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# Evaluation of the Fire Resistance of Reinforced Concrete Columns with Rectangular Cross-Section

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Canada

# EVALUATION OF THE FIRE RESISTANCE OF REINFORCED CONCRETE COLUMNS WITH RECTANGULAR CROSS-SECTION

## 1 INTRODUCTION

Joint studies between the National Research Council of Canada and the Portland Cement Association on reinforced concrete columns were started a number of years ago for the purpose of updating the information on fire resistance ratings for these columns in North American building codes. These studies include the development of mathematical models for the calculation of the fire resistance of columns of various sizes and shapes, as well as experimental studies.

An extensive test program, in which the behaviour of over 40 full-scale reinforced concrete columns were examined under fire conditions, was recently completed [1]. Among the columns tested were columns with rectangular cross-section. It is the intent to discuss in this study the development of a mathematical model for the calculation of the fire resistance of these columns and the validation of the model.

## 2 TEST SPECIMENS

Four test specimens were examined. The specimens consisted of two square and two rectangular tied reinforced concrete columns. They are illustrated in Figs. 1-4. Details of the specimens and their fabrication are given below.

### 2.1 Dimensions

All columns were 3810 mm (12 ft 6 in.) long from end plate to end plate. Two of the columns had square sections of 305 mm (12 in.), one a rectangular section of 305 x 457 mm (12 x 18 in.) and one of 203 x 915 mm (8 x 36 in.).

### 2.2 Materials

Cement: Type 1, a general purpose cement for the construction of reinforced concrete structures, was used.

Aggregate: Siliceous sand and gravel were from Eau Claire, Wisconsin. The maximum size of the aggregate was 19 mm (3/4 in.). The petrographic information, given in Table 1, was obtained using the procedures of ASTM C295-79 [2].

Physical properties of aggregate: Specific gravity of sand (2.63); specific gravity of gravel (2.57); moisture content of sand (4.0%); moisture content of gravel (1.0%); saturated surface dry unit weight of gravel (1678 kg/m$^3$) (104.9 lb/ft$^3$); fineness modulus of fine aggregate (2.69); fineness modulus of coarse aggregate (1.73).

Steel reinforcement: Deformed bars meeting requirements of ASTM Designation A615-80 [3] were used for main ties and bars. The longitudinal steel bars in the columns were symmetrical arrangements of No. 6, 7 or 8 bars. All ties were No. 3 bars. The yield and ultimate strength of the bars are listed in Table 2.

Concrete mix: The concrete mixes were designed to produce a 34.5 MPa (5000 psi) strength non-air-entrained concrete. A water/cement ratio of 0.5 was used. The slump was 83 mm (3.27 in). Batch quantities are as follows: cement, 307 kg/m$^3$ (19.2 lb/ft$^3$); coarse aggregate, 1054 kg/m$^3$ (1776 lb/yd$^3$); sand, 871 kg/m$^3$ (1467 lb/yd$^3$); water, 154 kg/m$^3$ (259 lb/yd$^3$). The average measured properties of the concrete were: air content, 1.7%, density, 2400 kg/m$^3$ (150lb/ft$^3$); compressive 28-day strength, 39.0 MPa (5650 psi). The individual 28-day strength of the cylinders are given in Table 3.

## 2.3 Fabrication

The columns were cast in specially designed forms. The reinforcement cage was assembled by welding the longitudinal bars to a steel end plate. Chromel-alumel thermocouples were secured to the reinforcing steel at specified locations after the cage was properly positioned in the form. To avoid possible dislocation of the thermocouples during casting, a careful working plan was followed as described below.

## 2.4 Reinforcing Bars and Steel Plates

The size and number of reinforcing bars varied. The amount of steel that was present in each column is listed in Table 3. Illustrations of the main reinforcing bars and cross-sections are provided in Figures 1-4.

Each column length was 3810 mm (12 ft 6 in.) measured from end plate to end plate. The longitudinal reinforcing bars were cut to 3800 mm (12 ft 5-1/2 in.) and machined at both ends. Holes with a diameter of 1.6 mm (1/16 in.) greater than that of the machined ends were drilled through the end plates to accommodate the longitudinal bars. This information is summarized in Table 4.

The main ties and bars were tied together to complete the steel cage. The cage then was vertically placed on a leveled-end plate in such a way that the machined segments of the bars were positioned in the holes.

## 2.5 Welding

The provisions of the AWS Designation D12.1-75 [4] were followed when welding the plates and bars. To prevent any possible brittle failure during welding, these members were preheated with a propane torch to 288°C (550°F). The side fillet weld was done around bars on the inner face of the bottom plate. McKay E10018-D2 and DYTRON-579 welding rods were used. Both types of welding rods have tensile strength of 835 Mpa (120 ksi). Mild-steel welding rods were used to fill up the holes on the outer faces of the plate, drilled to accommodate the reinforcing bars. The rough surface of the welded joints on the outer face of the plate were ground to a smooth finish.

The welding of the top steel plate was performed after the casting of the columns. Before positioning the top plate, a 6 mm (1/4 in.) layer of mortar was spread over the top of the column to ensure good contact between the steel plate and concrete. The mortar was made of 1 part cement and 3 parts siliceous sand. Using the same procedure as for the bottom plate, the top plate was welded to the outer side to the bars and smoothed.

## 2.6 Forms

Forms were made of smooth plywood, with the front side left open for depositing fresh concrete. As the casting progressed upwards, window pieces made of plywood were bolted to the form to close the opening.

## 2.7 Thermocouples

Butt-welded chromel-alumel thermocouples with a thickness of 0.91 mm (0.036 in.) were used to make thermocouple frames for measuring concrete temperatures at several locations in different cross sections of the columns. Each frame consisted of a number of thermocouples tied to steel rods that were firmly secured to the main reinforcing bars.

For the 305 x 305 mm (12 x 12 in.) column with four reinforcing bars, temperatures were measured at three levels: at one-quarter height, at mid-height and at three-quarter height of the column. At mid-height, the temperatures were measured along the whole length of an axis and a diagonal of the section; at the other two levels, the temperatures measured were measured only along half of the axis and half of the diagonal of the section.

For all other columns, only the frame at mid-height, or a similar one, was used.

In addition, a number of thermocouples were mounted on the reinforcing steel bars and ties of all columns. The exact location and numbering of the thermocouples are shown in Figures 5-15.

## 2.8 Concrete Placement

Concrete was mixed in a 0.17 $m^3$ (6 cu ft) tilting drum mixer. Shovels and scoops were used to deposit concrete in the form. A small internal vibrator was carefully applied to consolidate the concrete. As the casting progressed upward, the window pieces were successively closed and tightly bolted to the form to avoid possible mortar leaks. The top surface of the column was screened and finished with a small wood float.

Lifting hooks were embedded on opposite sides of the specimen at 0.8 m (2 ft 7 in.) from the top of the column. A humidity well was positioned at mid-point for measuring relative humidity at mid-depth of the columns [5].

## 2.9 Curing

Concrete was cured under damp burlap for 7 days at 21 to 24°C (70 to 75°F). Forms were then stripped and conditioned in an atmosphere controlled at the same temperature and 30 to 40% relative humidity.

# 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. 16). The characteristics and instrumentation of the furnace are described in detail in Reference 6. Only a brief description of the furnace and the main components is given here.

## 3.1 Loading Device

Three hydraulic jacks produce forces along the three principal axes. The jack along the axis of the test column is located at the bottom of the furnace chamber and has a loading capacity of 1000 t (2200 kips). The plate on top of this jack can be used as a platform to which the column can be attached.

## 3.2 Furnace Chamber

The furnace chamber has a floor 2642 x 2642 mm (8 ft 8 in. x 8 ft 8 in.) and is 3048 mm (10 ft) high. The interior faces of the chamber are lined with insulating materials that will 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 allows a high degree of temperature uniformity in the furnace chamber. The pressure in the furnace chamber is also adjustable. It was set somewhat lower than atmospheric pressure.

## 3.3 Instrumentation

The furnace temperatures are measured with the aid of eight chromel-alumel thermocouples. The junction of each thermocouple was located 305 mm (1 ft) from the test specimen, at various heights. Two thermocouples were placed opposite each other every 610 mm (2 ft) along the height of the furnace chamber. The locations of their junctions and their numbering are shown in Fig. 17. Thermocouples No. 4 and 6 were located at a height of 610 mm (2 ft) from the floor, Thermocouples No. 2 and 8 at 1220 mm (4 ft), Thermocouples No. 3 and 5 at 1830 mm (6 ft) and Thermocouples No 1 and 7 at 2440 mm (8 ft). The temperatures measured by the thermocouples are averaged automatically and the average temperature used as the criterion for controlling the furnace temperature.

The loads are controlled and measured using pressure transducers. The accuracy of controlling and measuring loads is about 20 kN (5 kips) at lower levels and better at higher loads.

The axial deformation of the test specimen is determined by measuring the displacement of the jack that supports the column. The displacement is measured with the aid of transducers with an accuracy of 0.002 mm (0.0001 in.).

# 4 TEST CONDITIONS AND PROCEDURES

The columns were installed in the furnace by bolting their end plates to a loading head at the top and a hydraulic jack at the bottom. The end conditions were fixed-fixed.

Before each test, the moisture condition in the centre of the column was measured with a Monfore humidity gauge [5]. These readings are recorded in Table 3.

### 4.1 Loading

The columns were tested under concentric loads which were applied at least 40 minutes before the test. The loads were lower than the maximum allowable. They are listed in Table 3.

### 4.2 Fire Exposure

The columns, with the exception of Column No. 2, were exposed to heating controlled in such a way that the average temperature in the furnace closely followed the standard ASTM-E119 (ULC-S101) [7, 8] temperature-time curve. This curve can be approximated by the following equation:

$$T_f = 20 + 750\,(1\text{-}\exp(-3.79553\sqrt{t}) + 1741\sqrt{t}$$

where

$T_f$ = temperature in °C, and
t = time in h

or by

$$T_f = 68 + 1350\,(1\text{-}\exp(-3.79553\sqrt{t}) + 306.74\sqrt{t}$$

where

$T_f$ = temperature in °F

Because of malfunction of the temperature control system of the furnace, Column No. 3 was exposed to a fire whose temperature and duration can be approximated by the standard temperature-time relation up to one half hour and after that by the equation:

$$T_f = 14.88\,t + 831.8$$

### 4.3 Recording of results

Readings were taken at each thermocouple location at intervals of 5 or 10 minutes. Axial strain was also measured.

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

## 5. CALCULATION METHOD

The calculation of the fire resistance of columns is carried out in various steps. It involves the calculation of the temperatures in the column and its deformations and strength during the exposure to fire.

## 5.1 Temperatures of Column

The column temperatures are calculated by a finite difference method [9]. This method has been previously applied to the calculation of temperatures of various building components exposed to fire [10,11,12]. Because the method of deriving the heat transfer equations and of calculating the temperatures for square and rectangular columns is described in detail in those studies, it will not be discussed here; only the equations for the calculation of the column temperatures and calculated results will be given.

### 5.1.1 Division of cross-section into elements

The cross-sectional area of the column is subdivided into a number of elements, arranged in a triangular network (Fig. 18). The elements are square inside the column and triangular at the surface. For the inside elements, the temperature at the centre is taken as representative of the entire element. For the triangular surface elements, the representative points are located on the centre of each hypotenuse.

For reasons of symmetry, only one-quarter of the section need be considered when calculating the temperature distribution in columns with square or rectangular cross-section. As illustrated in Fig. 18, in an x-y co-ordinate system, a point $p_{m,n}$ has the co-ordinates $x=(n-1)\Delta\xi/2$ and $y=(m-1)\Delta\xi/2$.

### 5.1.2 Equations for the fire-concrete boundary

It is assumed that the columns are exposed on all sides to the heat of a fire whose temperature course follows that of the standard fire described in ASTM-E119 [7] or ULC-S101 [8]. This temperature course can be approximately described by the following expression:

$$T_f^j = 20 + 750[1-\exp(-3.79553\sqrt{t})] + 170.41\sqrt{t} \qquad (1)$$

where t is the time in hours and $T_f^j$ is the fire temperature in °C at time $t=j\Delta t$.

The temperature rise in the layer can be derived by creating a heat balance for each element. In the following, all calculations will be carried out for a unit length of the column. For the elements at the surface of the column along the x-axis, the temperature at time $t=(j+1)\Delta t$ is given by the expression:

$$T_{1,n}^{j+1} = T_{1,n}^{j} + \frac{2\Delta t}{[(\rho_c c_c)_{1,n}^{j} + \rho_w c_w \phi_{1,n}^{j}]\,(\Delta\xi)^2}$$

$$\left\{ \left(\frac{k_{2,(n-1)}^{j} + k_{1,n}^{j}}{2}\right) \left(T_{2,(n-1)}^{j} - T_{1,n}^{j}\right) \right.$$

$$+ \left(\frac{k_{2,(n+1)}^{j} + k_{1,n}^{j}}{2}\right) \left(T_{2,(n+1)}^{j} - T_{1,n}^{j}\right)$$

$$+ \sqrt{2}\, \varepsilon_f \varepsilon_c \sigma \Delta\xi \left[(T_f^j + 273)^4 - (T_{1,n}^j + 273)^4\right]\Bigg\} \tag{2}$$

For the elements at the surface of the column along the y-axis, the temperature at the time t=(j+1)Δt is given by:

$$T_{m,N}^{j+1} = T_{m,N}^j + \frac{2\Delta t}{[(\rho_c c_c)_{m,N}^j + \rho_w c_w \phi_{m,N}^j]\,(\Delta\xi)^2}$$

$$\Bigg\{ \left(\frac{k_{(m-1),(N-1)}^j + k_{m,N}^j}{2}\right) \left(T_{(m-1),(N-1)}^j - T_{m,N}^j\right)$$

$$+ \left(\frac{k_{(m+1),(N-1)}^j + k_{m,N}^j}{2}\right) \left(T_{(m+1),(N-1)}^j - T_{m,N}^j\right)$$

$$+ \sqrt{2}\, \varepsilon_f \varepsilon_c \sigma \Delta\xi \left[(T_f^j + 273)^4 - (T_{m,N}^j + 273)^4\right]\Bigg\} \tag{3}$$

## 5.1.3 Equations for inside the concrete

For the elements in the concrete, the temperature at time t=(j+1)Δt is given by:

$$T_{m,n}^{j+1} = T_{m,n}^j + \frac{\Delta t}{[(\rho_c c_c)_{m,n}^j + \rho_w c_w \phi_{m,n}^j]\,(\Delta\xi)^2}$$

$$\Bigg[ \left(\frac{k_{(m-1),(n-1)}^j + k_{m,n}^j}{2}\right) \left(T_{(m-1),(n-1)}^j - T_{m,n}^j\right) + \left(\frac{k_{(m+1),(n-1)}^j + k_{m,n}^j}{2}\right)$$

$$\left(T_{(m+1),(n-1)}^j - T_{m,n}^j\right) + \left(\frac{k_{(m-1),(n+1)}^j + k_{m,n}^j}{2}\right) \left(T_{(m-1),(n+1)}^j - T_{m,n}^j\right)$$

$$+ \left(\frac{k_{(m+1),(n+1)}^j + k_{m,n}^j}{2}\right) \left(T_{(m+1),(n+1)}^j - T_{m,n}^j\right)\Bigg] \tag{4}$$

### 5.1.4 Auxiliary equations

To calculate the temperatures along the lines of symmetry A-D and C-D, the temperature has to satisfy the following symmetry conditions:

line A-D

$$T^{j+1}_{m,1} = T^{j+1}_{m,3} \qquad (5)$$

line C-D

$$T^{j+1}_{(M+1),n} = T^{j+1}_{(M-1),n} \qquad (6)$$

### 5.1.5 Effect of Moisture

The effect of moisture is taken into account by assuming that in each element, the moisture starts to evaporate when the temperature of the element reaches 100°C (212°F). During the period of evaporation all the heat supplied to an element is used for the evaporation of the moisture, until the element is dry.

For the elements at the boundary between fire and concrete along the x-axis, the initial volume of moisture is given by:

$$V_{1,n} = \frac{(\Delta\xi)^2}{2}\,\phi_{1,n} \qquad (7)$$

From a heat balance equation it can be derived that, per unit length of the column, the volume $\Delta V_{1,n}$ evaporated in the time $\Delta t$ from the concrete element, is:

$$\Delta V_{1,n} = \frac{\Delta t}{\rho_w \lambda_w}\left\{\left(\frac{k^j_{2,(n-1)} + k^j_{1,n}}{2}\right)\left(T^j_{2,(n-1)} - T^j_{1,n}\right) + \left(\frac{k^j_{2,(n+1)} + k^j_{1,n}}{2}\right)\left(T^j_{2,(n+1)} - T^j_{1,n}\right) + \sqrt{2}\,\varepsilon_f \varepsilon_c \sigma \Delta\xi \left[(T^j_f + 273)^4 - (T^j_{1,n} + 273)^4\right]\right\} \qquad (8)$$

For the elements at the boundary between fire and concrete along the y-axis, the initial volume of moisture is given by:

$$V_{m,N} = \frac{(\Delta\xi)^2}{2} \phi_{m,N} \tag{9}$$

From a heat balance equation it can be derived that, per unit length of the column, the volume $\Delta V_{m,N}$ evaporated in the time $\Delta t$ from the concrete element is:

$$\Delta V_{m,N} = \frac{\Delta t}{\rho_w \lambda_w} \left\{ \left( \frac{k^j_{(m-1),(N-1)} + k^j_{m,N}}{2} \right) \left( T^j_{(m-1),(N-1)} - T^j_{m,N} \right) + \left( \frac{k^j_{(m+1),(N-1)} + k^j_{m,N}}{2} \right) \left( T^j_{(m+1),(N-1)} - T^j_{m,N} \right) + \sqrt{2}\, \varepsilon_f \varepsilon_c \sigma \Delta\xi \left[ (T^j_f + 273)^4 - (T^j_{m,N} + 273)^4 \right] \right\} \tag{10}$$

For the concrete elements inside the column, the initial volume of moisture is given by:

$$V_{m,n} = (\Delta\xi)^2)\ \phi_{m,n} \tag{11}$$

Similarly, as for the surface concrete elements, it can be derived that, per unit length of the column, the volume $\Delta V_{m,n}$, evaporated in the time $\Delta t$ from these layers is:

$$\Delta V_{m,n} = \frac{\Delta t}{\rho_w \lambda_w} \left[ \left( \frac{k^j_{(m-1),(n-1)} + k^j_{m,n}}{2} \right) \left( T^j_{(m-1),(n-1)} - T^j_{m,n} \right) + \left( \frac{k^j_{(m+1),(n-1)} + k^j_{m,n}}{2} \right) \left( T^j_{(m+1),(n-1)} - T^j_{m,N} \right) + \left( \frac{k^j_{(m-1),(n+1)} + k^j_{m,n}}{2} \right) \left( T^j_{(m-1),(n+1)} - T^j_{m,N} \right) + \left( \frac{k^j_{(m+1),(n+1)} + k^j_{m,n}}{2} \right) \left( T^j_{(m+1),(n+1)} - T^j_{m,N} \right) \right] \tag{12}$$

### 5.1.6 Stability criterion

In order to ensure that any error existing in the solution at some time level will not be amplified in subsequent calculations, a stability criterion has to be satisfied which, for a selected value of $\Delta\xi$, limits the maximum of time step $\Delta t$. Following the method described in Reference [9], it can be derived that, for the fire-exposed column, the criterion of stability is most restrictive along the boundary between fire and concrete. It is given the condition:

$$\Delta t \leq \frac{(\Delta\xi)^2}{\dfrac{4k_{max} + 2\sqrt{2}\,\Delta\xi\, h_{max}}{(\rho_c c_c)_{min}}} \tag{13}$$

where the maximum value of the coefficient of heat transfer during exposure to the standard fire ($h_{max}$) is approximately 3 x $10^6$J/m$^2$h°C (147 Btu/ft$^2$h°F).

## 5.2 Strength of Column During Fire

### 5.2.1 Transformation into square network

To calculate the deformations and stresses in the column, and its strength, the triangular network is transformed into a square network. In Fig. 19 a quarter section of this network, consisting of square elements arranged parallel to the x- and y-axis of the section, are shown. The arrangement of the elements in the three other quarter sections is identical to this. The width of each element of this network is $\Delta\xi/\sqrt{2}$. The temperatures, deformations and stresses of each element are represented by those of the centre of the element. The temperature at the centre of each element is obtained by averaging the temperatures of the elements in the triangular network according to the relation:

$$\left(T^j_{m,n}\right)_{square} = \left(\frac{T^j_{(m+1),(n+1)} + T^j_{m,(n+2)}}{2}\right)_{triangular} \tag{14}$$

where the subscripts square and triangular refer to the elements of the square and triangular network.

For the steel reinforcing bars also, a representative bar temperature can be indicated. Measurements at various locations during fire tests showed that the differences in temperature in the bar and sections are small [12]. A close approximation of the average bar temperature is obtained by considering the column as consisting entirely of concrete and selecting the temperature at the location of the centre of the bar section as the representative bar temperature. Thus, for a steel reinforcing bar, the centre of whose section is located in an element $p_{m,n}$, the representative temperature is equal to that of $p_{m,n}$, which is given by Eq. (14).

Similarly it is assumed that the stresses and deformations at the centre of an element are representative of those of the whole element.

### 5.2.2 Assumptions in the calculation of strength during fire

During exposure to fire, the strength of the column decreases with the duration of exposure. The strength of the column can be calculated by a method based on a load deflection analysis [13].

In this method, the columns, which are fixed at the ends during the tests, are idealized as pin-ended columns of length KL (Fig. 20). The load on the column is intended to be concentric. Due to imperfections of the columns and the loading device, a small eccentricity exists. The loading system and the test columns were made with high precision, however. Therefore, in the calculations, a very small initial load eccentricity will be assumed. The real eccentricity, however, is unknown. After calculations showed that for eccentricities up to 3 mm (0.12 in.) the influence on fire resistance is small, an arbitrary value of 0.2 mm (0.008 in.), reflecting a nearly concentric load, has been selected for the initial eccentricity. The selection of a finite value for the initial eccentricity is needed in order to make the computer program work.

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. 20. For such a relation, the deflection at mid-height Y, in terms of curvature $\chi$ of the column at this height, can be given by:

$$Y = \chi \frac{(KL)^2}{12} \tag{15}$$

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 further made:

1. The properties to the concrete and steel are those described in the Appendix.

2. Concrete has no tensile strength.

3. Plane sections remain plane.

4. The reduction in column length before exposure to fire, consisting of free shrinkage of the concrete, creep, and shortening of the column due to load, is negligible. This reduction can be eliminated by selecting the length of the shortened column as initial length from which the changes during exposure to fire are determined.

Based on these assumptions the column strength during exposure to fire was calculated. In the calculations, the network of elements shown in Fig. 19 was used. Because the strains and stresses of the elements are not symmetrical with respect to the y-axis, the calculations were performed for both the network shown and an identical network at the left of the y-axis. 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 strength of the column during exposure to fire are given below.

### 5.2.3 Equations for the concrete

The strain in the concrete for the elements at the right of the y-axis (Fig. 19) can be given by:

$$(\varepsilon_c)_R = -(\varepsilon_T)_c + \varepsilon + \frac{x_c}{\rho} \tag{16}$$

and for the elements at the left of the y-axis by:

$$(\varepsilon_c)_L = -(\varepsilon_T)_c + \varepsilon - \frac{x_c}{\rho} \tag{17}$$

where $(\varepsilon_T)_c$ = the thermal expansion of the concrete (m $m^{-1}$)
$\varepsilon$ = the axial strain of the column (m $m^{-1}$)
$x_c$ = the horizontal distance from the centre of the elements to the vertical plane through the y-axis of the column section (m)
$\rho$ = the radius of curvature (m)

The stresses in the elements are calculated using the same stress-strain relations for concrete, given in Reference [12]. These relations are given by the Eqs. (20)-(24) in the Appendix.

### 5.2.4 Equations for the steel

The strain in the steel reinforcing bars can be given as the sum of the thermal expansion of the steel $(\varepsilon_T)_s$ and the axial strain of the column $x_s/\rho$, where $x_s$ is the horizontal distance of the centre of the section of steel bar to the vertical plane through the y-axis of the column section and $\rho$ is the radius of curvature. For the steel bars at the right of the y-axis, the strain $(\varepsilon_s)_R$ is given by:

$$(\varepsilon_s)_R = -(\varepsilon_T)_s + \varepsilon + \frac{x_s}{\rho} \tag{18}$$

For the steel bars at the left of the y-axis, the strain $(\varepsilon_s)_L$ is given by:

$$(\varepsilon_s)_L = -(\varepsilon_T)_s + \varepsilon - \frac{x_s}{\rho} \tag{19}$$

The stresses in the steel are calculated using the same stress-strain relations for steel, given in Reference [12]. These relations are given by Eqs. (33)-(36) in the Appendix.

### 5.2.5 Procedure for calculation of column strength

With the aid of Eqs. (16)-(19) and (33)-(36), the stresses at mid-section in the concrete elements and in the steel bars can be calculated for any value of the axial strain and curvature

$1/\rho$. From these stresses, the load that each element and each reinforcing bar 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 gradually reduces 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 point is the fire resistance of the column.

# 6 RESULTS AND DISCUSSION

## 6.1 Measured Results

The temperatures, measured during the tests at various locations in the concrete and on the steel, are given for the four columns in Tables 5-9, 11-13, 15-17 and 19-21.

In Tables 10, 14, 18 and 22 the axial deformations of the four columns, measured during the tests, are given as functions of time.

## 6.2 Discussion

Using the mathematical model described in this paper, the temperatures in the columns and the axial deformations of the columns were calculated. In the calculations, the thermal and mechanical properties of the concrete and steel and the specifics of the column furnace, given in the Appendix, were used.

In Figs. 21-23 calculated temperatures are compared with those measured at various depths in a square column (Column No. 1) and the columns with rectangular cross-section (Columns No. 3 and No. 4). It can be seen that, with the exception of the temperatures measured at the centre of the specimen at an early stage, there is good agreement between calculated and measured column temperatures. The temperatures measured at the centre of the columns show initially a relatively rapid rise in temperature, followed by a period of nearly constant temperatures in the early stages of the test. This temperature behaviour may be the result of thermally induced migration of the moisture towards the centre of the column where, as shown in the figures, the influence of migration is most pronounced. Although the model takes into account evaporation of moisture, is does not take into account the migration of the moisture towards the centre. That migration appears to account for the deviation between calculated and measured temperatures at the earlier stages of fire exposure. At a later stage, however, which is the important stage from the point of view of predicting the fire resistance of the columns, there is good agreement between calculated and measured temperatures.

In Figs. 24-27, the calculated and measured axial deformations of the columns during exposure to fire are shown. It can be seen that the mathematical model predicts reasonably well the trend in the progression of the axial deformations with time. The largest differences between calculated and measured axial deformations are on the order of 5 mm, which may be regarded as small when considering that these are differences between calculated and measured deformations for columns of a length of about 3800 mm. It must also be noted that these columns deform axially as a result of several factors, namely, load, thermal expansion, bending and creep, which cannot be completely taken into account in the calculations.

This was particularly the case with column No. 4 (Fig. 26). Whereas the model defines the failure point as the point at which the column can no longer support the applied load and assumes that failure at this point is instantaneous, in the test the column, which was relatively slender, contracted considerably before it was crushed.

In Fig. 28, the calculated strengths of the columns are shown as a function of the time exposure. The strength decreases with time until it becomes so low that the column can no longer support the load. The time to reach this point is the fire resistance of the column. The calculated fire resistances of the columns are given in Table 3 together with the measured fire resistances. It can be seen that there is good agreement between calculated and measured fire resistances for Columns No. 1-3, but the calculated fire resistance of Column No. 4 is about 30% lower than that measured, due to the considerable contraction of the column, which the model can only partly take into account.

Fig. 28 also shows the influence of the amount of steel and the influence on cross-section shape and size on the fire resistance of the columns. It can be seen, by comparing the fire resistances of Columns No. 1 and No. 2, that under commensurate loads, the fire resistance of the column increases somewhat with the amount of steel. Columns with rectangular cross-section, however, have substantially higher fire resistances than those with square cross-section with the same thickness. The fire resistance of Column No. 3, for example, is almost twice that of the square columns with the same thickness. Column No. 4, which is much thinner than the square columns, namely 203 mm in thickness in comparison with the 305 mm thickness of the square columns, has a fire resistance that is approximately equal to that of the square columns. The main reason for the relatively higher fire resistance of the rectangular columns is probably that the heating of the core of columns with rectangular cross-section approaches that of a wall, which is heated on two sides, whereas the columns with square cross-section are heated on four sides.

## 7 CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1. The mathematical model employed in this study is capable of predicting the fire resistance of rectangular reinforced concrete columns with an accuracy that is adequate for practical purposes.

2. The model will enable the expansion of existing data on the fire resistance of reinforced concrete columns, which at present consists predominantly of data for square columns, with that for rectangular columns.

3. Rectangular columns have, under commensurate loads, substantially higher fire resistances than square columns of the same thickness.

4. Using the model, the fire resistance of square and rectangular reinforced concrete columns can be evaluated for any value of the significant parameters, such as load, column section size, column length, concrete strength and percentage of reinforcing steel, without the necessity of testing.

5. The model can also be used for the calculation of fire resistance of columns made with concretes other than those investigated in this study; for example, lightweight or carbonate aggregate concretes, if the relevant material properties are known.

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# APPENDIX A: MATERIAL PROPERTIES AND SPECIFICS OF COLUMNS AND FURNACE

The values of the material properties used in this study are the same as those used in Reference 12 for the calculation of the fire resistance of reinforced concrete columns with square cross section.

## CONCRETE PROPERTIES

### Stress-strain relations

for $\varepsilon_c \leq \varepsilon_{max}$

$$f_c = f'_c[1 - (\frac{\varepsilon_c - \varepsilon_{max}}{3\varepsilon_{max}})^2] \tag{20}$$

where

$$\varepsilon_{max} = 0.0025 + (6.0T + 0.04T^2) \times 10^{-6} \tag{21}$$

and

for 0°C < T < 450°C

$$f'_c = f'_{co} \tag{22}$$

for 450°C ≤ T ≤ 874°C

$$f'_c = f'_c[2.011 - 2.353(\frac{T-20}{1000})] \tag{23}$$

for T > 874°C

$$f'_c = 0 \tag{24}$$

### Thermal capacity

for 0 ≤ T ≤ 200°C

$$\rho_c c_c = (0.005T + 1.7) \times 10^6\ Jm^{-3}\,{}^\circ C^{-1} \tag{25}$$

for 200°C < T ≤ 400°C

$$\rho_c c_c = 2.7 \times 10^6\ Jm^{-3}\,{}^\circ C^{-1} \tag{26}$$

For 400°C < T ≤ 500°C

$$\rho_c c_c = (0.013T - 2.5) \times 10^6\ Jm^{-3}\,{}^\circ C^{-1} \tag{27}$$

for $500°C < T \le 600°C$

$$\rho_c c_c = (-0.013T + 10.5) \times 10^6 \, Jm^{-3} \, °C^{-1} \tag{28}$$

for $T > 600°C$

$$\rho_c c_c = 2.7 \times 10^6 \, Jm^{-3} \, °C^{-1} \tag{29}$$

**Thermal conductivity**

For $0 \le T \le 800°C$

$$k_c = -0.00085T + 1.9 \, Wm^{-1} °C^{-1} \tag{30}$$

For $T > 800°C$

$$k_c = 1.22 \, Wm^{-1} °C^{-1} \tag{31}$$

**Coefficient of thermal expansion**

$$\alpha_c = (0.008T + 6) \times 10^{-6} \tag{32}$$

## STEEL PROPERTIES

**Stress-strain relations**

for

$$\varepsilon_s \le \varepsilon_p$$

$$f_y = \frac{f(T, 0.001)}{0.001} \varepsilon_s \tag{33}$$

where

$$\varepsilon_p = 4 \times 10^{-6} f_{yo} \tag{34}$$

and

$$f(T, 0.001) = (50 - 0.04T) \times [1 - \exp((-30 + 0.03T)\sqrt{0.001})] \times 6.9 \tag{35}$$

for

$$\varepsilon_s > \varepsilon_p$$

$$f_y = \frac{f(T, 0.001)}{0.001} \varepsilon_p + f(T, (\varepsilon_s - \varepsilon_p + 0.001)) - f(T, 0.001)] \tag{36}$$

**Thermal capacity**

for $0°C \le T \le 650°C$

$$\rho_s c_s = (0.004T + 3.3) \times 10^6 \, Jm^{-3} °C^{-1} \tag{37}$$

for $650°C < T \le 725°C$

$$\rho_s c_s = (0.068T - 38.3) \times 10^6 \, Jm^{-3} °C^{-1} \tag{38}$$

for $725°C < T \le 800°C$

$$\rho_s c_s = (-0.086T + 73.35) \times 10^6 \, Jm^{-3} °C^{-1} \tag{39}$$

for $T > 800°C$

$$\rho_s c_s = 4.55 \times 10^6 \, Jm^{-3} °C^{-1} \tag{40}$$

**Thermal conductivity**

for $0°C \le T \le 900°C$

$$k_s = -0.022T + 48 \, Wm^{-1} °C^{-1} \tag{41}$$

for $T > 900°C$

$$k_s = 28.2 \, Wm^{-1} °C^{-1} \tag{42}$$

**Coefficient of thermal expansion**

for $T < 1000°C$

$$\alpha_s = (0.004T + 12) \times 10^{-6} °C^{-1} \tag{43}$$

for $T \ge 1000°C$

$$\alpha_s = 16 \times 10^{-6} °C^{-1} \tag{44}$$

## WATER PROPERTIES

**Thermal capacity**

$$\rho_w c_w = 4.2 \times 10^6 \, Jm^{-3} °C^{-1} \tag{45}$$

**Heat of vaporization**

$$\lambda_w = 2.3 \times 10^6 \ \mathrm{Jkg^{-1}} \tag{46}$$

## SPECIFICS OF COLUMNS AND FURNACE

$\varepsilon_f$ = emissivity of column furnace fire: 0.75
$\varepsilon_c$ = emissivity of concrete: 0.8
KL = effective length of columns: 2.0 m for fire resistance calculations
l = length of column that contributes to axial deformation: 3.5 m
$\phi$ = concentration of moisture in insulation by volume: 0.05

# APPENDIX B: NOMENCLATURE

## Notations

| | |
|---|---|
| c | specific heat ($Jkg^{-1}{}^{\circ}C^{-1}$) |
| $f_c$ | compressive strength of concrete at temperature T (MPa) |
| $f'_c$ | cylinder strength of concrete at temperature T (MPa) |
| $f'_{co}$ | cylinder strength of concrete at room temperature (MPa) |
| $f_y$ | strength of steel at temperature T (MPa) |
| $f_{yo}$ | yield strength of steel at room temperature (MPa) |
| h | coefficient of heat transfer at fire exposed surface ($Wm^{-2}{}^{\circ}C^{-1}$) |
| k | thermal conductivity ($Wm^{-1}{}^{\circ}C^{-1}$) |
| K | effective length factor |
| l | length of column used in the calculation of axial deformation (m) |
| L | unsupported length of column (m) |
| M | number of points along y-axis |
| N | number of points along x-axis |
| p | point |
| t | time (h) |
| T | temperature (°C) |
| V | volume of moisture ($m^3$) |
| x | coordinate (m) |
| y | coordinate (m) |
| Y | lateral deflection of column at mid-height (m) |

## Greek Letters

| | |
|---|---|
| $\alpha$ | coefficient of thermal expansion |
| $\Delta$ | increment |
| $\Delta\xi$ | mesh width (m) |
| $\varepsilon$ | emissivity, strain ($m\ m^{-1}$) |
| $\lambda$ | heat of vaporization ($Jkg^{-1}$) |
| $\rho$ | density ($kgm^{-3}$), radius of curvature (m) |
| $\sigma$ | Stefan-Boltzmann constant ($Wm^{-2}K^{-4}$) |
| $\phi$ | concentration of moisture (fraction of volume) |
| $\chi$ | curvature of column at mid-height ($m^{-1}$) |

## Subscripts

| | |
|---|---|
| o | at room temperature |
| c | of concrete |
| f | of the fire |
| m,M | at the points m, M in a column |
| max | maximum |
| min | minimum |
| n,N | at the points n, N in a row |
| L | left of the x-axis |
| R | right of the x-axis |
| p | pertaining to proportional stress-strain relation |
| s | of steel |
| T | pertaining to temperature |
| w | of water |
| 1, 2 | at the points 1, 2 |

## Superscripts

| | |
|---|---|
| j | at $t = j\Delta t$ |

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Table 1 Petrography of Sand and Gravel used as Siliceous Aggregate

Composition of Sieve Fraction, Percent on Sieve of Size Indicated

| Component | 19 mm | 12.5 mm | 9.5 mm | 6 mm | No. 4 | No. 8 | No. 16 | No. 30 | No. 50 | No. 100 | No. 200 | Percent Passing Through No. 200 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Granite | 37.9 | 32.9 | 25.5 | 31.3 | 27.0 | 27.6 | 12.3 | 7.4 | 1.9 | 4.4 | 0.6 | - - |
| Quartzite | 21.6 | 29.2 | 34.8 | 24.6 | 24.5 | 20.0 | 12.3 | 12.6 | 10.9 | 3.1 | 2.2 | - - |
| Quartz | 6.3 | 3.1 | 4.9 | 4.8 | 5.5 | 18.8 | 52.2 | 62.0 | 73.1 | 79.5 | 74.2 | 92.0 |
| Chert (a) | 10.8 | 7.0 | 5.2 | 8.1 | 9.8 | 5.9 | 7.7 | 3.5 | 2.0 | 0.8 | 2.8 | 2.0 |
| Sandstone-Quartz Conglomerate | 1.9 | 0.8 | 3.1 | 5.1 | 5.5 | 8.3 | - - | - - | - - | - - | - - | - - |
| Rhyolite-Dacite | 13.9 | 6.2 | 2.2 | 5.1 | 7.2 | 4.1 | 0.8 | 2.6 | 1.6 | 0.8 | 0.9 | - - |
| Feldspar | - - | - - | - - | - - | - - | - - | 1.3 | 5.0 | 6.6 | 5.0 | 10.8 | 4.0 |
| Diorite | 1.9 | 1.4 | 3.1 | 1.8 | 1.2 | - - | - - | - - | - - | - - | - - | - - |
| Graywake (b) | 1.3 | 9.5 | 5.8 | 5.4 | 4.3 | 6.5 | 2.3 | 1.5 | 0.3 | - - | 0.6 | - - |
| Gneiss-Schist | 2.5 | 5.1 | 10.5 | 9.3 | 7.5 | 4.1 | 6.4 | 1.8 | 0.9 | 1.1 | 0.6 | - - |
| Basalt | 1.9 | 4.5 | 4.0 | 3.9 | 6.9 | 3.2 | 2.6 | 2.4 | 0.7 | - - | 0.3 | - - |
| Misc. Igneous Rocks and Opaque Minerals (c) | - - | 0.3 | 0.9 | 0.6 | 0.6 | 1.5 | 2.1 | 1.2 | 2.0 | 5.3 | 7.0 | 2.0 |

| Particle Shape | 19 to 6 mm (%) | No. 4 to No. 16 (%) | No. 30 to No. 200 (%) |
|---|---|---|---|
| Subrounded to rounded | 30 | 20 | 10 |
| Subrounded to subangular | 40 | 40 | 40 |
| Angular | 30 | 40 | 50 |

(a) "Ironstone," made up of jasper and hematite, is included in the chert classification.
(b) Includes metagraywake.
(c) The miscellaneous igneous rocks were severely altered and positive identification was impossible. The opaque minerals occurred in the No. 50 and smaller sieve sizes were largely magnetite.

Table 2 Tensile Strength of Steel

| Bar # | Yield Stress MPa (ksi) | Ultimate Strength MPa (ksi) |
|---|---|---|
| 3 | 427 (61.8) | 671 (97.3) |
| 6 | 442 (64.1) | 721 (105) |
| 7 | 414 (60) minimum | not tested |
| 8 | 444 (64.3) | 730 (106) |

Table 3 Summary of Test Parameters and Results

| Column No. | X-section (in.) | Steel (%) | R.H. (%) | fc' (MPa) | | Test Load (kN) | Allow. Load (kN) | Failure* Mode | Failure (hrs) | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | 28 day | test | | | | Theory | Actual |
| 1 | 12 x 12 | 2.19 | 74 | 35.3 | 36.1 | 1067 | 1244 | C | 3:16 | 3:28 |
| 2 | 12 x 12 | 4.38 | 61 | 41.4 | 42.6 | 978 | 1618 | C | 3:51 | 4:12 |
| 3 | 12 x 18 | 2.22 | 65 | 44.2 | 42.5 | 1413 | 2102 | C | 6:44 | 6:36 |
| 4 | 8 x 36 | 1.22 | 58 | 39.2 | 42.1 | 756 | 1360 | C | 3:39 | 5:30 |

*Failure Mode : C = Compression

Table 4 Reinforcing Bars and Steel Plates

| Column Size (in.) | Machining | | Plate Dimensions | |
|---|---|---|---|---|
| | Diameter (mm (in.)) | Depth (mm (in.)) | (mm) | (in.) |
| 12 x 12 | 19 (3/4) | 19 (3/4) | 533 x 533 x 25 | 21 x 21 x 1 |
| 12 x 18 | 16 (5/8) | 32 (1 1/4) | 533 x 864 x 38 | 21 x 34 x 1 1/2 |
| 8 x 36 | 13 (1/2) | 19 (3/4) | 1016 x 533 x 25 | 40 x 21 x 1 |

Table 5 Concrete Temperatures Measured in Frame A, Column No. 1

| Time (min) | Temperature (°C) Measured at Thermocouple #: | | | | | | | | | | | | | | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | |
| 0 | 20 | 21 | 21 | 21 | 21 | 21 | 21 | 22 | 21 | 21 | 21 | 21 | 21 | 21 | 20 |
| 5 | 112 | 77 | 43 | 29 | 23 | 22 | 21 | 22 | 23 | 30 | 62 | 101 | 158 | 219 | 534 |
| 10 | 203 | 141 | 91 | 58 | 30 | 22 | 22 | 22 | 33 | 71 | 132 | 193 | 305 | 400 | 689 |
| 20 | 370 | 276 | 162 | 114 | 67 | 32 | 24 | 51 | 115 | 141 | 274 | 379 | 513 | 602 | 770 |
| 30 | 496 | 387 | 245 | 164 | 108 | 76 | 40 | 79 | 113 | 226 | 390 | 501 | 641 | 726 | 844 |
| 40 | 567 | 461 | 312 | 215 | 126 | 104 | 60 | 91 | 133 | 319 | 490 | 595 | 720 | 780 | 865 |
| 50 | 627 | 518 | 363 | 256 | 146 | 110 | 83 | 103 | 173 | 385 | 561 | 671 | 760 | 831 | 908 |
| 60 | 667 | 558 | 405 | 292 | 172 | 116 | 101 | 118 | 216 | 438 | 623 | 699 | 722 | 858 | 928 |
| 70 | 699 | 593 | 441 | 322 | 199 | 128 | 115 | 131 | 255 | 481 | 671 | 712 | 751 | 786 | 934 |
| 80 | 726 | 622 | 471 | 349 | 225 | 139 | 121 | 144 | 291 | 516 | 706 | 740 | 769 | 789 | 958 |
| 90 | 751 | 649 | 500 | 376 | 251 | 153 | 123 | 161 | 325 | 547 | 739 | 760 | 783 | * | 976 |
| 100 | 779 | 680 | 530 | 405 | 278 | 172 | 129 | 184 | 359 | 578 | 769 | 776 | 790 | * | 984 |
| 110 | 796 | 702 | 556 | 435 | 304 | 193 | 138 | 210 | 392 | 608 | 793 | 780 | * | * | 986 |
| 120 | 820 | 728 | 584 | 463 | 331 | 216 | 157 | 235 | 424 | 634 | 812 | 784 | * | * | 1011 |
| 130 | 839 | 750 | 612 | 491 | 357 | 240 | 182 | 261 | 454 | 658 | 831 | 788 | * | * | 1013 |
| 140 | 855 | 770 | 637 | 518 | 384 | 266 | 209 | 288 | 483 | 681 | 848 | * | * | * | 1019 |
| 150 | 869 | 789 | 660 | 542 | 410 | 292 | 237 | 314 | 510 | 701 | 863 | * | * | * | 1025 |
| 160 | 884 | 807 | 682 | 565 | 435 | 317 | 263 | 340 | 535 | 721 | 876 | * | * | * | 1045 |
| 170 | 898 | 823 | 702 | 588 | 459 | 342 | 289 | 365 | 559 | 740 | 889 | * | * | * | 1040 |
| 180 | * | 837 | 721 | 610 | 482 | 366 | 314 | 389 | 583 | 757 | 901 | * | * | * | 1048 |
| 190 | * | 845 | 741 | 632 | 505 | 389 | 339 | 415 | 606 | 774 | * | * | * | * | 1060 |
| 200 | * | * | 743 | 650 | 527 | 415 | 369 | 449 | 628 | 787 | * | * | * | * | 1047 |
| 205 | * | * | 751 | 658 | 539 | 430 | 388 | 472 | 638 | * | * | * | * | * | 1066 |

Table 6 Concrete Temperatures Measured in Frame B, Column No. 1

| Time (min) | Temperature (°C) Measured at Thermocouple #: | | | | | | | | | | | | | | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | |
| 0 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 20 |
| 5 | 124 | 88 | 46 | 32 | 22 | 21 | 21 | 21 | 22 | 29 | 60 | 90 | 158 | 211 | 534 |
| 10 | 226 | 162 | 98 | 61 | 30 | 22 | 21 | 22 | 31 | 65 | 131 | 178 | 312 | 397 | 689 |
| 20 | 391 | 306 | 180 | 121 | 65 | 32 | 24 | 47 | 110 | 132 | 269 | 362 | 518 | 601 | 770 |
| 30 | 521 | 423 | 268 | 170 | 109 | 63 | 37 | 70 | 108 | 220 | 390 | 491 | 648 | 726 | 844 |
| 40 | 589 | 495 | 338 | 225 | 123 | 98 | 72 | 93 | 117 | 288 | 484 | 583 | 721 | 741 | 865 |
| 50 | 653 | 556 | 392 | 273 | 154 | 106 | 93 | 106 | 161 | 368 | 557 | 661 | 783 | 744 | 908 |
| 60 | 697 | 599 | 438 | 317 | 188 | 110 | 101 | 114 | 208 | 422 | 618 | 713 | 820 | 767 | 928 |
| 70 | 729 | 637 | 480 | 357 | 222 | 117 | 107 | 127 | 253 | 466 | 669 | 753 | 848 | 780 | 934 |
| 80 | 761 | 670 | 516 | 393 | 253 | 130 | 117 | 141 | 295 | 503 | 705 | 783 | 862 | 797 | 958 |
| 90 | 788 | 700 | 548 | 427 | 281 | 147 | 126 | 162 | 333 | 536 | 736 | 812 | * | 801 | 976 |
| 100 | 814 | 730 | 581 | 458 | 306 | 166 | 133 | 184 | 369 | 568 | 765 | 837 | * | * | 984 |
| 110 | 828 | 749 | 607 | 486 | 329 | 187 | 141 | 209 | 401 | 599 | 785 | * | * | * | 986 |
| 120 | 852 | 774 | 632 | 513 | 355 | 208 | 154 | 234 | 433 | 624 | 804 | * | * | * | 1011 |
| 130 | 867 | 793 | 657 | 539 | 384 | 234 | 178 | 260 | 463 | 647 | 821 | * | * | * | 1013 |
| 140 | 882 | 811 | 679 | 563 | 413 | 261 | 210 | 288 | 491 | 669 | 836 | * | * | * | 1019 |
| 150 | 892 | 828 | 700 | 588 | 439 | 289 | 238 | 314 | 516 | 689 | 844 | * | * | * | 1025 |
| 160 | * | 844 | 719 | 612 | 464 | 316 | 265 | 341 | 540 | 709 | * | * | * | * | 1045 |
| 170 | * | 859 | 738 | 634 | 488 | 343 | 295 | 366 | 563 | 727 | * | * | * | * | 1040 |
| 180 | * | 872 | 755 | 655 | 512 | 372 | 340 | 392 | 587 | 743 | * | * | * | * | 1048 |
| 190 | * | 887 | 772 | 672 | 542 | 418 | 438 | 424 | 612 | 751 | * | * | * | * | 1060 |
| 200 | * | * | * | 688 | 594 | 503 | 566 | 486 | 638 | * | * | * | * | * | 1047 |
| 205 | * | * | * | 695 | 625 | 552 | 609 | 534 | 653 | * | * | * | * | * | 1066 |

Table 7 Concrete Temperatures Measured in Frame C, Column No. 1

| Time (min) | Temperature (°C) Measured at Thermocouple #: | | | | | | | | | | | | | | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 | 49 | 50 | 51 | 52 | |
| 0 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 20 |
| 5 | 149 | 98 | 52 | 33 | 23 | 21 | 21 | 21 | 23 | 33 | 68 | 113 | 189 | 257 | 534 |
| 10 | 275 | 176 | 106 | 64 | 32 | 22 | 21 | 22 | 34 | 78 | 134 | 212 | 357 | 456 | 689 |
| 20 | 468 | 342 | 197 | 116 | 81 | 40 | 24 | 59 | 119 | 147 | 278 | 411 | 558 | 651 | 770 |
| 30 | 585 | 444 | 262 | 129 | 96 | 55 | 39 | 64 | 104 | 218 | 394 | 538 | 696 | 774 | 844 |
| 40 | 646 | 513 | 331 | 180 | 110 | 72 | 57 | 78 | 119 | 299 | 495 | 631 | 758 | 738 | 865 |
| 50 | 702 | 569 | 381 | 223 | 130 | 95 | 80 | 98 | 157 | 357 | 569 | 704 | 816 | 777 | 908 |
| 60 | 739 | 611 | 422 | 264 | 159 | 110 | 99 | 114 | 199 | 401 | 630 | 750 | 844 | 797 | 928 |
| 70 | 764 | 646 | 459 | 301 | 188 | 117 | 106 | 128 | 240 | 423 | 679 | 787 | 845 | 864 | 934 |
| 80 | 792 | 675 | 490 | 335 | 218 | 127 | 112 | 139 | 279 | 440 | 715 | 816 | * | 885 | 958 |
| 90 | 817 | 703 | 522 | 368 | 248 | 145 | 119 | 161 | 317 | 467 | 748 | 844 | * | 903 | 976 |
| 100 | 841 | 731 | 552 | 401 | 277 | 165 | 127 | 186 | 352 | 494 | 778 | 871 | * | 924 | 984 |
| 110 | 852 | 749 | 580 | 431 | 305 | 186 | 139 | 210 | 384 | 519 | 802 | 884 | * | 932 | 986 |
| 120 | * | 772 | 607 | 462 | 332 | 208 | 156 | 235 | 416 | 544 | 822 | * | * | 951 | 1011 |
| 130 | * | 791 | 634 | 491 | 360 | 233 | 181 | 261 | 448 | 566 | 842 | * | * | 963 | 1013 |
| 140 | * | 808 | 659 | 520 | 387 | 260 | 209 | 288 | 479 | 586 | 858 | * | * | 973 | 1019 |
| 150 | * | 821 | 682 | 547 | 414 | 289 | 236 | 316 | 507 | 605 | 872 | * | * | 975 | 1025 |
| 160 | * | 825 | 704 | 579 | 440 | 321 | 263 | 350 | 535 | 624 | 886 | * | * | * | 1045 |
| 170 | * | * | 724 | 613 | 467 | 367 | 292 | 410 | 561 | 644 | 898 | * | * | * | 1040 |
| 180 | * | * | 743 | 648 | 496 | 438 | 326 | 511 | 587 | 664 | 907 | * | * | * | 1048 |
| 190 | * | * | 759 | 680 | 539 | 527 | 372 | 608 | 614 | 699 | * | * | * | * | 1060 |
| 200 | * | * | * | 696 | 605 | 608 | 431 | 673 | 649 | 717 | * | * | * | * | 1047 |
| 205 | * | * | * | 702 | 635 | 635 | 462 | 692 | 667 | 722 | * | * | * | * | 1066 |

Table 8 Concrete Temperatures measured in Frame D, Column No. 1

| Time (min) | Temperature (°C) Measured at Thermocouple #: | | | | | | | | | | | | | | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 53 | 54 | 55 | 56 | 57 | 58 | 59 | 60 | 61 | 62 | 63 | 64 | 65 | 66 | |
| 0 | 21 | 21 | 20 | 20 | 20 | 20 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 21 | 20 |
| 5 | 114 | 78 | 45 | 31 | 23 | 22 | 22 | 21 | 22 | 32 | 61 | 103 | 159 | 212 | 534 |
| 10 | 212 | 143 | 89 | 57 | 30 | 23 | 22 | 22 | 30 | 70 | 132 | 202 | 313 | 395 | 689 |
| 20 | 374 | 269 | 164 | 106 | 63 | 34 | 26 | 45 | 112 | 138 | 270 | 393 | 526 | 598 | 770 |
| 30 | 488 | 367 | 241 | 154 | 102 | 72 | 51 | 79 | 107 | 247 | 393 | 521 | 654 | 720 | 844 |
| 40 | 560 | 441 | 305 | 202 | 116 | 82 | 65 | 87 | 122 | 340 | 497 | 617 | 726 | 777 | 865 |
| 50 | 619 | 502 | 357 | 244 | 142 | 100 | 93 | 102 | 157 | 405 | 570 | * | 747 | 746 | 908 |
| 60 | 659 | 543 | 398 | 281 | 168 | 113 | 106 | 111 | 196 | 456 | 632 | 659 | 769 | 772 | 928 |
| 70 | 685 | 575 | 432 | 313 | 192 | 122 | 113 | 122 | 235 | 498 | 679 | 724 | 770 | 783 | 934 |
| 80 | 715 | 604 | 461 | 341 | 216 | 132 | 119 | 140 | 274 | 532 | 713 | 751 | 787 | 791 | 958 |
| 90 | 741 | 633 | 490 | 369 | 241 | 149 | 127 | 163 | 310 | 563 | 744 | 767 | 796 | 793 | 976 |
| 100 | 767 | 664 | 521 | 399 | 268 | 170 | 134 | 188 | 344 | 595 | 773 | 772 | * | * | 984 |
| 110 | 784 | 686 | 548 | 428 | 296 | 193 | 144 | 213 | 377 | 625 | 795 | 766 | * | * | 986 |
| 120 | 810 | 714 | 576 | 457 | 324 | 218 | 164 | 238 | 409 | 651 | 815 | 767 | * | * | 1011 |
| 130 | 830 | 739 | 606 | 487 | 352 | 244 | 193 | 264 | 440 | 672 | 831 | 770 | * | * | 1013 |
| 140 | 849 | 763 | 634 | 516 | 380 | 271 | 221 | 292 | 470 | * | 840 | 773 | * | * | 1019 |
| 150 | 866 | 784 | 660 | 542 | 407 | 298 | 248 | 318 | 499 | 680 | 852 | 774 | * | * | 1025 |
| 160 | 882 | 804 | 683 | 567 | 433 | 324 | 274 | 344 | 528 | 696 | 862 | * | * | * | 1045 |
| 170 | 895 | 819 | 705 | 593 | 458 | 348 | 300 | 370 | 557 | 711 | * | * | * | * | 1040 |
| 180 | 905 | * | 724 | 616 | 482 | 372 | 324 | 395 | 589 | 717 | * | * | * | * | 1048 |
| 190 | 916 | * | 743 | 639 | 505 | 395 | 347 | 427 | 619 | 719 | * | * | * | * | 1060 |
| 200 | * | * | 744 | 656 | 526 | 418 | 369 | 475 | 641 | 722 | * | * | * | * | 1047 |
| 205 | * | * | 754 | 665 | 536 | 429 | 380 | 500 | 652 | 723 | * | * | * | * | 1066 |

Table 9 Steel Temperatures, Column No. 1

| Time (min) | Temperature (°C) Measured at Thermocouple #: 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 21 | 21 | 21 | 21 | 21 | 20 | 21 | 21 | 21 | 21 | 20 |
| 5 | 25 | 26 | 25 | 24 | 25 | 23 | 32 | 35 | 23 | 22 | 534 |
| 10 | 47 | 50 | 46 | 38 | 41 | 38 | 67 | 72 | 38 | 30 | 689 |
| 20 | 123 | 119 | 120 | 116 | 119 | 123 | 127 | 121 | 119 | 97 | 770 |
| 30 | 121 | 141 | 129 | 119 | 125 | 126 | 195 | 170 | 117 | 111 | 844 |
| 40 | 162 | 197 | 177 | 158 | 167 | 170 | 257 | 221 | 157 | 132 | 865 |
| 50 | 214 | 252 | 229 | 203 | 218 | 220 | 305 | 265 | 205 | 169 | 908 |
| 60 | 264 | 304 | 278 | 249 | 267 | 269 | 346 | 307 | 251 | 212 | 928 |
| 70 | 311 | 352 | 324 | 294 | 312 | 314 | 384 | 345 | 295 | 255 | 934 |
| 80 | 352 | 395 | 365 | 336 | 354 | 355 | 417 | 380 | 335 | 295 | 958 |
| 90 | 391 | 435 | 402 | 374 | 392 | 392 | 448 | 414 | 370 | 332 | 976 |
| 100 | 427 | 471 | 437 | 411 | 427 | 426 | 476 | 446 | 404 | 367 | 984 |
| 110 | 462 | 505 | 470 | 446 | 461 | 459 | 503 | 473 | 436 | 400 | 986 |
| 120 | 494 | 533 | 501 | 479 | 491 | 489 | 527 | 498 | 466 | 432 | 1011 |
| 130 | 523 | 559 | 530 | 509 | 520 | 517 | 551 | 526 | 495 | 462 | 1013 |
| 140 | 550 | 585 | 557 | 536 | 546 | 543 | 576 | 554 | 522 | 490 | 1019 |
| 150 | 577 | 609 | 585 | 561 | 572 | 568 | 601 | 580 | 547 | 516 | 1025 |
| 160 | 603 | 633 | 616 | 586 | 598 | 592 | 626 | 608 | 575 | 539 | 1045 |
| 170 | 627 | 656 | 650 | 611 | 626 | 615 | 648 | 638 | 600 | 563 | 1040 |
| 180 | 650 | 676 | 683 | 636 | 657 | 637 | 670 | 675 | 624 | 587 | 1048 |
| 190 | 673 | 697 | 709 | 663 | 688 | 659 | 693 | 709 | 649 | 610 | 1060 |
| 200 | 696 | 714 | 720 | 689 | 714 | 681 | 709 | 720 | 677 | 633 | 1047 |
| 205 | 705 | 720 | 719 | 698 | 721 | 689 | 714 | 719 | 690 | 643 | 1066 |

Table 10 Axial Deformation, Column No. 1

| Time (min) | Expansion (mm) |
|---|---|
| 0 | 0.0 |
| 5 | 0.3 |
| 10 | 0.7 |
| 20 | 2.3 |
| 30 | 2.7 |
| 40 | 3.0 |
| 50 | 3.7 |
| 60 | 4.1 |
| 75 | 5.0 |
| 90 | 5.7 |
| 105 | 6.0 |
| 120 | 6.0 |
| 130 | 5.9 |
| 140 | 5.5 |
| 150 | 5.0 |
| 160 | 4.2 |
| 170 | 2.8 |
| 180 | 1.4 |
| 190 | -0.4 |
| 200 | -4.0 |
| 205 | -4.7 |

Table 11 Concrete Temperatures, Column No. 2

| Time (min) | Temperature (°C) Measured at Thermocouple #: 13 | 14 | 15 | 16 | 17 | 18 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 33 | 24 | 17 | 16 | 15 | 15 | 14 | 14 | 16 | 20 | 29 | 51 | 86 | 91 | 373 |
| 5 | 105 | 81 | 45 | 25 | 17 | 15 | 14 | 18 | 34 | 73 | 119 | 169 | 232 | 198 | 571 |
| 10 | 167 | 132 | 88 | 48 | 25 | 16 | 16 | 32 | 79 | 136 | 200 | 290 | 381 | 320 | 675 |
| 15 | 238 | 185 | 122 | 80 | 39 | 20 | 21 | 73 | 117 | 189 | 291 | 400 | 499 | 429 | 738 |
| 20 | 310 | 244 | 146 | 101 | 59 | 29 | 42 | 107 | 142 | 254 | 372 | 482 | 589 | 517 | 781 |
| 25 | 370 | 298 | 182 | 119 | 85 | 45 | 58 | 114 | 181 | 316 | 439 | 541 | 653 | 577 | 816 |
| 30 | 422 | 345 | 222 | 138 | 106 | 57 | 64 | 112 | 194 | 374 | 499 | 600 | 708 | 624 | 838 |
| 35 | 465 | 387 | 259 | 170 | 112 | 78 | 84 | 119 | 255 | 420 | 548 | 649 | 745 | 666 | 858 |
| 40 | 499 | 421 | 289 | 194 | 115 | 91 | 94 | 139 | 311 | 463 | 594 | 693 | 773 | 703 | 881 |
| 45 | 528 | 451 | 316 | 216 | 126 | 97 | 98 | 161 | 348 | 500 | 634 | 728 | 796 | 723 | 886 |
| 50 | 552 | 477 | 340 | 236 | 140 | 102 | 101 | 183 | 378 | 532 | 667 | 755 | 819 | 745 | 894 |
| 55 | 576 | 500 | 361 | 255 | 155 | 106 | 105 | 206 | 403 | 562 | 695 | 781 | 841 | 769 | 907 |
| 60 | 598 | 521 | 382 | 274 | 169 | 110 | 111 | 229 | 426 | 591 | 720 | 800 | 854 | 785 | 914 |
| 70 | 636 | 557 | 419 | 309 | 197 | 120 | 126 | 274 | 467 | 641 | 757 | 832 | 875 | 817 | 934 |
| 80 | 668 | 592 | 453 | 341 | 225 | 130 | 142 | 318 | 500 | 679 | 790 | 851 | * | 844 | 954 |
| 90 | 696 | 623 | 484 | 372 | 254 | 145 | 162 | 358 | 532 | 714 | 818 | * | * | 868 | 968 |
| 100 | 722 | 652 | 512 | 401 | 283 | 166 | 184 | 394 | 565 | 745 | 843 | * | * | 886 | 980 |
| 110 | 748 | 679 | 539 | 429 | 312 | 189 | 210 | 428 | 599 | 773 | 866 | * | * | 907 | 993 |
| 120 | 769 | 703 | 564 | 456 | 339 | 216 | 239 | 460 | 631 | 799 | 885 | * | * | 923 | 1006 |
| 140 | 813 | 749 | 616 | 507 | 394 | 272 | 296 | 517 | 679 | 839 | 919 | * | * | 951 | 1019 |
| 160 | 848 | 787 | 663 | 554 | 448 | 337 | 352 | 565 | 721 | 870 | 938 | * | * | 977 | 1042 |
| 180 | * | * | 703 | 619 | 571 | 563 | 405 | 616 | 754 | * | 955 | * | * | 1001 | 1055 |
| 200 | * | * | 729 | 719 | 714 | 706 | 483 | 681 | 761 | * | * | * | * | 1006 | 1077 |
| 220 | * | * | 742 | 740 | 731 | 735 | 673 | 720 | * | * | * | * | * | * | 1097 |
| 240 | * | * | 759 | 760 | 753 | 755 | 736 | 732 | * | * | * | * | * | * | 1104 |
| 250 | * | * | 767 | 772 | 761 | 766 | 759 | 749 | * | * | * | * | * | * | 1114 |

Table 12 Concrete Temperatures, Column No. 2

| Time (min) | Temperature (°C) Measured at Thermocouple #: 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 49 | 22 | 16 | 14 | 13 | 13 | 13 | 14 | 16 | 26 | 48 | 89 | 124 | 373 |
| 5 | 129 | 70 | 37 | 19 | 14 | 13 | 13 | 19 | 41 | 98 | 148 | 219 | 286 | 571 |
| 10 | 219 | 121 | 72 | 32 | 16 | 13 | 15 | 36 | 89 | 158 | 258 | 376 | 463 | 675 |
| 15 | 306 | 172 | 106 | 53 | 21 | 14 | 25 | 82 | 137 | 244 | 372 | 500 | 587 | 738 |
| 20 | 383 | 225 | 130 | 80 | 30 | 19 | 53 | 107 | 162 | 319 | 463 | 583 | 670 | 781 |
| 25 | 440 | 273 | 160 | 114 | 47 | 30 | 48 | 103 | 202 | 383 | 529 | 639 | 733 | 816 |
| 30 | 488 | 317 | 201 | 115 | 72 | 40 | 56 | 106 | 234 | 436 | 580 | 692 | 773 | 838 |
| 35 | 532 | 355 | 237 | 125 | 83 | 57 | 68 | 108 | 281 | 482 | 626 | 733 | 730 | 858 |
| 40 | 566 | 388 | 266 | 138 | 89 | 78 | 78 | 117 | 330 | 523 | 663 | 761 | 756 | 881 |
| 45 | 594 | 417 | 292 | 153 | 93 | 88 | 87 | 138 | 374 | 560 | 695 | 781 | 767 | 886 |
| 50 | 619 | 442 | 315 | 170 | 98 | 89 | 96 | 165 | 414 | 597 | 725 | 802 | 768 | 894 |
| 55 | 644 | 465 | 337 | 187 | 103 | 96 | 104 | 194 | 448 | 630 | 751 | 825 | * | 907 |
| 60 | 663 | 486 | 357 | 205 | 103 | 102 | 108 | 220 | 476 | 659 | 774 | 841 | * | 914 |
| 70 | 698 | 524 | 394 | 241 | 119 | 103 | 121 | 267 | 518 | 707 | 812 | 870 | * | 934 |
| 80 | 728 | 557 | 427 | 273 | 138 | 106 | 139 | 311 | 553 | 744 | * | 877 | * | 954 |
| 90 | 756 | 588 | 457 | 303 | 159 | 116 | 162 | 351 | 589 | 775 | * | * | * | 968 |
| 100 | 780 | 617 | 485 | 331 | 180 | 127 | 186 | 387 | 623 | 802 | * | * | * | 980 |
| 110 | 805 | 644 | 511 | 358 | 202 | 144 | 212 | 422 | 655 | 826 | * | * | * | 993 |
| 120 | 825 | 670 | 536 | 385 | 228 | 165 | 239 | 455 | 678 | 846 | * | * | * | 1006 |
| 140 | 857 | 718 | 587 | 438 | 283 | 220 | 296 | 513 | 722 | 881 | * | * | * | 1019 |
| 160 | 884 | 761 | 635 | 490 | 339 | 277 | 351 | 563 | 762 | 911 | * | * | * | 1042 |
| 180 | * | 800 | 678 | 537 | 412 | 334 | 404 | 605 | 799 | 937 | * | * | * | 1055 |
| 200 | * | 803 | 717 | 584 | 617 | 506 | 454 | 660 | 831 | 956 | * | * | * | 1077 |
| 220 | * | * | 735 | 637 | 714 | 693 | 502 | 716 | 853 | * | * | * | * | 1097 |
| 240 | * | * | 743 | 703 | 729 | 727 | 588 | 746 | * | * | * | * | * | 1104 |
| 250 | * | * | 746 | 726 | 742 | 741 | 652 | 755 | * | * | * | * | * | 1114 |

Table 13 Steel Temperatures, Column No. 2

| Time (min) | Temperature (°C) Measured at Thermocouple #: | | | | | | | | | | | | | | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 41 | 42 | 43 | 44 | |
| 0 | 20 | 18 | 15 | 14 | 4 | * | 17 | 12 | 12 | 15 | 13 | 13 | 14 | 14 | 373 |
| 5 | 27 | 24 | 25 | 21 | 10 | 6 | 35 | 25 | 21 | 19 | 18 | 20 | 24 | 20 | 571 |
| 10 | 49 | 46 | 50 | 39 | 29 | 27 | 69 | 51 | 41 | 33 | 34 | 38 | 50 | 40 | 675 |
| 15 | 96 | 88 | 106 | 84 | 69 | 68 | 103 | 83 | 93 | 69 | 72 | 83 | 111 | 104 | 738 |
| 20 | 113 | 116 | 123 | 113 | 107 | 112 | 125 | 109 | 119 | 105 | 106 | 113 | 123 | 120 | 781 |
| 25 | 117 | 123 | 127 | 114 | 114 | 116 | 150 | 129 | 121 | 113 | 112 | 112 | 129 | 117 | 816 |
| 30 | 131 | 136 | 147 | 126 | 118 | 129 | 184 | 145 | 134 | 115 | 113 | 121 | 147 | 130 | 838 |
| 35 | 150 | 155 | 172 | 147 | 132 | 149 | 222 | 175 | 155 | 127 | 129 | 140 | 171 | 151 | 858 |
| 40 | 173 | 179 | 200 | 170 | 151 | 174 | 253 | 204 | 180 | 146 | 149 | 163 | 198 | 177 | 881 |
| 45 | 198 | 206 | 230 | 193 | 174 | 199 | 280 | 229 | 208 | 167 | 171 | 186 | 226 | 205 | 886 |
| 50 | 223 | 233 | 258 | 218 | 198 | 225 | 305 | 251 | 235 | 189 | 194 | 210 | 255 | 233 | 894 |
| 55 | 248 | 259 | 286 | 241 | 223 | 250 | 327 | 272 | 262 | 212 | 216 | 233 | 282 | 260 | 907 |
| 60 | 274 | 283 | 312 | 264 | 247 | 274 | 348 | 292 | 288 | 233 | 239 | 256 | 309 | 287 | 914 |
| 70 | 321 | 330 | 360 | 306 | 292 | 321 | 386 | 328 | 336 | 276 | 281 | 299 | 357 | 335 | 934 |
| 80 | 365 | 373 | 403 | 346 | 332 | 364 | 420 | 361 | 379 | 316 | 322 | 340 | 400 | 378 | 954 |
| 90 | 405 | 412 | 443 | 383 | 368 | 404 | 451 | 392 | 418 | 354 | 359 | 377 | 440 | 417 | 968 |
| 100 | 441 | 448 | 479 | 418 | 402 | 442 | 479 | 422 | 454 | 389 | 395 | 413 | 476 | 453 | 980 |
| 110 | 475 | 482 | 513 | 453 | 434 | 477 | 505 | 450 | 488 | 423 | 429 | 447 | 510 | 487 | 993 |
| 120 | 507 | 514 | 544 | 485 | 465 | 509 | 530 | 478 | 520 | 456 | 462 | 481 | 541 | 519 | 1006 |
| 140 | 563 | 570 | 603 | 543 | 522 | 566 | 580 | 530 | 577 | 517 | 522 | 540 | 598 | 576 | 1019 |
| 160 | 619 | 626 | 662 | 597 | 573 | 618 | 629 | 581 | 633 | 571 | 577 | 596 | 652 | 636 | 1042 |
| 180 | 671 | 677 | 716 | 652 | 626 | 665 | 673 | 630 | 680 | 624 | 640 | 647 | 700 | 694 | 1055 |
| 200 | 716 | 720 | 726 | 708 | 675 | 705 | 710 | 675 | 712 | 672 | 704 | 693 | 726 | 716 | 1077 |
| 220 | 745 | 729 | 728 | 739 | 718 | 744 | 719 | 712 | 720 | 713 | 730 | 729 | 736 | 730 | 1097 |
| 240 | 787 | 756 | 758 | * | 739 | 770 | 736 | 726 | 751 | 723 | 736 | * | 756 | 758 | 1104 |
| 250 | 809 | 770 | 772 | * | 751 | 785 | 751 | 742 | 767 | 730 | 738 | * | 766 | 773 | 1114 |

Table 14 Axial Deformation, Column No. 2

| Time (min) | Expansion (mm) |
|---|---|
| 0 | 0.0 |
| 10 | 1.1 |
| 20 | 3.1 |
| 30 | 4.0 |
| 40 | 4.6 |
| 50 | 5.5 |
| 60 | 6.5 |
| 70 | 7.7 |
| 80 | 8.9 |
| 90 | 10.0 |
| 100 | 11.1 |
| 110 | 12.1 |
| 120 | 12.9 |
| 130 | 13.7 |
| 140 | 14.3 |
| 150 | 14.6 |
| 160 | 14.8 |
| 170 | 14.8 |
| 180 | 14.8 |
| 185 | 14.6 |
| 190 | 14.3 |
| 195 | 13.9 |
| 200 | 13.4 |
| 205 | 12.9 |
| 210 | 12.0 |
| 215 | 11.0 |
| 220 | 9.9 |
| 225 | 8.7 |
| 230 | 7.2 |
| 235 | 5.6 |
| 240 | 3.7 |
| 245 | 1.6 |
| 250 | -1.4 |
| 252 | -69.4 |

Table 15 Concrete Temperatures, Column No. 3

| Time (min) | Temperature (°C) Measured at Thermocouple #: 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 22 | 20 | 19 | 18 | 20 | 18 | 18 | 18 | 18 | 107 |
| 5 | 136 | 94 | 47 | 31 | 19 | 18 | 18 | 18 | 19 | 585 |
| 10 | 228 | 160 | 100 | 64 | 11 | 19 | 18 | 19 | 24 | 674 |
| 20 | 400 | 296 | 169 | 119 | 76 | 31 | 21 | 55 | 88 | 796 |
| 30 | 539 | 412 | 257 | 182 | 122 | 118 | 51 | 80 | 81 | 840 |
| 40 | 541 | 441 | 314 | 240 | 129 | 120 | 110 | 113 | 111 | 794 |
| 50 | 591 | 492 | 351 | 268 | 140 | 123 | 122 | 126 | 131 | 819 |
| 60 | 618 | 519 | 384 | 298 | 159 | 124 | 122 | 133 | 138 | 833 |
| 80 | 671 | 576 | 450 | 367 | 238 | 136 | 119 | 146 | 198 | 881 |
| 100 | 691 | 613 | 496 | 417 | 288 | 168 | 129 | 186 | 266 | 880 |
| 120 | 707 | 641 | 535 | 461 | 335 | 212 | 159 | 230 | 322 | 865 |
| 140 | 727 | 663 | 560 | 488 | 363 | 240 | 184 | 258 | 356 | 875 |
| 150 | 734 | 673 | 573 | 501 | 377 | 255 | 199 | 273 | 372 | 880 |
| 165 | 745 | 687 | 591 | 519 | 398 | 278 | 224 | 295 | 396 | 881 |
| 180 | 756 | 700 | 607 | 537 | 419 | 301 | 249 | 318 | 418 | 884 |
| 195 | 766 | 712 | 623 | 553 | 438 | 324 | 274 | 340 | 440 | 893 |
| 210 | 739 | 699 | 632 | 569 | 457 | 346 | 298 | 362 | 461 | 862 |
| 230 | 774 | 726 | 647 | 585 | 479 | 375 | 328 | 390 | 486 | 888 |
| 250 | 785 | 740 | 665 | 606 | 501 | 401 | 356 | 415 | 509 | 889 |
| 270 | 794 | 751 | 681 | 624 | 522 | 427 | 383 | 439 | 530 | 891 |
| 290 | 795 | 754 | 692 | 640 | 540 | 450 | 408 | 461 | 549 | 894 |
| 310 | 804 | 765 | 703 | 653 | 558 | 473 | 432 | 480 | 568 | 894 |
| 330 | 814 | 777 | 717 | 668 | 576 | 493 | 455 | 496 | 587 | 898 |
| 350 | 819 | 786 | 729 | 682 | 592 | 512 | 476 | 513 | 606 | 900 |
| 365 | 821 | 790 | 736 | 691 | 604 | 524 | 490 | 528 | 623 | 898 |

Table 16 Concrete Temperatures, Column No. 3

| Time (min) | Temperature (°C) Measured at Thermocouple #: 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 18 | 19 | 19 | 21 | 23 | 26 | 22 | 20 | 18 | 107 |
| 5 | 22 | 41 | 81 | 129 | 188 | 230 | 153 | 109 | 58 | 585 |
| 10 | 48 | 103 | 155 | 221 | 324 | 382 | 248 | 176 | 111 | 674 |
| 20 | 113 | 169 | 302 | 415 | 514 | 587 | 433 | 316 | 188 | 796 |
| 30 | 119 | 183 | 414 | 542 | 640 | 713 | 541 | 390 | 234 | 840 |
| 40 | 132 | 173 | 431 | 554 | 635 | 690 | 530 | 400 | 274 | 794 |
| 50 | 148 | 204 | 468 | 600 | 685 | 738 | 578 | 442 | 306 | 819 |
| 60 | 180 | 330 | 523 | 639 | 715 | 763 | 607 | 470 | 339 | 833 |
| 80 | 290 | 461 | 638 | 723 | 781 | 821 | 674 | 549 | 432 | 881 |
| 100 | 368 | 527 | 689 | 757 | 803 | 727 | 706 | 601 | 494 | 880 |
| 120 | 433 | 584 | 722 | 712 | 810 | 724 | 725 | 640 | 546 | 865 |
| 140 | 469 | 617 | 745 | 724 | 826 | 731 | 747 | 669 | 580 | 875 |
| 150 | 486 | 631 | 755 | 728 | 831 | 735 | 756 | 681 | 596 | 880 |
| 165 | 509 | 650 | 767 | 735 | 838 | 739 | 768 | 698 | 617 | 881 |
| 180 | 530 | 667 | 778 | 739 | 846 | 741 | 781 | 714 | 637 | 884 |
| 195 | 549 | 683 | 788 | 741 | 851 | 743 | 791 | 729 | 656 | 893 |
| 210 | 569 | 696 | 786 | * | * | * | 764 | 719 | 667 | 862 |
| 230 | 590 | 707 | 795 | * | * | * | 799 | 747 | 685 | 888 |
| 250 | 612 | 724 | 807 | * | * | * | 810 | 761 | 703 | 889 |
| 270 | 633 | 738 | 815 | * | * | * | 818 | 773 | 719 | 891 |
| 290 | 651 | 749 | * | * | * | * | * | 776 | 729 | 894 |
| 310 | 666 | 755 | * | * | * | * | * | 786 | 739 | 894 |
| 330 | 679 | 764 | * | * | * | * | * | 797 | 753 | 898 |
| 350 | 690 | 765 | * | * | * | * | * | 804 | 763 | 900 |
| 365 | 693 | * | * | * | * | * | * | * | 766 | 898 |

Table 17 Steel Temperatures, Column No. 3

| Time (min) | Temperature (°C) Measured at Thermocouple #: | | | | | | | | | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 7 | 8 | 9 | 10 | |
| 0 | 18 | 18 | 18 | 18 | 19 | 19 | 17 | 19 | 18 | 107 |
| 5 | 20 | 21 | 22 | 21 | 20 | 25 | 27 | 20 | 19 | 585 |
| 10 | 32 | 36 | 49 | 39 | 28 | 47 | 56 | 29 | 30 | 674 |
| 20 | 108 | 120 | 119 | 115 | 71 | 107 | 126 | 73 | 78 | 796 |
| 30 | 120 | 127 | 105 | 111 | 121 | 136 | 167 | 121 | 120 | 840 |
| 40 | 163 | 178 | 118 | 128 | 132 | 203 | 239 | 133 | 152 | 794 |
| 50 | 200 | 217 | 132 | 147 | 148 | 235 | 272 | 151 | 179 | 819 |
| 60 | 237 | 257 | 183 | 189 | 183 | 265 | 306 | 186 | 205 | 833 |
| 80 | 319 | 343 | 311 | 304 | 248 | 326 | 375 | 253 | 265 | 881 |
| 100 | 394 | 417 | 395 | 387 | 299 | 379 | 433 | 304 | 319 | 880 |
| 120 | 459 | 480 | 463 | 455 | 343 | 428 | 485 | 348 | 368 | 865 |
| 140 | 495 | 516 | 501 | 492 | 370 | 458 | 516 | 375 | 398 | 875 |
| 150 | 511 | 532 | 518 | 509 | 383 | 472 | 530 | 389 | 412 | 880 |
| 165 | 533 | 553 | 541 | 533 | 403 | 493 | 549 | 408 | 432 | 881 |
| 180 | 553 | 573 | 563 | 554 | 422 | 512 | 569 | 428 | 452 | 884 |
| 195 | 574 | 593 | 584 | 576 | 442 | 530 | 589 | 447 | 471 | 893 |
| 210 | 594 | 612 | 605 | 597 | 460 | 547 | 611 | 465 | 489 | 862 |
| 230 | 615 | 631 | 626 | 618 | 482 | 565 | 636 | 487 | 510 | 888 |
| 250 | 635 | 651 | 648 | 639 | 503 | 587 | 664 | 508 | 530 | 889 |
| 270 | 654 | 670 | 670 | 659 | 523 | 607 | 688 | 528 | 549 | 891 |
| 290 | 671 | 686 | 688 | 677 | 542 | 625 | 703 | 546 | 568 | 894 |
| 310 | 683 | 694 | 701 | 691 | 559 | 640 | 710 | 564 | 588 | 894 |
| 330 | 692 | 700 | 712 | 703 | 577 | 657 | 719 | 582 | 613 | 898 |
| 350 | 698 | 702 | 721 | 713 | 596 | 673 | 725 | 599 | 644 | 900 |
| 365 | 701 | 705 | 724 | 716 | 611 | 684 | 728 | 611 | 664 | 898 |

Table 18 Axial Deformation, Column No. 3

| Time (min) | Expansion (mm) |
|---|---|
| 0 | 0.0 |
| 10 | 0.4 |
| 20 | 1.6 |
| 30 | 2.3 |
| 40 | 2.8 |
| 50 | 3.6 |
| 60 | 4.1 |
| 70 | 4.6 |
| 80 | 5.2 |
| 90 | 5.7 |
| 100 | 6.0 |
| 120 | 6.6 |
| 140 | 6.9 |
| 160 | 7.0 |
| 180 | 7.0 |
| 200 | 7.0 |
| 220 | 6.7 |
| 240 | 6.3 |
| 260 | 5.5 |
| 280 | 4.7 |
| 300 | 3.5 |
| 310 | 2.9 |
| 320 | 2.2 |
| 330 | 1.4 |
| 340 | 0.5 |
| 350 | -0.6 |
| 360 | -1.9 |
| 396 | -6.1 |

Table 19 Concrete Temperatures, Column No. 4

| Time (min) | Temperature (°C) Measured at Thermocouple #: | | | | | | | | | | | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 21 | 22 | |
| 0 | 19 | 18 | 17 | 17 | 27 | 17 | 20 | 19 | 18 | 17 | 17 | 80 |
| 10 | 176 | 129 | 85 | 54 | 19 | 18 | 261 | 189 | 150 | 107 | 64 | 683 |
| 20 | 333 | 254 | 156 | 109 | 73 | 35 | 483 | 386 | 319 | 207 | 130 | 782 |
| 30 | 452 | 361 | 239 | 162 | 116 | 81 | 600 | 508 | 445 | 293 | 151 | 840 |
| 40 | 524 | 437 | 306 | 220 | 134 | 144 | 679 | 597 | 522 | 328 | 181 | 874 |
| 50 | 561 | 487 | 360 | 272 | 150 | 149 | 727 | 657 | 582 | 405 | 237 | 902 |
| 60 | 599 | 529 | 403 | 315 | 185 | 146 | 771 | 708 | 641 | 480 | 300 | 922 |
| 70 | 645 | 571 | 444 | 352 | 216 | 156 | 808 | 752 | 689 | 534 | 349 | 939 |
| 80 | 685 | 608 | 481 | 386 | 248 | 185 | 838 | 788 | 730 | 582 | 395 | 955 |
| 90 | 719 | 642 | 515 | 418 | 280 | 219 | 864 | 818 | 764 | 627 | 440 | 969 |
| 100 | 747 | 672 | 545 | 449 | 311 | 252 | 885 | 844 | 794 | 667 | 483 | 981 |
| 110 | 772 | 699 | 573 | 478 | 342 | 284 | 903 | 866 | 820 | 702 | 523 | 994 |
| 120 | 795 | 724 | 600 | 506 | 372 | 315 | 919 | 886 | 844 | 732 | 557 | 1006 |
| 130 | 814 | 746 | 626 | 532 | 400 | 344 | 933 | 904 | 865 | 760 | 592 | 1006 |
| 140 | 834 | 767 | 651 | 557 | 428 | 372 | 946 | 919 | 884 | 785 | 625 | 1029 |
| 150 | 853 | 788 | 674 | 581 | 455 | 399 | 957 | 931 | 900 | 808 | 656 | 1038 |
| 160 | 870 | 808 | 697 | 606 | 480 | 425 | 967 | 941 | 915 | 829 | 685 | 1043 |
| 170 | 886 | 826 | 719 | 630 | 504 | 451 | 976 | 947 | 928 | 848 | 711 | 1055 |
| 180 | 902 | 844 | 740 | 654 | 526 | 475 | 984 | 952 | 940 | 866 | 737 | 1065 |
| 200 | 923 | 871 | 777 | 696 | 567 | 520 | 996 | * | 957 | 894 | 782 | 1081 |
| 220 | 929 | 894 | 807 | 725 | 611 | 558 | 997 | * | 961 | 906 | 814 | 1093 |
| 240 | * | * | * | 745 | 663 | 660 | * | * | * | * | * | 1108 |
| 260 | * | * | * | 750 | 713 | 729 | * | * | * | * | * | 1121 |
| 280 | * | * | * | * | 735 | 745 | * | * | * | * | * | 1136 |
| 300 | * | * | * | * | 753 | * | * | * | * | * | * | 1145 |
| 320 | * | * | * | * | 771 | * | * | * | * | * | * | 1167 |
| 330 | * | * | * | * | 786 | * | * | * | * | * | * | 1169 |

Table 20 Concrete Temperatures, Column No. 4

| Time (min) | Temperature (°C) Measured at Thermocouple #: 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 17 | 16 | 16 | 21 | 19 | 17 | 17 | 19 | 21 | 18 | 18 | 80 |
| 10 | 35 | 24 | 22 | 216 | 160 | 98 | 61 | 29 | 23 | 19 | 19 | 683 |
| 20 | 105 | 77 | 50 | 409 | 325 | 194 | 136 | 108 | 80 | 56 | 36 | 782 |
| 30 | 129 | 116 | 103 | 451 | 346 | 144 | 109 | 110 | 103 | 93 | 88 | 840 |
| 40 | 159 | 138 | 141 | 293 | 230 | 120 | 104 | 117 | 130 | 129 | 132 | 874 |
| 50 | 189 | 156 | 151 | 537 | 451 | 279 | 180 | 127 | 137 | 139 | 144 | 902 |
| 60 | 223 | 182 | 173 | 602 | 520 | 350 | 238 | 158 | 139 | 141 | 146 | 922 |
| 70 | 255 | 207 | 203 | 640 | 565 | 403 | 287 | 201 | 155 | 148 | 152 | 939 |
| 80 | 289 | 236 | 235 | 688 | 613 | 460 | 346 | 252 | 191 | 168 | 178 | 955 |
| 90 | 325 | 268 | 267 | 731 | 660 | 516 | 407 | 302 | 234 | 199 | 212 | 969 |
| 100 | 362 | 302 | 299 | 771 | 701 | 565 | 462 | 351 | 275 | 238 | 244 | 981 |
| 110 | 397 | 335 | 330 | 804 | 736 | 610 | 507 | 396 | 315 | 274 | 276 | 994 |
| 120 | 431 | 367 | 360 | 834 | 767 | 649 | 547 | 436 | 353 | 309 | 308 | 1006 |
| 130 | 464 | 397 | 388 | 859 | 795 | 684 | 587 | 476 | 389 | 341 | 337 | 1006 |
| 140 | 495 | 427 | 416 | 881 | 821 | 715 | 623 | 511 | 423 | 372 | 365 | 1029 |
| 150 | 523 | 455 | 443 | 901 | 844 | 744 | 656 | 543 | 456 | 402 | 393 | 1038 |
| 160 | 549 | 482 | 468 | 917 | 865 | 770 | 687 | 573 | 487 | 431 | 420 | 1043 |
| 170 | 575 | 507 | 492 | * | 877 | 793 | 716 | 607 | 520 | 465 | 458 | 1055 |
| 180 | 603 | 531 | 515 | * | * | * | 734 | 649 | 585 | 545 | 551 | 1065 |
| 200 | 655 | 576 | 554 | * | * | * | 727 | 719 | 723 | 718 | 715 | 1081 |
| 220 | 699 | 622 | 594 | * | * | * | 758 | 759 | 774 | 771 | 766 | 1093 |
| 240 | 718 | 665 | 646 | * | * | * | 779 | 776 | 784 | 788 | 785 | 1108 |
| 260 | 722 | 707 | 706 | * | * | * | 814 | 787 | 787 | * | 834 | 1121 |
| 280 | 747 | 729 | 740 | * | * | * | 866 | 858 | 817 | 800 | 886 | 1136 |
| 300 | 772 | 752 | 764 | * | * | * | 903 | 901 | 869 | 901 | 917 | 1145 |
| 320 | 802 | 780 | 791 | * | * | * | 917 | 930 | 917 | 905 | * | 1167 |
| 330 | 816 | 792 | 846 | * | * | * | * | * | * | * | * | 1169 |

Table 21 Steel Temperatures, Column No. 4

| Time (min) | Temperature (°C) Measured at Thermocouple #: 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 10 | Furnace Temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 17 | 16 | 17 | 16 | 17 | 16 | 17 | 16 | 22 | 80 |
| 10 | 33 | 29 | 38 | 32 | 26 | 29 | 42 | 56 | * | 683 |
| 20 | 121 | 119 | 122 | 118 | 70 | 89 | 107 | 116 | 90 | 782 |
| 30 | 114 | 113 | 129 | 119 | 118 | 123 | 144 | 168 | 124 | 840 |
| 40 | 107 | 108 | 146 | 125 | 140 | 139 | 196 | 210 | 149 | 874 |
| 50 | 145 | 135 | 202 | 181 | 165 | 179 | 244 | 265 | 185 | 902 |
| 60 | 201 | 187 | 254 | 232 | 202 | 217 | 285 | 312 | 224 | 922 |
| 70 | 249 | 234 | 301 | 279 | 235 | 251 | 320 | 351 | 257 | 939 |
| 80 | 296 | 281 | 347 | 326 | 266 | 284 | 352 | 387 | 288 | 955 |
| 90 | 342 | 329 | 392 | 372 | 297 | 316 | 384 | 421 | 319 | 969 |
| 100 | 386 | 375 | 435 | 415 | 329 | 348 | 414 | 454 | 350 | 981 |
| 110 | 429 | 418 | 476 | 456 | 360 | 379 | 445 | 485 | 379 | 994 |
| 120 | 469 | 458 | 514 | 494 | 390 | 437 | 474 | 514 | 407 | 1006 |
| 130 | 506 | 495 | 548 | 529 | 419 | 468 | 503 | 541 | 433 | 1006 |
| 140 | 539 | 529 | 580 | 559 | 447 | 496 | 530 | 567 | 458 | 1029 |
| 150 | 571 | 559 | 613 | 593 | 473 | 523 | 555 | 594 | 481 | 1038 |
| 160 | 604 | 593 | 644 | 624 | 498 | 549 | 581 | 622 | 505 | 1043 |
| 170 | 635 | 624 | 673 | 654 | 522 | 575 | 607 | 656 | 527 | 1055 |
| 180 | 667 | 660 | 700 | 682 | 545 | 603 | 633 | 699 | 549 | 1065 |
| 200 | 717 | 722 | 724 | 716 | 642 | 707 | 702 | 724 | 630 | 1081 |
| 220 | 734 | 733 | 745 | 747 | 735 | 741 | 748 | 739 | 720 | 1093 |
| 240 | 771 | 772 | 783 | 786 | 773 | 783 | 775 | 778 | 770 | 1108 |
| 260 | 799 | 805 | 813 | 821 | 792 | 809 | 794 | 811 | 789 | 1121 |
| 280 | 835 | 858 | 848 | 887 | * | 840 | 803 | 860 | * | 1136 |
| 300 | 871 | 877 | 875 | 895 | * | 877 | 855 | 891 | 862 | 1145 |
| 320 | 894 | 897 | 913 | 918 | * | 910 | 921 | 918 | 889 | 1167 |
| 330 | 896 | 911 | 924 | 929 | * | * | 934 | 926 | 903 | 1169 |

Table 22 Axial Deformation, Column No. 4

| Time (min) | Expansion (mm) |
|---|---|
| 0 | 0.0 |
| 10 | 1.8 |
| 20 | 4.4 |
| 30 | 6.4 |
| 40 | 7.4 |
| 50 | 8.2 |
| 60 | 9.1 |
| 70 | 10.0 |
| 80 | 11.0 |
| 90 | 12.1 |
| 100 | 13.1 |
| 110 | 14.2 |
| 120 | 15.1 |
| 130 | 16.0 |
| 140 | 16.7 |
| 150 | 17.2 |
| 160 | 17.6 |
| 170 | 17.8 |
| 180 | 18.0 |
| 190 | 18.1 |
| 200 | 18.1 |
| 210 | 17.8 |
| 220 | 17.4 |
| 230 | 16.8 |
| 240 | 16.2 |
| 250 | 15.3 |
| 260 | 14.0 |
| 270 | 12.3 |
| 280 | 10.3 |
| 290 | 7.8 |
| 300 | 4.8 |
| 310 | 0.9 |
| 320 | -4.7 |
| 330 | -14.8 |

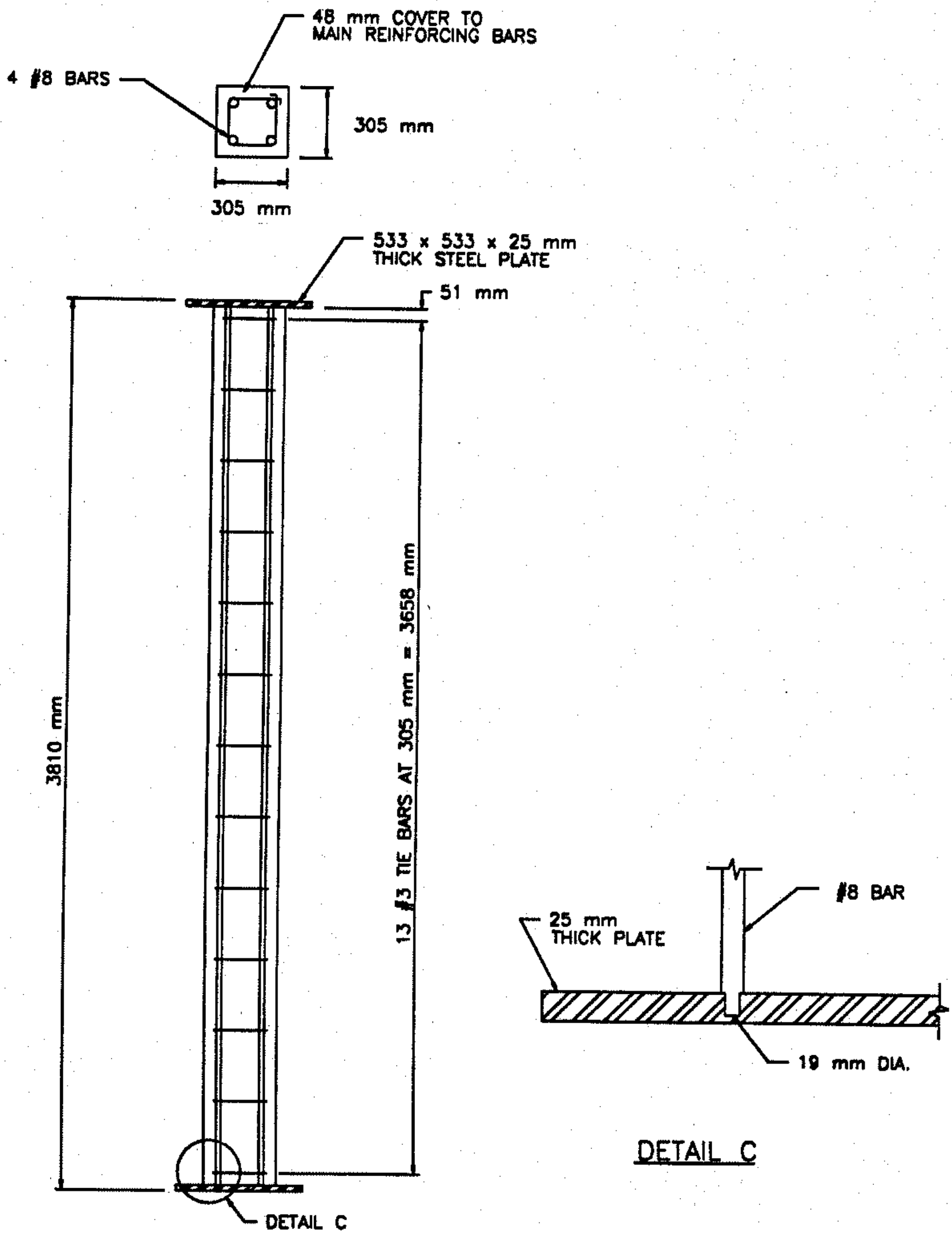


FIGURE 1 ELEVATION, CROSS-SECTION AND FINISHING DETAIL: COLUMN NO. 1 (305 x 305 mm, 4 BARS)

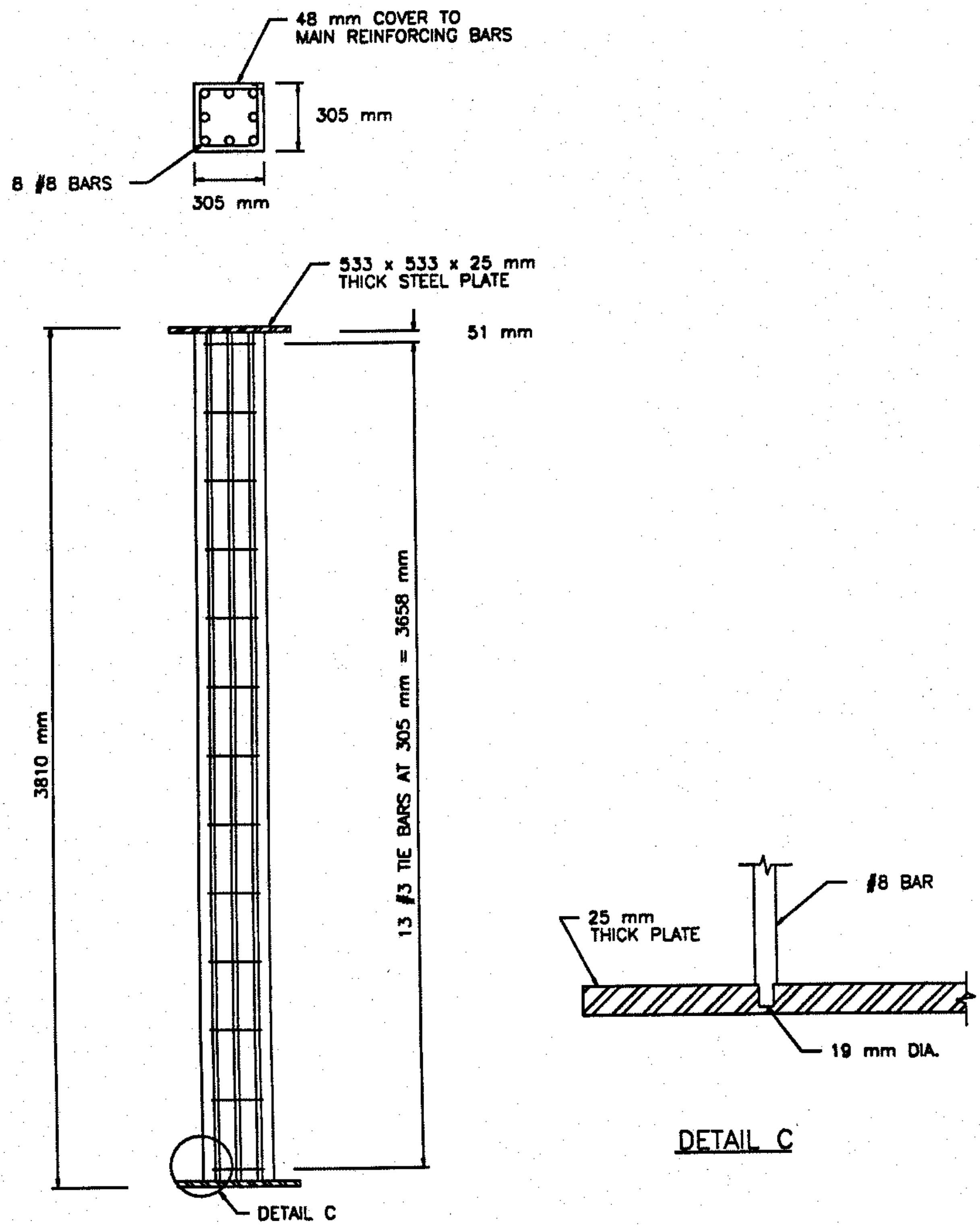


FIGURE 2 ELEVATION, CROSS-SECTION AND FINISHING DETAIL: COLUMN NO. 2 (305 x 305 mm, 8 BARS)

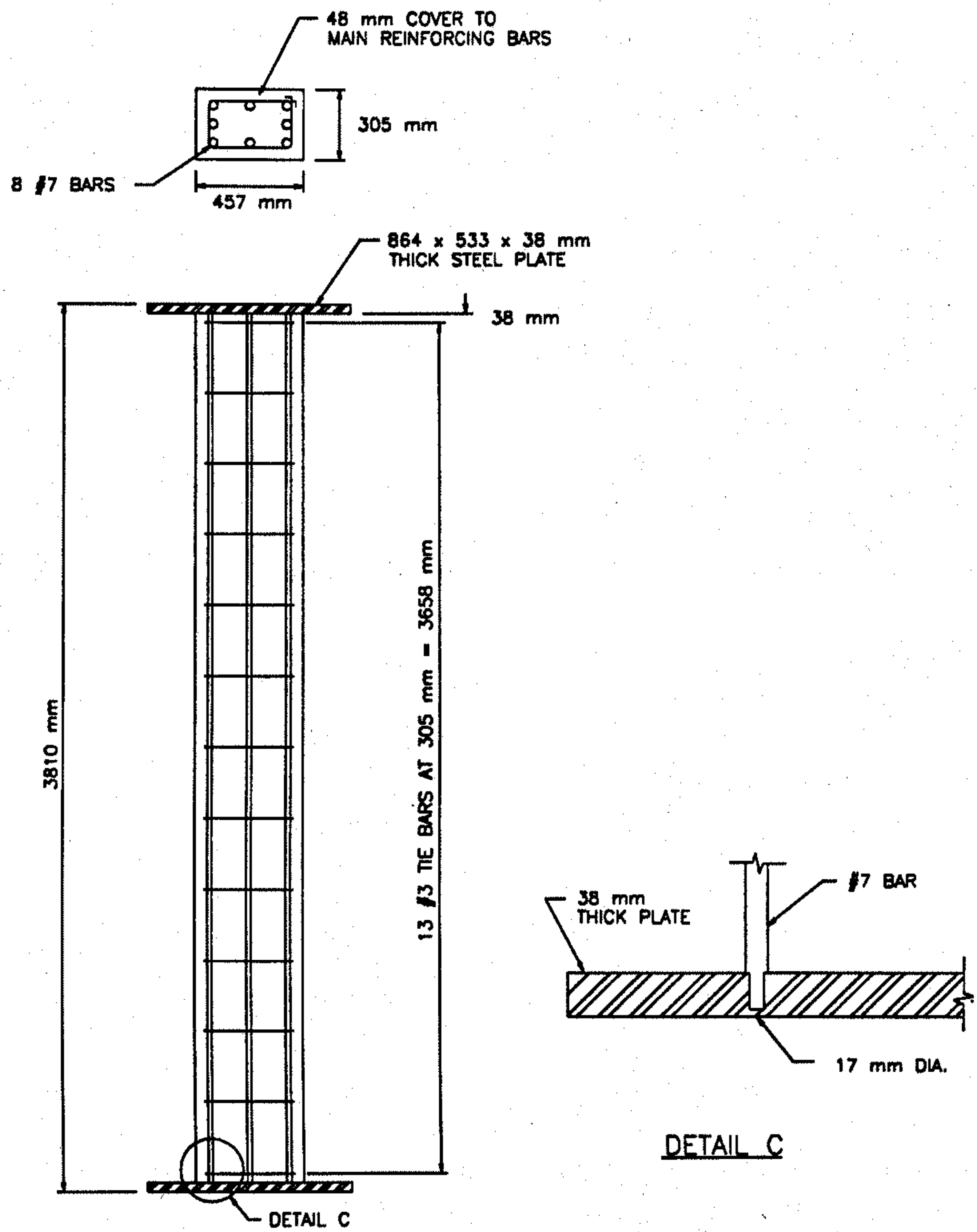


FIGURE 3 ELEVATION, CROSS-SECTION AND FINISHING DETAIL: COLUMN NO. 3 (305 x 457 mm)

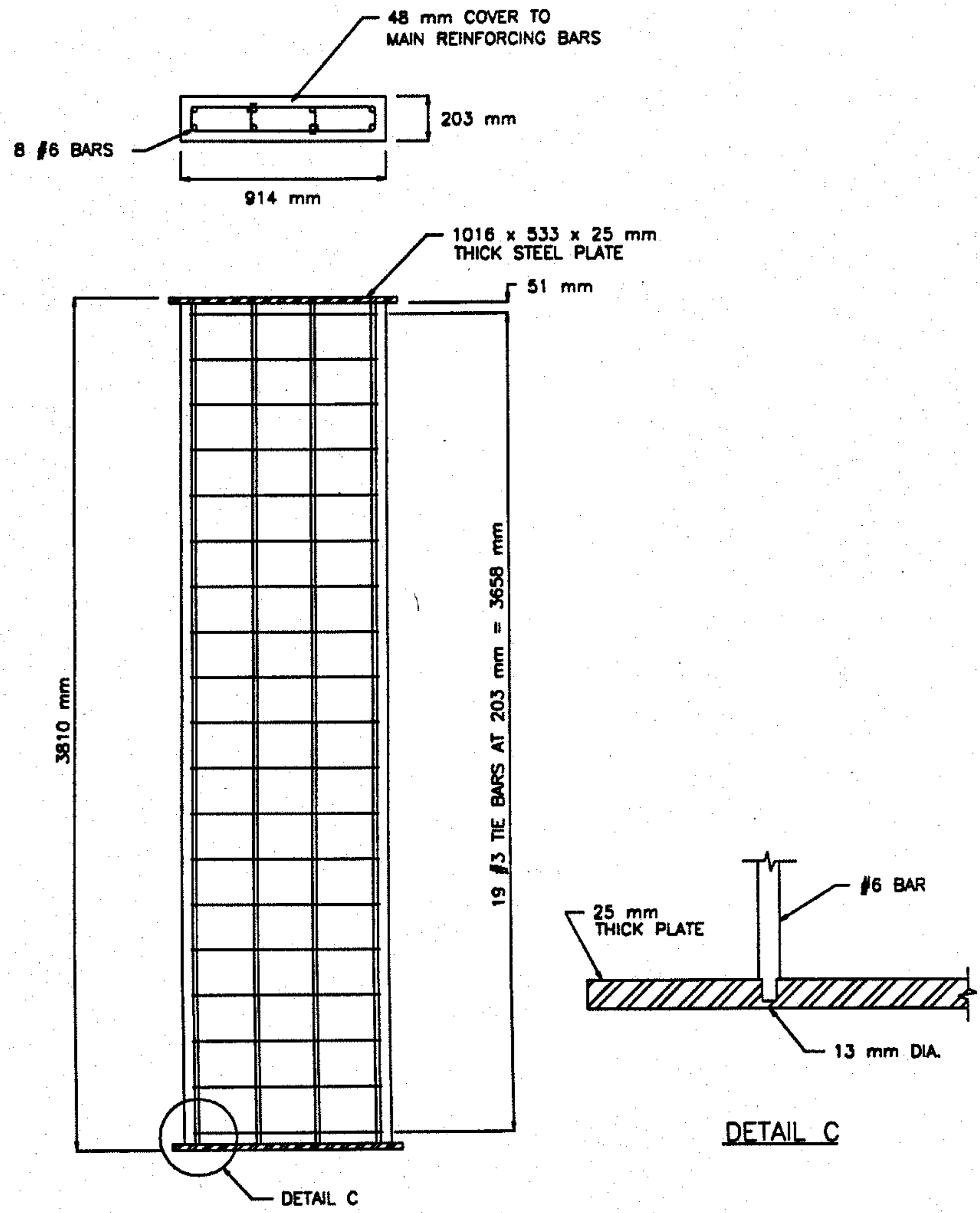


FIGURE 4 ELEVATION, CROSS-SECTION AND FINISHING DETAIL: COLUMN NO. 4 (203 x 914 mm)

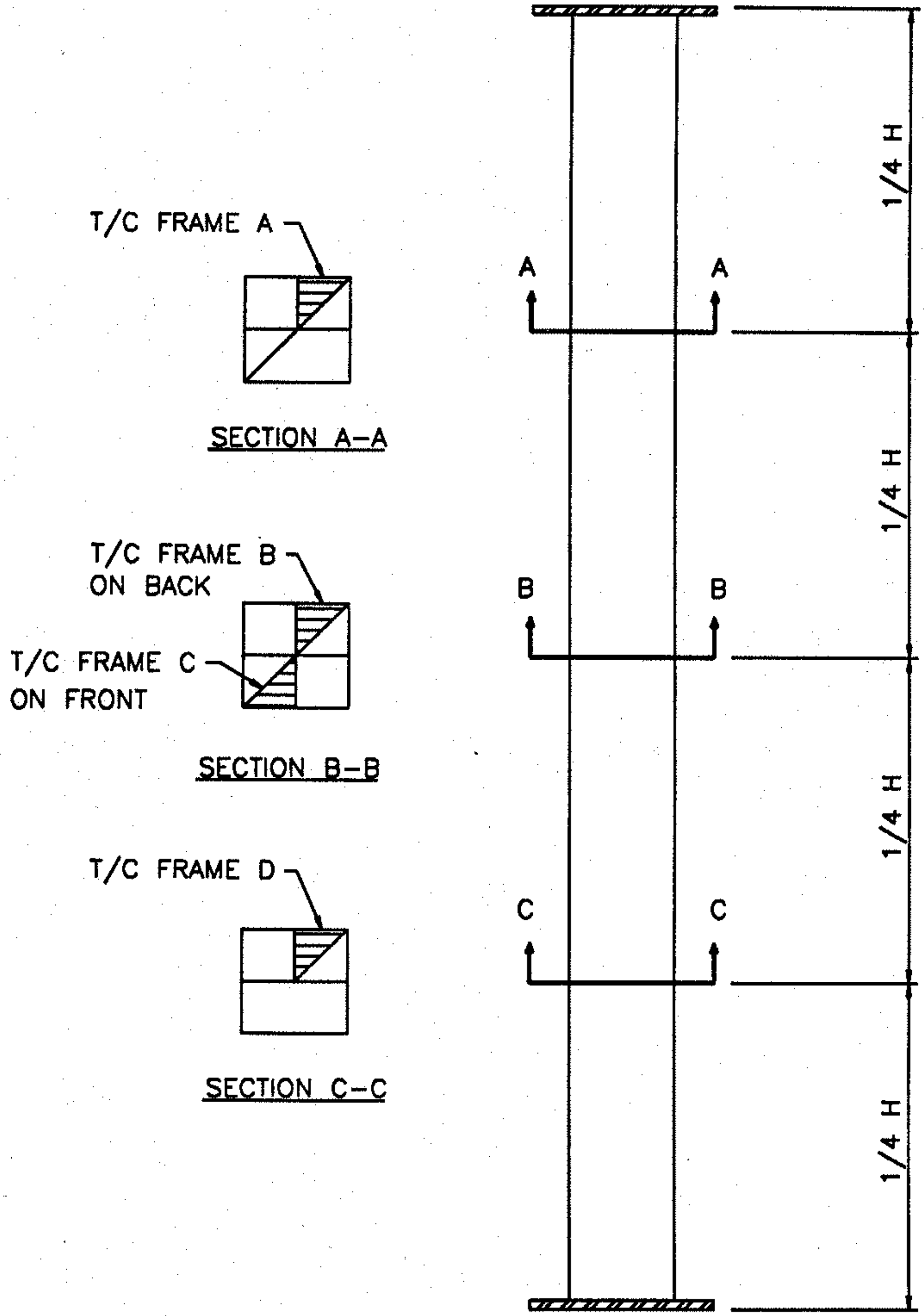


FIGURE 5 LAYOUT OF T/C FRAMES IN CONCRETE: COLUMN NO. 1 (305 x 305 mm, 4 BARS)

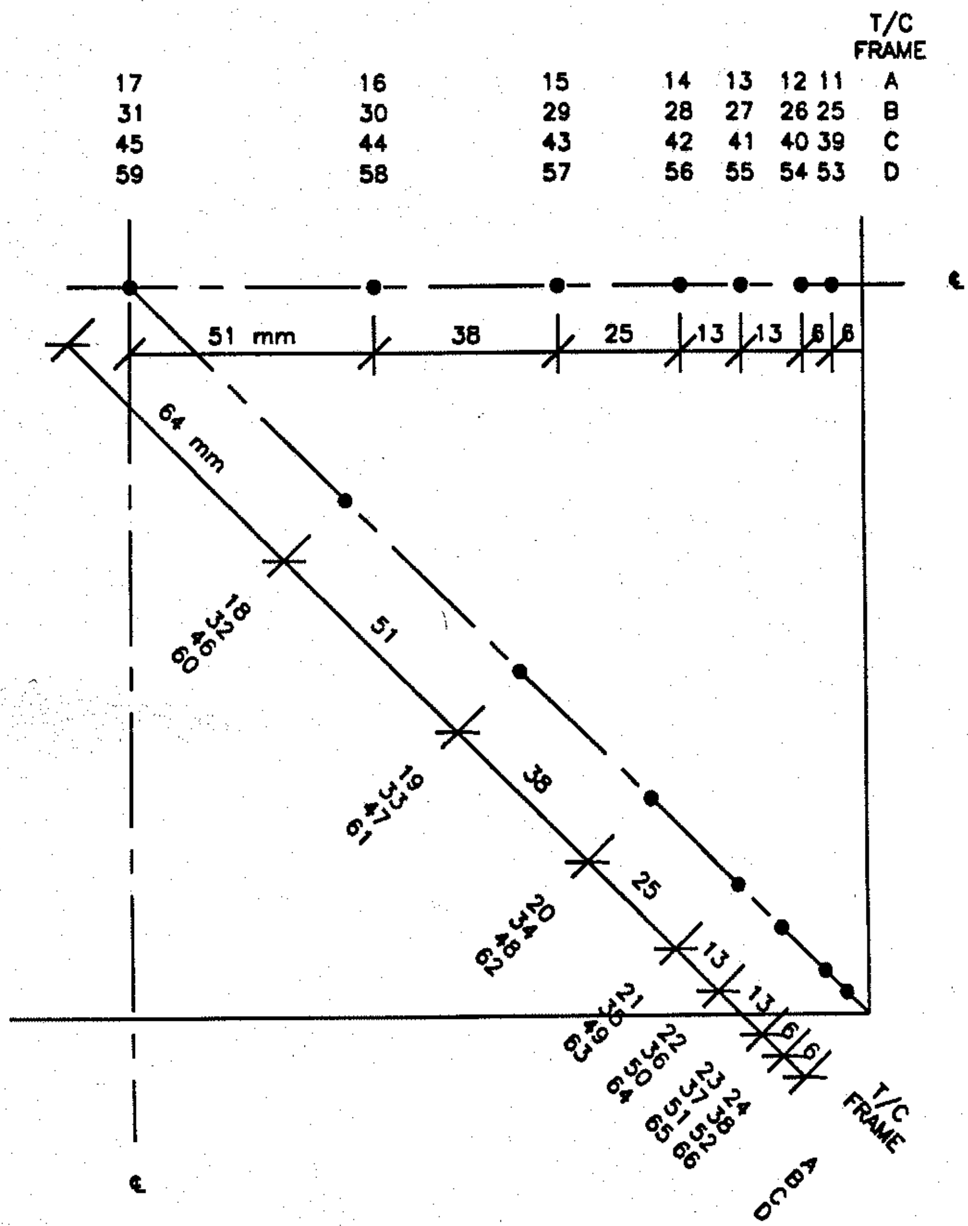


FIGURE 6 LOCATIONS OF T/C'S IN FRAMES: COLUMN NO. 1
(305 x 305 mm, 4 BARS)

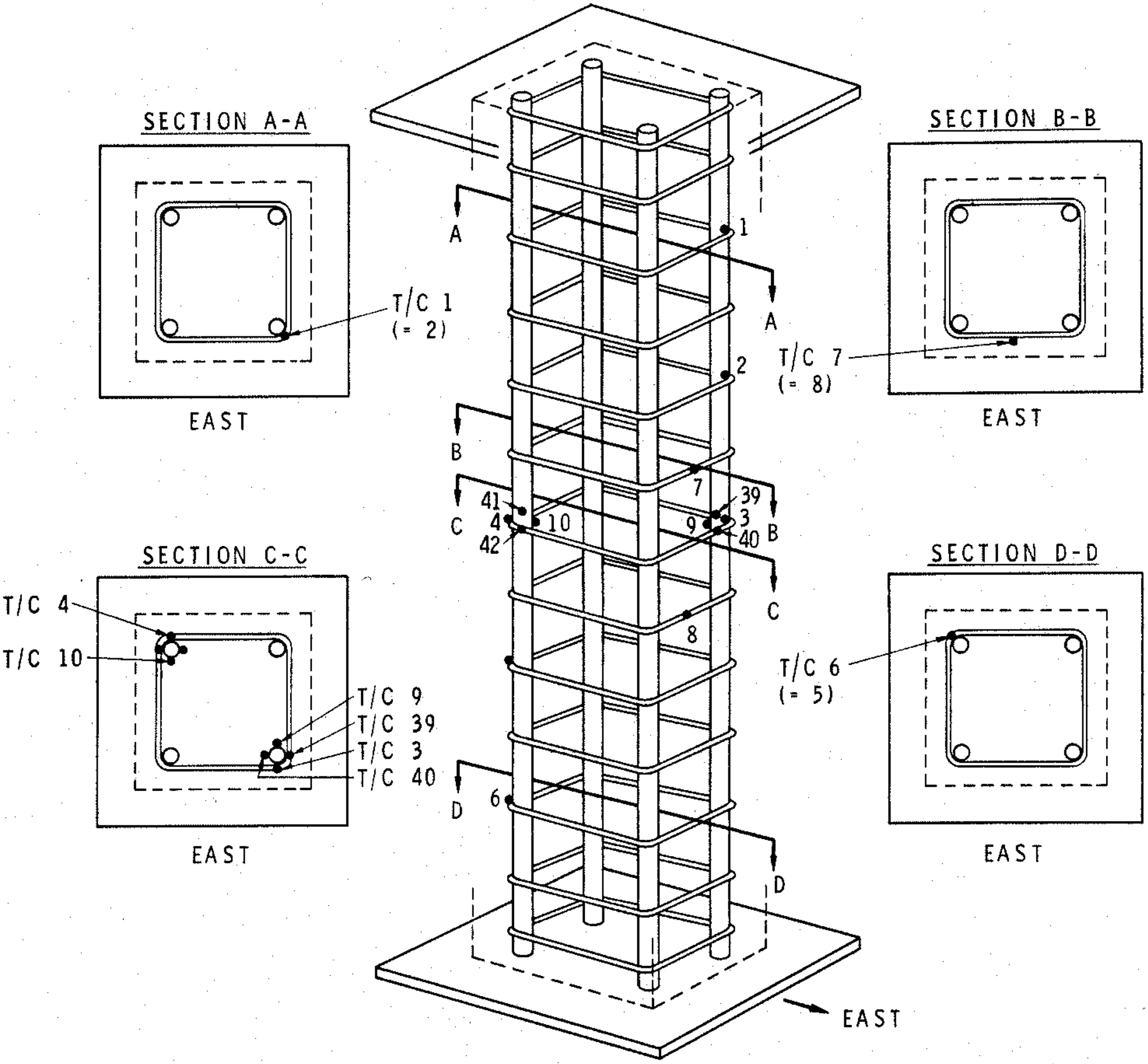


FIGURE 7 LOCATIONS OF T/C'S ON REINFORCING BARS:
COLUMN NO. 1 (305 x 305 mm, 4 BARS)

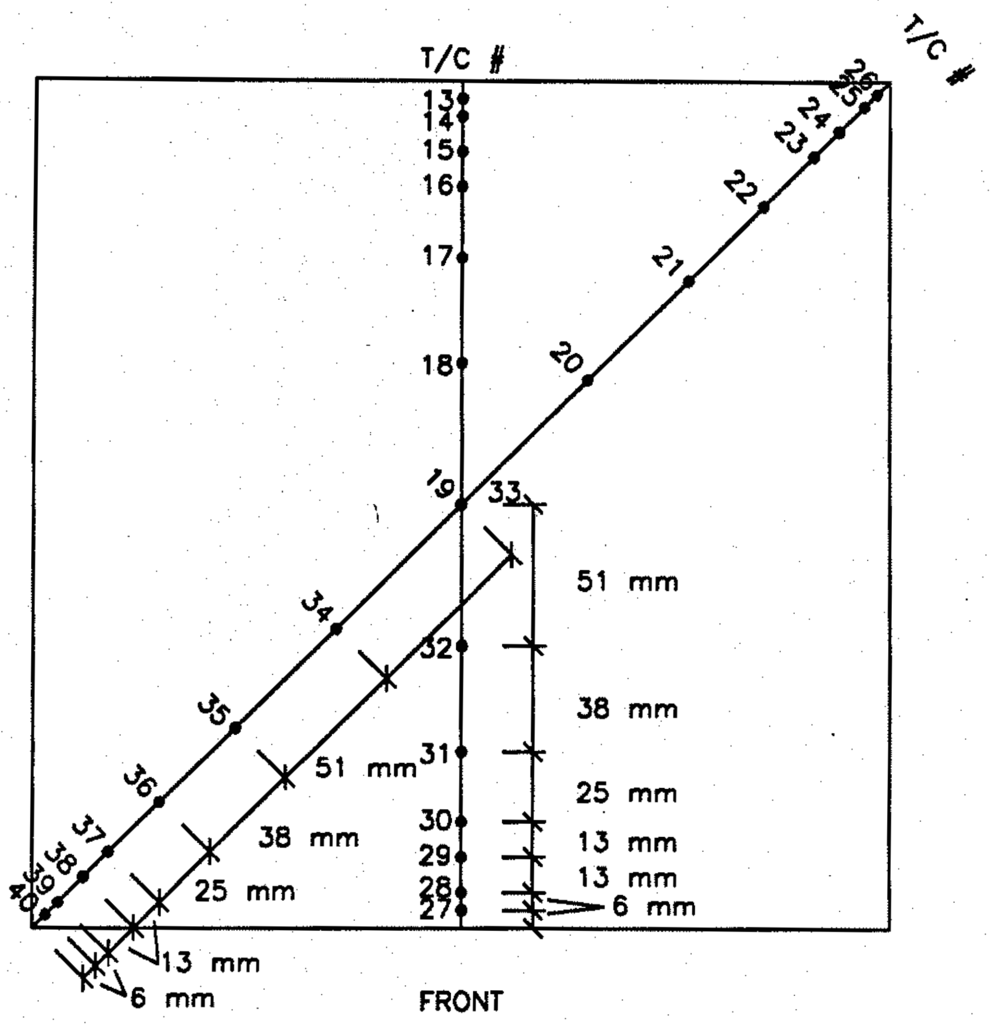


FIGURE 8 LOCATIONS OF T/C'S IN FRAMES: COLUMN NO. 2 (305 x 305 mm, 8 BARS)

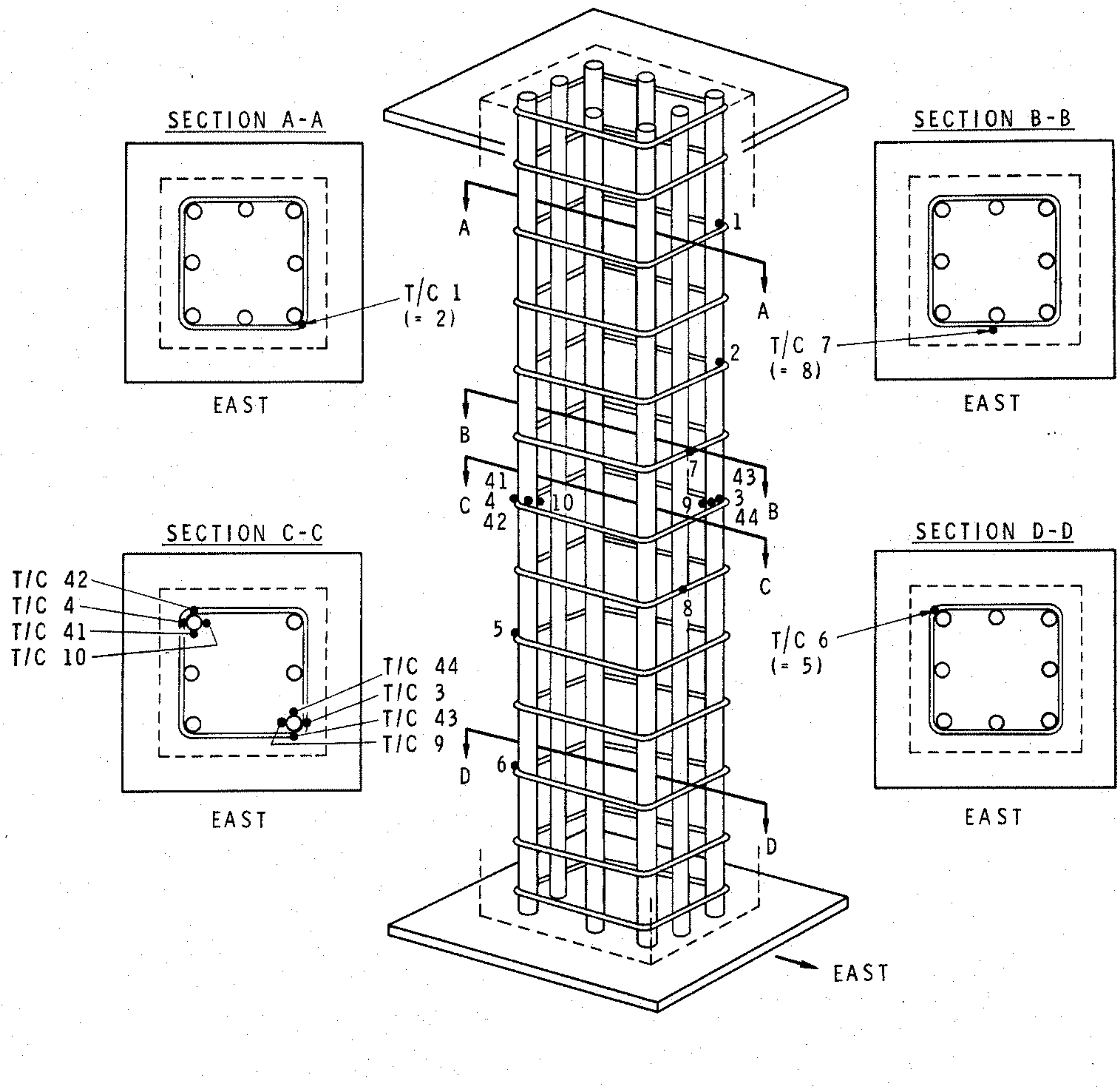


FIGURE 9 LOCATIONS OF T/C'S ON REINFORCING BARS: COLUMN NO. 2 (305 x 305 mm, 8 BARS)

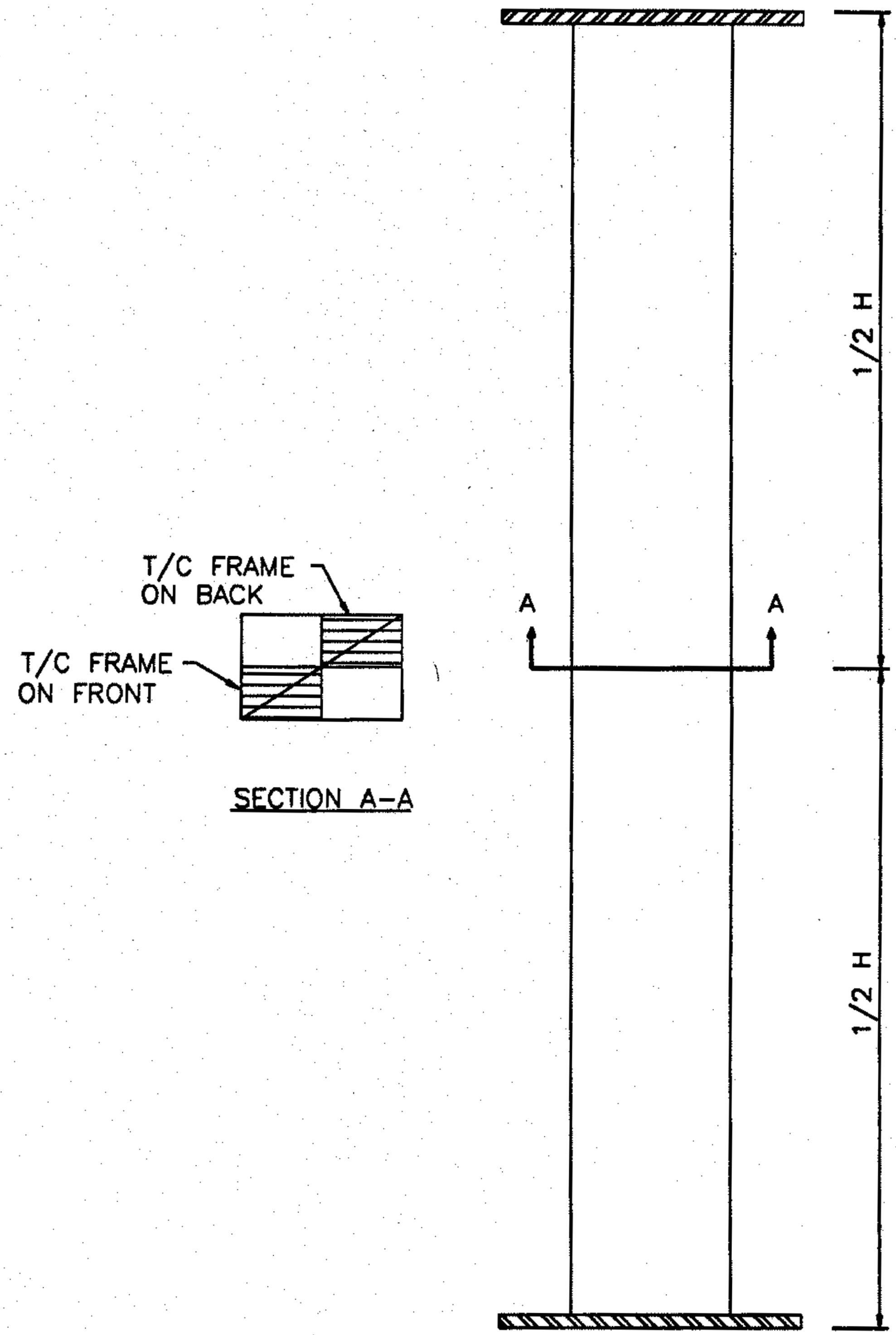


FIGURE 10 LAYOUT OF T/C FRAMES IN CONCRETE: COLUMN NO. 3 (305 x 457 mm)

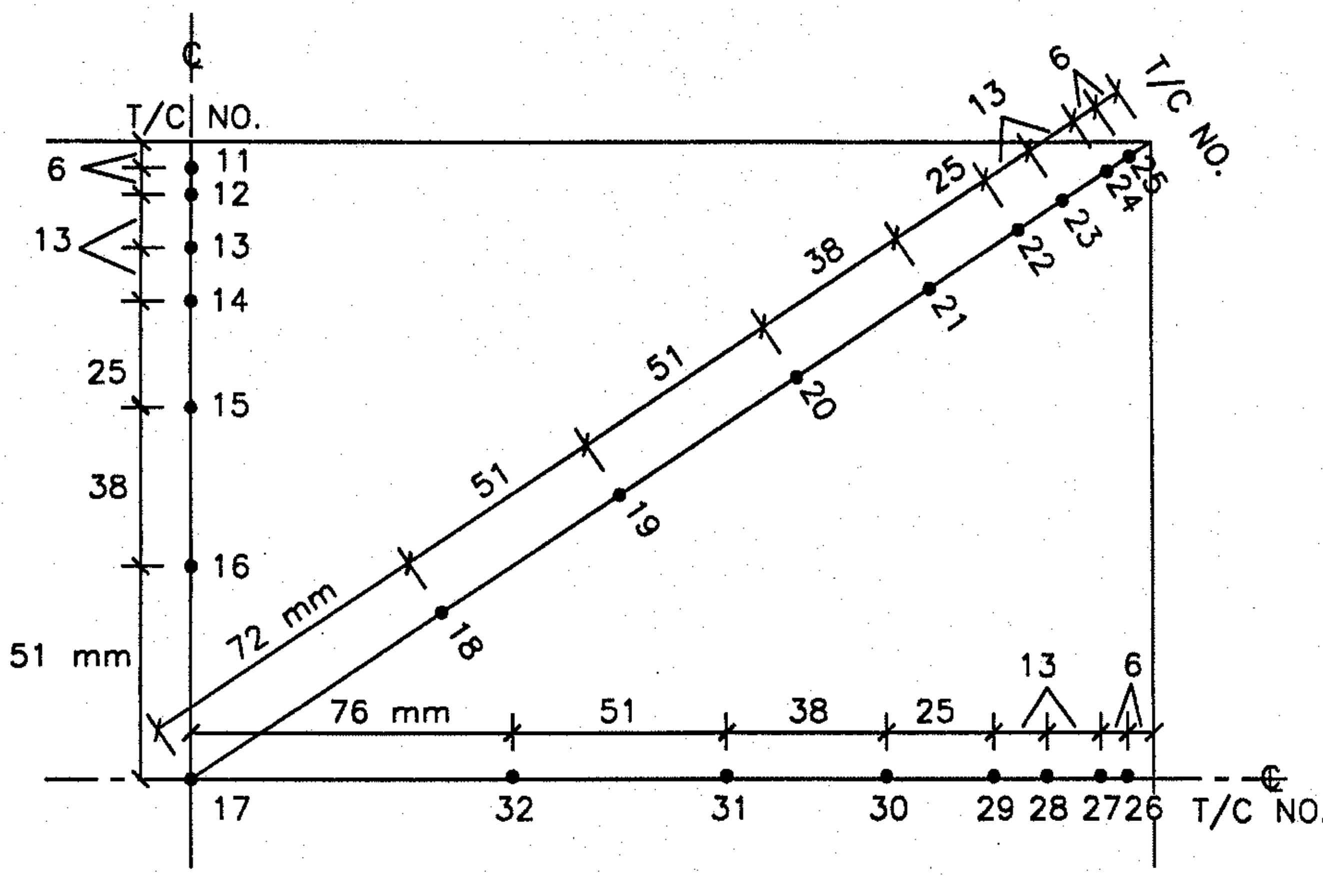


FIGURE 11 LOCATIONS OF T/C'S IN FRAMES: COLUMN NO. 3
(305 x 457 mm)

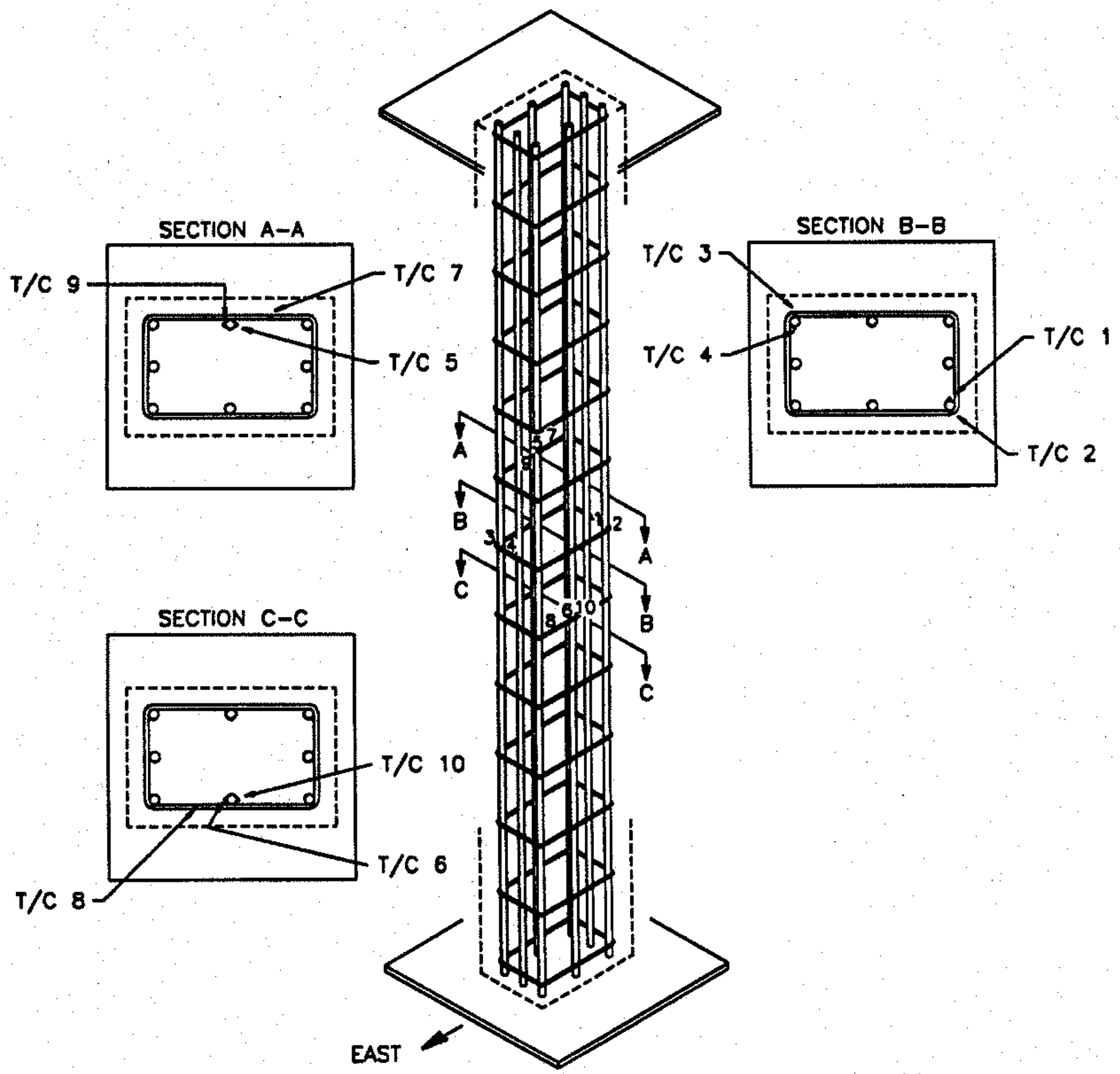


FIGURE 12 LOCATIONS OF T/C'S ON REINFORCING BARS: COLUMN NO. 3 (305 x 457 mm)

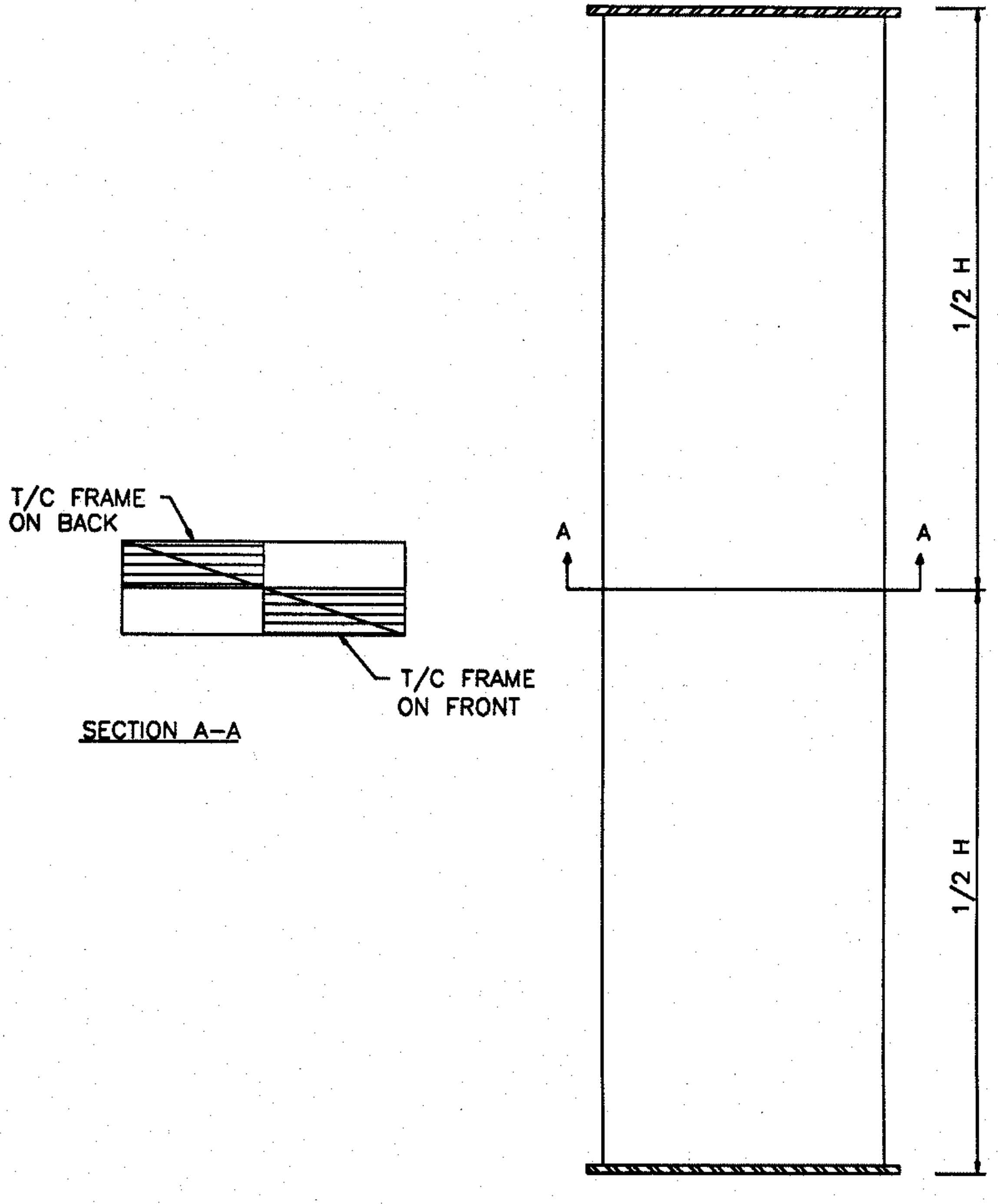


FIGURE 13 LAYOUT OF T/C FRAMES IN CONCRETE: COLUMN NO. 4 (203 x 914 mm)

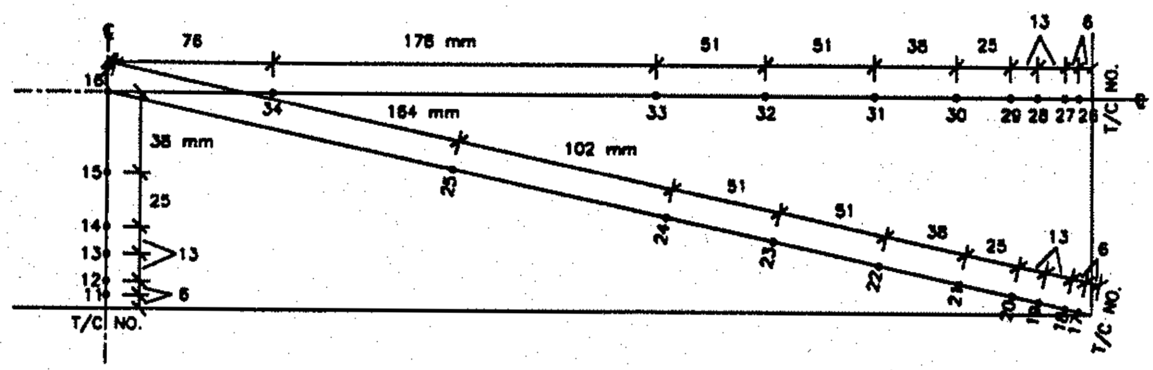

FIGURE 14 LOCATIONS OF T/C'S IN FRAMES: COLUMN NO. 4 (203 x 914 mm)

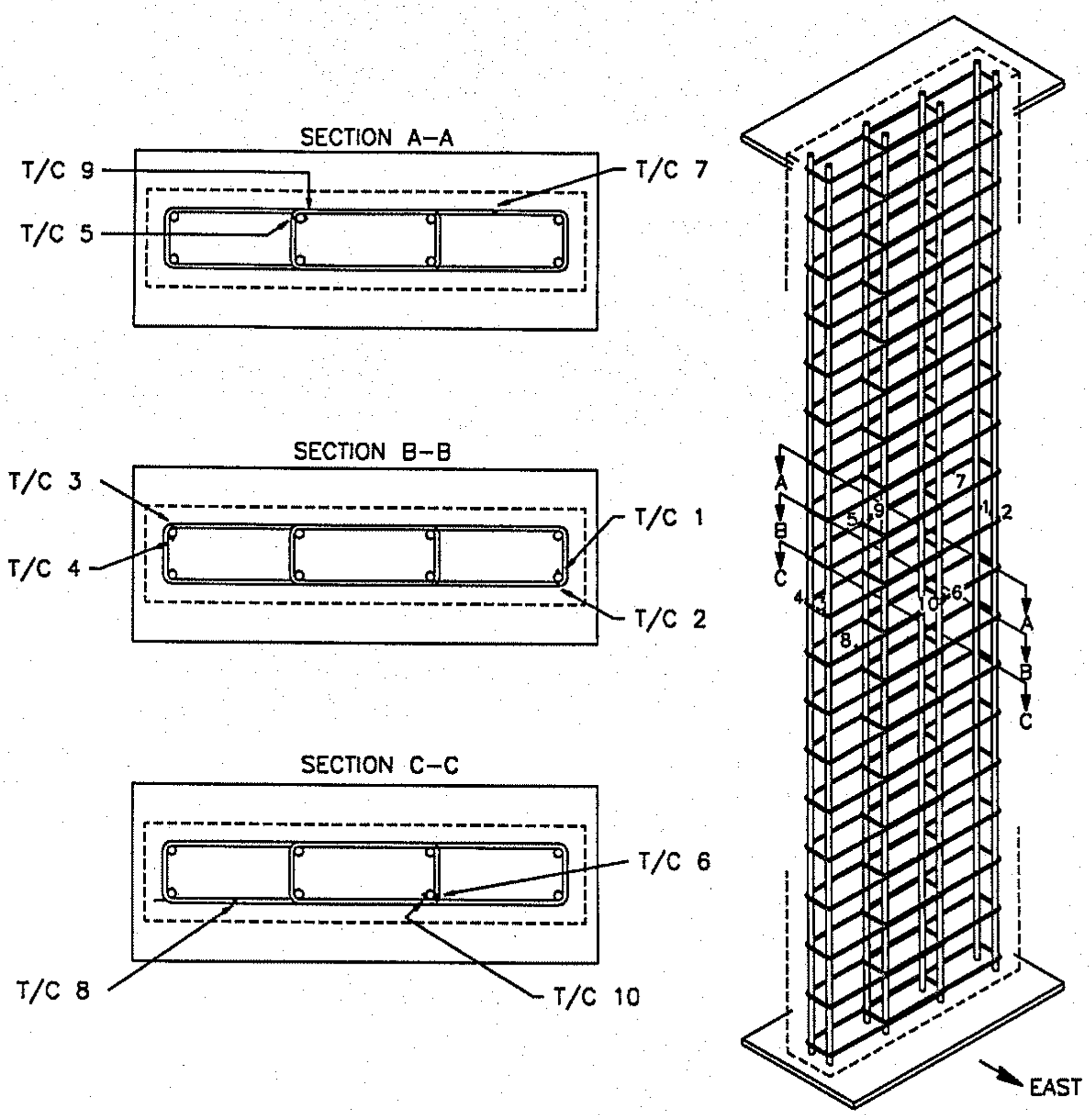


FIGURE 15 LOCATIONS OF T/C'S ON REINFORCING BARS: COLUMN NO. 4 (203 x 914 mm)

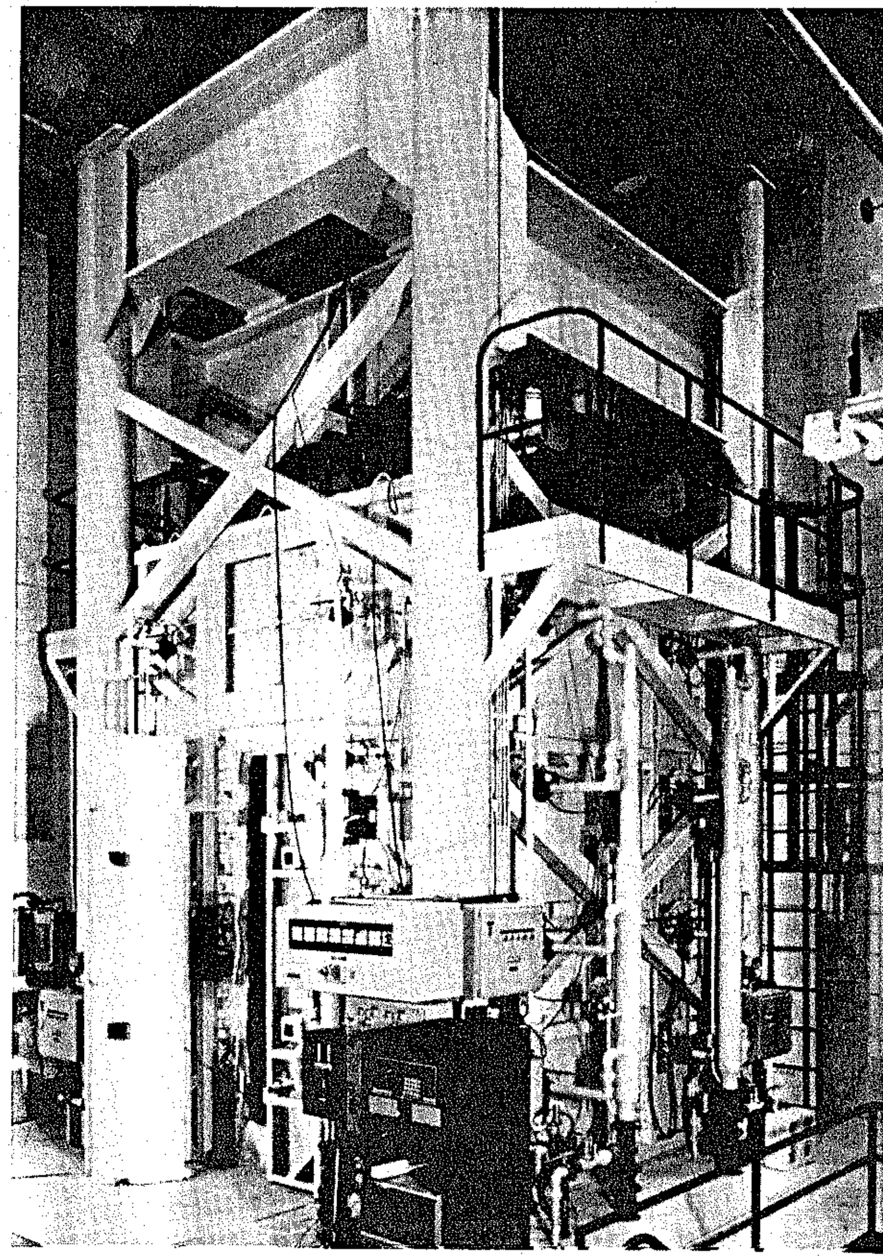

FIGURE 16 COLUMN FURNACE

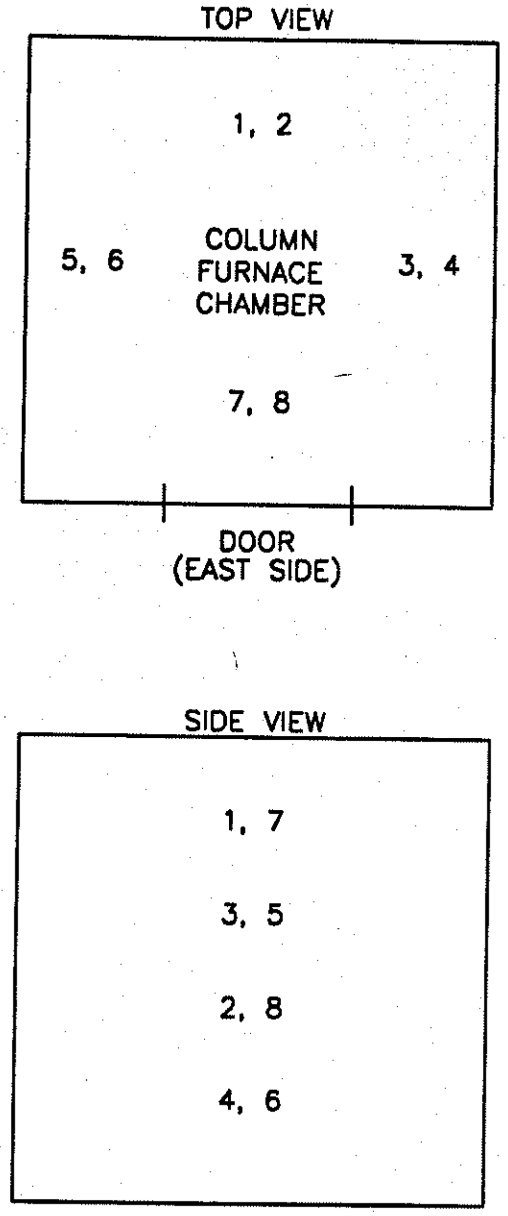


FIGURE 17 T/C LOCATIONS FOR FURNACE TEMPERATURES

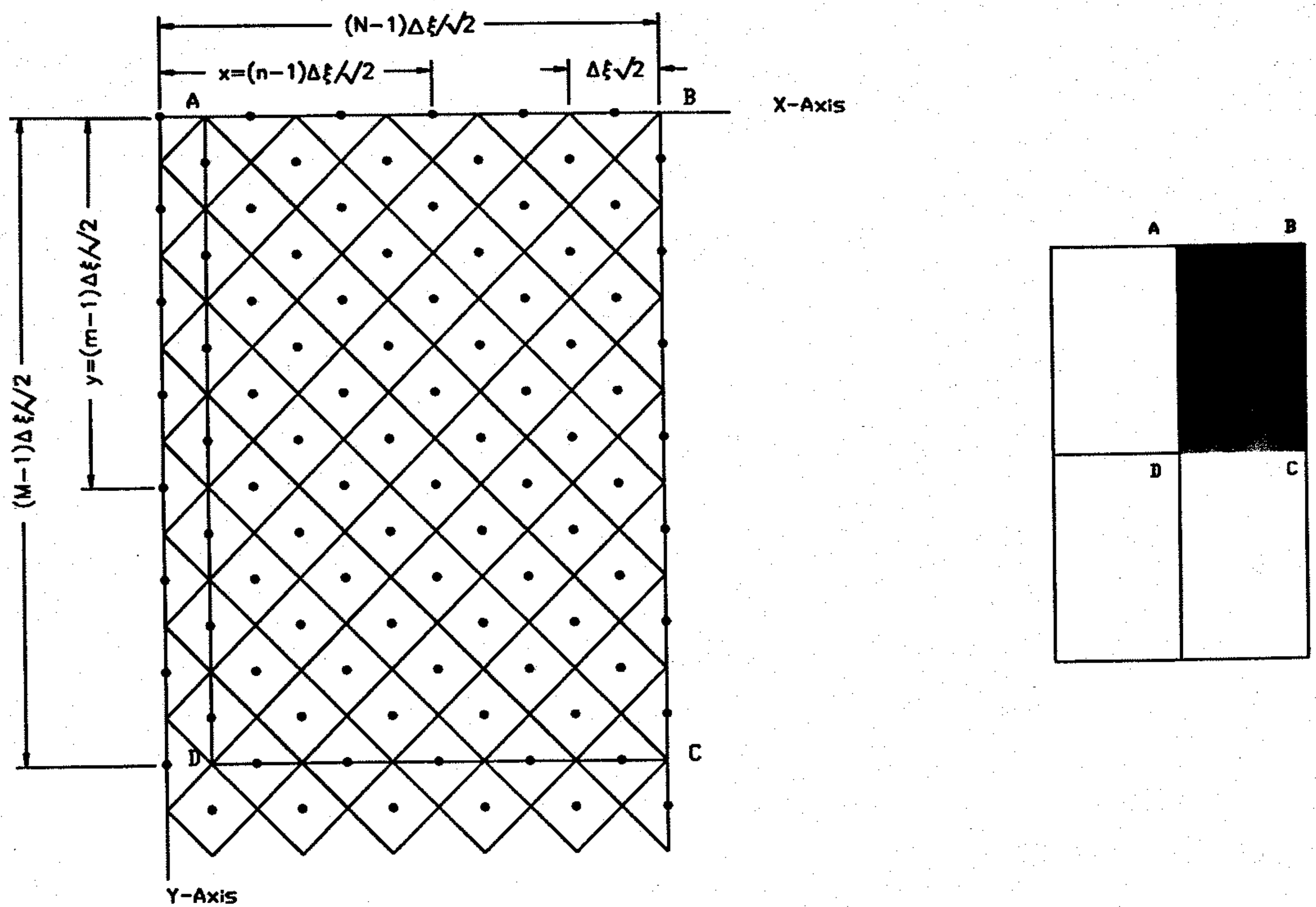


FIGURE 18 THERMAL NETWORK IN 1/4 CROSS-SECTION

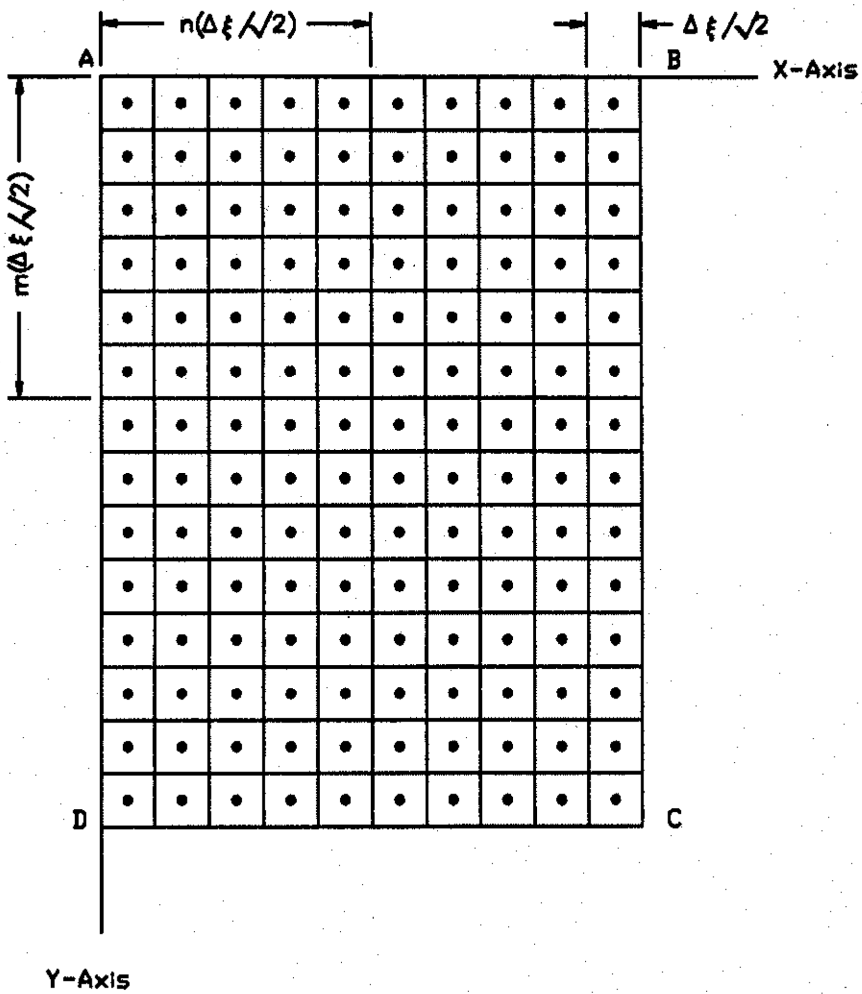


FIGURE 19 STRESS-STRAIN NETWORK IN 1/4 CROSS-SECTION

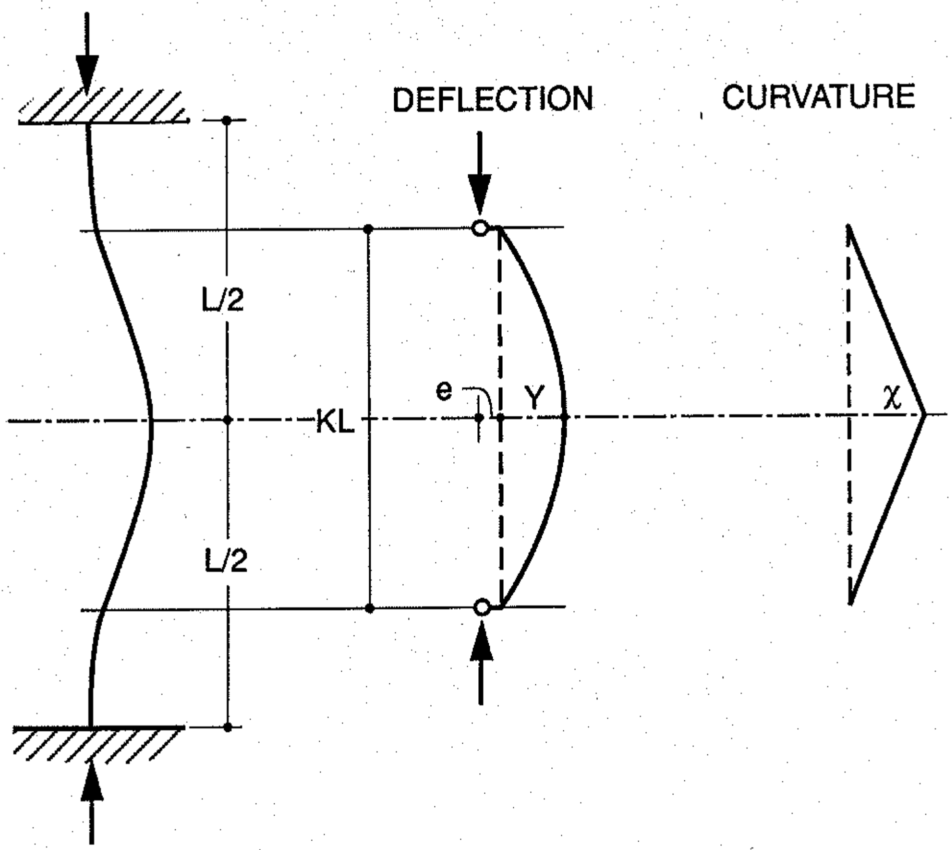


FIGURE 20. LOAD DEFLECTION ANALYSIS

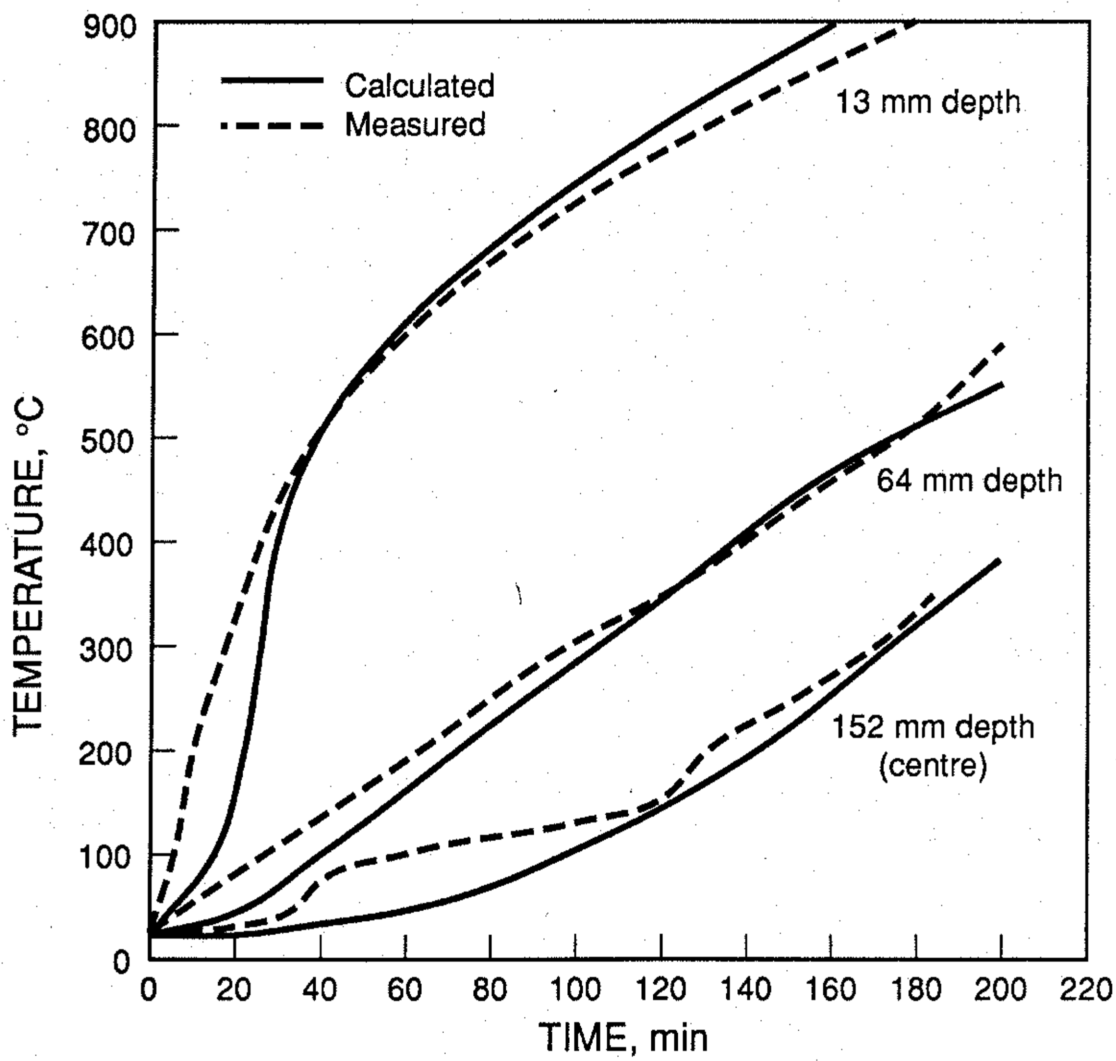


FIGURE 21. TEMPERATURES OF CONCRETE AT VARIOUS DEPTHS ALONG CENTRELINE OF SQUARE COLUMN NO. 1 (305 x 305 mm) AS A FUNCTION OF EXPOSURE TIME

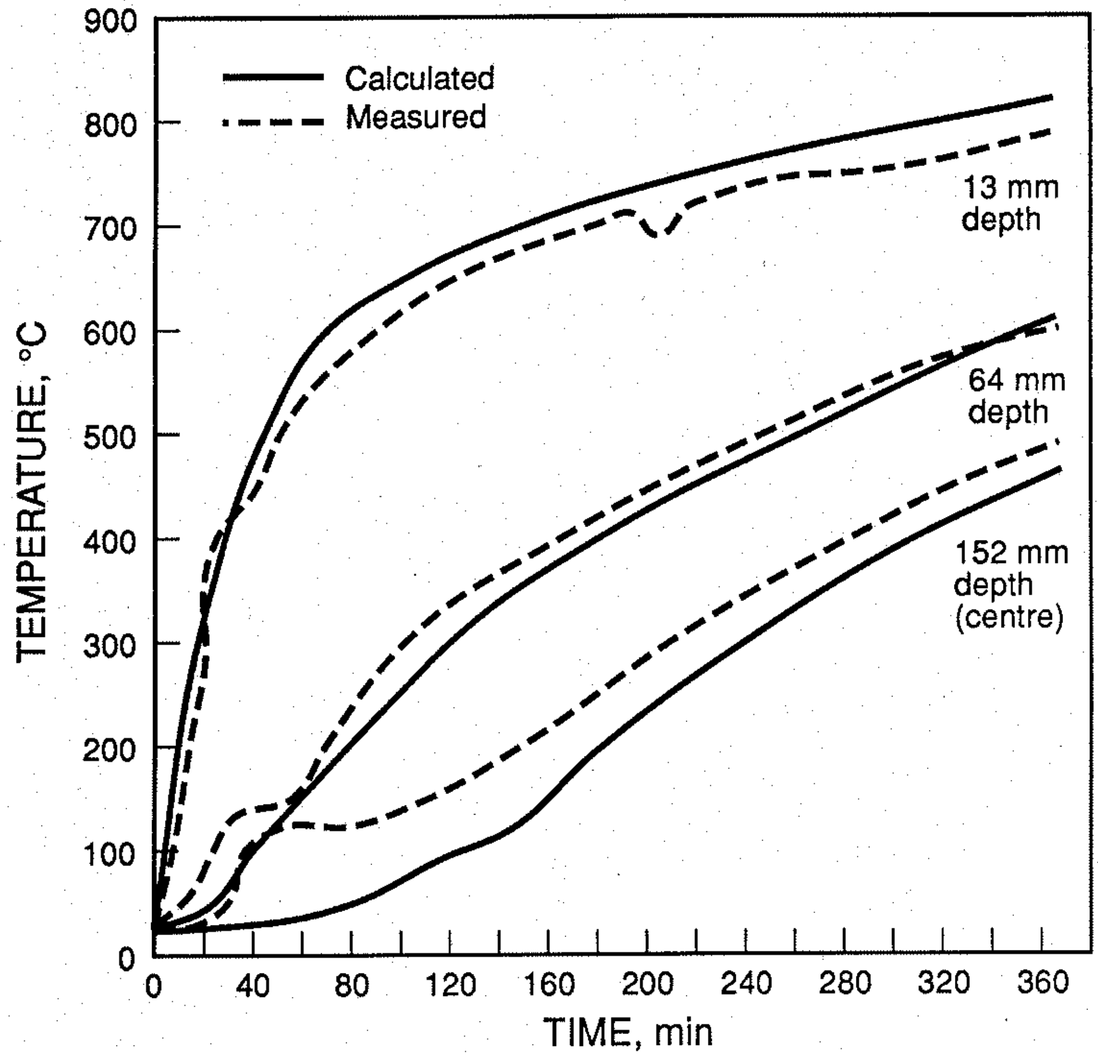


FIGURE 22. TEMPERATURES OF CONCRETE AT VARIOUS DEPTHS ALONG CENTRELINE PARALLEL TO SHORTEST SIDE OF COLUMN NO. 3 (305 x 457 mm) AS A FUNCTION OF EXPOSURE TIME

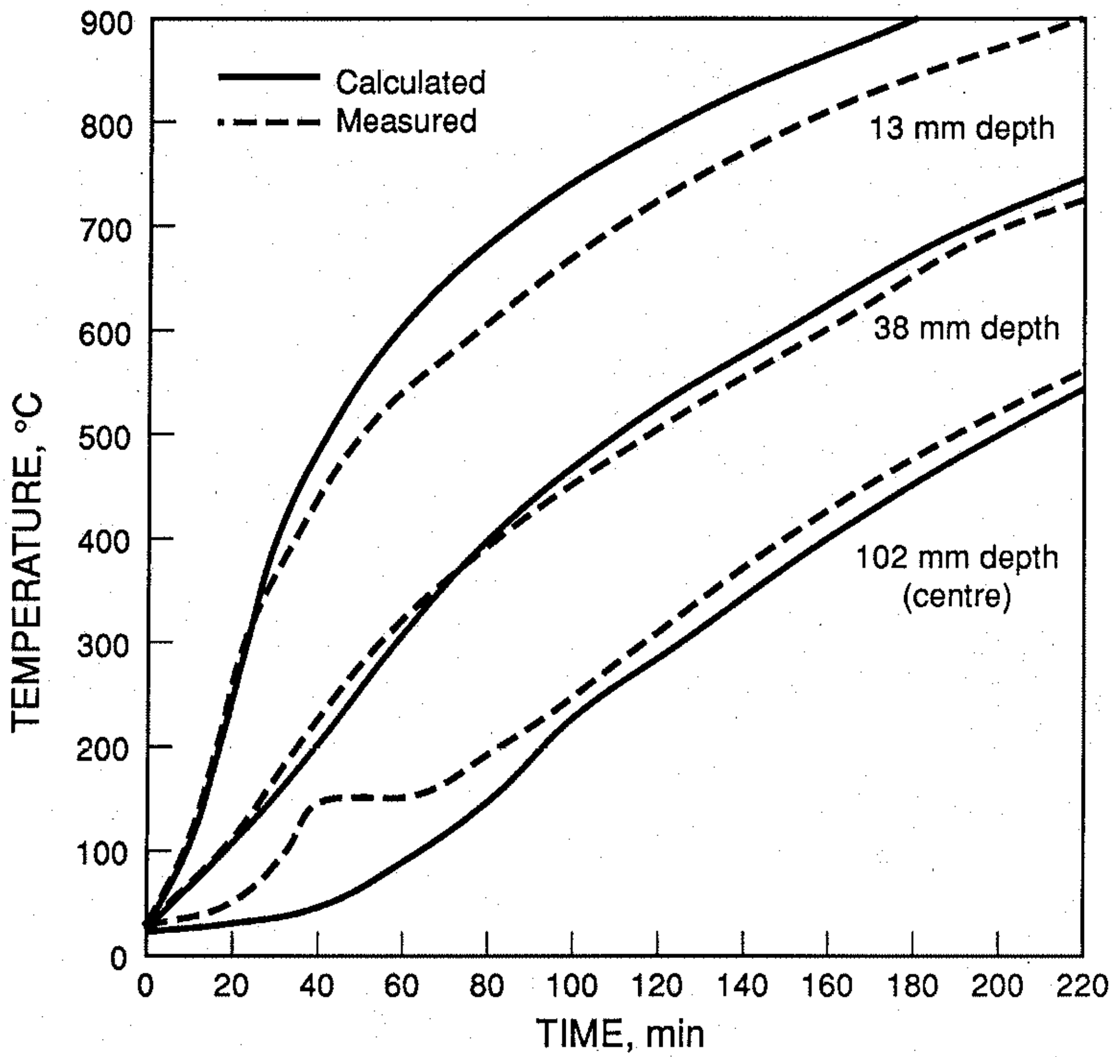


FIGURE 23. TEMPERATURES OF CONCRETE AT VARIOUS DEPTHS ALONG CENTRELINE PARALLEL TO SHORTEST SIDE OF COLUMN NO. 4 (203 x 914 mm) AS A FUNCTION OF EXPOSURE TIME

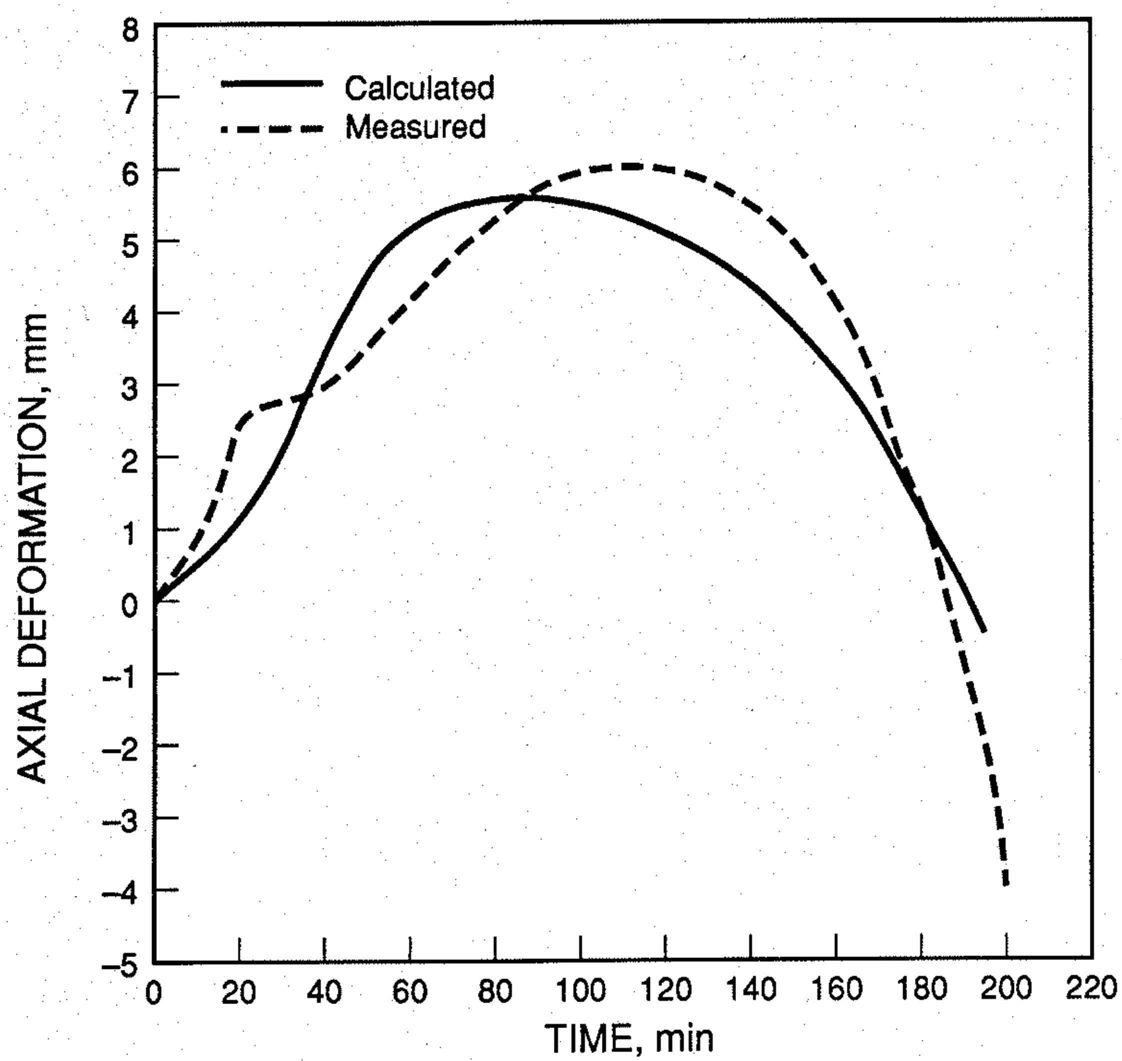


FIGURE 24. CALCULATED AND MEASURED AXIAL DEFORMATIONS OF COLUMN NO. 1 (305 x 305 mm, 4 BARS) AS A FUNCTION OF EXPOSURE TIME

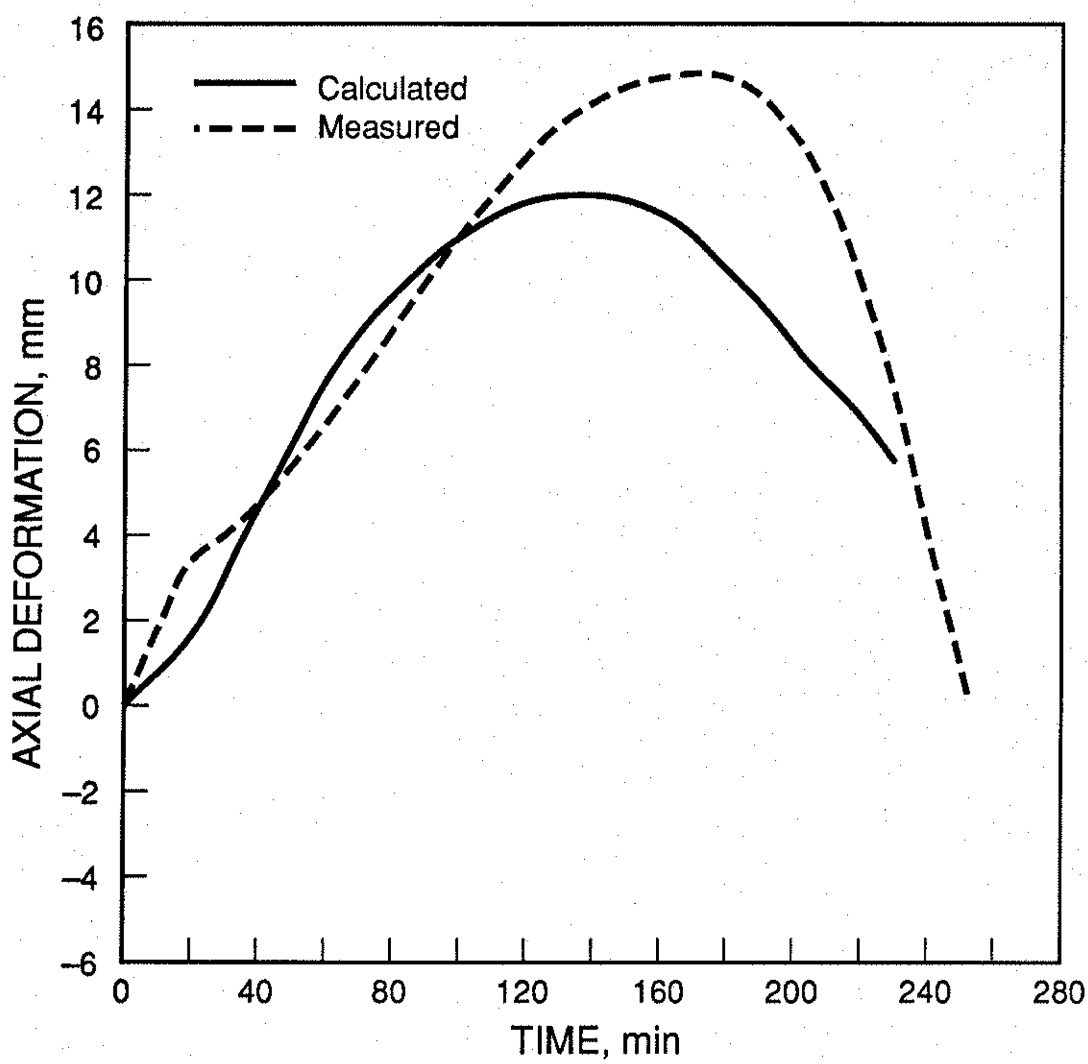


FIGURE 25. CALCULATED AND MEASURED AXIAL DEFORMATIONS OF COLUMN NO. 2 (305 x 305 mm, 8 BARS) AS A FUNCTION OF EXPOSURE TIME

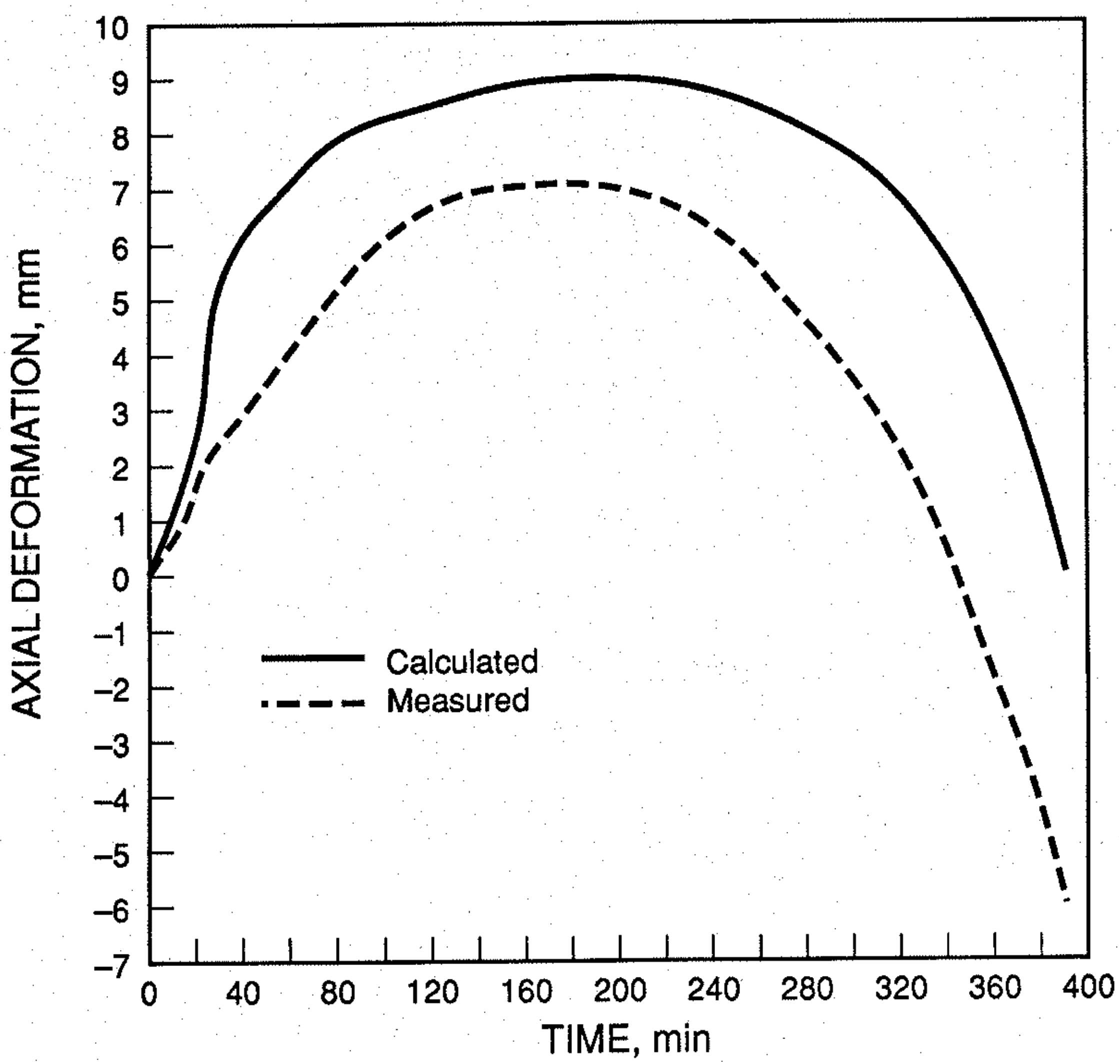


FIGURE 26. CALCULATED AND MEASURED AXIAL DEFORMATIONS OF COLUMN NO. 3 (305 x 457 mm) AS A FUNCTION OF EXPOSURE TIME

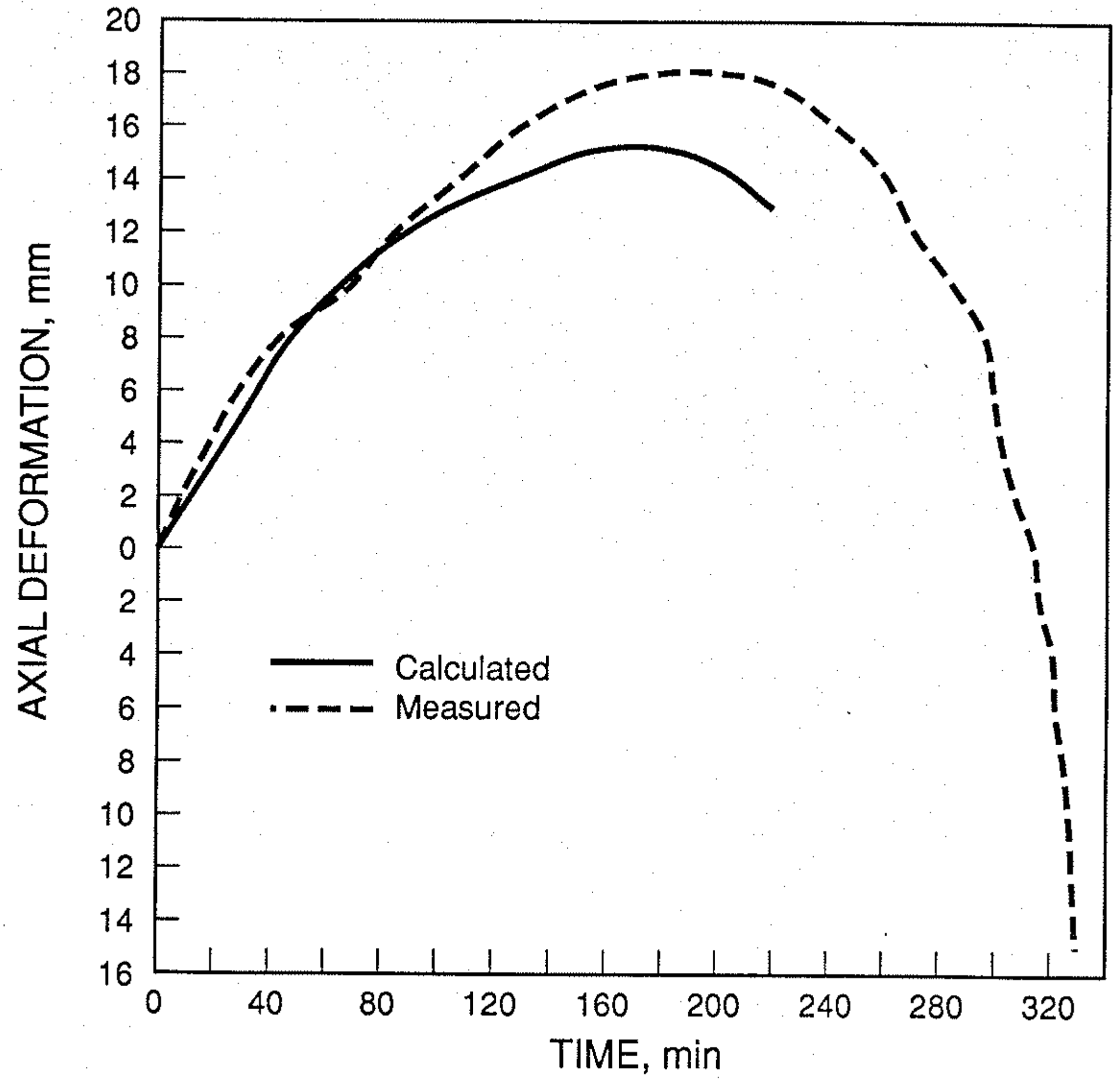


FIGURE 27. CALCULATED AND MEASURED AXIAL DEFORMATIONS OF COLUMN NO. 4 (203 x 914 mm) AS A FUNCTION OF EXPOSURE TIME

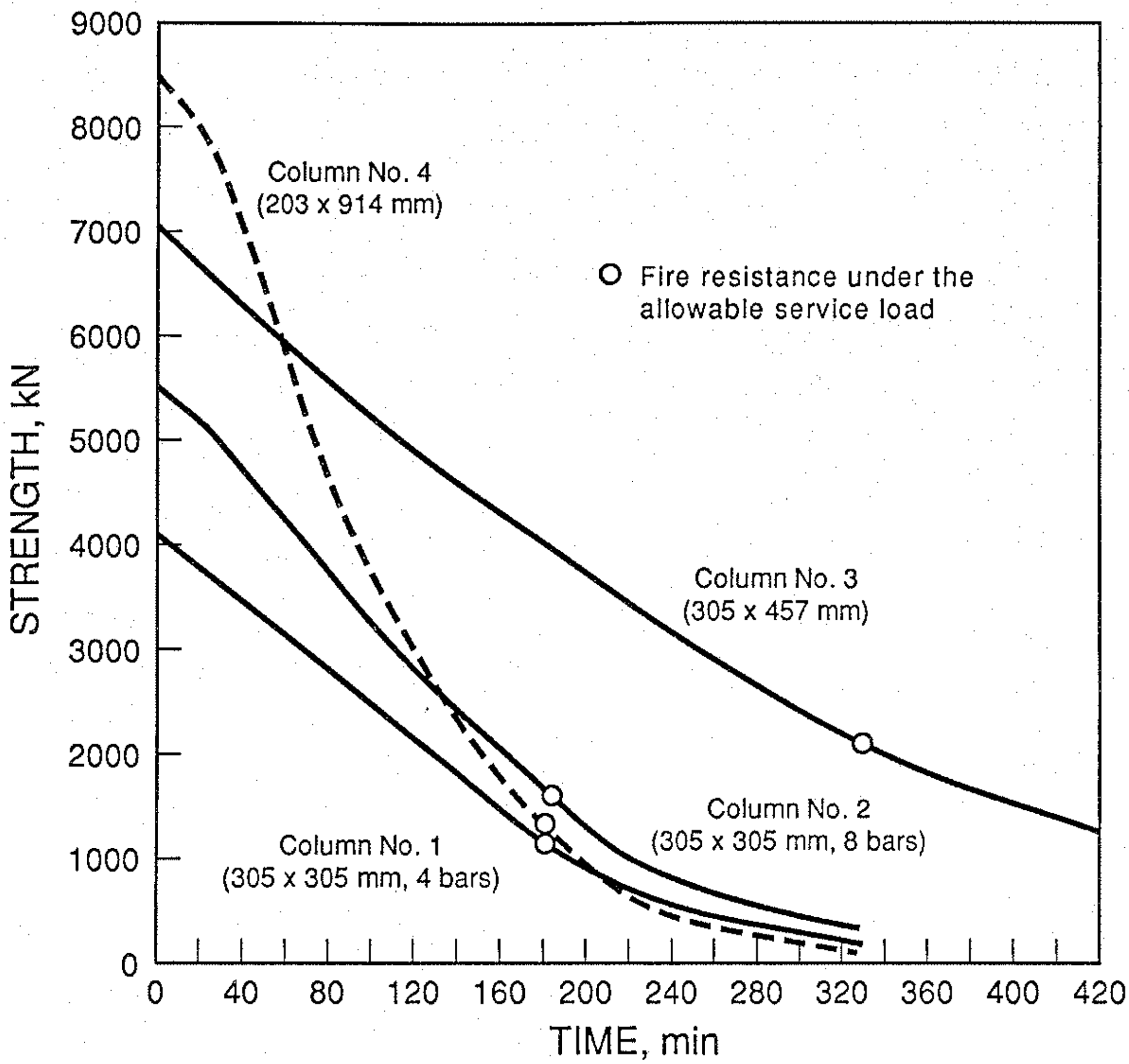


FIGURE 28. CALCULATED STRENGTHS OF COLUMNS AS A FUNCTION OF EXPOSURE TIME AND CALCULATED COLUMN FIRE RESISTANCES UNDER THE ALLOWABLE SERVICE LOAD ACCORDING TO ACI 318-89 AND CSA A23.3-M84

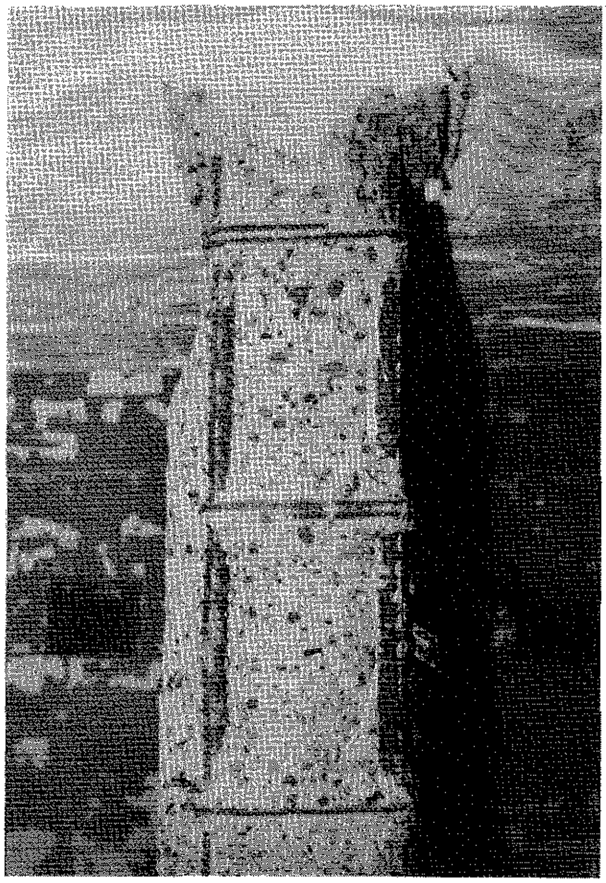

FIGURE 29 COLUMN NO.1 (305 x 305 mm, 4 BARS) AFTER TEST

FIGURE 30 COLUMN NO. 2 (305 x 305 mm, 8 BARS) AFTER TEST

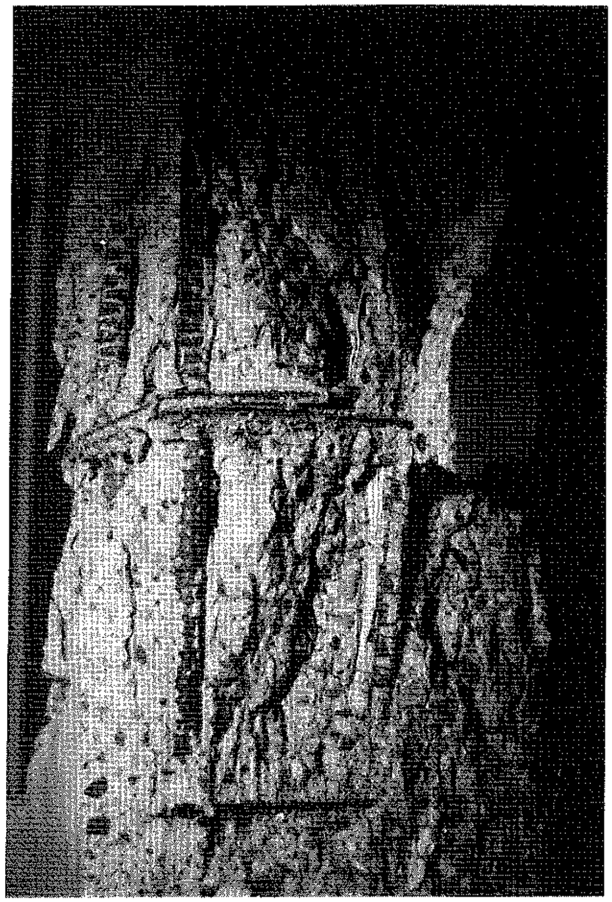

FIGURE 31 COLUMN NO. 3 (305 x 457 mm) AFTER TEST

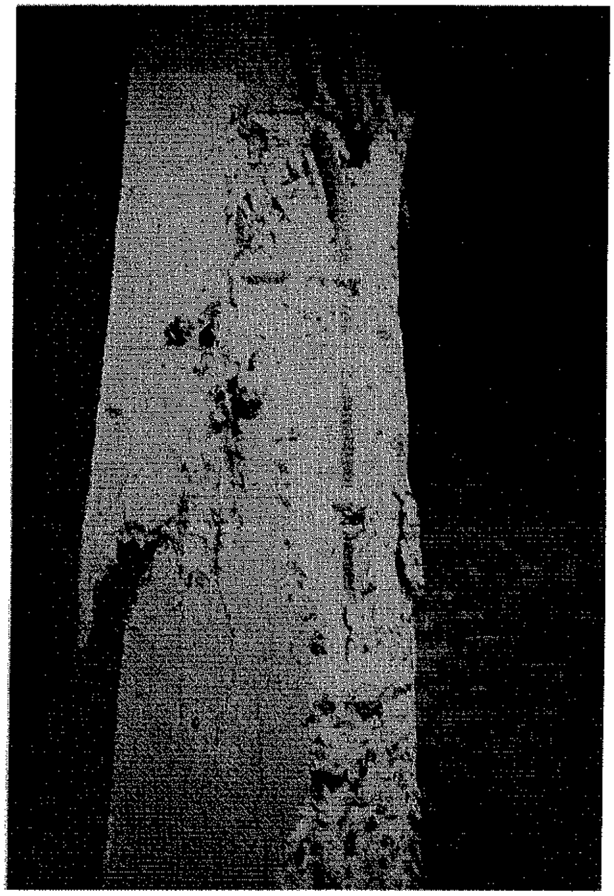

FIGURE 32   COLUMN NO. 4 (203 x 914 mm) AFTER TEST