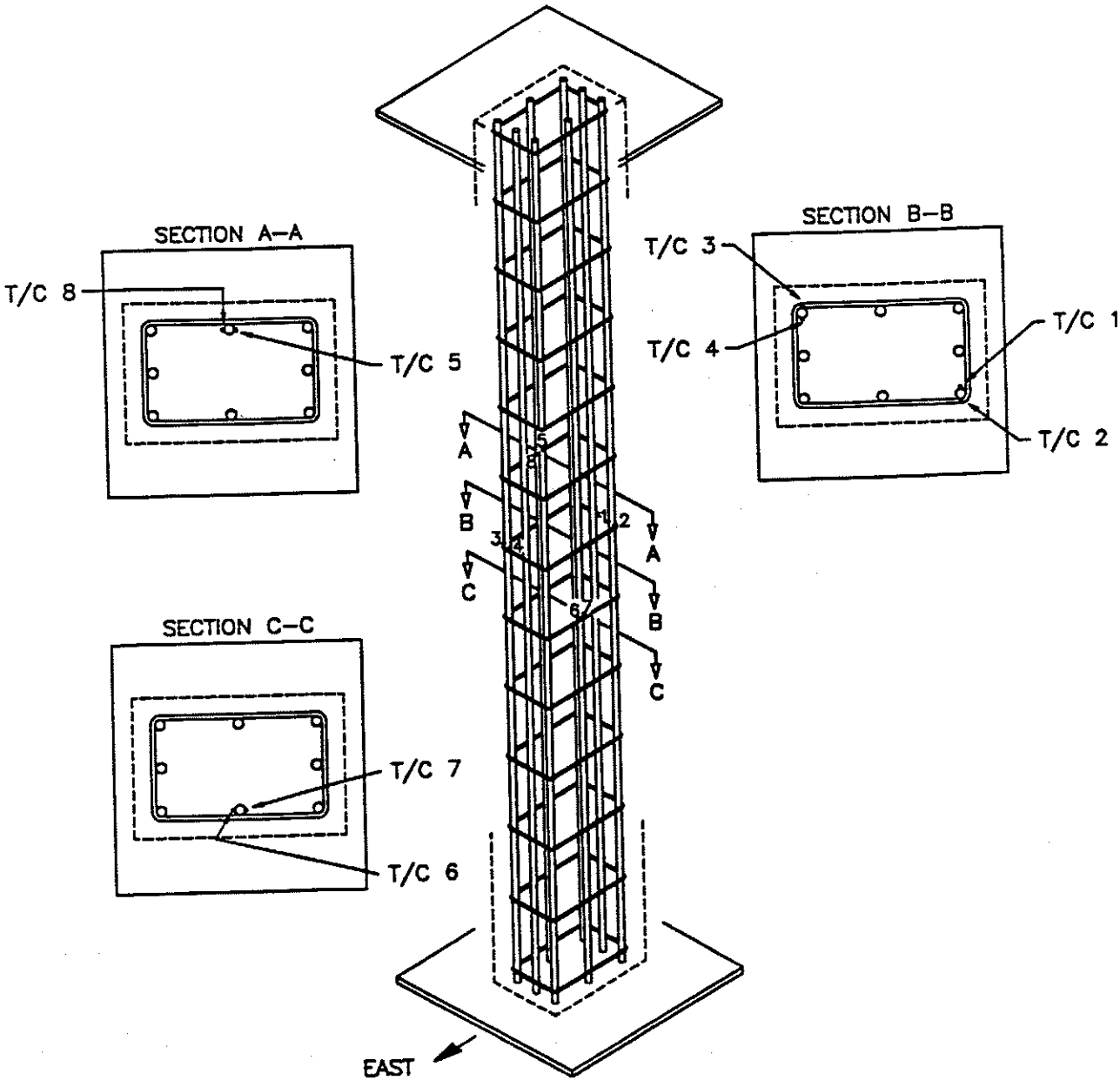


Figure 4. Locations of Thermocouples on Steel Bars Column 1 (TFRI)

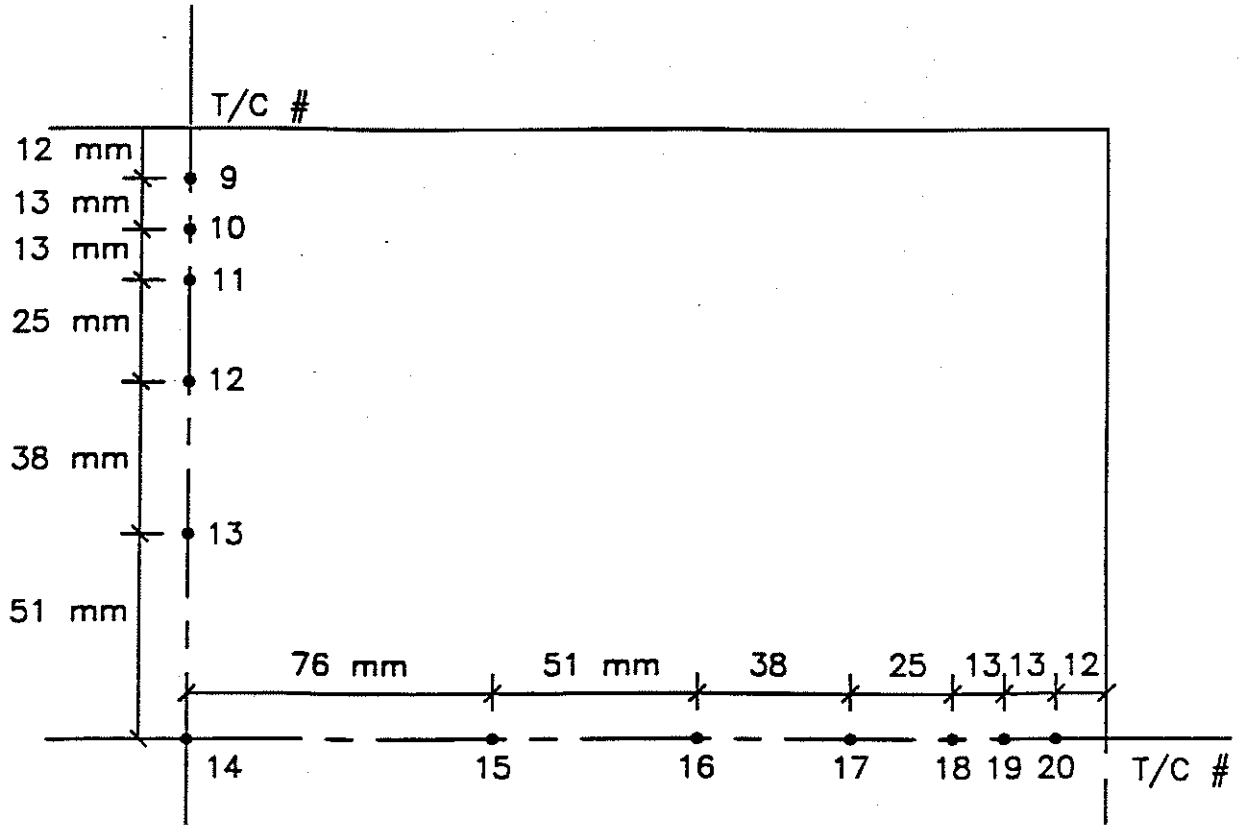


Figure 5. Locations of Thermocouples at Mid-Height Section: Column 1 (TFRI)

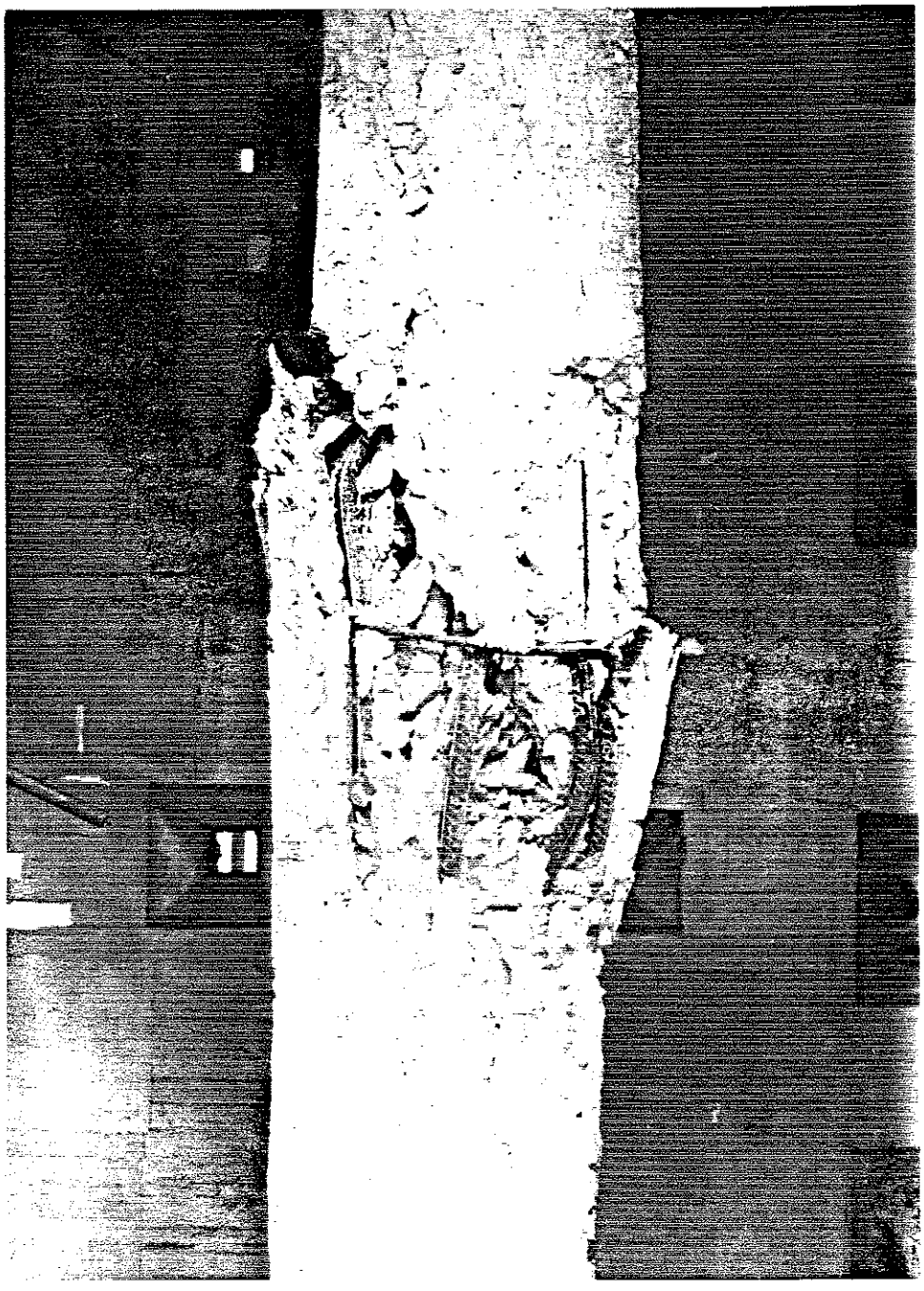


Figure 6. Column 1 After Test (TFRI)

Table 3. Axial Deformation, Column 1 (TFRI)

Time (min)	Expansion (mm)
0	0.0
10	0.3
20	0.9
30	1.2
40	1.5
50	1.9
60	2.1
70	2.1
80	2.1
90	2.0
100	2.0
110	1.9
120	1.8
130	1.7
140	1.5
150	1.3
160	1.0
170	0.7
180	0.4
190	-0.1
200	-0.7
210	-1.5
220	-2.3
230	-3.4
240	-4.7
250	-6.4
256	-7.8

Table 4. Steel Bar Temperatures, Column 1 (TFRI)

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	5	6	7	8	Furnace Temperature (°C)
0	32	32	32	32	32	32	32	32	32
10	90	98	92	82	68	55	57	68	664
20	107	110	107	106	117	110	111	114	787
30	118	124	119	116	117	119	122	112	846
40	154	172	163	149	133	150	153	123	886
50	200	223	213	195	185	186	191	183	919
60	253	269	259	247	238	220	226	236	949
70	303	312	303	296	278	252	259	275	968
80	347	352	342	340	312	382	289	309	991
90	385	388	378	378	342	309	315	339	1010
100	418	420	411	411	368	333	340	364	1022
110	448	450	441	440	390	355	362	387	1041
120	475	477	468	467	410	376	382	407	1052
130	500	502	494	492	429	394	401	425	1064
140	523	526	517	515	446	412	418	442	1079
150	544	547	539	537	463	429	435	459	1085
160	563	566	558	556	478	444	450	475	1096
170	582	584	577	575	494	459	465	490	1108
180	599	601	593	592	508	474	480	505	1115
190	615	616	609	608	522	489	494	519	1121
200	630	630	623	623	536	503	508	533	1128
210	644	644	637	637	548	517	522	546	1142
220	657	657	650	650	562	530	534	558	1150
230	670	670	663	662	573	542	546	570	1161
240	682	683	675	674	584	554	558	582	1165
250	694	694	687	685	595	565	569	592	1164
256	701	701	693	693	601	572	576	598	1170

Table 5. Concrete Temperatures, Column 1 (TFRI)

Time (min)	Temperatures (°C) Measured at Thermocouple #: 9	10	11	12	13	14	15	16	17	18	19	20	Furnace Temperature (°C)
0	32	32	32	32	32	32	32	32	32	32	32	32	32
10	163	121	91	46	33	32	32	32	41	79	112	162	664
20	353	186	116	104	66	37	34	41	72	111	151	274	787
30	461	290	165	106	93	71	45	57	90	128	218	348	846
40	531	354	208	106	102	97	62	71	100	189	285	412	886
50	579	400	252	106	103	100	80	86	112	231	335	462	919
60	618	444	303	130	103	101	94	103	131	267	376	503	949
70	653	484	348	178	103	102	103	106	151	300	410	536	968
80	682	518	387	222	106	102	103	116	173	330	441	564	991
90	709	547	419	257	117	102	106	123	196	358	468	589	1010
100	733	571	446	286	136	102	110	132	221	384	494	613	1022
110	751	592	469	310	158	104	115	146	247	409	518	633	1041
120	772	610	490	332	177	107	119	164	273	433	539	653	1052
130	791	628	510	351	195	113	128	185	298	456	560	671	1064
140	807	643	527	370	211	122	144	208	322	478	579	688	1079
150	822	658	543	387	228	141	166	231	346	499	597	704	1085
160	836	672	559	405	246	161	189	254	368	519	614	719	1096
170	850	686	573	422	265	184	210	276	390	537	630	734	1108
180	863	700	588	440	285	207	231	297	411	554	645	750	1115
190	874	713	602	457	305	228	251	318	431	571	659	762	1121
200	885	725	615	473	324	248	271	338	450	586	673	776	1128
210	895	738	627	488	342	267	290	358	469	601	687	789	1142
220	902	747	638	503	359	286	309	376	486	615	699	799	1150
230	914	759	649	517	377	305	327	394	502	628	711	811	1161
240	927	771	660	530	393	322	344	411	518	641	724	824	1165
250	939	782	671	543	409	339	361	427	532	654	736	834	1164
256	957	793	679	550	417	348	371	436	540	661	744	844	1170

5.3 Column 2

Specimen Properties

Cross-Section: 305 x 305 mm
Length: 3810 mm
Aggregate: Siliceous
Reinforcement: 2.533% as 6ϕ22 mm bars
Elevation, Cross-Section and Finishing Detail: Figure 7
Locations of T/C's on Steel Bars: Figure 8
Locations of T/C's at Mid-Height Section: Figure 9

Measured Properties

Concrete Cube Strength: 29.50 MPa on test date
Relative Humidity: 92.4%
Actual Loading: 910 kN, Concentric; 49 kN, Eccentric

Test Results

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

Observations

0:38 Small cracks developed on the east face.
1:00 One crack about 0.6 cm in width was visible on the south face.
1:30 Maximum cracks on the south face reached 1.5 cm in width.
2:00 The column buckled and failed (Figure 10).

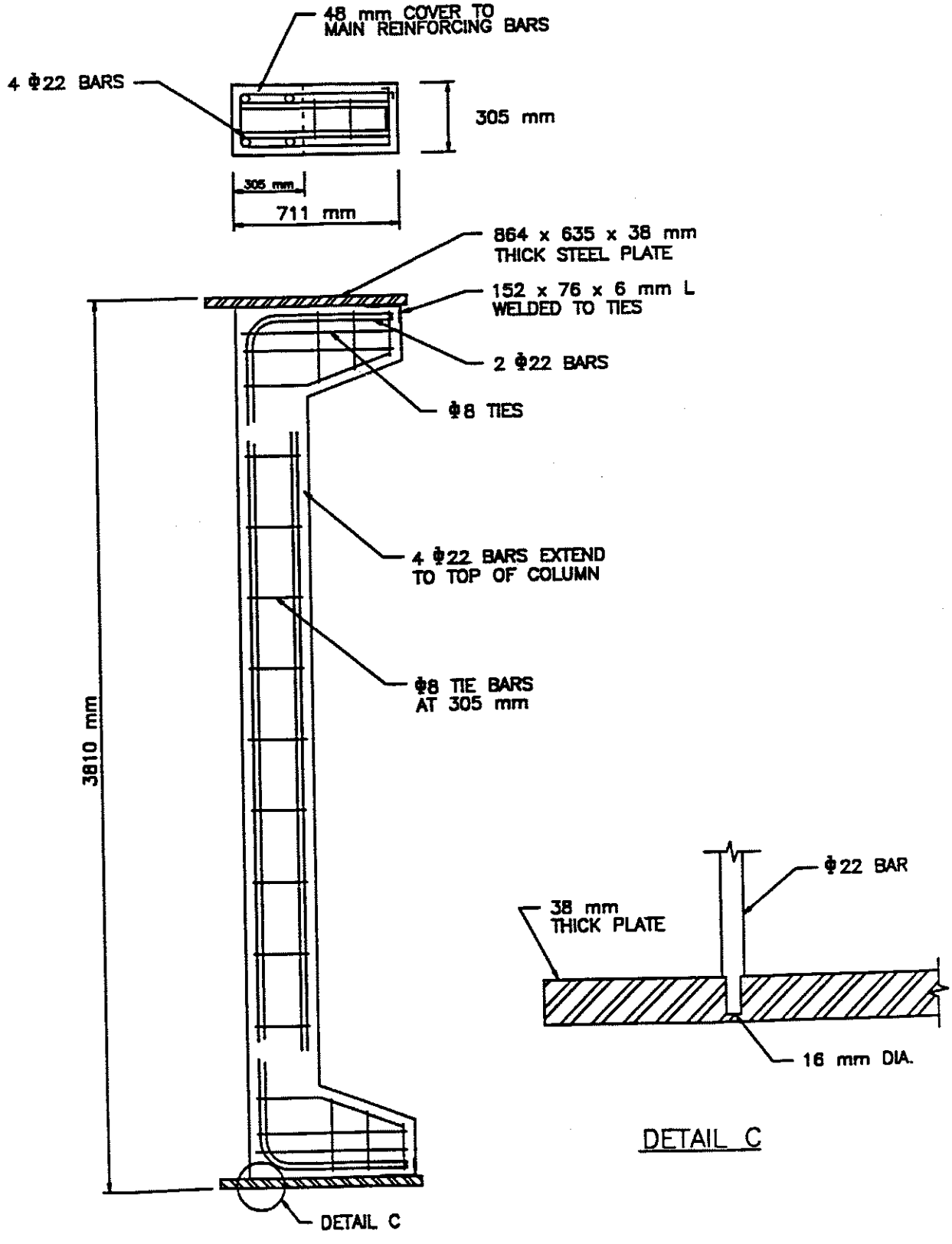


Figure 7. Elevation, Cross-Section and Finishing Detail: Column 2 (TFRI)

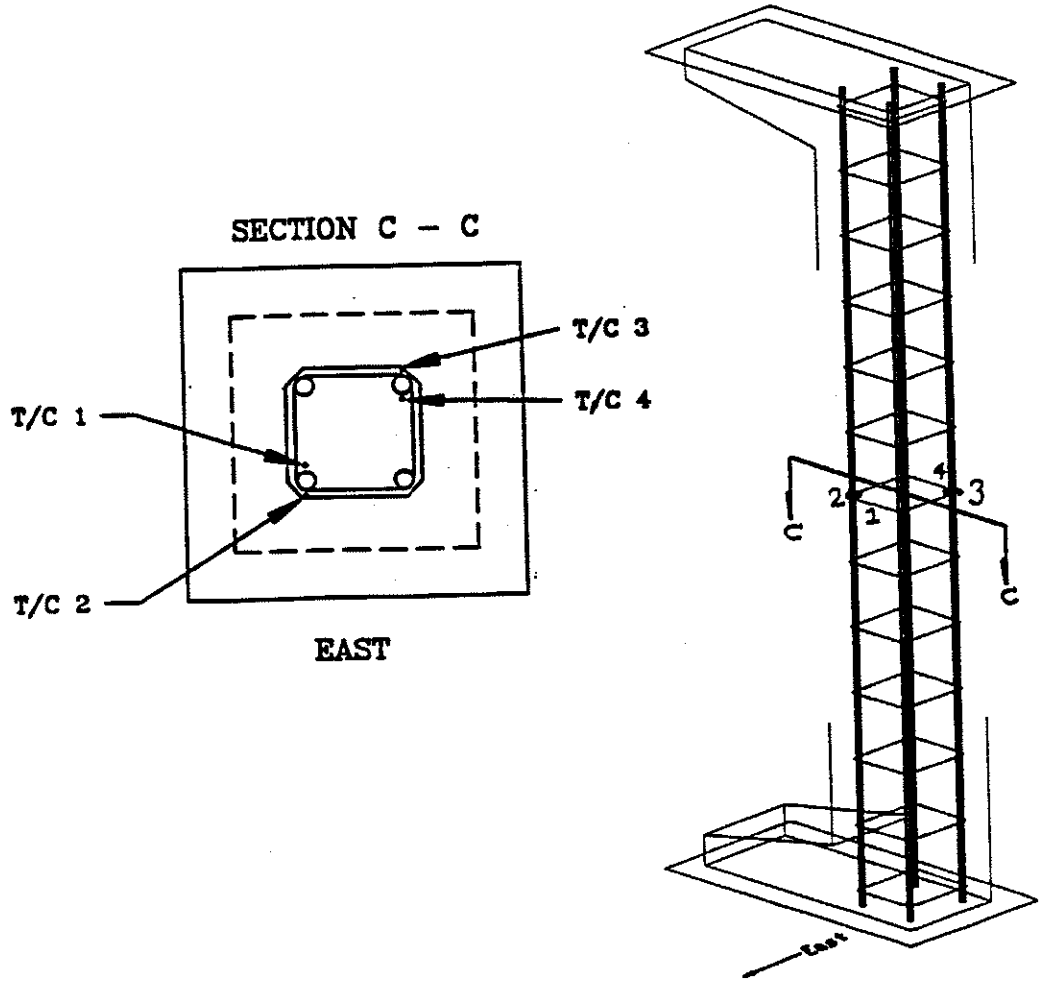


Figure 8. Locations of Thermocouples on Steel Bars Column 2 (TFRI)

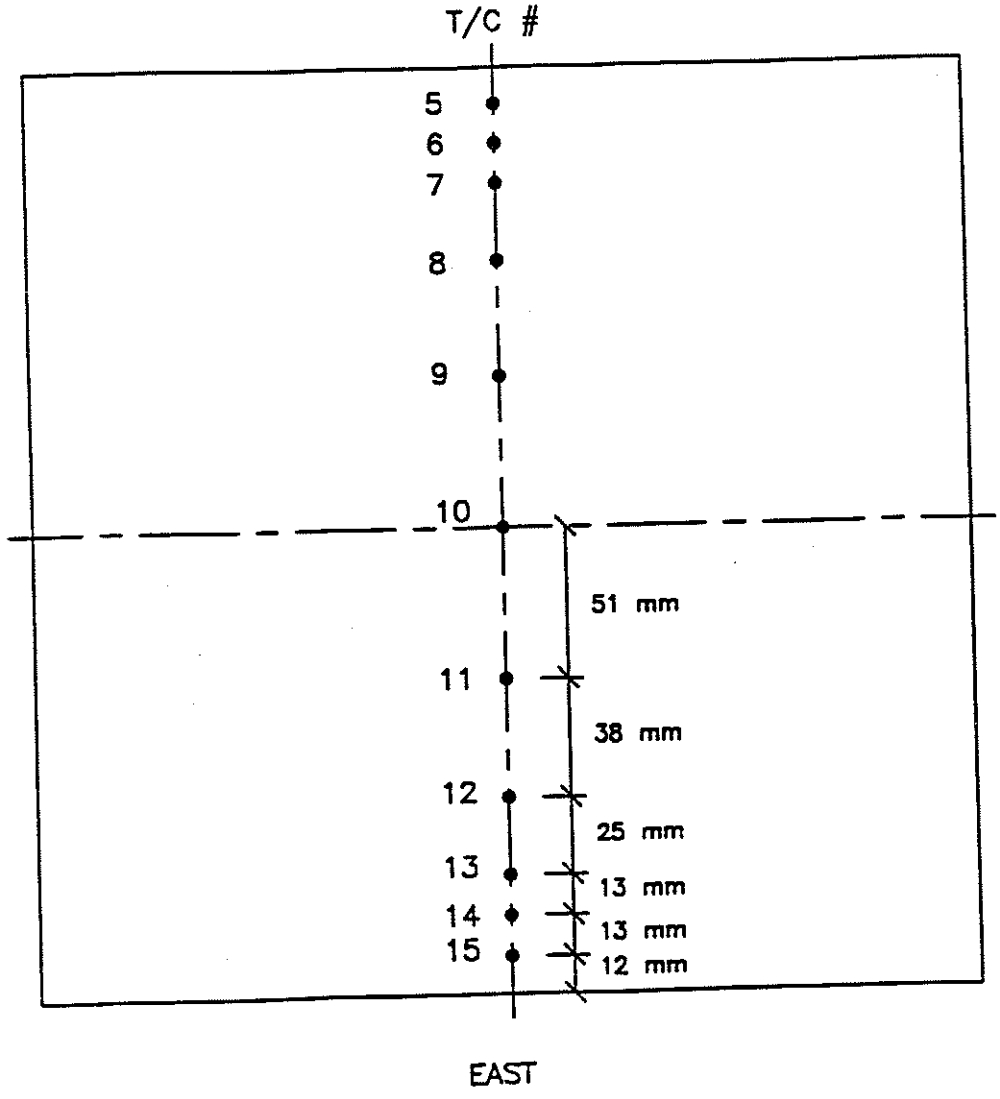


Figure 9. Locations of Thermocouples at Mid-Height Section: Column 2 (TFRI)

Table 6. Axial Deformation, Column 2 (TFRI)

Time (min)	Expansion (mm)
0	0.0
10	0.7
20	1.8
30	1.9
40	2.4
50	2.9
60	3.3
70	3.6
80	3.6
90	3.6
100	3.6
110	3.3
120	1.2

Table 7. Steel Bar Temperatures, Column 2 (TFRI)

Time (min)	Temperatures (°C) Measured at Thermocouples #: 1	2	3	4	Furnace Temperature (°C)
0	29	29	29	29	29
10	84	94	86	91	679
20	108	108	114	116	782
30	119	119	152	166	842
40	150	152	213	231	885
50	192	194	276	298	918
60	234	237	338	361	945
70	275	279	394	418	969
80	315	319	445	469	989
90	353	358	491	515	1006
100	390	395	534	557	1022
110	425	432	574	596	1036
120	458	465	613	624	1049

Table 8. Concrete Temperatures, Column 2 (TFRI)

Time (min)	Temperatures (°C) Measured at Thermocouple #: 5	6	7	8	9	10	11	12	13	14	15	Furnace Temperature (°C)
0	29	29	29	29	29	29	29	29	29	29	29	29
10	239	138	98	54	32	30	31	51	96	138	258	557
20	370	234	138	89	53	39	53	88	119	244	400	675
30	443	305	198	100	73	59	75	101	177	325	485	787
40	502	365	255	112	88	76	86	100	223	381	536	847
50	548	411	298	136	100	90	94	119	265	426	581	890
60	585	450	333	162	107	99	99	153	308	473	629	925
70	609	478	364	189	118	105	100	188	349	518	675	953
80	645	512	396	217	131	104	110	221	388	560	713	994
90	687	551	431	246	151	106	124	254	424	599	746	1012
100	725	591	468	277	175	114	146	287	460	635	774	1029
110	760	629	505	311	201	129	173	321	495	666	800	1043
120	790	665	541	345	225	161	203	358	528	695	824	1049

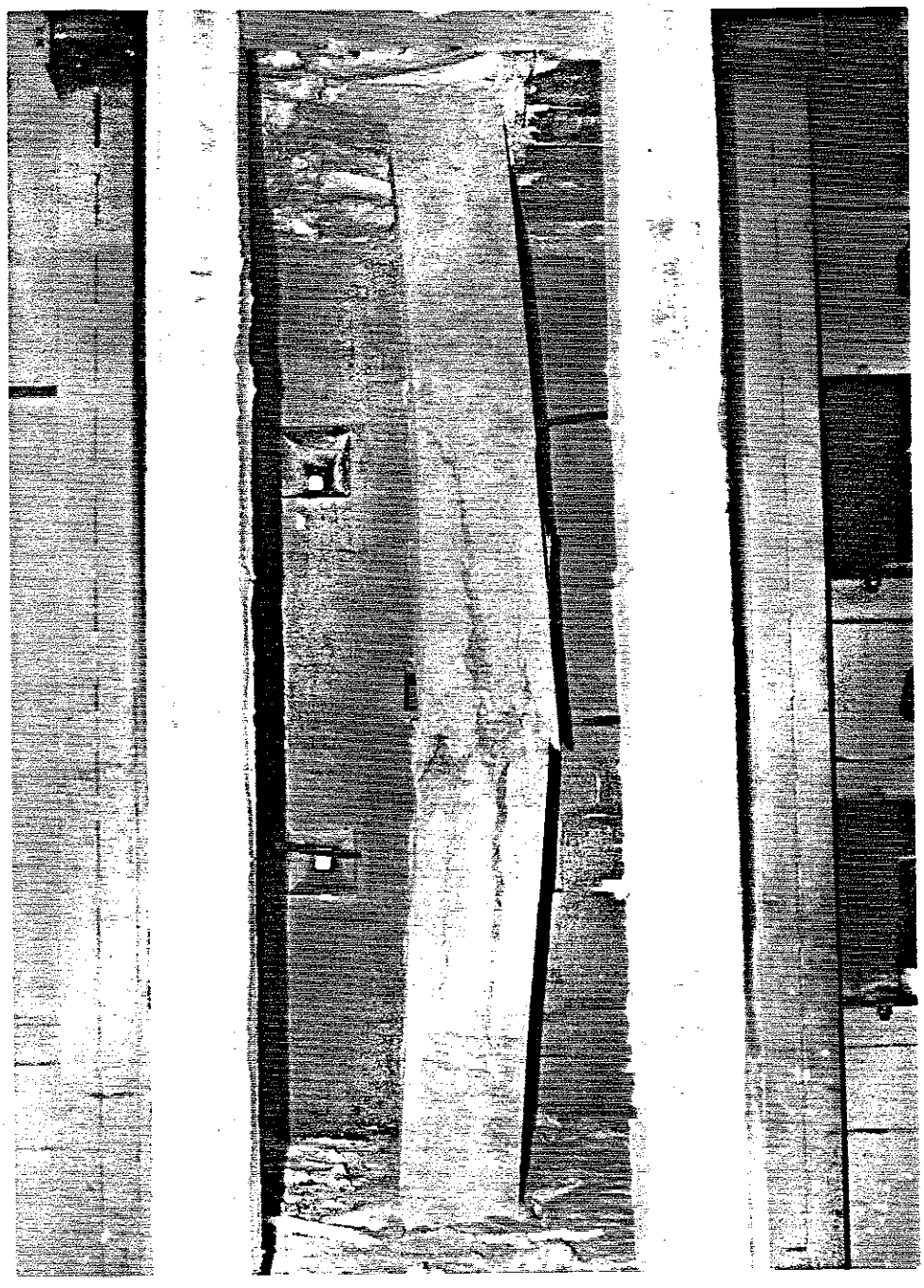


Figure 10. Column 2 After Test (TFRI)

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. Wu, H.J., and Lie, T.T., *Fire Resistance of Reinforced Concrete Columns - Experimental Studies*, IRC Internal Report No. 632, Institute For Research in Construction, National Research Council of Canada, Ottawa, 1992.
5. Fire Resistance Tests - Elements of Building Construction, ISO-834, International Organization for Standardization, 1975.