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SHEET STEEL AS A PROTECTIVE MEMBRANE FOR STEEL BEAMS AND COLUMNS

by

W. W. Stanzak

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SHEET STEEL AS A PROTECTIVE MEMBRANE FOR STEEL BEAMS AND COLUMNS

by

W. W. Stanzak*

A protective membrane is a continuous layer separating the member to be protected from the fire, without coming into direct thermal contact with the member.

This report describes the results of fire tests on a steel beam and two columns, protected with insulating materials enclosed in a sheet steel membrane case.

The practice of protecting structures against fire by a protective membrane has been carried out for many years. It was only in the late 1950's, however, that protective materials other than plaster and gypsum wallboards were used widely as membrane fire protection. This development was due to a marked increase in the number of sponsored fire tests carried out by materials manufacturers.

A fire test on a steel beam protected with a membrane of gypsum-sanded plaster has been described in DBR Fire Study No. 19 (1). The results of 8 fire tests on steel column sections protected with gypsum-sanded plaster are given in Fire Study No. 20 (2).

The available fire test data, as well as some tests in a small floor furnace (3) clearly show that the most vital characteristic of a protective membrane is its ability to remain in place. This was demonstrated in the small furnace by the fact that a 16-ga (0.0598 in.) steel sheet membrane increased the fire endurance time of a brick floor by about 23 per cent. Inserting a lightweight mineral wool in the airgap between the steel and the brick resulted in a 220 per cent increase in the fire endurance time.

In addition to its ability to remain in place, a protective membrane, to be really effective, should have a low thermal conductivity and a high thermal capacity. Materials displaying these properties are rather expensive and hard to find. Unfortunately, many materials that act as good insulators deteriorate seriously from the effects of fire and become prematurely dislodged. It has been difficult, therefore, to develop membrane protection to its full potential.

Sheet steel has not been previously considered as a potential fire protective material. However, its ability to remain in place, and the fact that

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its presence as a radiation shield causes the fire endurance time of a construction to increase, suggested that this possibility should be investigated.

PART I: BEAM TEST

DESCRIPTION OF SPECIMEN

Details of the test specimen are shown in Figure 1. Figure 2 shows the exposed surface of the beam installed in the furnace, and Figure 3 shows the unexposed surface and hydraulic loading equipment. The item numbers below correspond to the part numbers in Figure 1.

1. Steel wide-flange beam, 8 in. by $5\frac{1}{4}$ in by 17 lb/ft, 16 ft 0 in. long, steel specification CSA G40.12.
2. Haydite Slab, 4 by 31 by 36 in., average density 106 lb/ft^3.
3. Steel plate, $\frac{1}{4}$ by 18 by 36 in. tack welded to steel beam.
4. Mineral wool insulation, 3 in. thick (Johns Manville Type 413).
5. Sheet steel membrane, brake-formed from 36 in. by 48 in. galvanized 20 ga (0.0359) sheets.
6. Refractory insulation.

TEST METHOD

The fire test was carried out essentially in accordance with a tentative revision of ASTM specification E119-61: Tests of Loaded Beams (4). A deviation from the specification was that the floor slab was less than the minimum 5-ft width specified.

Furnace temperature was measured by nine symmetrically disposed thermocouples enclosed in a 13/16 in. O.D. Inconel tube having 0.035 in. wall thickness. The hot junctions of the thermocouples were in carbon steel caps on the Inconel tubes and were placed 12 in. below the plane of the underside of the floor slab. Both the individual temperatures at nine points of the furnace and the average of the nine thermocouples were recorded. The fuel input into the furnace was controlled automatically in such a way that the average temperature closely followed the prescribed standard temperature-time correlation.

The steel temperatures were measured by 16 chromel-alumel thermocouples, peened into the beam at locations shown in Figure 4. Temperatures were measured at four sections, symmetrically located along the length of the beam. One of the thermocouples was located on the bottom flange at midspan, as a hot region was expected to develop there.

The beam was loaded so as to develop the stresses contemplated by the design. A typical loading calculation for a beam test is given in Appendix A of Reference 1. Load was applied by two pairs of hydraulic jacks, each pair connected with a cross-beam, 36 in. on either side of midspan.

Vertical deflections were measured at the centre and quarter points of the span by means of three measuring tapes connected to the floor slab by a mechanical system. The accuracy of the measurements is ± 0.01 in.*

OBSERVATIONS DURING FIRE TEST

The deflection due to the applied live load was 0.75 in. This was close enough to the calculated theoretical deflection of 0.775 in. to indicate that the required live load was being carried by the beam.

- 0 min - fire on
- 10 min - sheet metal protection started bulging west of the centre of the beam
- 15 min - thermocouple No. 11 on the steel beam near the bulge registered higher readings than corresponding thermocouples at other stations
- 90 min - beam bowed evenly downward without lateral deformation. Protection still in place and without gaps, but warped in places.
- 97 min - explosive spalling at centre of concrete slab on the north side
- 103 min - test terminated due to excessive deflection of the beam; fire out and load removed.

RESULTS

The temperature rise curve for the beam is given in Figure 5 and the deflection curve in Figure 6.

In order that fire tests might be terminated prior to, but reasonably close to ultimate collapse, Robertson and Ryan (5) proposed that the point

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* In beam tests in which the deflection wire is attached to the floor slab, deflection readings may be erratic during early portions of the fire exposure. Warping of the floor slab or failure of the slab to follow the deflection of the beam are responsible for this. Deflections during the final stages of the fire test are, however, usually quite reliable, because by this time the slab has weakened sufficiently to follow the deflection of the beam closely.

at which <u>both</u> $\delta_c \geq \frac{\ell^2}{800\,d}$ and $\delta'_c \geq \frac{\ell^2}{150\,d}$ can be regarded as an indication of load failure. In these expressions δ_c = central deflection, in.; δ'_c = rate of deflection, in./hr; ℓ = clear span of principal structural element, in., and d = distance between the upper and lower extreme fibres of the principal structural element, in. The critical rate of deflection was not exceeded during the fire test, although the deflection was large. Therefore, no load failure occurred according to the Robertson/Ryan criteria.

When the test was terminated (103 min) the beam had a large central deflection and could obviously no longer perform its structural function. The fire endurance time of the specimen may, therefore, be assigned at 103 min. The fire resistance classification is $1\frac{1}{2}$ hr.

CONCLUSIONS

1. The fire endurance time of the specimen was 103 min providing a fire resistance classification of $1\frac{1}{2}$ hr.

2. The average temperature on the lower flange of the beam was 1270°F when the test was terminated. This is about 100° higher than the critical temperature for non-composite beams of ASTM A-36 steel (6). However, 1270°F should not be regarded as the critical temperature for non-composite beams of CSA G40.12 steel, as load failure according to the Robertson Ryan criteria had <u>not</u> occurred when the test was terminated.

3. A similarly constructed specimen having a beam of A-36 steel would fail at about 75 min (assuming a critical temperature of 1170°F) and receive a fire resistance rating of 1 hr. Therefore a beam (CSA G40.12) having superior creep properties yields a substantial increase in fire endurance time.

COMMENTS

The fire test clearly demonstrated that the concept of a sheet steel protective membrane for wide-flange beams is valid. Although the present test yielded a fire endurance time of only $1\frac{1}{2}$ hr, it should be possible to develop an economical form of protection capable of providing a 2-hr fire resistance using the sheet steel membrane.

This was the first test on a CSA G40.12 beam to be conducted at this laboratory. The superior creep properties of the CSA G40.12 steel give the beam excellent fire enduring qualities.

PART II: COLUMN TESTS

This portion of the report describes two fire tests conducted on steel column sections protected with insulating materials enclosed by a sheet metal membrane. The insulating materials were chosen, not only for their economy, but because they are not proprietary products.

The tests were carried out in the DBR floor furnace and the specimens were not loaded.

DESCRIPTION OF TEST SPECIMENS

Construction details of a typical test specimen are shown in Figure 7. The item numbers below correspond to the part numbers in the figure.

Specimen No. 1.

1. Wide-flange steel column section: 10 WF 112, 8 ft 4 in. long, Steel Specification ASTM A36-61T.
2. 1-in. Mesh Chicken Wire (0.028 in. diameter), galvanized.
3. Mineral Wool Building Insulation
   - (a) Conforms to CSA Standard A 101 (7), Type 1A.
   - (b) Dimensions: 3 by 23 by 48 in.
   - (c) Composition: Mineral wool fibers produced from blast furnace slag.
   - (d) Mechanical and Physical Properties:

     Resilience: returns to reference thickness after release.

     Weight: 3.6 lb per batt.

     Density: 1.9 lb per cubic foot.

     Thermal conductivity (in oven-dry condition at 75°F): $0.28 \frac{\text{Btu/in.}}{(\text{hr})(\text{ft}^2)(°\text{F}}$
4. Standard Gypsum Wallboard, $\frac{1}{2}$-in. thick.
5. 26 ga (0.0217) wiped zinc galvanized sheet steel.
6. #8 Sheet Metal Screw, 3/8 in. long at 8-in. O.C.

The outside dimensions were 18 by 18 in.

Specimen No. 2

1. Wide-flange steel column section: 8 WF 48, 8 ft 4 in. long, Steel Specification ASTM A36-61T. Other details of this specimen were the same as for No. 1 except that the gypsum wallboard (part No. 4) was not included.

   The outside dimensions were 14 by 16 in.

CONSTRUCTION OF TEST SPECIMENS

All construction was carried out by members of the staff of the Division of Building Research.

The bare columns were wrapped with chicken wire, lapped approximately 5 in. at the vertical joint, and tied with 0.040 in. stove-pipe wire about 8 in. on centre. The insulation, in 4-ft lengths was tied in position to this inner mesh with four pieces of tie wire per piece, symmetrically placed. The outer mesh was then applied over the insulation in the same manner described above.

For Specimen No. 1 gypsum wallboard was cut and applied in the 8-foot direction by tying at 3 locations with 0.064 in. soft black steel tie wire. One tie was located at the centre and the others were about 8-in. from the top, bottom and end plates. The wallboard was not applied to Specimen No. 2.

The sheet steel, supplied in 8-ft lengths, had been brake formed into unequal leg U-channels as shown in Figure 7. Two such channels were fitted together on each column and fastened at the joints with sheet metal screws spaced approximately 8-in. on centre.

The workmanship was judged to be good. Figure 8 shows both columns under construction; the one on the right is Specimen No. 1. Figure 9 shows Specimen No. 2 completed and ready to install in the furnace.

TEST METHOD

The fire endurance tests were carried out essentially in accordance with CSA Standard B54.3-1964 (8): Alternate tests of Protection For Steel Columns. The test deviated from the standard in measuring the temperature on the column by using only 9 thermocouples at 3 levels, as shown in Figure 10. Two intermediate levels were omitted because there was no reason to expect failure at these cross-sections. The chromel-alumel thermocouples were peened into the steel section, and readings were recorded on a multi-point recorder each minute during the test.

The furnace temperature was measured by nine thermocouples installed in a metal frame constructed from 13/16-in. O.D. Inconel tubes having 0.035-in. wall thickness. The location of the furnace thermocouples is shown in Figure 11. The hot junction of the thermocouples was 12 in. away from the surface of the specimen. Both the individual temperatures at nine points of the furnace and the average of the nine thermocouples were recorded. The fuel input to the furnace was controlled to make the average temperature follow as closely as possible the prescribed temperature versus time curve. The elevation of the burners in the DBR floor furnace is approximately at level 3 on the column. In past tests at this laboratory, failure has often occurred at this level, due to slightly higher furnace temperatures. However, this was not the case in either of these tests, for reasons which will become apparent in subsequent sections.

Figure 12 shows column No. 2 installed in the furnace immediately before the fire test.

OBSERVATIONS DURING FIRE TESTS

Test. No. 1

uring the first ten minutes the furnace was dark, making observations difficult. However, flaming was seen at the joints of the sheet metal at 3 minutes, and the flaming continued until about 30 minutes. By this time the furnace temperature was sufficiently high to permit good observations, and it was noticed that the steel cover was warping somewhat and appeared to be oxidizing on the surface. The warping, never too severe, continued progressively until about 2 hours. At 2 hours the sheet steel cover buckled outward slightly below the centre of the column thus exposing the rock wool insulation near the top directly to the fire.

At 2 hours and 8 minutes the steel had slid well down the column (about 18 in.) and the rock wool insulation had also moved, so that about 6 in. of the steel section at the top was exposed to the fire. By 2 hours and 15 minutes 18 in. of the column were bare, and the sheet steel had warped and collapsed to about 3 ft from the top of the specimen. Only rock wool showed above the steel; not the gypsum wallboard.

The fire test was terminated at 2 hours and 20 minutes. Figure 13 shows the condition of the column still in the furnace after the fire test. Figure 14 was taken after the column had been removed from the furnace and the sheet steel and gypsum wallboard had been discarded.

Test No. 2

Nothing visibly significant happened throughout the test. At 50 minutes the steel was still in good condition, although slightly bulged in certain areas. No vertical movement of the protection was observed throughout the test.

The fire test was terminated at 58 minutes. Figure 15 shows the condition of the specimen in the furnace after the test, and Figure 16 is a picture of the column outside the furnace with the insulation removed. The closeup in Figure 17 shows the condition of the rock wool insulation at the joint. This occurred at the mid height (level 2) of the column.

RESULTS

The average furnace temperature during the fire tests was always within the allowable limits. Figure 18 is a plot showing the temperature rise of the columns.

Specimen No. 1 failed at level 1 at 135 minutes.

Specimen No. 2 exceeded the 1000° F allowable average temperature at level 2 (centre) at 52 minutes.

Accordingly the specimens would receive fire endurance classifications of 2-hr and 3/4-hr respectively.

COMMENTS

These tests both had interesting failures. The sliding down of insulation on specimen No. 1 caused the failure to occur at level 1, because only the rock wool remained as insulation at that height. It is also possible, that because about 18 inches of the steel column was exposed directly to the fire, vertical heat conduction along the steel section made a contribution to the higher temperatures at level 1. At the time of failure (135 min) the average temperature at level 1 was 110° F higher than the next highest average temperature at level 2.

Specimen No. 2 failed at level 2, which is where the joint in the rock wool insulation occurred (Figure 17). This result emphasizes the importance of placing thermocouples at such locations. At the time of failure (52 min) the average temperature at level 2 was 95 to 100° higher than levels 1 and 3, which were at approximately the same average temperature.

The sheet metal was chosen, in addition to its fire resisting abilities, for its attractiveness and durability as a column cover. Its primary function, however, is to act as a radiation shield, and in the case of specimen No. 1, to hold the deteriorating wallboard insulation in place. That it performed the latter function for a long time was shown clearly by the way the steel cover suddenly collapsed due to buildup of the disintegrated wallboard near the bottom. If thicker steel had been used, the collapse would have occurred at a later time. (Measurements on the steel after the test showed that it had oxidized to an average thickness of about 0.012 in. - almost one-half the original thickness).

Nevertheless, it was shown that inexpensive insulating materials, protected by a cover of a sheet steel membrane, can provide fire protection to steel column sections for up to 2 hours.

PART III: CONCLUSIONS

1. The sheet steel membrane case, in conjunction with inexpensive insulating materials was shown to provide:

   (a) fire endurance classification of $1\frac{1}{2}$-hr for a steel beam

   (b) fire endurance classification of 3/4 to 2-hr for steel columns

2. Thin sheet steel, when applied as a protective membrane, remains in place for periods of over 2 hours.

3. Sheet steel is effective as a membrane protection when applied over insulation on vertically and horizontally placed members or construction components.

ACKNOWLEDGEMENT

The author wishes to thank Mr. E. Porteous and Mr. J. Berndt, who carried out the fire tests.

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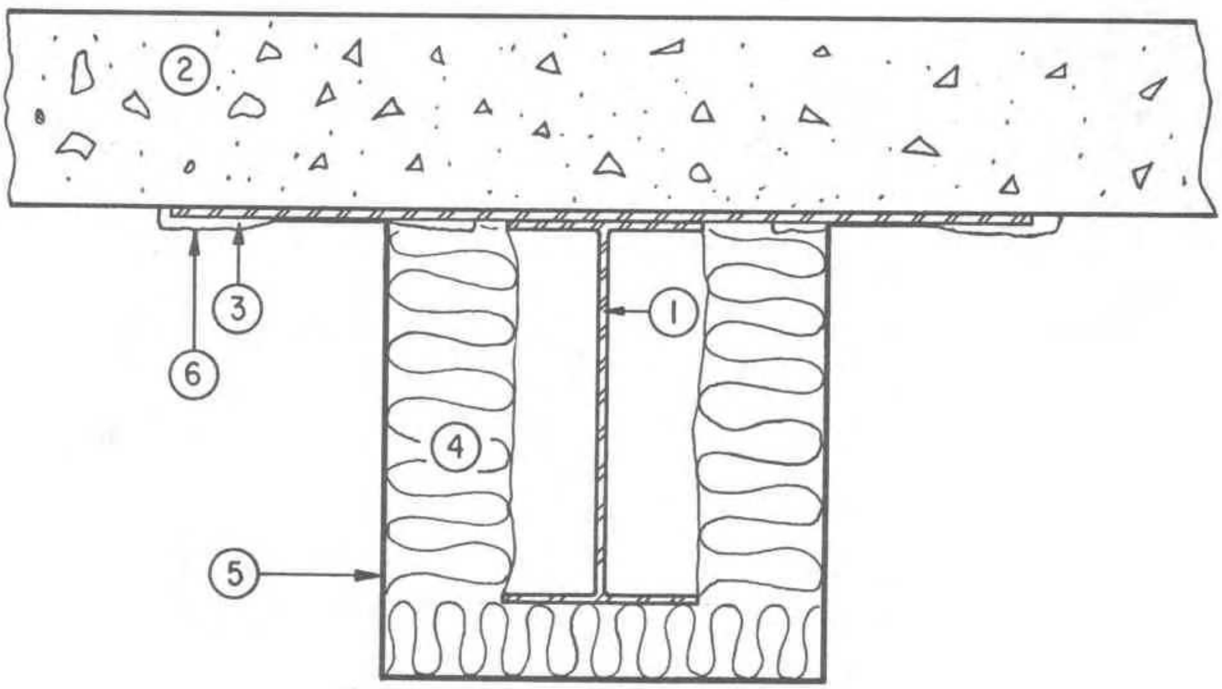


FIGURE I

CONSTRUCTION DETAILS OF SPECIMEN USED IN BEAM TEST

BR. 4010-1

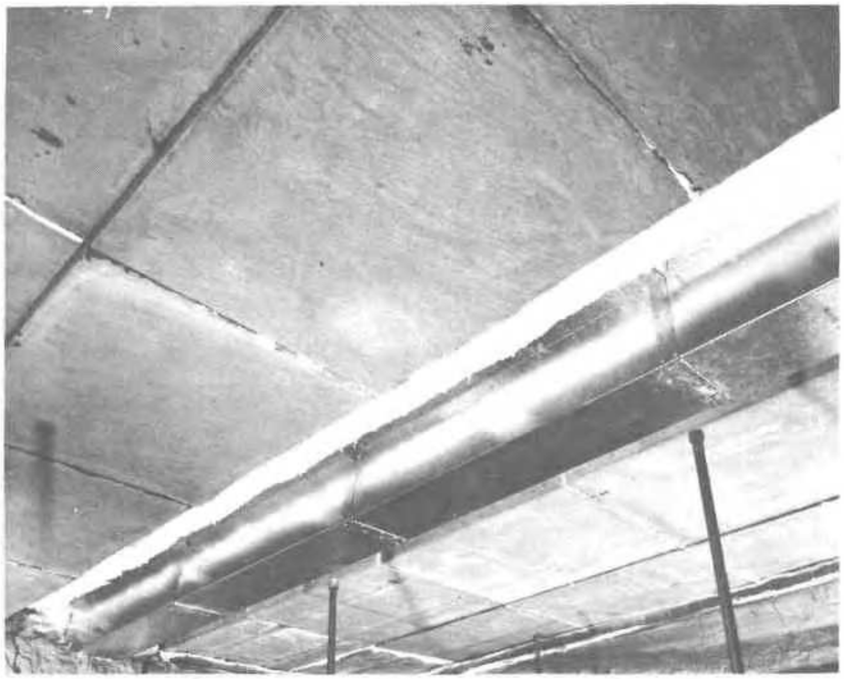


Figure 2. Exposed surface before fire test.

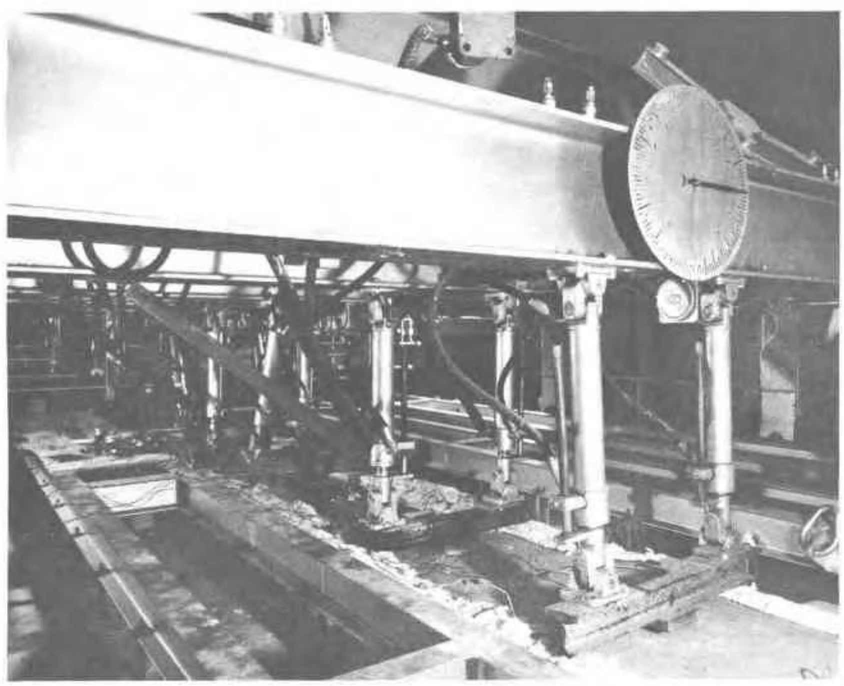


Figure 3. Unexposed surface before fire test.

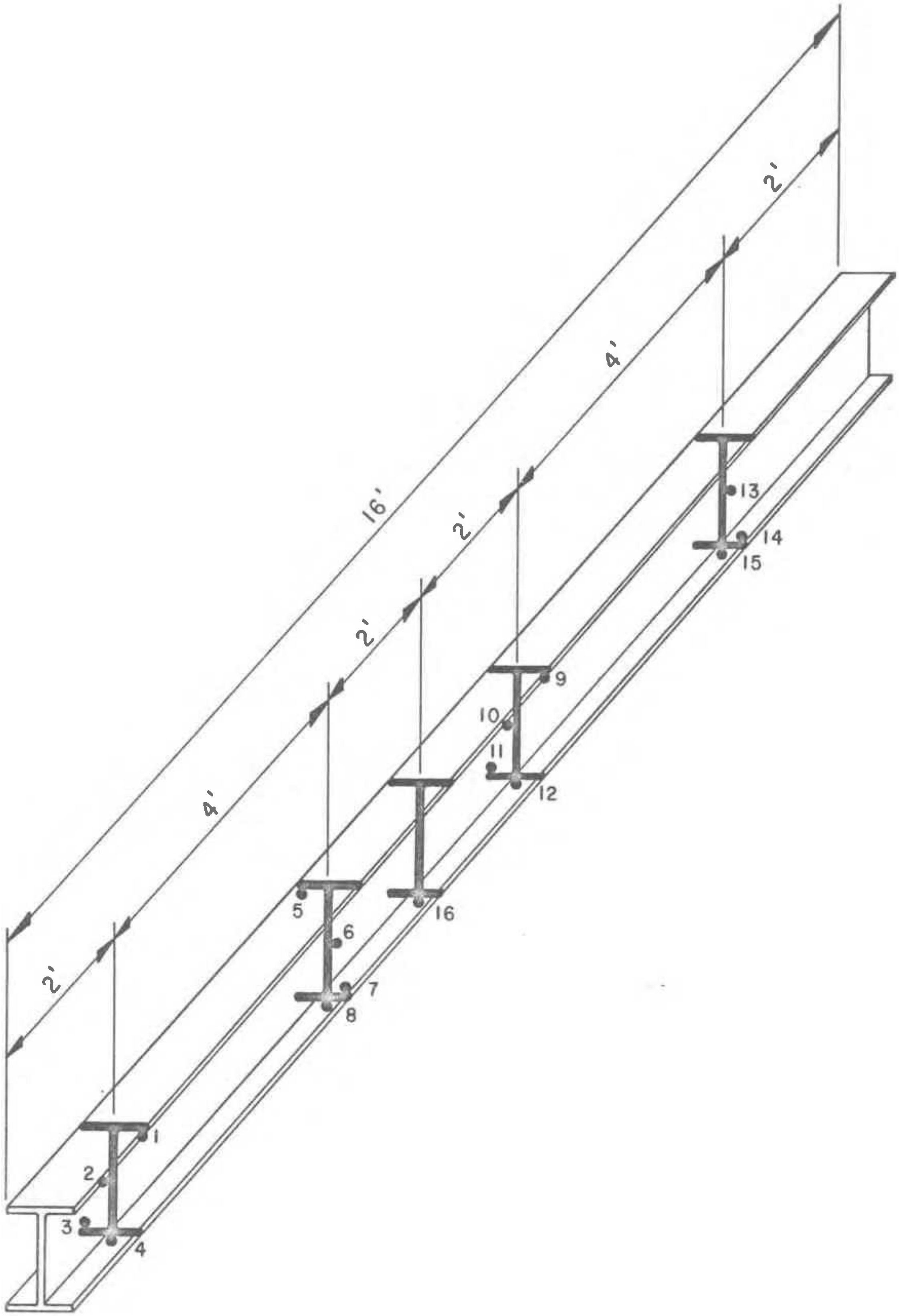


FIGURE 4 THERMOCOUPLE LOCATIONS

BR 4010-2

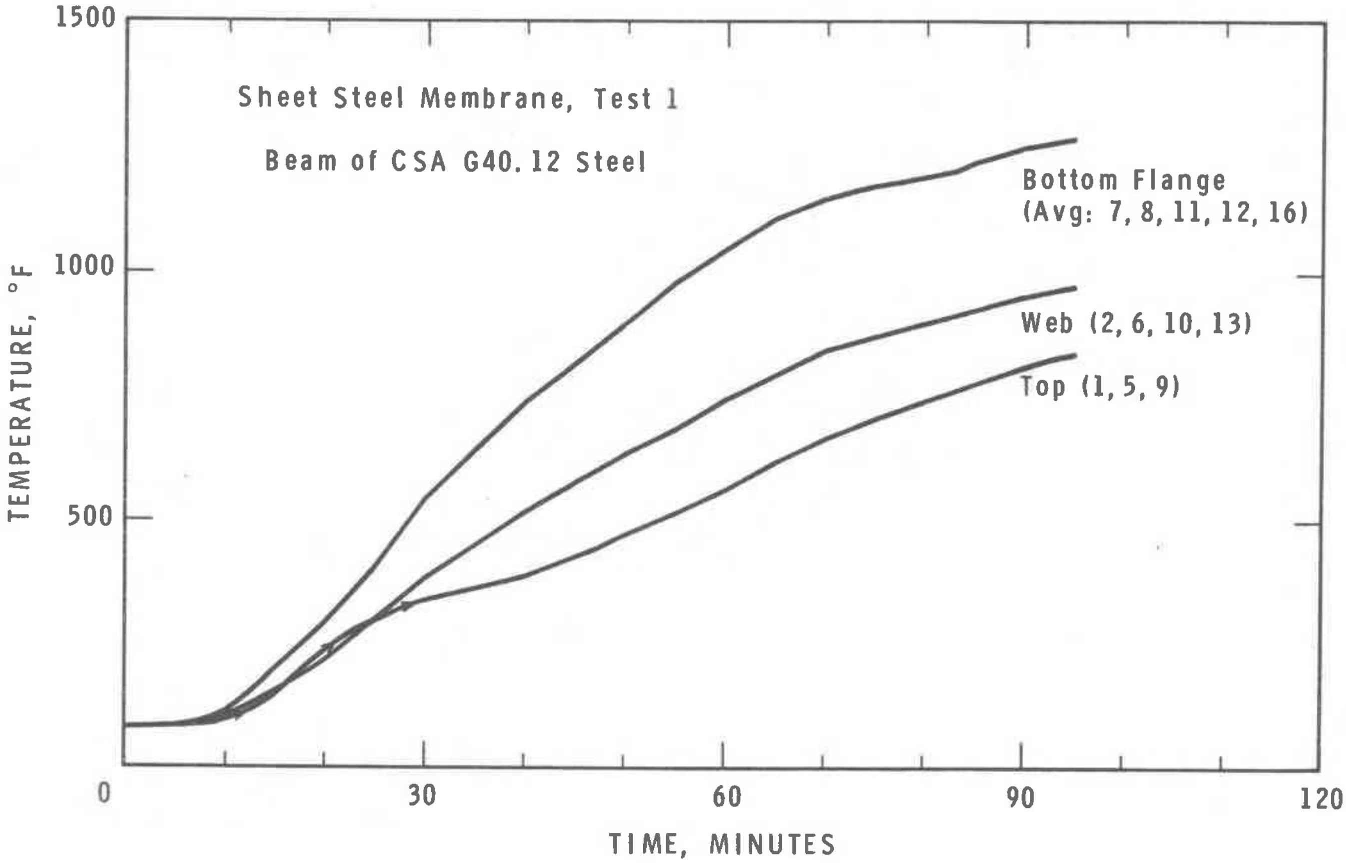


FIGURE 5 BEAM TEMPERATURES

BR 4010-3

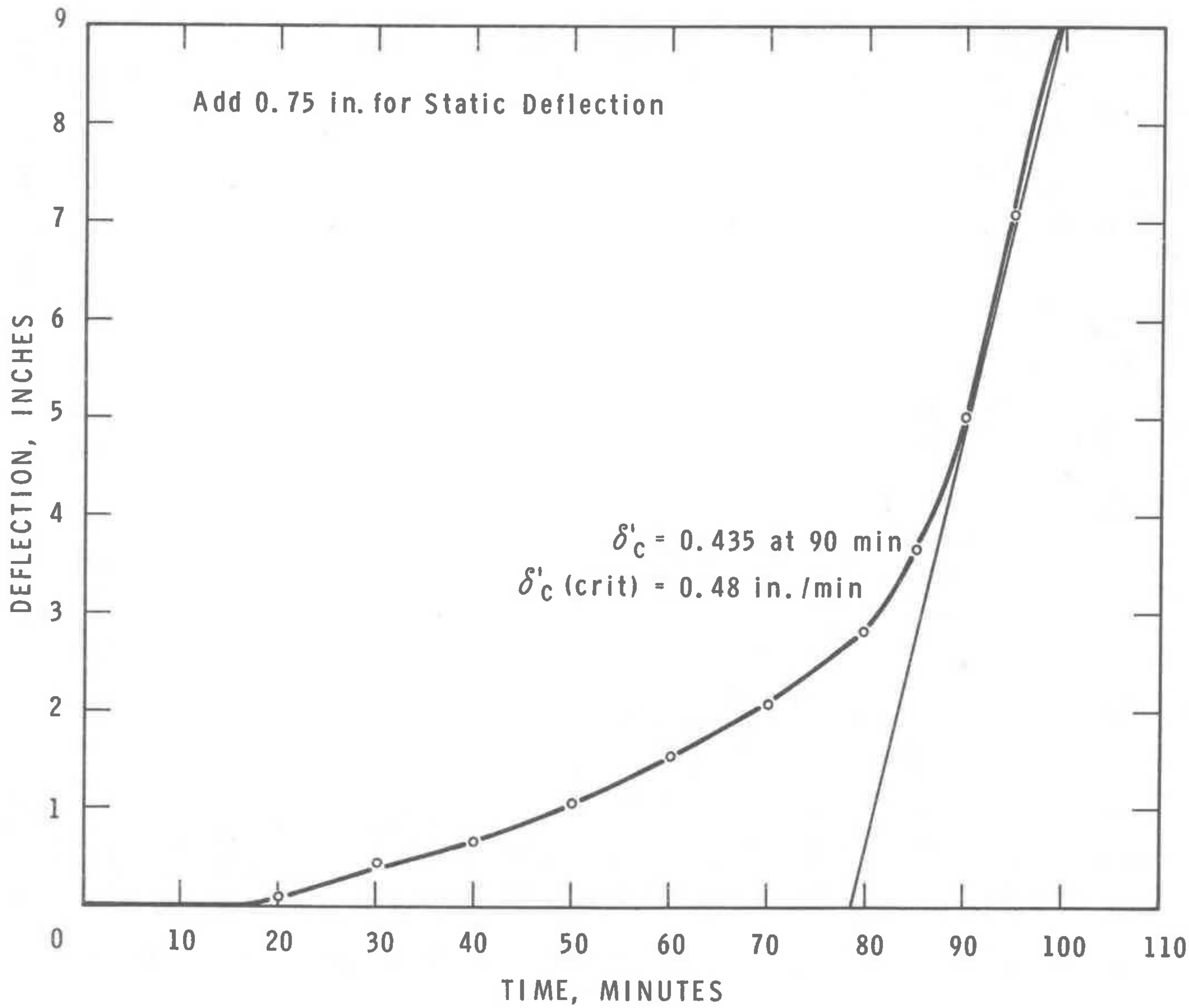


FIGURE 6

DEFLECTION AND RATE OF DEFLECTION

BR 4010-4

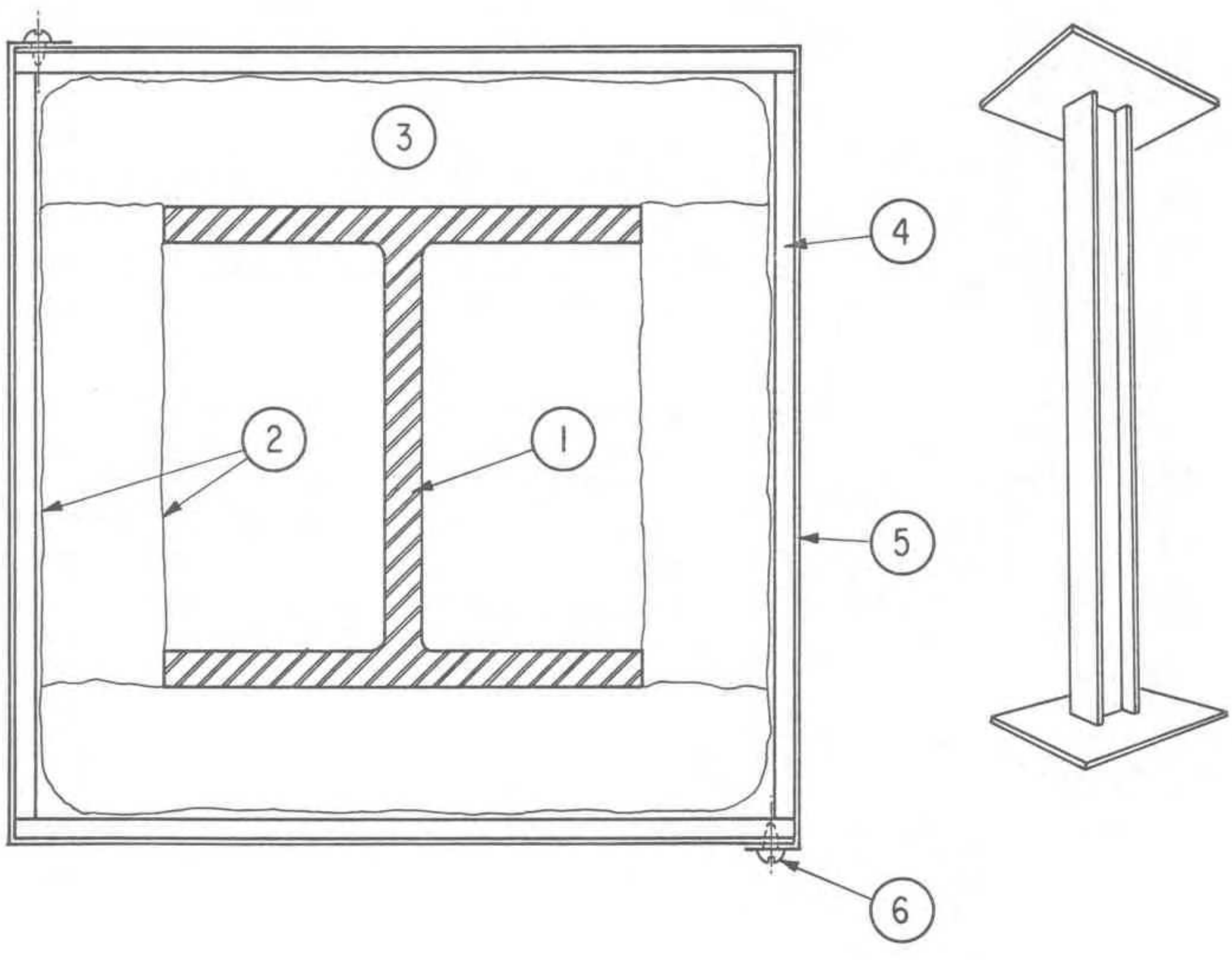


FIGURE 7
CONSTRUCTION DETAILS OF SPECIMENS USED IN COLUMN TESTS

BR. 4422-1

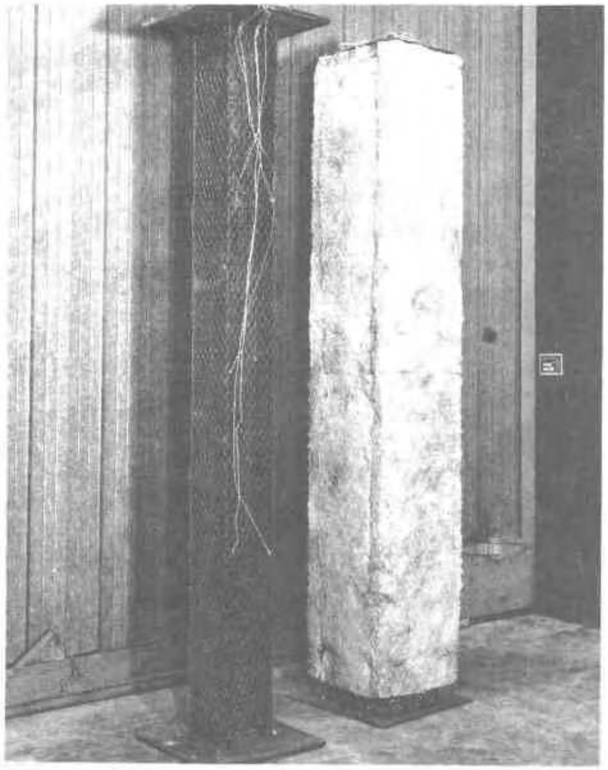


Figure 8. Columns under construction.

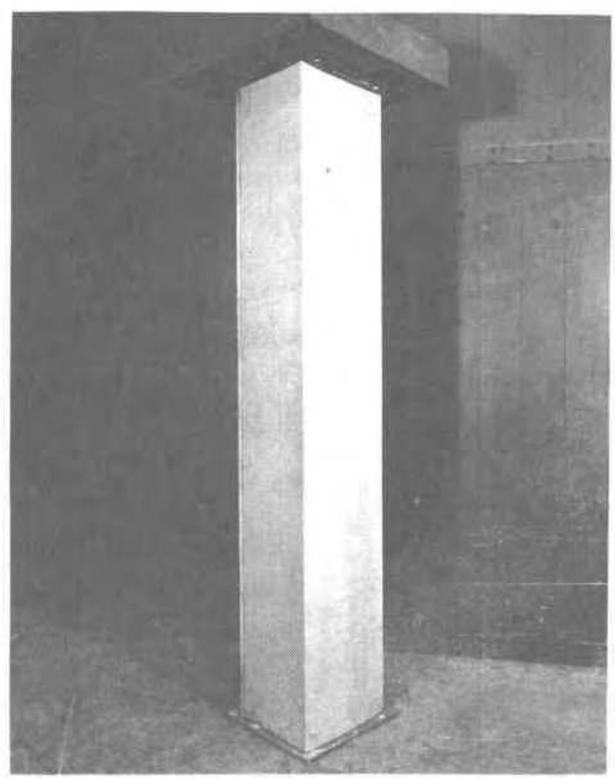
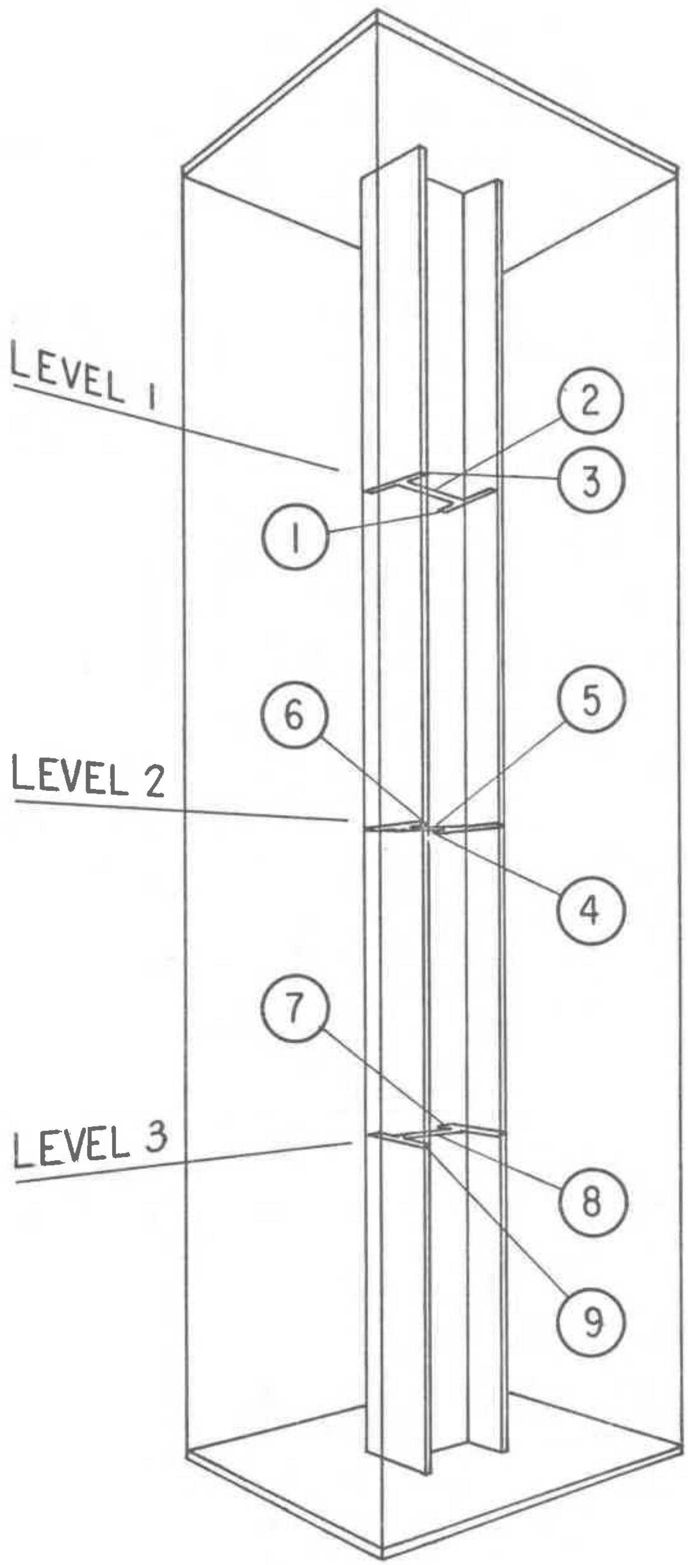


Figure 9. Column No. 2 completed.



DISTANCE FROM THE BOTTOM PLATE

LEVEL 3, 2 FT $1^1/_4$ IN.

LEVEL 2, 4 FT $1^1/_4$ IN.

LEVEL 1, 6 FT $1^1/_4$ IN.

FIGURE 10 LOCATION OF THERMOCOUPLES

BR. 4422-3

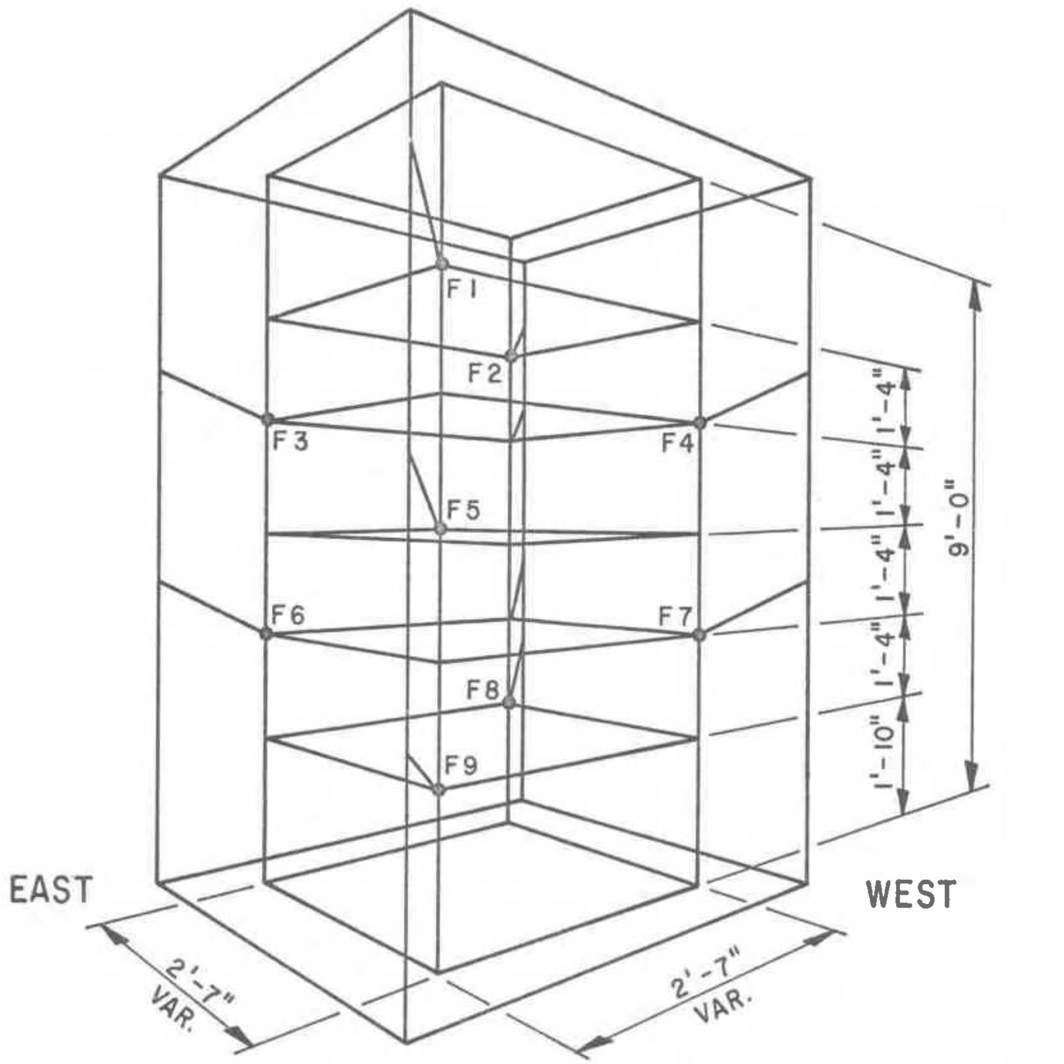


FIGURE II
FURNACE THERMOCOUPLE LOCATIONS

BR 4026-2

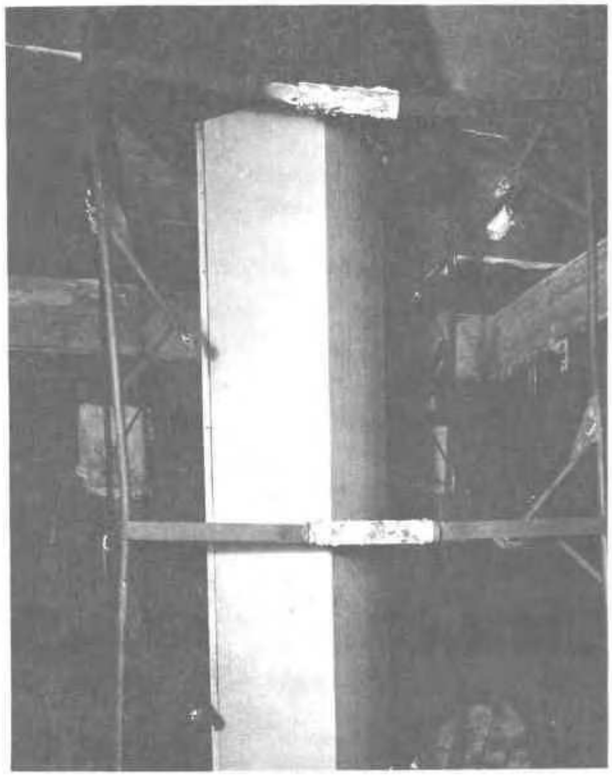
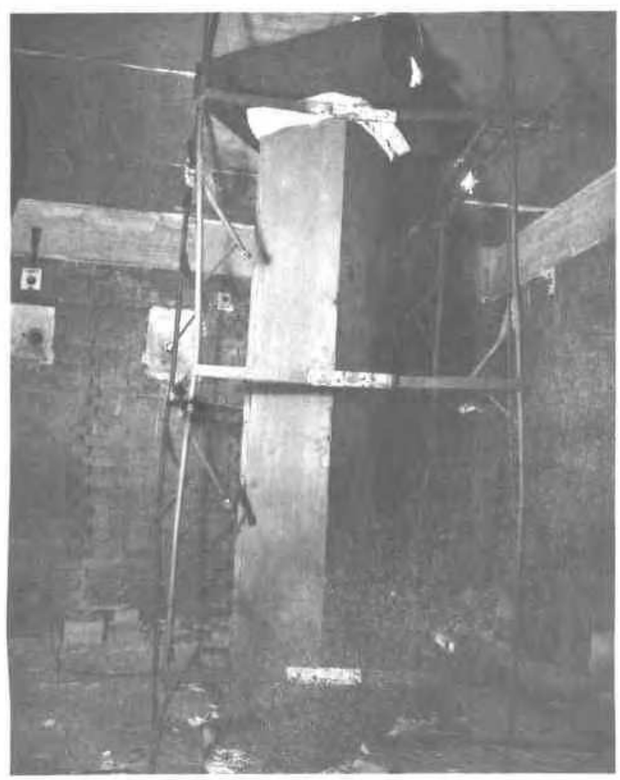


Figure 12. Column No. 2 installed in furnace.

Figure 13. Column No. 1 after test.

Figure 14. Column No. 1 partly dismantled after fire test.

Figure 15. Column No. 2 after fire test.



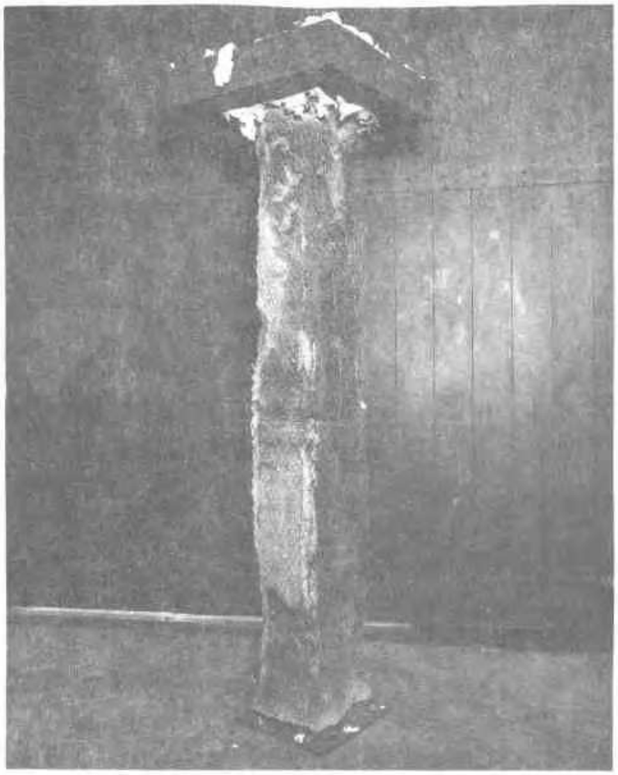


Figure 16. Column No. 2 with steel cover removed after fire test.

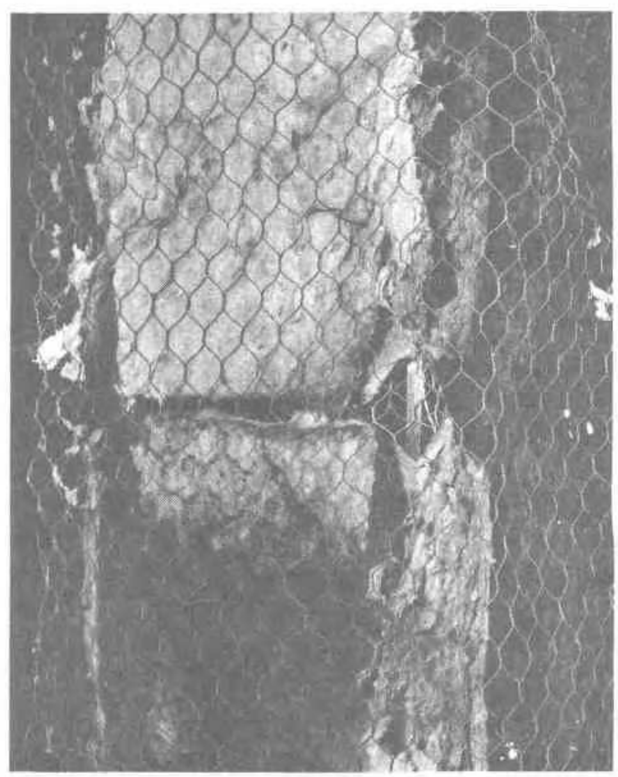


Figure 17. Column No. 2: insulation joint after test.

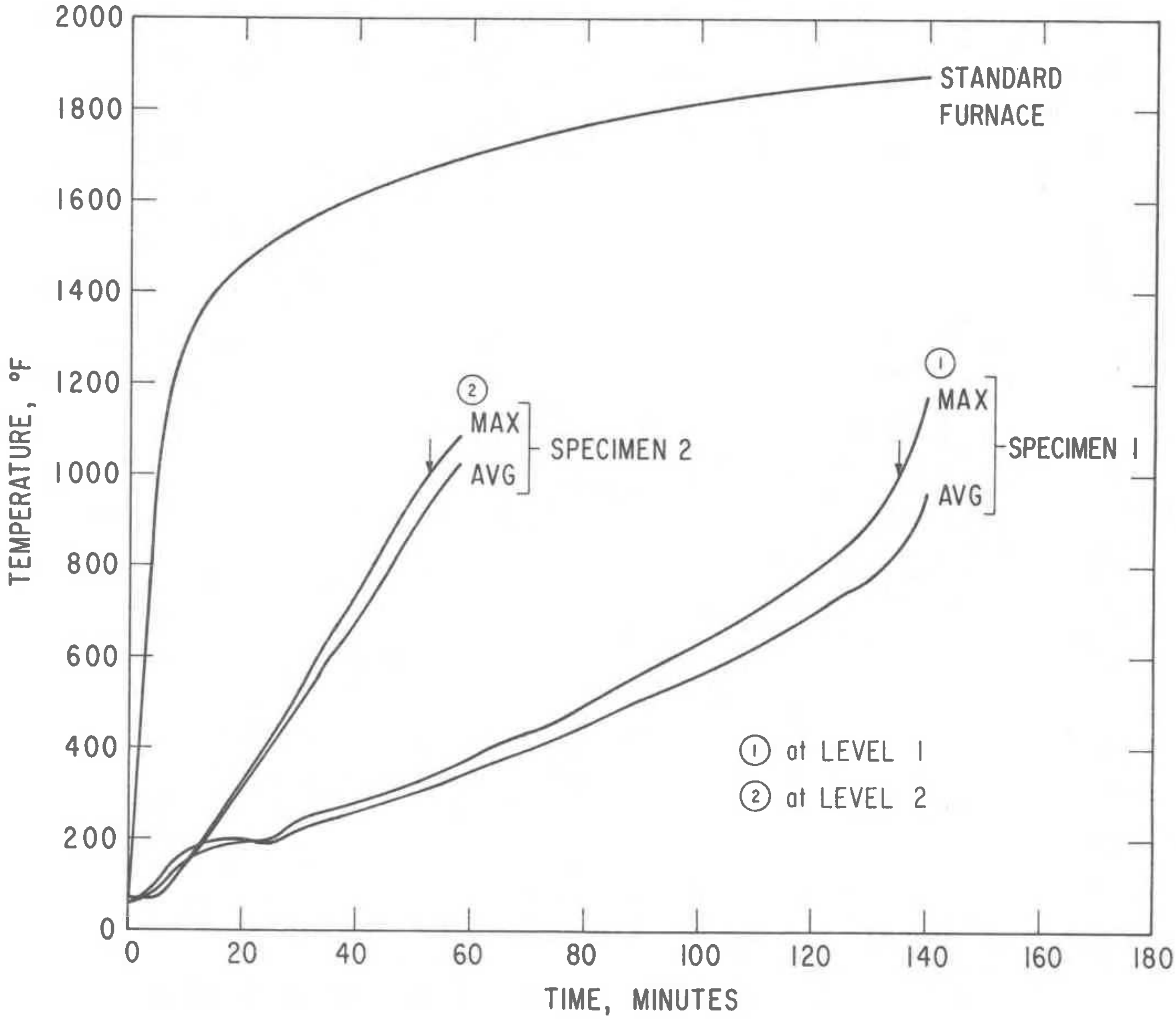


FIGURE 18 COLUMN TEMPERATURES

BR. 4422-2