Evaluation of the Fire Resistance of Protected Steel Columns

Lie, T. T.; Macauley, B. A.

Publisher's version / Version de l'éditeur:
https://doi.org/10.4224/20358595
Internal Report (National Research Council of Canada. Institute for Research in Construction), 1989-10

National Research Council Canada
Institute for Research in Construction

Conseil national de recherches Canada
Institut de recherche en construction

Evaluation of the Fire Resistance of Protected Steel Columns

T.T. Lie and B.A. Macaulay

Internal Report No. 583

Date of issue: October 1989

Canada

1. INTRODUCTION

During a fire, building structural members may be exposed to heating at very high temperatures, and as a consequence their strength may decrease substantially. To prevent loss of strength that could result in failure, steel members are usually protected with an insulating material.

There is a critical temperature at which structural steel loses so much strength that it can no longer support the load. The critical temperature depends on many factors; one of the most important is the load to which the member is subjected. This critical temperature increases with decreasing load and, therefore, the fire resistance of the member, which can be defined as the time it takes to reach the critical steel temperature, also increases if the load is decreased.

The objective of this study is to determine the critical temperature of wide flange steel columns and their fire resistance as a function of load. For this purpose the results of three fire tests carried out on loaded columns and calculated fire resistances [1,2] using a mathematical model, that has been developed, will be examined.

2. TEST SPECIMENS

The specimens consisted of three protected steel columns as specified in Table 1.

The columns were 3810 mm in total length including 533 x 533 x 25 mm endplates (Fig. 1). The cross-sectional dimensions of the columns and insulation are shown in Fig. 2 and are listed in Table 2.

The temperature of the steel column was measured with 0.91 mm thick chromel-alumel thermocouples, which were peened into the steel at four levels. The location of the thermocouples is shown in Fig. 3.

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 consists of a steel framework supported by four steel columns, with the furnace chamber inside the framework (Fig. 4). The characteristics and instrumentation of the furnace are described in detail in Ref. [4]. Only a brief description of the furnace and its main components is given here.

3.1 Loading Device

A hydraulic jack with capacity of 1000 t acted along the axis of the column to produce a load. The jack was located at the bottom of the furnace chamber. The plate on top of the jack was used as a platform to which the column was attached.

3.2 Furnace Chamber

The furnace chamber has a floor area of 2642 x 2642 mm and is 3048 mm high. The interior faces of the chamber are lined with insulating materials that efficiently transfer heat to the specimen. There are 32 propane gas burners in the furnace chamber, arranged in eight columns containing four burners each. The total capacity of the burners is 4700 kW (16 million Btu/h). Each burner can be adjusted individually, which ensures a high degree of temperature uniformity in the furnace chamber. The pressure in the furnace chamber is adjustable and was set somewhat lower than atmospheric pressure.

3.3 Instrumentation

The furnace temperatures were measured with the aid of eight chromel-alumel thermocouples. Each thermocouple was located 305 mm from the test specimen, at various heights. Two thermocouples were placed opposite each other at intervals of 610 mm along the height of the furnace chamber. The location of their junctions and their numbering are shown in Fig. 5. Thermocouples 4 and 6 were located at a height of 610 mm from the floor, Thermocouples 2 and 8 at 1220 mm, Thermocouples 3 and 5 at 1830 mm and Thermocouples 1 and 7 at 2440 mm. The temperatures measured by the thermocouples are averaged automatically and the average temperature was 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 is approximately 20 kN at lower load levels and relatively better at higher loads.

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

The column end plates were bolted to the load head at the top and the hydraulic jack at the bottom. End conditions were fixed-fixed for all three tests.

4.1 Loading

Prior to commencing the fire tests the columns were tested under concentric loads applied in stages, the last stage occuring at least 45 minutes before testing. Column No. 1 was subjected to a load of 1760 kN and Columns Nos. 2 and 3 to a load of 1424 kN.

4.2 Fire Exposure

The columns were exposed to heating such that the average temperature in the furnace closely followed the ASTM-E119 [5] or ULC-S101 [6] standard temperature-time curve. This curve can be approximated by the following equation:

$$T_f = 20 + 750 [1 - \exp (-3.79553\sqrt{\tau}.)] + 170.41\sqrt{\tau}$$

where : T_f = temperature in °C
τ = time in hours

4.3 Recording of Results

Temperature readings were taken at each thermocouple location at two minute intervals. Axial strain was also measured.

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.

5. CALCULATION METHOD

The calculation of the fire resistance of a steel column is a two step process. First, the temperatures reached by the column at any time during the fire must be determined, either by test, by semi-empirical prediction formulas [7] or by thermal analysis [2]. Because the thermal properties of the material protecting the steel were not known, the steel temperatures during exposure to fire were determined by measurement during tests.

The next step in the calculation of fire resistance is determining the structural response of the column. The behavior of the column can be assessed by analysis of stresses and strains in the loaded column, and determining the strength, i.e. the maximum load that the column can carry during the exposure to the fire. For any given load there is a critical steel temperature at which strength becomes insufficient to carry the load. By calculating the time it takes to reach the critical temperature the fire resistance of the column can be derived as a function of the load.

5.1 Critical Steel Temperature

In typical structural design for steel members, a factor of safety on strength and load is incorporated to take into account variability of material performance and the load to which the member may be subjected. If a steel member is heated in fire, however, it may reach the temperature at which its strength or stiffness decreases to the point that this safety factor is reduced to zero and the member fails. This temperature, which is a function of the type of member, its end support conditions and the load applied, is the actual critical temperature of the member. This critical temperature, which for the columns considered in this study may be defined as the average steel temperature at the midheight section at the point of failure, can be derived by analysis of the behaviour of the member at elevated temperatures. For this purpose, the relevant high temperature properties of the steel need to be known.

5.2 Steel Properties

When exposed to fire, steel gradually loses strength and stiffness. These properties, characterised by the yield strength and modulus of elasticity of the steel, decrease as the temperature increases. Data concerning the dependence of these properties on temperature have been reported by several authors Ref. [2]. In this study, material properties will be used that are somewhat conservative but are reasonably representative of those reported in most of the literature. The steel properties used in this study are given in Appendix A in this paper.

5.3 Calculation of Strength During Fire

The strength of the column during exposure to fire can be calculated by a method based on a load deflection analysis described in Reference [8]. In this method, the columns, which are fixed at the ends during the tests, are idealised as pin-ended columns of length KL (Fig. 6). In a previous study [9] it was estimated that for columns tested fixed at the ends, the effective length KL is about 2000mm.

The load on the column is intended to be concentric. Due to imperfections of the column and the loading device, a small eccentricity exists. Therefore in the calculations a very small initial load eccentricity will be assumed. After runs of the computer program showed that for small eccentricities up to about 10mm,

the influence of eccentricity on fire resistance is very small, a value of 0.2mm reflecting a nearly concentric load, was selected for the initial eccentricity.

The curvature of the column is assumed to vary from pin-end to mid-height according to a straight line relation, as illustrated in Fig. 6. For such a relation the deflection at mid-height y, in terms of the curvature χ of the column at this height, can be given by

$$y = \chi \frac{(KL)^2}{12} \qquad (1)$$

For any given curvature, and thus for any given deflection at mid-height, the axial strain is varied until the internal moment at the mid-section is in equilibrium with the applied moment given by the product

load x (deflection + eccentricity)

In this way, a load deflection curve can be calculated for specific times during the exposure to fire. From these curves the strength of the column, i.e. the maximum load that the column can carry, can be determined for each time. In the calculation of column strength, the following assumptions were made:

(1) The properties of the steel are those described in Appendix A.
(2) Plane sections remain plane.
(3) The insulation does not contribute to carrying the load.

Based on these assumptions, the change of column strength during exposure to fire was calculated. In the calculation method, which is described in Ref. [2], the section is divided in a number of elements. For each element the strains, stresses and the load carried by the element are calculated. The load that the column can carry and the moments in the section were obtained by adding the loads carried by each element and the moments contributed by them.

The equations used in the calculation of the strength of the column during exposure to fire are given below. The strain in an element of the steel can be given as the sum of the thermal expansion of the steel $(\varepsilon_T)_S$, the axial strain of the column ε and the strain due to bending of the column z_S/ρ, where z_S is the horizontal distance of the steel element to the vertical plane through the x-axis of the column section, and ρ is the radius of curvature. For the steel at the right of the x-axis the strain $(\varepsilon_s)_R$ is given by

$$(\varepsilon_S)_R = -(\varepsilon_T)_S + \varepsilon + z_S/\rho \qquad (2)$$

For the steel elements at the left of the x-axis the strain $(\varepsilon_S)_L$ is given by

$$(\varepsilon_S)_L = -(\varepsilon_T)_S + \varepsilon - z_S/\rho \qquad (3)$$

The stresses in the elements of the network are calculated using the stress-strain relations for steel given by the Eqs. (4)-(10) in Appendix A. These relations are illustrated in Fig. 7.

With the aid of Eqs. (1)-(12), the stresses at mid-section in the steel elements can be calculated for any value of the axial strain ε and curvature ρ. From these stresses, the load that each element carries and its contribution to the internal moment at mid-section can be derived. By adding the loads and moments, the load that the column carries and the total internal moment at mid-section can be calculated.

The fire resistance of the column is derived by calculating the strength i.e. the maximum load that the column can carry at several consecutive times during the exposure to fire. This strength reduces gradually with time. At a certain point the strength becomes so low that it is no longer sufficient to support the load, and the column fails. The time to reach this failure point is the fire resistance of the column.

6. RESULTS

6.1 Measured Results

The temperatures measured during the fire test at four levels in Column No. 1 are listed in Tables 3-6, those measured in Column No. 2 in Tables 9-12, and those measured in Column No. 3 in Tables 15-18.

In Tables 7, 13 and 19, the average steel temperature at midheight of the columns, the average of all temperatures in each column, the average furnace temperatures and the standard furnace temperatures are given. The furnace temperatures during the three tests are also plotted in Figs 8-10.

The average steel temperature at midheight of each column was obtained by averaging the temperatures measured at Levels 2 and 3. These midheight steel temperatures are shown for the three columns in Figs 11-13. They were used as input data in the calculation of the fire resistance of the columns.

In the Tables 8,14 and 20, the axial deformations of the three test columns, measured during the tests, are given. The test columns after the tests are shown in Figs. 14-16.

6.2 Calculated Results

In Figs 11-13 curves are shown, consisting of a number of straight lines, that are representative of the average temperatures at midheight of the columns during the tests. The use of these curves as input data will facilitate the calculation of the fire resistance of the columns. The expressions describing the temperature curves are given in Appendix B by the Eqs. (13)-(21).

Using the mathematical model, described earlier in this paper, calculations were made of the axial deformations of the columns during the exposure to fire. Calculations were also made of the critical temperature and the fire resistance of the columns as a function of the load.

In Figs. 17-19 calculated axial deformations are compared with measured axial deformations. It can be seen that calculated deformations are somewhat higher than those measured. The differences, which near the failure points are in the order of 5 mm may be regarded as small, if it is taken into account that these are the differences between calculated and measured deformations for a column length of about 3800 mm. It is likely that the main cause of the differences is creep of steel, which becomes more pronounced at higher temperatures. A part of the creep, however, is implicitly taken into account in the mechanical properties of steel used.

In Table 21, the calculated and measured failure times of the columns are given for various failure criteria. At present, there are no generally accepted failure criteria for columns. It has been customary to consider attainment of a specific lateral deflection of the column during a fire test as failure. This deflection varies from country to country but lies in the range of 50-150 mm, corresponding to an axial deformation of about 2-15mm for a column of 3000mm length.

At the Institute for Research in Construction, the column is considered to have failed when the hydraulic loading system can no longer apply the contemplated load. This criterion, although well defined because of the fixed maximum ram speed, is dependent on the capabilities of the loading system. Since the maximum ram speed is high (76 mm/min) the loading system will be able to apply the load until very large deflections occur, as can be seen in Figs. 17-19. Therefore the use of this criterion will result in relatively favourable failure times. According to the results given in Table 21, these failure times are about 10-15 minutes greater than the times at which the column becomes unstable i.e. reaches the maximum expansion and begins to deflect.

In this study the failure point has been defined as the point at which the column reaches the maximum expansion. For steel columns it appears to be a better criterion than the criterion of maintaining the load by the ram. If this failure criterion is used, calculated failure times, which are defined as the times at which the column can no longer support the applied load, are in good agreement with the measured failure times.

Using the mathematical model the fire resistances and critical temperatures of the tested columns were calculated as a function of the load. The calculated results are given in Table 22 and are plotted in Figs. 20 and 21. It can be seen that the fire resistance and critical steel temperature are considerably dependent on the load. In the practical region, namely, for loads below about 2200 kN for Column No. 1, and loads below about 1700 kN for the Columns Nos. 2 and 3, the fire resistance as well as the critical steel temperature vary with the load approximately linearly. This will facilitate extension of fire resistance and critical temperature from one load to other loads. Because the relation between fire resistance, critical temperature and load is known, the fire resistance can be derived for any given load and insulation by determining on unloaded columns the time it takes to reach the critical steel temperature.

CONCLUSION

The mathematical model employed in this study is capable of predicting the critical steel temperature and fire resistance of protected steel columns with an accuracy that is adequate for practical purposes. The maximum difference between calculated and measured fire resistances is about six percent when the maximum expansion of the columns is taken as criterion of failure.

If the thermal properties of the insulation are not known the fire resistance of the column can be derived by calculating for a given load the critical steel temperature of the column, using the mathematical model, and determining by testing of an unloaded column the time it takes for the steel to reach the critical steel temperature. If the thermal properties of the protecting material are known, the temperature course of the steel can be calculated using existing validated mathematical models for the determination of the steel temperature of fire exposed protected steel columns, and the fire resistance of the column can be determined entirely by calculation.

REFERENCES

1. Lie, T.T. and Harmathy, T.Z., A Numerical Procedure toCalculate the Temperature of Protected Steel Columns Exposed to Fire, Fire Study No. 28, Division of Building Research, National Research Council of Canada, NRCC 12535, 1972.

2. Lie, T.T. and Almand, K.H.,A Method to Predict the Fire Resistance of Steel Building Columns, To be published.

3. Handbook of Steel Construction, Canadian Institute of Steel Construction, Willowdale, 1976.

4. Lie, T.T., New Facility to Determine Fire Resistance of Columns, Canadian Journal of Civil Engineering, Vol 7, 1980.

5. Standard Methods of Fire Tests of Building Construction and Materials, ASTM E119-83, American Society for Testing and Materials.

6. Standard Methods of Fire Endurance Tests of Building Construction and Materials CAN4-S101-M82, Underwriters Laboratories of Canada.

7. European Recommendations for the Fire Safety of Steel Structures, Calculation of the Fire Resistance of Load Bearing Elements and Structural Assemblies Exposed to the Standard Fire, Elsevier, Amsterdam-Oxford-New York, 1983.

8. Allen, D.E. and T.T. Lie, Further Studies of the Fire Resistance of Reinforced Concrete Columns, National Research Council of Canada, Division of Building Research, NRCC 14047,1974.

9. Centre Technique Industriel de la Construction Metallique (CTICM), Methode de Prévision par la Calcul du Comportement au Feu des Structures en Acier, Document Technique Unifié (DTU), Revue Construction Metallique, No. 3, 1982.

APPENDIX A

Material Properties of Steel

The strength and modulus of elasticity of steel at elevated temperatures are based on the formulas for these properties given in Ref.[9]. The stress-strain relations (Eqs. (4)-(10)) were derived using these formulas for stresses and strains up to the 0.002 offset yield strength. For greater stresses it was conservatively assumed, based on information in the literature,that the stress-strain relations are straight lines through the 0.002 offset points and the points defined by a 0.01 offset and a stess equal to 1.1 of the yield strength. The stress-strain relations for various temperatures are illustrated in Fig.5.

Stress-strain relations

for $e_s \leq e_p$

$$f_T = E_T e_s \tag{4}$$

for $e_s > e_p$

$$f_T = 12.5 f_{yT} \varepsilon_s + 0.975 f_{yT} - 12.5 (f_{yT})^2 / E_T \tag{5}$$

where the proportional limit

$$\varepsilon_p = \frac{0.975 f_{yt} - 12.5 (f_{yt})^2 E_T}{E_T - 12.5 f_{yT}} \tag{6}$$

the yield strength

for $0 < T \leq 600°C$

$$f_{yT} = [1.0 + \frac{T}{900 1n(T/1750}] f_{yo} \tag{7}$$

for $600 < T < 1000°C$

$$f_{yT} = \frac{340 - 0.34 T}{-240 + T} f_{yo} \tag{8}$$

and the modulus of elasticity

for $0 < T \leq 600°C$

$$E_T = [1.0 + \frac{T}{2000 \ln (T/1100)}]E_o \qquad (9)$$

for $600 < T < 1000°C$

$$E_T = \frac{690 - 0.69\,T}{T - 53.5} E_o \qquad (10)$$

In the calculations the following values for f_{yo} and E_o have been used:

$f_{yo} = 300$ MPa
$E_o = 200000$ MPa

Coefficient of thermal expansion

for $T < 1000°C$

$$a_s = (0.004\ T + 12) \times 10^{-6} \qquad (11)$$

for $T \geq 1000°C$

$$a_s = 16 \times 10^{-6} \qquad (12)$$

APPENDIX B

Equations for the Average Temperature of the Columns at Midheight during Fire Tests (for use as Input Data)

Column No. 1

for $0 \leq \tau \leq 16.7$

$$T_{as} = 5.89 + 0.57\ \tau \qquad (13)$$

for $16.7 < \tau \leq 59.27$

$$T_{as} = -24.21 + 2.41\ \tau \qquad (14)$$

for $\tau > 59.27$

$$T_{as} = -186.49 + 5.15\ \tau \qquad (15)$$

Column No. 2

for $0 \leq \tau \leq 9.85$

$$T_{as} = 16.48 + 0.55\ \tau \qquad (16)$$

for $9.85 < \tau \leq 29.63$

$$T_{as} = -15.14 + 3.76\ \tau \qquad (17)$$

for $29.63 < \tau \leq 49.17$

$$T_{as} = 77.85 + 0.62\ \tau \qquad (18)$$

for $\tau > 49.17$

$$T_{as} = -117.65 + 4.60\ \tau \qquad (19)$$

Column No. 3

for $0 \leq \tau \leq 19.97$

$$T_{as} = 5.94 + 3.66 \tau \tag{20}$$

for $\tau > 19.97$

$$T_{as} = -68.69 + 7.39 \tau \tag{21}$$

NOMENCLATURE

Notations

e	eccentricity of load (m)
E	modulus of elasticity
f_T	stress of steel at temperature T (MPa)
f_{yT}	yield strength of steel at temperature T (MPa)
f_{yo}	yield strength of steel at room temperature (MPa)
K	effective length factor
L	unsupported length of column (m)
T	temperature (°C)
y	lateral deflection of column at mid-height (m)
z	coordinate

Greek letters

α	coefficient of thermal expansion $°C^{-1}$
ε	strain ($m\ m^{-1}$)
π	radius of curvature (m)
τ	time (min)
ξ	curvature of column at mid-height (m^{-1})

Subscripts

a	average
o	at room temperature
f	of the fire
p	pertaining to the proportional stress-strain relation
s	of steel
T	pertaining to temperature

INDEX OF TABLES AND FIGURES

Table 1	Specifics of Test Specimens
Table 2	Dimensions of Column and Insulation
Table 3	Temperature Measured in Column No. 1, Level 1
Table 4	Temperature Measured in Column No. 1, Level 2
Table 5	Temperature Measured in Column No. 1, Level 3
Table 6	Temperature Measured in Column No. 1, Level 4
Table 7	Average Column and Furnace Temperatures (Column No. 1)
Table 8	Measured Axial Deformation of Column No. 1
Table 9	Temperature Measured in Column No. 2, Level 1
Table 10	Temperature Measured in Column No. 2, Level 2
Table 11	Temperature Measured in Column No. 2, Level 3
Table 12	Temperature Measured in Column No. 2, Level 4
Table 13	Average Column and Furnace Temperatures (Column No. 2)
Table 14	Measured Axial Deformation of Column No. 2
Table 15	Temperature Measured in Column No. 3, Level 1
Table 16	Temperature Measured in Column No. 3, Level 2
Table 17	Temperature Measured in Column No. 3, Level 3
Table 18	Temperature Measured in Column No. 3, Level 4
Table 19	Average Column and Furnace Temperatures (Column No. 3)
Table 20	Measured Axial Deformation of Column No. 3
Table 21	Failure Time for Various Failure Criteria
Table 22	Fire Resistance and Critical Temperature of Test Column as a Function of Load
Figure 1	Elevation and Cross Section of Test Columns
Figure 2	Cross Section of Columns and Insulation
Figure 3	Location of Thermocouples
Figure 4	Location and Numbers of Thermocouples in Column Furnace Chamber
Figure 5	Test Furnace
Figure 6	Load-Deflection Analysis
Figure 7	Stress-Strain Relations for Structural Steel
Figure 8	Furnace Temperature during Test of Column No. 1
Figure 9	Furnace Temperature during Test of Column No. 2
Figure 10	Furnace Temperature during Test of Column No. 3
Figure 11	Average Steel Temperature at Midheight of Column No. 1
Figure 12	Average Steel Temperature at Midheight of Column No. 2
Figure 13	Average Steel Temperature at Midheight of Column No. 3
Figure 14	Axial Deformation of Column No. 1 as a Function of Time
Figure 15	Axial Deformation of Column No. 2 as a Function of Time
Figure 16	Axial Deformation of Column No. 3 as a Function of Time
Figure 17	Fire Resistance of Test Columns as a Function of Load
Figure 18	Critical Steel Temperature of the Test Columns as a Function of Load
Figure 19	Column 1 after Test
Figure 20	Column 2 after Test
Figure 21	Column 3 after Test

Table 1. Specifics of Test Specimens

Column No.	Steel		Insulation		
	Section Ref.[3]	Mass (kg/m)	Type	Thickness (mm)	Density (kg/cu.m)
1	W10 x 60	89	Sprayed Mineral Fiber	55	200
2	W10 x 49	73	Cementitious Mixture	39	900
3	W10 x 49	73	Sprayed Mineral Fiber	30	200

Table 2. Dimensions of Column and Insulation

Column No.	Depth d (mm)	Width b (mm)	Thickness Flange, t (mm)	Thickness Web, w (mm)	Thickness Insulation, i (mm)
1	260	257	17.5	11.1	39
2	254	254	14.3	7.9	55
3	254	254	14.3	7.9	30

Table 3. Temperature (°C) Measured in Column No. 1, Level 1 (457mm)

Time (min)	Thermocouple No. 10	11	12	Average
0	9	*28.8	9	9
5	9	*28.7	9	9
10	9	*28.4	10	10
15	17	*24.8	17	17
20	27		26	27
25	37		36	36
30	47		47	47
35	57		60	59
40	69		73	71
45	80		83	82
50	88		94	91
55	95		109	102
60	108		125	116
65	126		143	134
70	149		164	156
75	172		187	180
80	198		212	205
85	223		239	231
90	250		266	258
95	276		292	284
100	303		319	311
105	329		344	337
110	356		370	363
115	381		396	388
120	407		421	414
125	431		444	438
130	455		467	461
135	477		488	483
140	499		510	505
145	520		531	525
150	539		551	545

*results unreliable and not averaged

Table 4. Temperature (°C) Measured in Column No. 1, Level 2 (1422mm)

Time (min)	Thermocouple No. 7	8	9	Average
0	7	7	7	7
5	7	7	7	7
10	9	8	9	8
15	17	12	16	15
20	26	20	24	24
25	35	30	34	33
30	46	41	46	44
35	58	52	59	56
40	71	64	72	69
45	81	75	82	80
50	91	85	96	91
55	105	91	110	102
60	122	94	128	115
65	142	106	149	132
70	165	127	173	155
75	190	152	198	180
80	216	179	225	207
85	242	207	252	234
90	269	235	279	261
95	294	263	306	288
100	321	290	333	315
105	346	317	358	340
110	373	343	385	367
115	398	368	410	392
120	422	393	435	417
125	445	417	457	440
130	469	439	480	462
135	491	459	500	483
140	513	480	521	505
145	534	502	541	526
150	553	527	560	547

Table 5. Temperature (°C) Measured in Column No. 1, Level 3 (2387mm)

Time (min)	Thermocouple No. 4	5	6	Average
0	8	8	8	8
5	8	8	8	8
10	12	9	11	11
15	19	15	18	17
20	27	23	26	25
25	37	32	36	35
30	49	43	49	47
35	63	54	64	60
40	77	67	77	73
45	90	79	93	87
50	106	88	111	101
55	122	93	129	115
60	141	104	151	132
65	162	124	177	154
70	188	149	206	181
75	216	176	235	209
80	244	205	265	238
85	272	234	294	267
90	301	263	321	295
95	328	291	348	322
100	356	320	375	350
105	383	347	402	377
110	411	376	428	405
115	437	404	453	431
120	463	433	477	458
125	489	460	500	483
130	514	485	523	507
135	537	510	544	530
140	560	534	566	553
145	580	556	587	574
150	630	577	629	612

Table 6. Temperature (°C) Measured in Column No. 1, Level 4 (3352mm)

Time (min)	Thermocouple No. 1	Thermocouple No. 2	Thermocouple No. 3	Average
0	10	10	10	10
5	10	10	10	10
10	13	10	14	12
15	20	15	20	18
20	28	22	27	26
25	36	31	35	34
30	47	40	46	45
35	60	50	59	56
40	72	61	72	68
45	84	73	87	81
50	98	83	109	97
55	112	90	125	109
60	128	95	143	122
65	147	108	164	139
70	169	130	189	163
75	194	156	214	188
80	220	183	241	214
85	246	210	267	241
90	273	238	295	269
95	300	265	320	295
100	328	292	344	321
105	355	318	369	347
110	382	344	395	373
115	407	370	419	399
120	432	397	443	424
125	457	423	465	448
130	481	451	487	473
135	503	475	508	495
140	526	499	528	518
145	547	522	548	539
150	567	543	565	558

Table 7. Average Column and Furnace Temperatures (°C) in Column No. 1

Time (min)	Average Mid Column	Average Total Column	Average Furnace	Standard Furnace
0	7	8	45	20
5	8	8	593	538
10	10	10	673	704
15	16	17	719	760
20	24	25	770	795
25	34	35	811	821
30	46	46	832	843
35	58	58	858	862
40	71	70	878	878
45	83	82	893	892
50	96	95	905	905
55	108	107	918	916
60	123	121	951	927
65	143	140	954	937
70	168	164	960	946
75	194	189	971	955
80	222	216	980	963
85	250	243	990	971
90	278	271	998	978
95	305	297	1004	985
100	332	324	1013	991
105	359	350	1031	996
110	386	377	1026	1001
115	412	403	1040	1006
120	437	428	1049	1010
125	461	452	1053	
130	485	476	1059	1017
135	507	498	1065	
140	529	520	1069	1024
145	550	541	1071	
150	579	565	1073	1031

Table 8. Measured Axial Deformation of Column No. 1

Time (min)	Deformation (mm)
0	-2.80
5	-2.80
10	-2.80
15	-2.80
20	-2.63
25	-2.28
30	-1.89
35	-1.45
40	-0.97
45	-0.50
50	-0.10
55	0.31
60	0.72
65	1.43
70	2.19
75	2.98
80	3.82
85	4.77
90	5.73
95	6.70
100	7.73
105	8.73
110	9.74
115	10.75
120	11.53
125	12.11
130	12.29
135	12.27
140	11.22
145	7.22
150	-24.67

(-) sign indicates contraction from initial length

Table 9. Temperature (°C) Measured in Column No. 2, Level 1 (457mm)

Time (min)	Thermocouple No. 10	11	12	Average
0	16	23	15	15
5	16	23	16	16
10	24	19	19	22
15	45	42	34	39
20	66	62	57	62
25	87	86	78	84
30	101	102	97	100
35	101	101	101	101
40	107	101	101	103
45	122	102	105	109
50	141	107	119	122
55	162	120	138	140
60	185	142	160	162
65	208	166	183	185
70	232	191	208	210
75	257	216	233	235
80	283	243	259	262
85	308	269	285	287
90	334	296	311	314
95	359	322	337	339
100	385	347	363	365
105	409	372	388	390
110	434	397	413	414
115	457	421	437	438
120	480	444	460	461
125	501	466	482	483
130	522	488	504	505
135	543	509	524	525
140	565	533	546	548
145	585	557	567	570
150	604	580	587	590
155	619	599	603	607
160	*	620	647	634

Table 10. Temperature (°C) Measured in Column No. 2, Level 2 (1422mm)

Time (min)	Thermocouple No. 7	8	9	Average
0	17	16	17	17
5	17	17	17	17
10	26	22	23	24
15	49	39	43	43
20	71	61	65	65
25	90	85	85	86
30	101	100	100	100
35	101	100	101	101
40	105	100	103	103
45	119	100	112	111
50	138	102	127	122
55	159	114	146	139
60	181	137	167	161
65	203	160	189	184
70	227	185	212	208
75	251	210	236	232
80	275	236	261	257
85	300	263	286	283
90	325	289	311	308
95	350	315	337	334
100	376	341	362	359
105	400	366	386	384
110	424	390	411	409
115	448	415	435	432
120	471	438	458	456
125	492	461	480	478
130	514	483	502	499
135	534	503	523	520
140	555	525	545	542
145	576	548	566	563
150	595	570	585	584
155	612	590	605	602
160	657	602	646	635

Table 11. Temperature (°C) Measured in Column No. 2, Level 3 (2387mm)

Time (min)	Thermocouple No. 4	5	6	Average
0	18	18	18	18
5	18	18	18	18
10	22	20	24	22
15	36	29	45	37
20	57	46	64	55
25	77	67	80	75
30	94	90	96	93
35	100	100	100	100
40	100	100	100	100
45	104	100	104	103
50	115	101	122	113
55	134	107	141	127
60	155	116	161	144
65	176	132	182	163
70	198	153	203	185
75	221	177	225	208
80	245	201	247	231
85	269	226	270	255
90	294	251	294	280
95	318	277	318	304
100	343	302	342	329
105	367	328	365	353
110	392	352	389	378
115	416	377	412	402
120	440	401	436	425
125	462	424	458	448
130	484	446	480	470
135	505	468	501	491
140	526	489	522	512
145	548	509	542	533
150	569	530	562	554
155	588	551	580	573
160	637	572	596	602

Table 12. Temperature (°C) Measured in Column No. 2, Level 4 (3352mm)

Time (min)	Thermocouple No. 1	2	3	Average
0	20	19	20	20
5	20	19	20	20
10	23	21	25	23
15	37	31	41	36
20	60	47	59	55
25	79	69	77	75
30	96	90	94	93
35	101	100	100	100
40	101	100	101	100
45	101	100	108	103
50	112	101	122	111
55	132	106	140	126
60	153	117	160	143
65	175	135	179	163
70	198	156	200	185
75	221	178	221	207
80	245	201	243	230
85	270	225	265	253
90	294	250	288	277
95	319	274	311	301
100	343	299	334	325
105	367	323	356	348
110	390	347	379	372
115	413	370	401	395
120	437	393	423	418
125	459	415	445	440
130	481	438	466	461
135	502	459	486	482
140	524	479	507	503
145	545	499	527	523
150	565	519	546	543
155	583	539	565	562
160	602	560	581	581

Table 13. Average Column and Furnace Temperatures (°C) in Column No. 2

Time (min)	Average Mid Column	Average Total Column	Average Furnace	Standard Furnace
0	17	17	45	20
5	18	18	576	538
10	23	23	667	704
15	40	39	719	760
20	60	59	771	795
25	81	80	807	821
30	97	96	831	843
35	100	101	870	862
40	102	102	877	878
45	107	106	894	892
50	117	117	909	905
55	133	133	929	916
60	153	153	935	927
65	174	174	949	937
70	196	197	964	946
75	220	221	973	955
80	244	245	976	963
85	269	270	991	971
90	294	295	998	978
95	319	320	1006	985
100	344	345	1015	991
105	369	369	1023	996
110	393	393	1029	1001
115	417	417	1036	1006
120	440	440	1041	1010
125	463	462	1051	
130	485	484	1059	1017
135	506	505	1110	
140	527	526	1059	1024
145	548	547	1040	
150	569	568	1042	1031
155	588	586	1076	
160	618	613	1103	1038

Table 14. Measured Axial Deformation of Column No. 2

Time (min)	Deformation (mm)
0	-2.80
5	-2.80
10	-2.80
15	-2.49
20	-1.83
25	-1.01
30	-0.28
35	0.11
40	0.20
45	0.38
50	0.70
55	1.24
60	1.92
65	2.71
70	3.61
75	4.57
80	5.56
85	6.56
90	7.56
95	8.62
100	9.66
105	10.67
110	11.66
115	12.61
120	13.51
125	14.17
130	14.78
135	15.09
140	15.15
145	15.11
150	13.77
155	8.71
160	-7.05

(-) sign indicates contraction from original length

Table 15. Temperature (°C) Measured in Column No. 3, Level 1 (457mm)

Time (min)	Thermocouple No. 10	11	12	Average
0	10	10	10	10
5	13	14	13	13
10	26	28	25	26
15	47	49	45	47
20	76	74	72	74
25	107	94	98	99
30	138	124	128	130
35	167	158	159	161
40	201	195	194	196
45	237	232	231	233
50	278	273	271	274
55	318	315	311	314
60	355	357	351	354
65	391	396	390	392
70	426	434	426	429
75	460	469	460	463
80	495	503	494	497
85	527	535	525	529
90	560	566	557	561
92	572	578	569	573

Table 16. Temperature (°C) Measured in Column No. 3, Level 2 (1422mm)

Time (min)	Thermocouple No. 7	8	9	Average
0	13	13	13	13
5	17	16	18	17
10	31	30	30	30
15	56	51	51	52
20	85	77	78	80
25	114	98	110	107
30	143	130	141	138
35	172	165	173	170
40	206	202	208	205
45	244	241	247	244
50	285	282	290	286
55	324	324	330	326
60	362	366	369	366
65	397	406	405	403
70	432	443	440	439
75	466	476	474	472
80	499	509	507	505
85	531	538	538	536
90	562	568	569	566
92	574	579	580	578

Table 17. Temperature (°C) Measured in Column No. 3, Level 3 (2387mm)

Time (min)	Thermocouple No. 4	Thermocouple No. 5	Thermocouple No. 6	Average
0	16	16	16	16
5	21	22	22	22
10	36	37	38	37
15	66	64	64	65
20	97	89	93	93
25	127	122	125	125
30	159	158	160	159
35	193	194	195	194
40	233	234	234	233
45	274	276	275	275
50	315	321	316	317
55	355	362	358	358
60	394	403	399	399
65	433	443	435	437
70	472	483	472	475
75	508	520	507	512
80	544	556	541	547
85	578	590	573	580
90	612	624	607	614
92	624	637	619	627

Table 18. Temperature (°C) Measured in Column No.3, Level 4 (3352mm)

Time (min)	Thermocouple No. 1	2	3	Average
0	19	18	19	18
5	23	23	23	23
10	36	36	36	36
15	63	59	60	61
20	88	83	85	85
25	117	109	111	112
30	147	142	140	143
35	179	176	172	176
40	215	213	207	211
45	254	251	245	250
50	295	292	286	291
55	336	333	326	332
60	378	374	366	373
65	418	414	404	412
70	459	453	443	452
75	497	491	480	489
80	535	527	516	526
85	571	561	550	561
90	607	595	584	595
92	620	608	597	608

Table 19. Average Column and Furnace Temperatures (°C) in Column No. 3

Time (min)	Average Mid Column	Average Total Column	Average Furnace	Standard Furnace
0	15	14	46	20
5	19	19	586	538
10	33	32	675	704
15	59	56	726	760
20	86	83	772	795
25	116	111	808	821
30	148	142	832	843
35	182	175	869	862
40	219	212	876	878
45	260	251	895	892
50	301	292	912	905
55	342	333	925	916
60	382	373	938	927
65	420	411	950	937
70	457	449	960	946
75	492	484	970	955
80	526	519	978	963
85	558	551	993	971
90	590	584	1004	978
92	602	596	1002	985

Table 20. Measured Axial Deformation of Column No. 3

Time (min)	Deformation (mm)
0	-2.80
5	-2.80
10	-2.79
15	-1.94
20	-0.96
25	-0.01
30	1.15
35	2.49
40	3.94
45	5.51
50	7.09
55	8.67
60	10.27
65	11.80
70	13.19
75	14.21
80	14.61
85	14.43
90	9.63
92	2.66

(-) sign indicates contraction from initial length

Table 21. Failure Time for Various Failure Criteria

Column No.	Failure Time (min)		
	Theoretical	Experimental	
		Max. Axial Deformation	Load can no longer be maintained
1	137	135	150
2	137	145	160
3	78	83	92

Table 22. Fire Resistance and Critical Temperature of Test Columns as a Function of Load

Column No.1 - W10x60, 39mm Sprayed fibre insulation Test load: 1760 kN			Column No.2 - W10x49, 55mm Cementitious mixture insulation Test load: 1424 kN			Column No.3 - W10x49, 30mm Sprayed fibre insulation Test load: 1424 kN		
Load (kN)	Fire Resist. (min)	Crit. Temp. (°C)	Load (kN)	Fire Resist. (min)	Crit. Temp. (°C)	Load (kN)	Fire Resist. (min)	Crit. Temp. (°C)
3400	0	6	2634	0	17	2641	0	6
3326	20	24	2592	20	60	2569	20	79
3263	40	72	2539	40	103	2459	30	153
3203	60	123	2448	60	158	2315	40	227
2983	80	226	2266	80	250	2143	50	301
2617	100	329	2028	100	342	1927	60	375
2202	120	432	1722	120	434	1672	70	449
1953	130	483	1553	130	480	1374	80	523
1672	140	535	1357	140	526	1204	85	560
1359	150	586	1140	150	572	1016	90	596
1039	160	638	906	160	618	837	95	633
906	165	663	711	170	664	689	100	670
789	170	689	553	180	710	562	105	707
685	175	715	423	190	756	455	110	744
590	180	741						

FIGURE 1. ELEVATION AND CROSS SECTION OF TEST COLUMNS

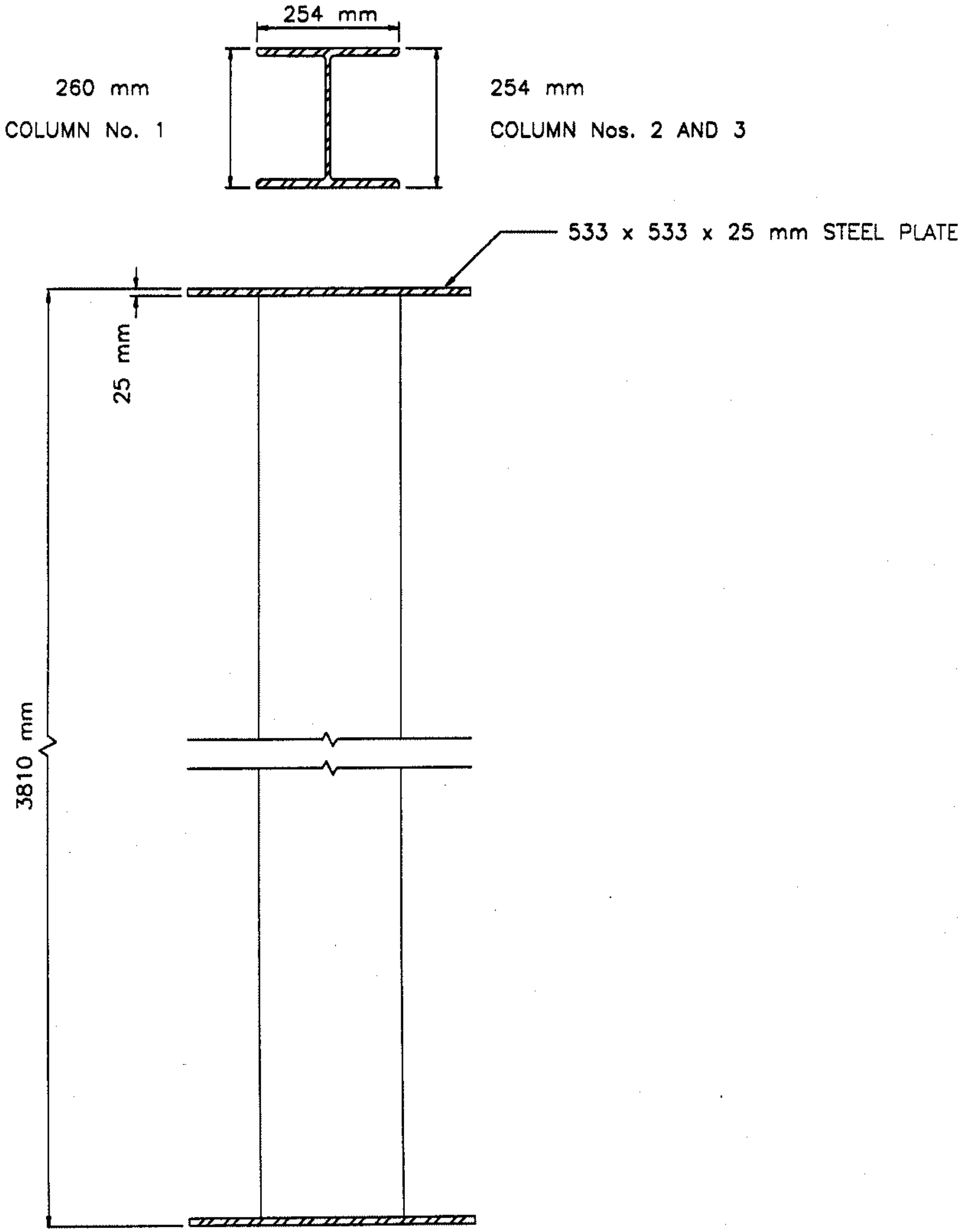


FIGURE 2. CROSS SECTION OF COLUMNS AND INSULATION

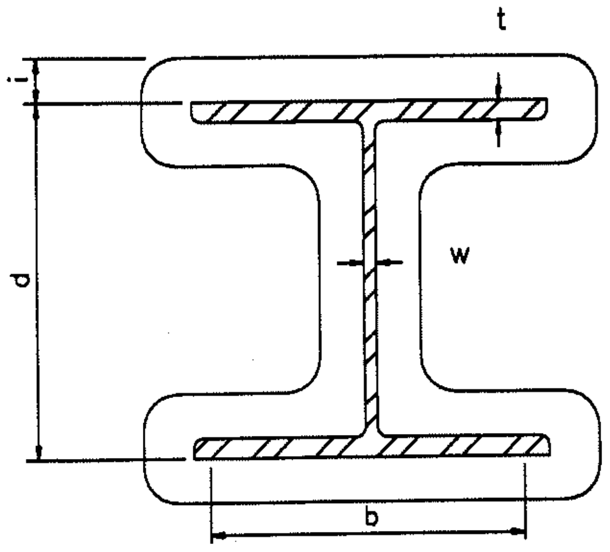
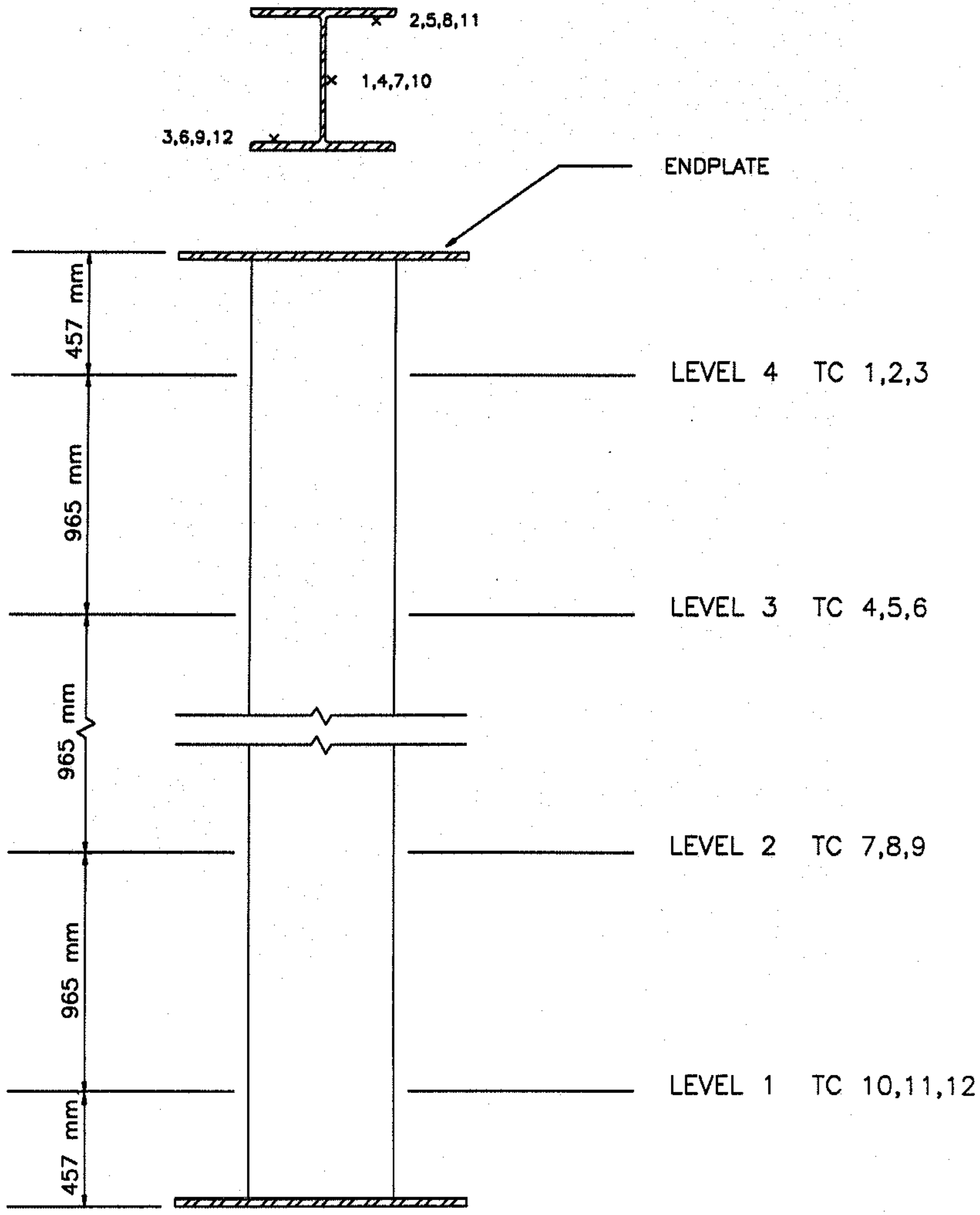


FIGURE 3. LOCATION OF THERMOCOUPLES



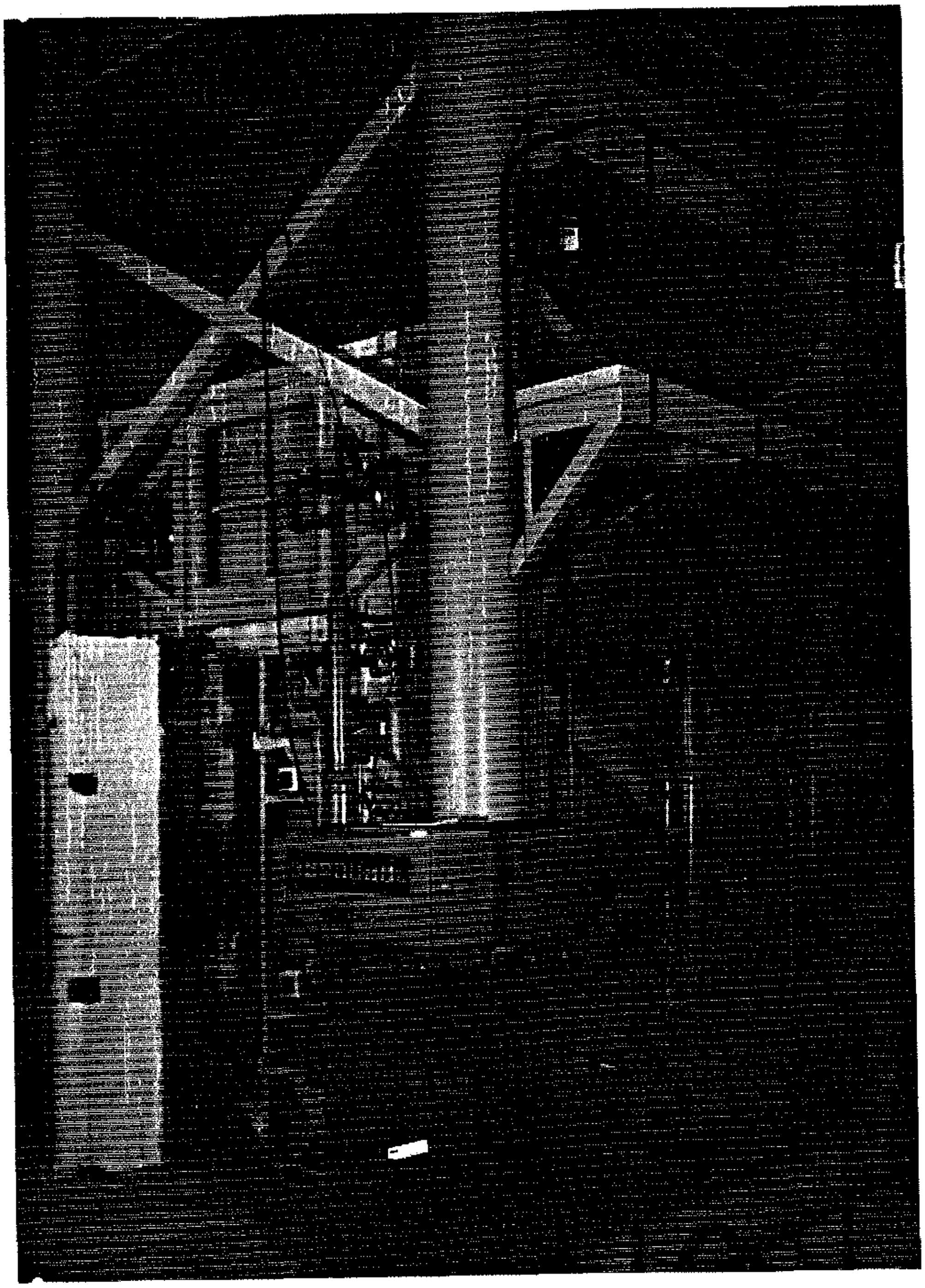


FIGURE 4. TEST FURNACE

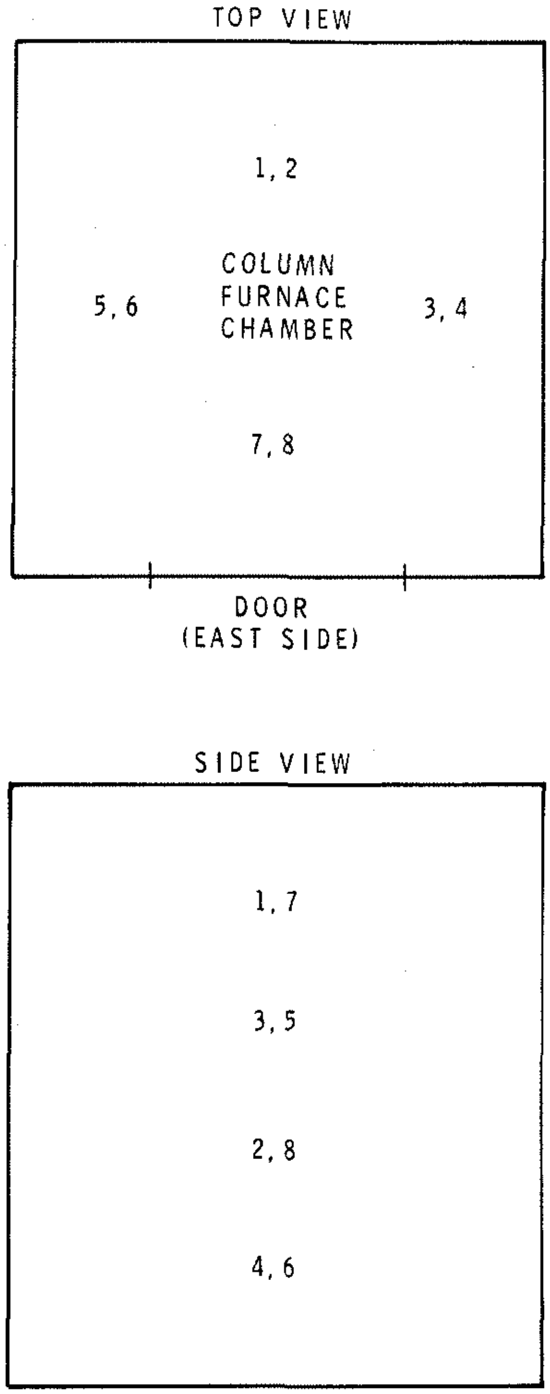


FIGURE 5. LOCATION OF THERMOCOUPLES IN FURNACE CHAMBER

BR 6432-7

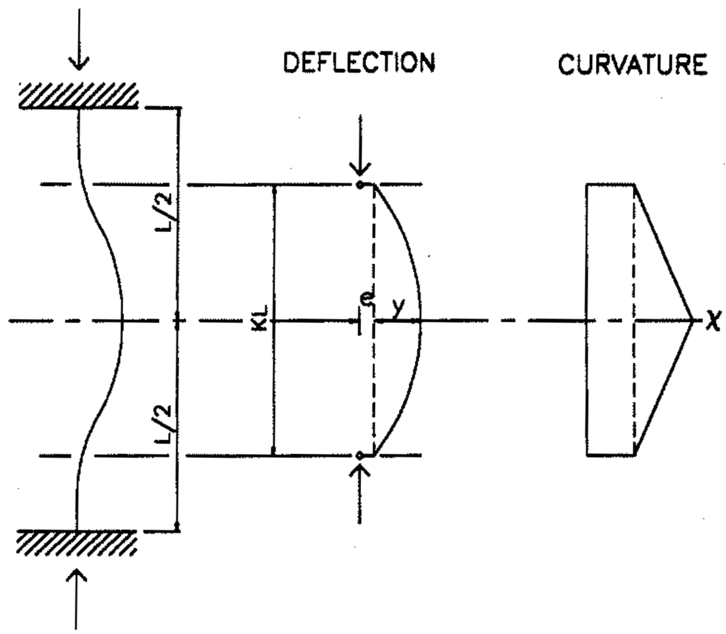


FIGURE 6. LOAD-DEFLECTION ANALYSIS

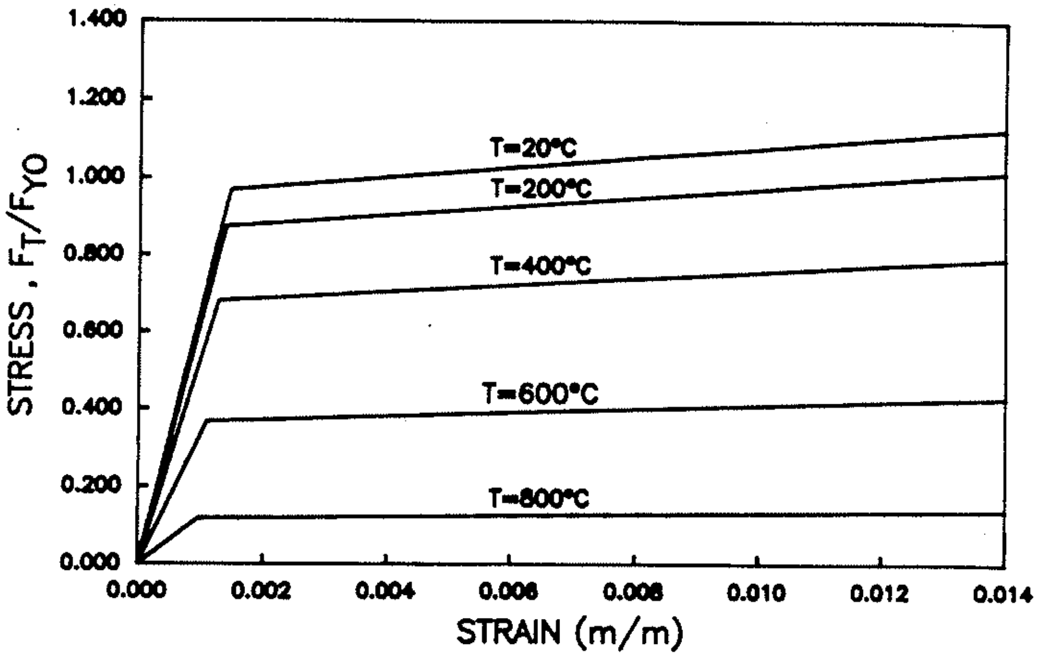


Figure 7. Stress–Strain Relations for Structural Steel

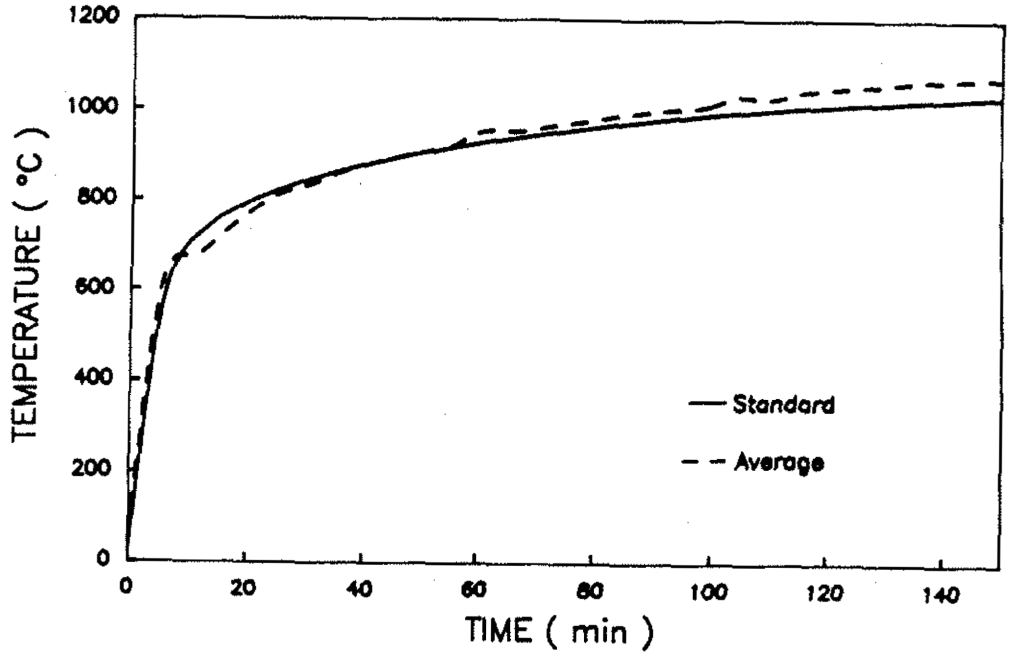


Figure 8. Furnace Temperature during Test of Column No. 1

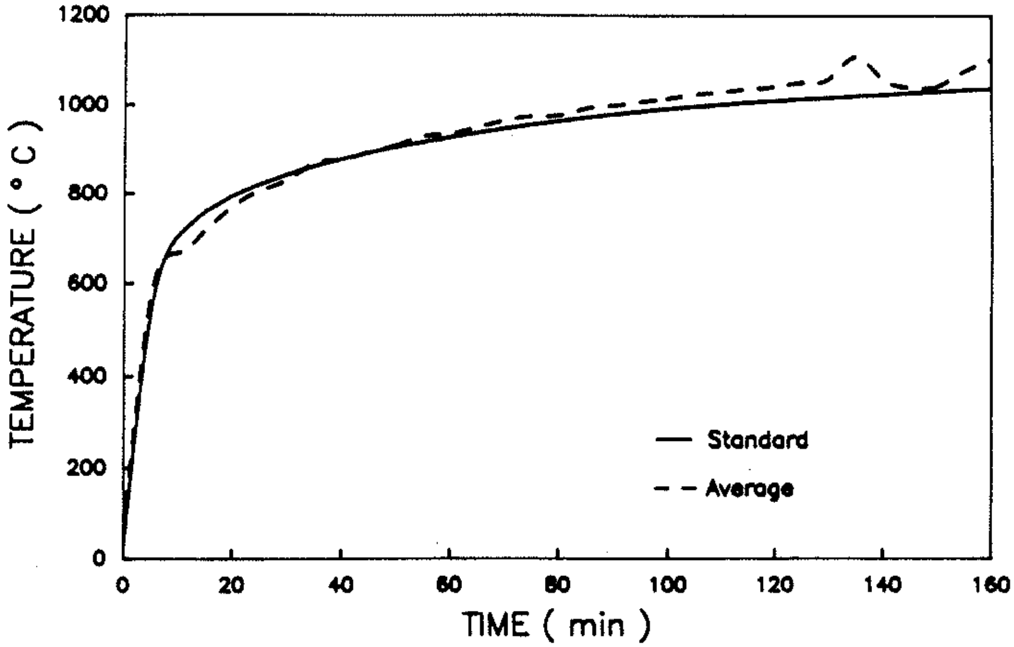


Figure 9. Furnace Temperature during Test of Column No. 2

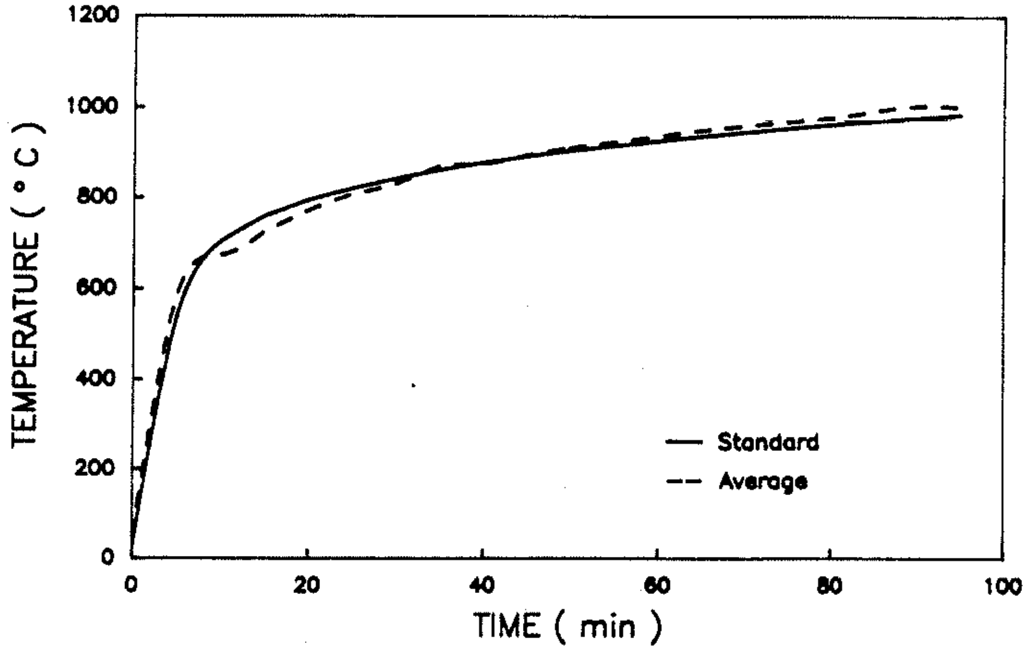


Figure 10. Furnace Temperature during Test of Column No. 3

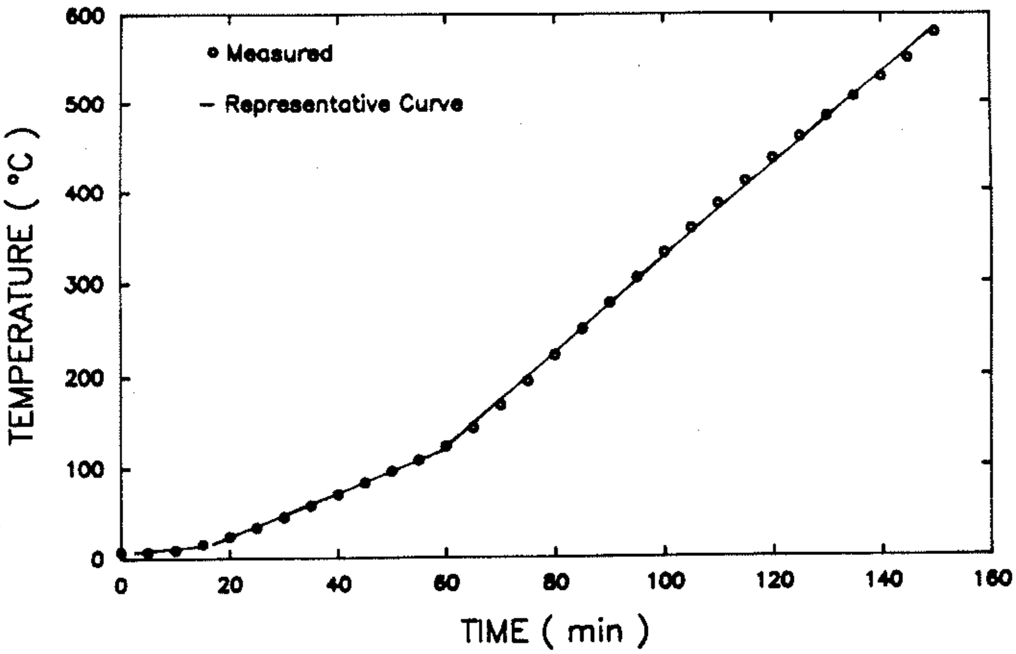


Figure 11. Average Steel Temperature at Midheight of Column No. 1

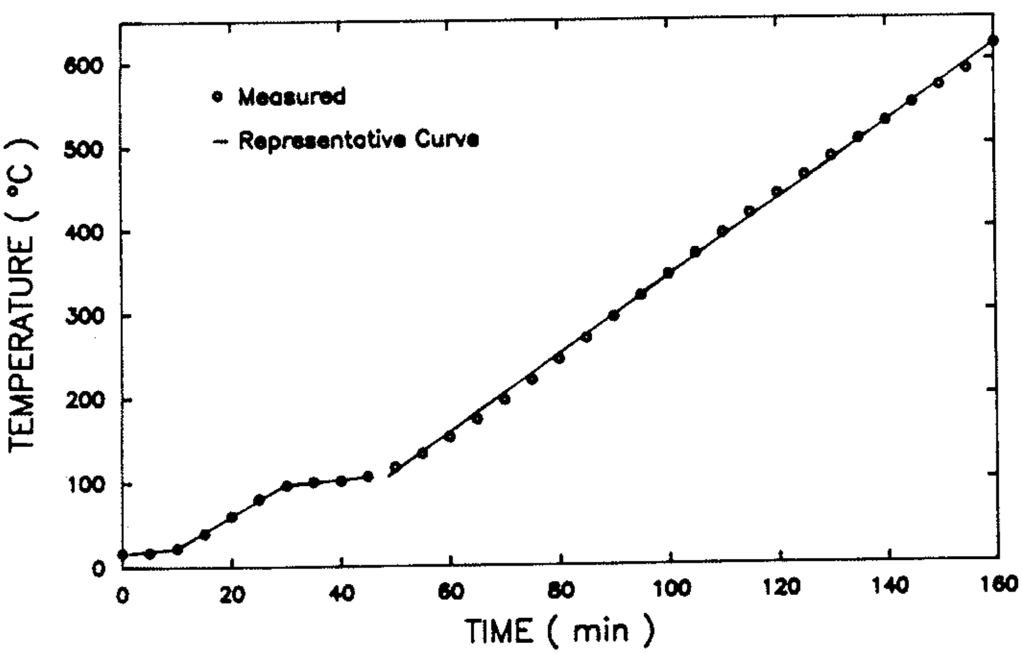


Figure 12. Average Steel Temperature at Midheight of Column No. 2

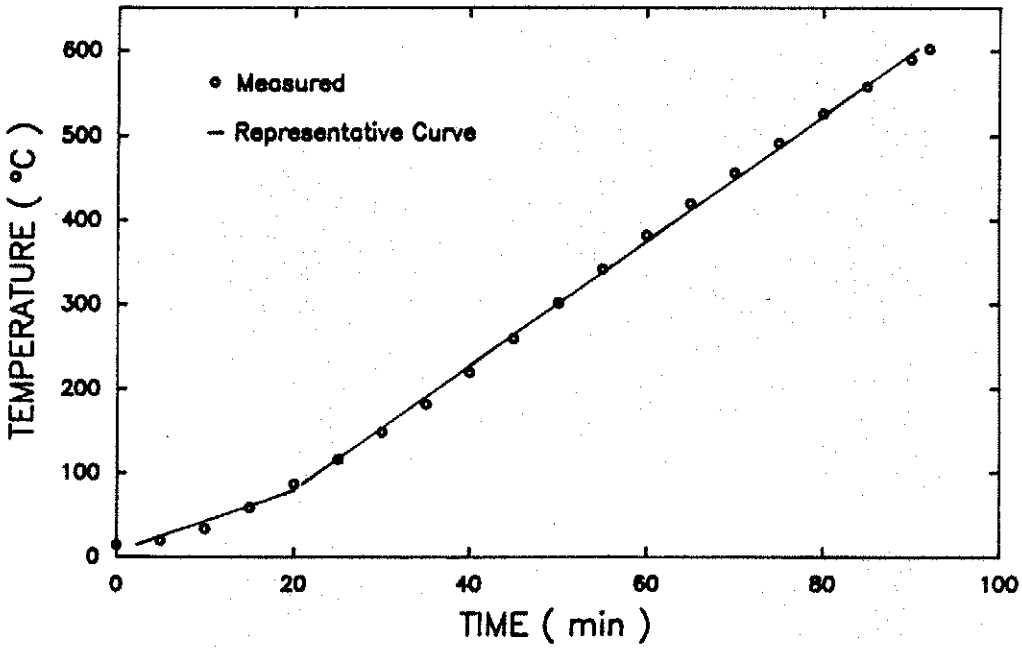


Figure 13. Average Steel Temperature at Midheight of Column No. 3

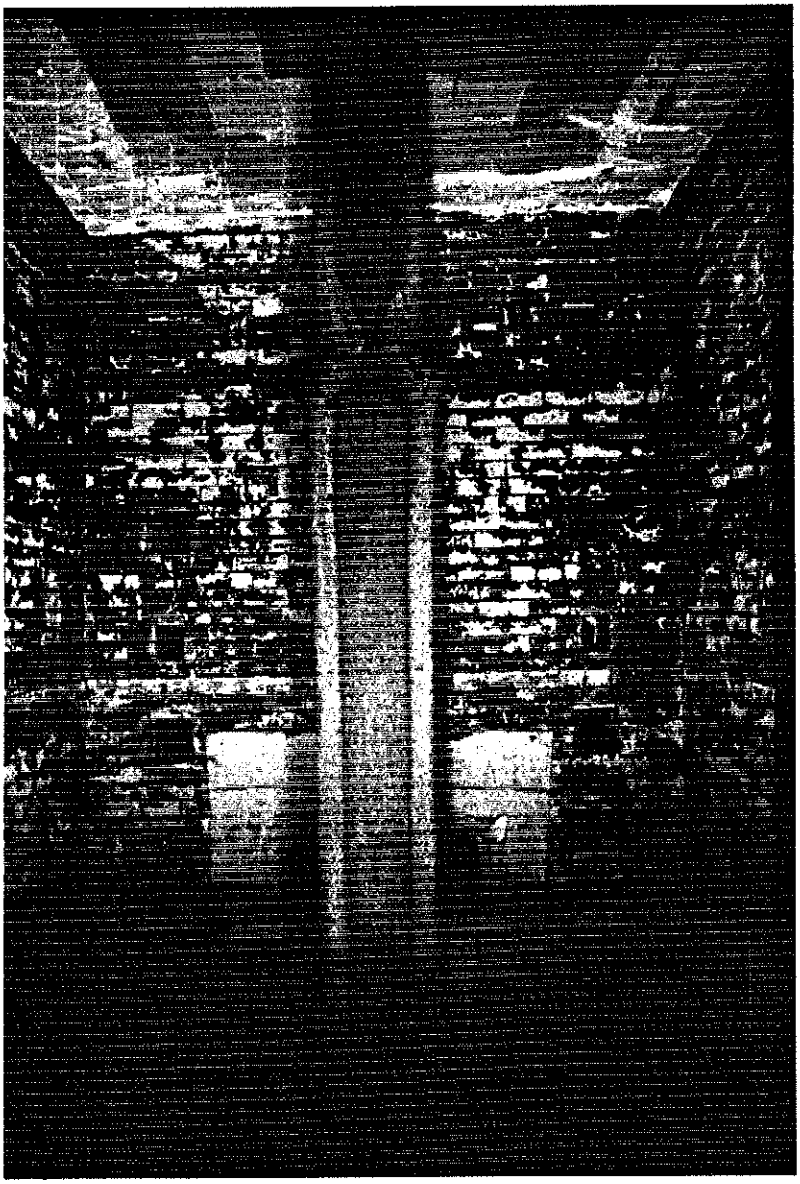


FIGURE 14. COLUMN 1 AFTER TEST

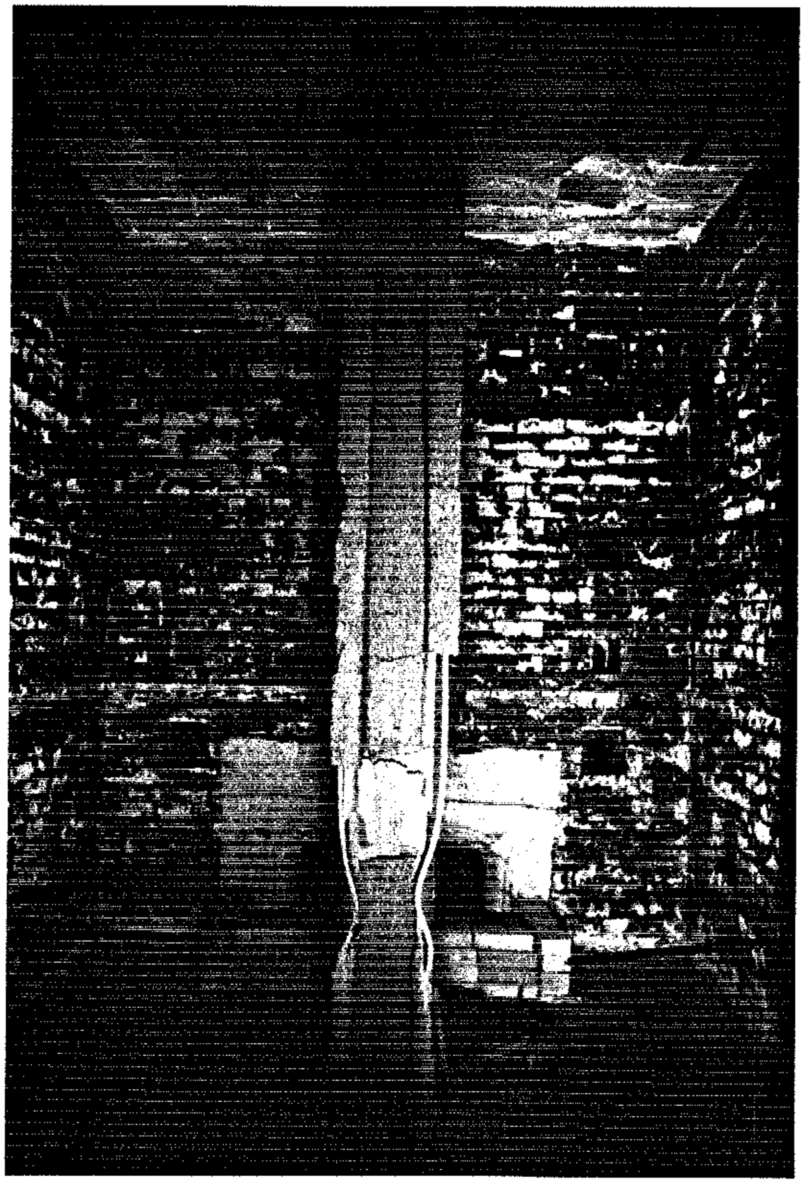


FIGURE 15. COLUMN 2 AFTER TEST

FIGURE 16. COLUMN 3 AFTER TEST

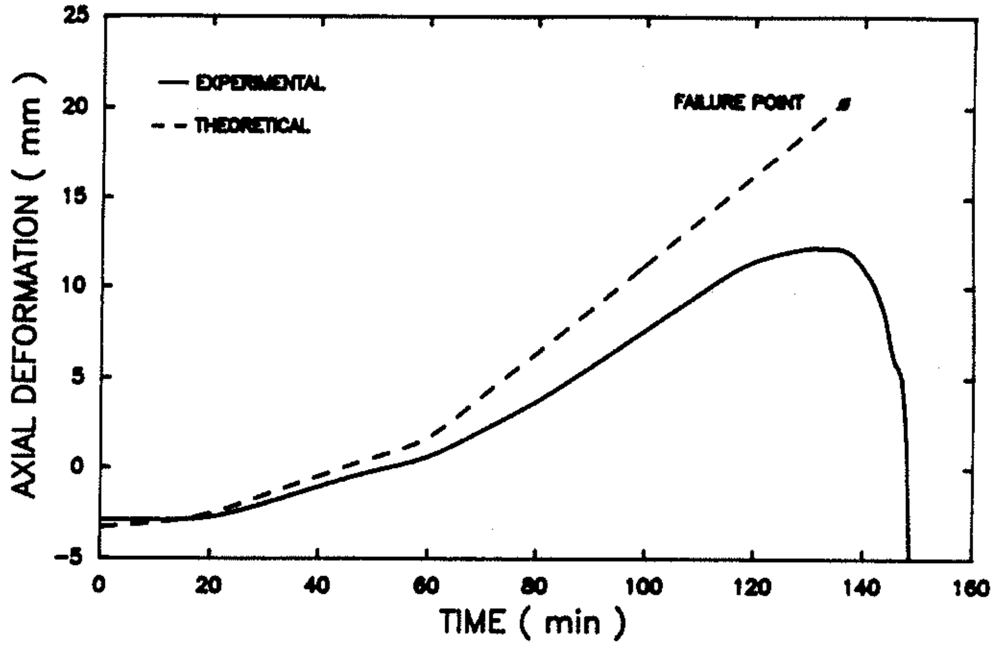


Figure 17. Axial Deformation of Column No. 1 as a Function of Time

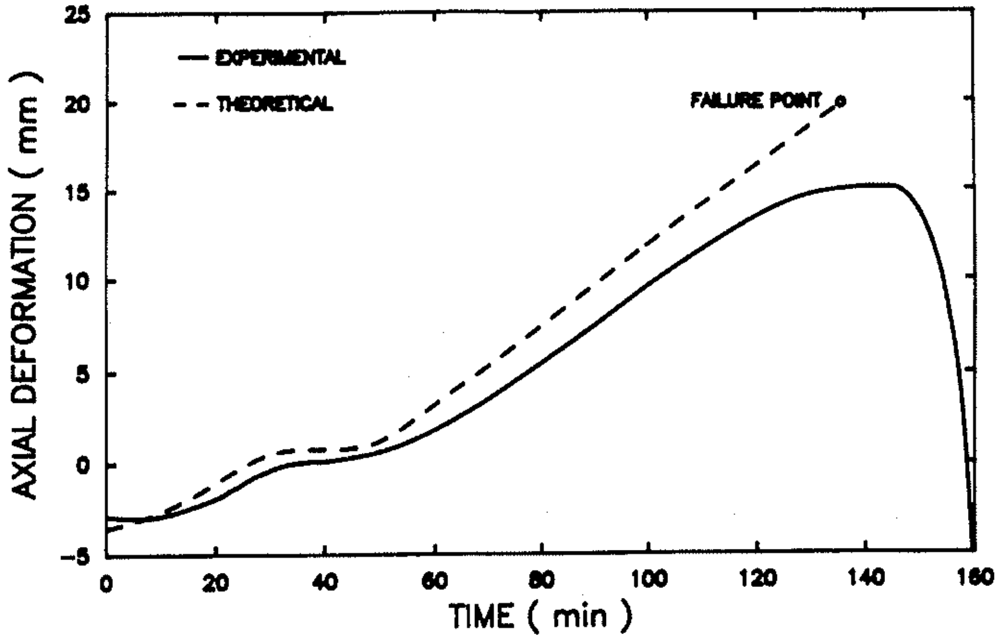


Figure 18. Axial Deformation of Column No. 2 as a Function of Time

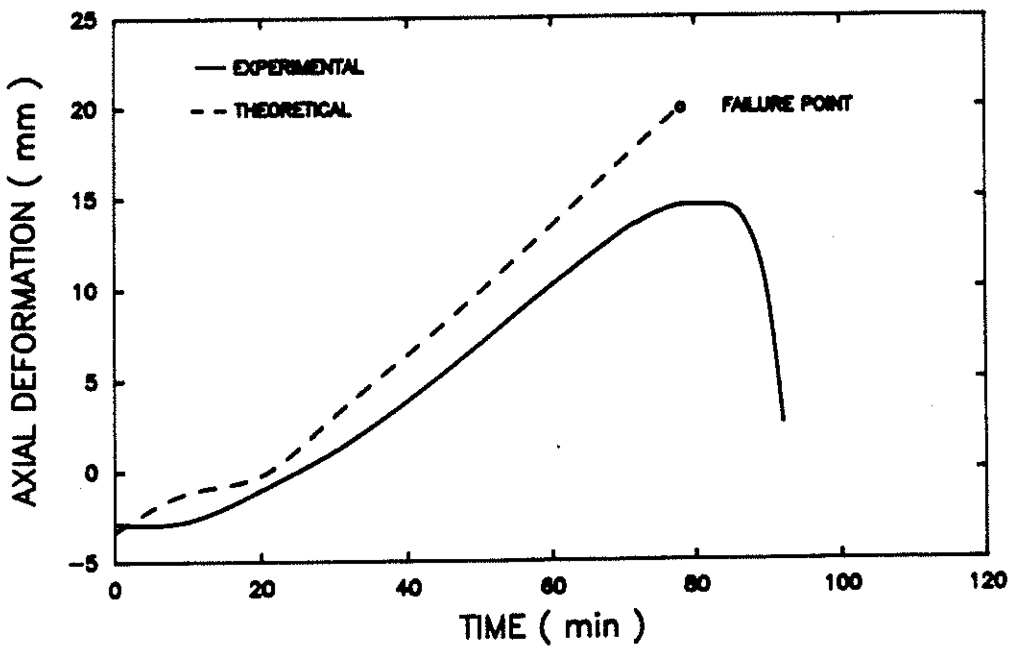


Figure 19. Axial Deformation of Column No. 3 as a Function of Time

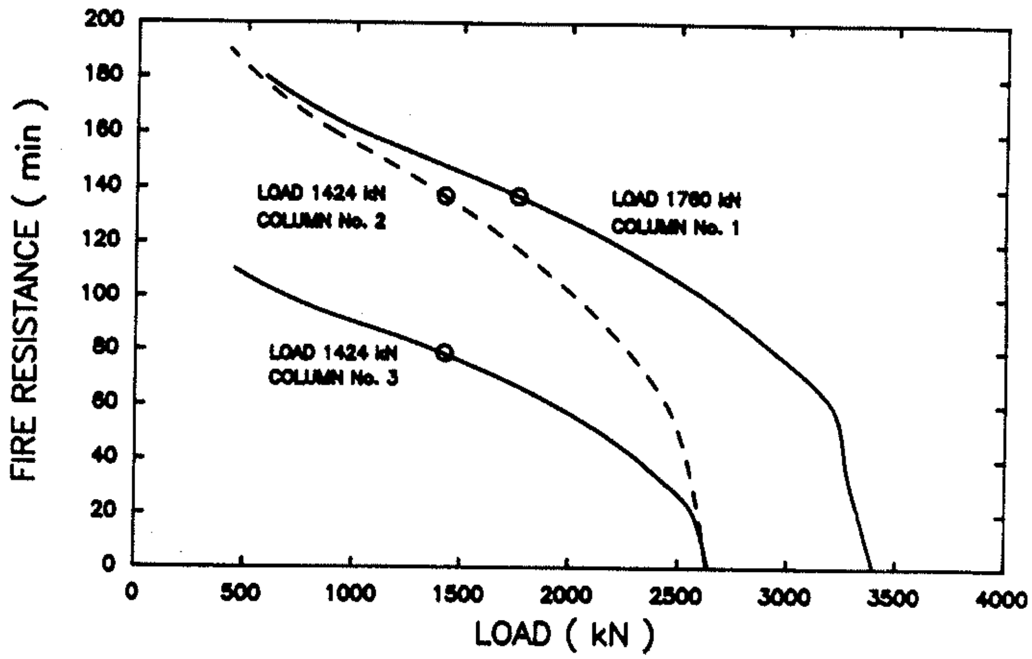


Figure 20. Fire Resistance of Test Columns as a Function of Load

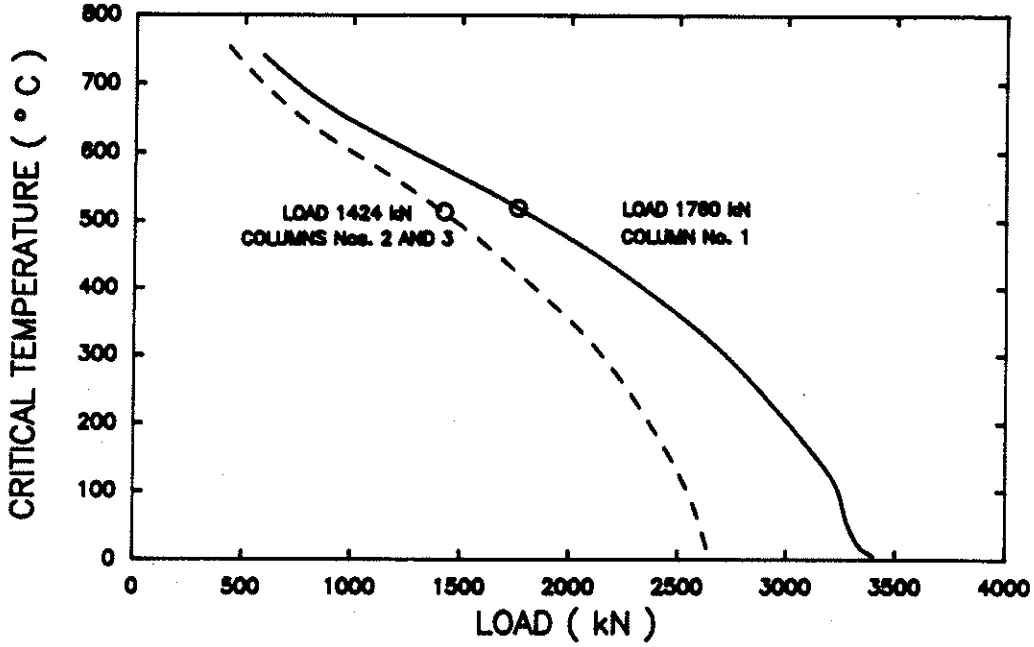


Figure 21. Critical Steel Temperature of the Test Columns as a Function of Load