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EXPERIMENTAL STUDY ON BEHAVIOUR OF STRUCTURAL ELEMENTS MADE OF HOT-ROLLED AND COLD-FORMED STEELS IN FIRE

by

L. Konicek

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ABSTRACT

Two types of open-web steel joists have been designed for the same span and the same loading conditions. The first type of joist was made of hot-rolled steel shapes. Cold-formed steel was used for construction of the second type. The effect of this difference on the behaviour of joists exposed to fire, is investigated in this experimental study.

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Identical roof assemblies supported by a particular type of steel joist were built. Each of them was tested according to "Standard for Fire Tests of Building Construction and Materials".[1] Results obtained, their evaluation, and a comparison of the behaviour of both samples tested, are presented in this report.

SPECIFICATIONS OF MATERIALS USED

1. Open-web steel joist, 16 in. deep (hot-rolled chords)

   Steel: Chord, G 40.12
   Web, A 36
   Applied load specified by manufacturer, 1020 plf
   Total cross-section area of chords, 1.920 $in.^2$
   Weight, 8.9 lb/ft

   For detail see Figure 1.

2. Open-web steel joist, 16 in. deep (cold-formed chords)

   Steel: Yield strength, 55000 psi
   Tensile strength, 67000 psi, minimum
   Applied load specified by manufacturer, 1138 plf
   Total cross-section area of chords, 1.868 $in.^2$
   Weight, 7.7 lb/ft

   For details see Figure 2.

3. Roof deck: 6 ft 2 in. countersunk one end to provide lap joint
   3 ft 7 in. countersunk one end to provide lap joint
   3 ft 7 in. plain ends
   Units fabricated from 16-gauge wiped coated (galvanized) sheet steel

4. Thermal insulation: 1-in. organic fibre insulating board

5. Fire protection: Cementitious sprayed protection, thickness 2 in. average density 16.2 lb/ft^3.

6. Asbestos paper: 1/16 in. thick, density 52 lb/ft^3.

CONSTRUCTION OF A ROOF ASSEMBLY

Two simply-supported open-web steel joists were placed in the concrete frame which forms part of the floor furnace. An arrangement of joists in the frame with detail of joist bracing and support can be seen in Figure 3. The steel roof deck was plug welded to the supporting structure and covered by thermal insulation with asbestos paper on its external surface. The method of construction of this part of the assembly can be seen in Figure 4. The unprotected roof deck is shown at the top of the picture, the roof deck protected by thermal insulation in the middle, and the completed external surface of the roof at the bottom and in Figure 5.

The thermocouples were peened to the surface of open-web steel joists in prescribed places (see Figure 6) and attached by screws to the steel roof deck (see Figure 7). Surface temperatures on the unexposed side were measured by a set of thermocouples covered by standard asbestos pads (see Figure 8).

After mounting all thermocouples and strain gauges, the surface of the construction exposed to fire was sprayed with cementitious fire protection. Incomplete fire protection of the assembly can be seen in Figure 9. The completed assembly is shown in Figure 10.

After careful curing, during which the moisture control in the sprayed fire protection reached a steady level, with only very small weight deviations (caused by variation in the relative humidity of the air in the laboratory), the assembly was ready for testing. The changes in density of the sprayed fire protection in relation to time are plotted in Figure 11. Both completed roof assemblies were stored in the laboratory for approximately two months prior to the fire tests.

INSTRUMENTATION

Furnace temperature was measured by nine chromel-alumel thermocouples enclosed in standard weight 1/2-in. black wrought-iron pipe. Individual temperatures, as well as the average recorded temperature of the nine thermocouples, were recorded.

A typical arrangement of thermocouples measuring the temperature course in an open-web steel joist cross-section can be seen in Figure 6. The locations of these typical cross-sections A-F are shown in the sketch of the roof assembly plan, again in Figure 6.

Temperatures on the steel roof deck were measured in locations G and H by thermocouples 1-4 (see Figure 7).

Unexposed surface temperatures were measured at nine locations shown in Figure 8; the thermocouples were covered with standard asbestos pads.

Strain on the loaded construction was measured before the fire test, by strain gauges, which were attached to the upper chord, the lower chord and the diagonal of each joist, in the middle of its span. This measurement, together with measured deflections at this stage of the experiment, proved correct load distribution.

The load permitted by the manufacturer's specification was applied by means of 30 hydraulic jacks.

Vertical deflections were measured at the centre of each open-web steel joist and in the middle of the tested roof assembly.

FIRE TESTS AND READINGS

The furnace temperature satisfactorily approached the standard time-temperature curve[1] throughout both tests (see Table 1 and Figure 12). Maximum deviation was always within the permissible limits and no correction factor was required.

Temperatures measured on the assembly made of hot-rolled steel are presented in Table II and Figure 13. When a reading on a thermocouple was higher at one location than at another comparable location (for example A = 1625°F), the reading was marked on that particular Table, and plotted in the corresponding figure as a course of maximum temperature in the measured place.

Deflection measurements for the "North" open-web steel joist using hot-rolled steel are shown in Table III and Figure 14. The joist collapsed at 98.5 min.

The data obtained from the fire test of the roof assembly, where cold-formed steel is used in the construction of the steel joists, are similarly presented. Temperatures are shown in Table IV and Figure 15; deflections are in Table III and Figure 14. The "North" joist collapsed at 95.5 min.

A particular comparison of measured deflections on open-web steel joists made of cold-formed steel and hot-rolled steel was made and its results can be found again in Table III and Figure 14.

OBSERVATIONS

Thermal protection of both assemblies was checked before the fire tests. There was no visible damage in the fire protection.

During the first hour of the fire tests no change in the quality of the fire protection was noticed. Later on, several very thin cracks were observed. Some of the cracks began to develop at 40 min, as indicated by several thermocouple readings.

After 70 minutes several cracks developed to a much larger extent. These disturbances caused the roof assembly using hot-rolled steel to collapse after 98.5 min. The assembly using cold-formed steel withstood 95.5 min of fire test. Details of the collapsed roof assemblies are shown in Figure 16 (a) to (e).

A picture of the surface of the roof assembly exposed to the fire test is shown in Figure 16 (a). Detail of the ruptured lower chord of the open-web steel joist is in Figure 16 (b). Deformed structural steel and resulting rupture of the lower chord of the open-web steel joist is shown in Figure 16 (c), (d), and (e). Figure 16 (a) to (e) shows the ruptured open-web steel joist where hot-rolled steel was used. Figure 17 shows a ruptured lower chord of open-web steel joist made of cold-formed steel.

When sprayed fire protection was taken off the joists after the fire tests, the surface of the joists was corroded. Figures 18 and 19 show the change in colour of the surface of the sprayed protection in contact with the steel (top part of Figures 18 and 19). Samples with marks of corrosion are compared to a sample not exposed to the fire test (lower part of Figures 18 and 19).

RESULTS

In the case of the assembly using hot-rolled steel, the average temperatures measured on the lower chord, upper chord and diagonals of the open-web steel joist, reached the ASTM critical steel temperature, t_c = 1100°F, after 80 min. The critical temperature was exceeded in several places much sooner (see Figure 13, Table II). Actual collapse occurred at 98.5 min, (when the lower chord of the open-web steel joist ruptured.)

The temperature measured on the upper chord of the open-web steel joist made of cold-formed steel reached its critical value in 60 min. Maximum measured temperatures in place A (see Figure 15) exceeded 1100°F at 60 min of the fire test. A rupture of the lower chord occurred at 95.5 min.

The deflections on an open-web steel joist made of cold-formed steel were bigger than those measured for the hot-rolled steel joist. The measured deflection values with particular comparisons are given in Table III and Figure 14.

During the tests described in this report, the formation of large cracks caused a steep increase in local steel temperatures. The load-bearing capacity of the steel was decreased with resulting rupture of lower chords for both tested open-web steel joists.

CONCLUSION

The tests have shown the following results:

Measured deflections in the middle of the span on the open-web steel joists made of cold-formed steel were greater than corresponding deflections of open-web steel joists made of hot-rolled steel.

Total collapse of a joist made of cold-formed steel came at 95.5 min; a joist made of hot-rolled steel collapsed at 98.5 min. This difference is so small that performance of both joists can be rated equal.

On the basis of these results we can conclude that there is no significant difference in the performance of open-web steel joists made of hot-rolled or cold-formed steels when exposed to fire. The fire resistance classification of both assemblies according to ASTM E119 was 1-1/2 hr.

ACKNOWLEDGEMENT

This project was undertaken at the request of the Steel Industries Fellowship Committee. The work was carried out under a cooperative program between DBR/NRC and the Canadian Steel Industries Construction Council, known as the Steel Industries Agreement.

The author wishes to thank Messrs. J.E. Berndt and E.O. Porteous, who carried out the fire tests and assisted in analysis of the data developed.

REFERENCE

1. Standard for Fire Tests of Building Construction and ASTM E119 Materials, Second Edition, September 1971.

TABLE I

FURNACE TEMPERATURES, PRESCRIBED AND EXPERIMENTAL *

TIME, min.	PRESCRIBED	EXP. - HOT-ROLLED STEEL	EXP. - COLD-FORMED STEEL
5	1000	1139	1042
10	1300	1352	1324
15	1399	1407	1371
20	1462	1442	1412
25	1510	1516	1546
30	1550	1552	1554
35	1584	1586	1584
40	1613	1621	1615
45	1638	1645	1641
50	1661	1667	1662
55	1681	1693	1691
60	1700	1721	1697
65	1718	1747	1731
70	1735	1764	1742
75	1750	1769	1761
80	1765	1786	1769
85	1779	1798	1787
90	1792	1811	1791
95	1804	1821	1802
100	-	-	-
105	-	-	-

* see Fig. 12

TABLE II

TEMPERATURES ON HOT-ROLLED STEEL OPEN-WEB JOIST (AVERAGE, MAXIMUM)

(see Fig. 13)

TIME, min.	TEMP JOIST "NORTH"			TEMP JOIST "SOUTH"		
	UPPER CHORD	LOWER CHORD	DIAGONAL	UPPER CHORD	LOWER CHORD	DIAGONAL
0	70	70	70	70	70	70
5	85	85	85	85	85	85
10	125	150	135	110	155	125
15	130	200	200	130	200	175
20	190	220	220	175	250	210
25	250	250	310	280	280	300
30	325	360	310	400	360	310
35	460	480	420	480	A=580 475	430
40	490	490	525	615	580	560
45	675	530	560	775	690	610
50	620	725	730	825	760	950
55	550	850	850	825	790	900
60	560	975	860	790	820	825
65	800	A=1060 830	880	700	870	760
70	700	A=1160 920	910	530	930	750
75	940	A=1260 980	970	600	1000	790
80	1060	A=1330 950	1110	875	1060	850
85	1120	A=1625 1085	1250	1280	1075	1100
90	1150	A=1525 1135	1220	1225	D=1200 1130	960
95	1325	A=1600 1220	1170	1300	1340	1180

TABLE III

DEFLECTIONS ON OPEN-WEB STEEL JOISTS, WHERE COLD-FORMED AND HOT-ROLLED STEELS ARE USED, COMPARISON WITH CALCULATED DIFFERENCE*

TIME (min)	DEFLECTION COLD-FORMED STEEL	DEFLECTION HOT-ROLLED STEEL	DIFFERENCE
0	0.53	0.54	-0.01
5	0.60	0.56	0.04
10	0.73	0.66	0.07
15	0.82	0.76	0.06
20	0.87	0.80	0.07
25	0.89	0.80	0.09
30	0.89	0.80	0.09
35	0.89	0.80	0.09
40	0.93	0.81	0.12
45	1.02	0.85	0.17
50	1.14	0.94	0.20
55	1.31	1.08	0.23
60	1.54	1.22	0.32
65	1.72	1.41	0.31
70	2.02	1.56	0.46
75	2.18	1.82	0.36
80	2.42	2.04	0.38
85	2.94	2.24	0.70
90	3.83	2.48	1.35
95	5.44	3.04	2.40
100	COLLAPSE 95.5 min	COLLAPSE 98.5 min	-

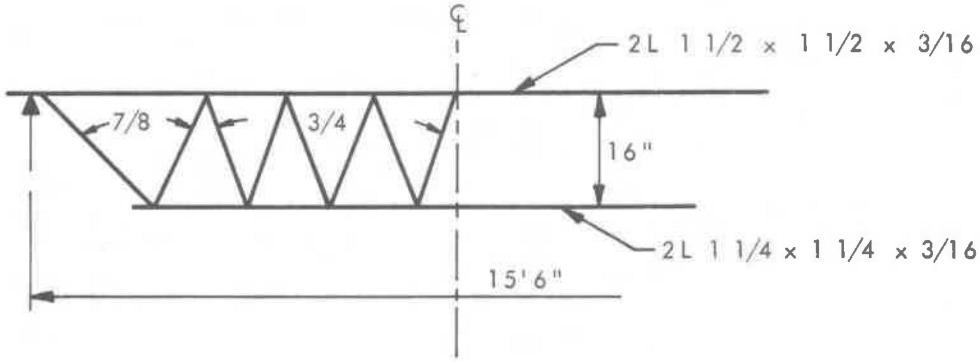
* see Fig. 14

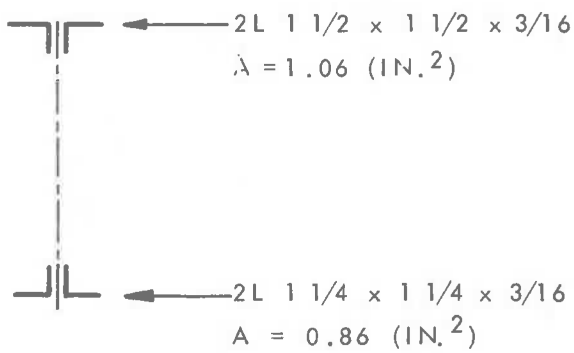
TABLE IV

TEMPERATURES ON COLD-FORMED OPEN-WEB STEEL JOISTS (MAXIMUM TEMPERATURE) *

TIME, min.	TEMP JOIST "SOUTH"			TEMP JOIST "NORTH"		
	UPPER CHORD	LOWER CHORD	DIAGONAL	UPPER CHORD	LOWER CHORD	DIAGONAL
0	70	70	70	70	70	70
5	90	90	90	90	90	90
10	100	135	150	100	150	145
15	170	190	190	110	190	185
20	190	200	200	120	210	200
25	200	220	230	195	280	280
30	220	255	300	280	320	370
35	375	315	420	400	335	475
40	400	350	520	530	430	600
45	D=1060 460	400	1020 620	715	490	630
50	D=1060 600	560	870 700	800	530	620
55	650	575	900 775	820	590	675
60	680	685	850	A=1000 790	675	740
65	880	750	910	A=1100 790	700	800
70	980	850	980	A=1150 860	730	875
75	1000	975	1050	A=1300	805	950
80	1010	1060	1100	A=1300	900	1030
85	1110	1120	1175	A=1430	960	1100
90	1180	1200	1210	A=1400	1050	1175
95	1200	1375	1290	A=1400	1100	1630

* see Fig. 15



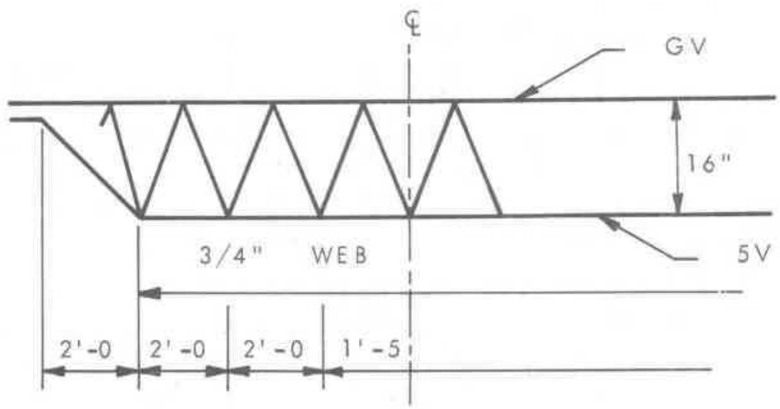


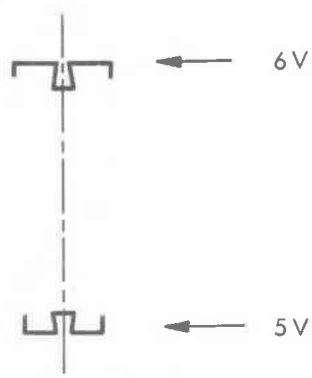
JOIST PARAMETERS SUPPLIED BY PRODUCER

SPAN: 15'-6"
W = 1020 PLF
STEEL: CHORDS-G40.12

FIGURE 1

SKETCH OF HOT-ROLLED OPEN-WEB STEEL JOIST WITH TECHNICAL PARAMETERS





$A_6 = 1.032\ (\text{IN.}^2)$

$A_5 = 0.836\ (\text{IN.}^2)$

$I_{CHORDS} = 111.14 (\text{IN.}^4)$

JOIST PARAMETERS SUPPLIED BY PRODUCER

SPAN: 15'6"
W = 1138 PLF
$R_R = R_L$ = 8820 LB

M = 410 IN.-KIPS

STEEL:

TENSILE STRENGTH: 67000 PSI MINIMUM
YIELD STRENGTH : 55000 PSI MINIMUM

FIGURE 2

SKETCH OF COLD-FORMED OPEN-WEB STEEL JOIST WITH TECHNICAL PARAMETERS

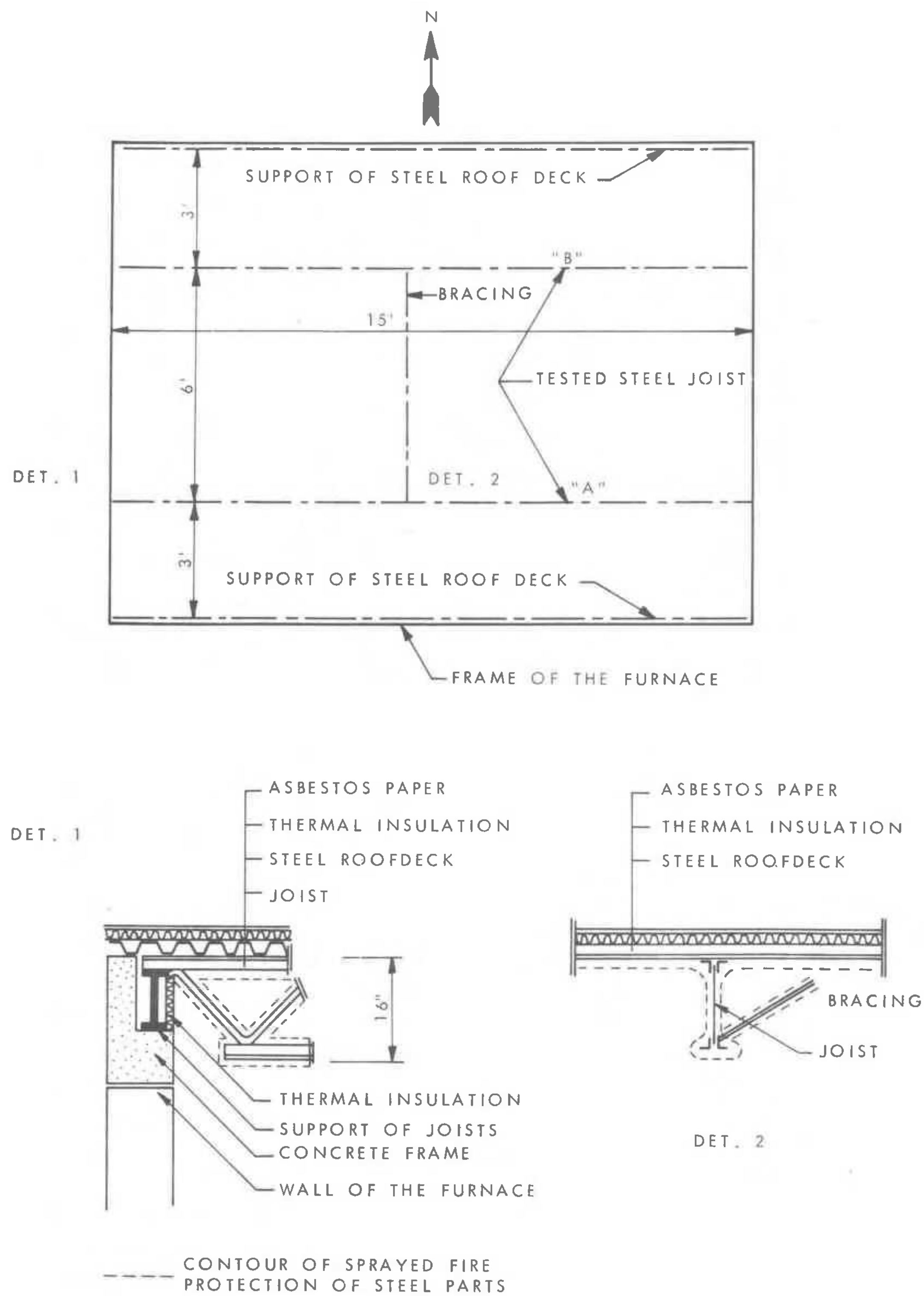


FIGURE 3

LOCATION OF JOISTS IN THE FURNACE WITH TWO DETAILS OF ROOF ASSEMBLY (SKETCH)

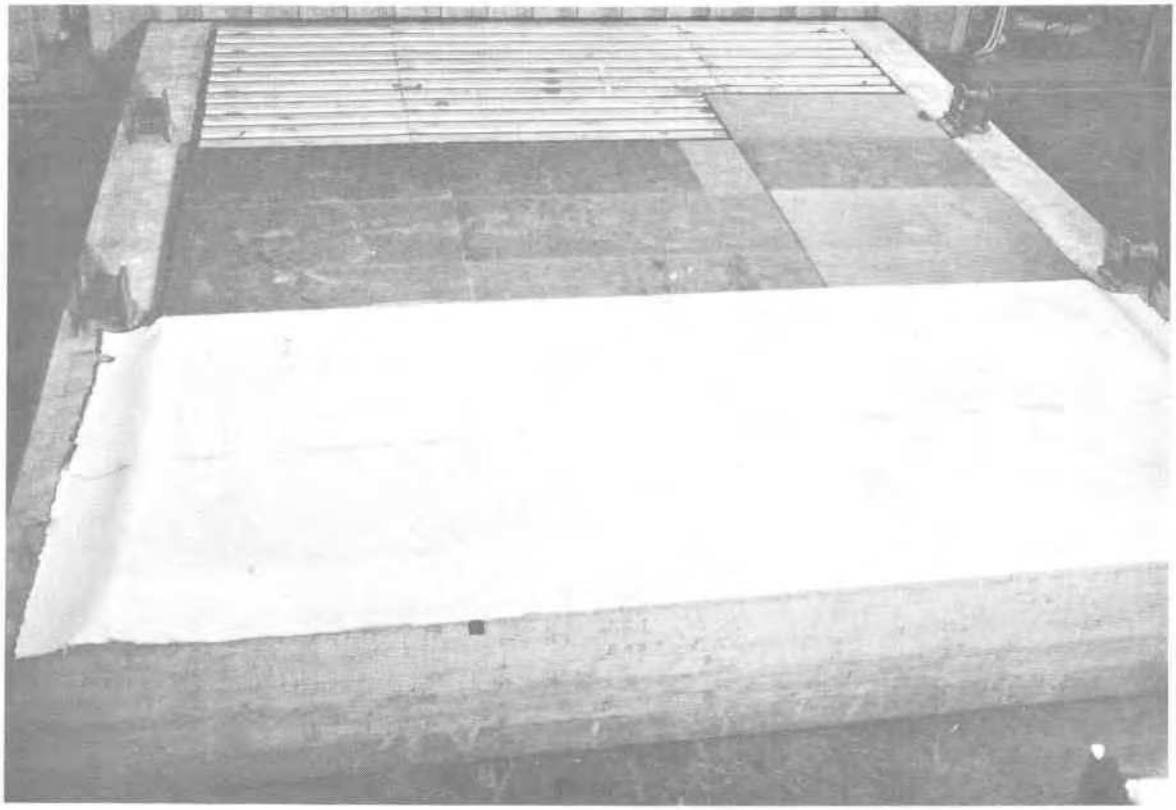


Fig. 4 Roof assembly under construction

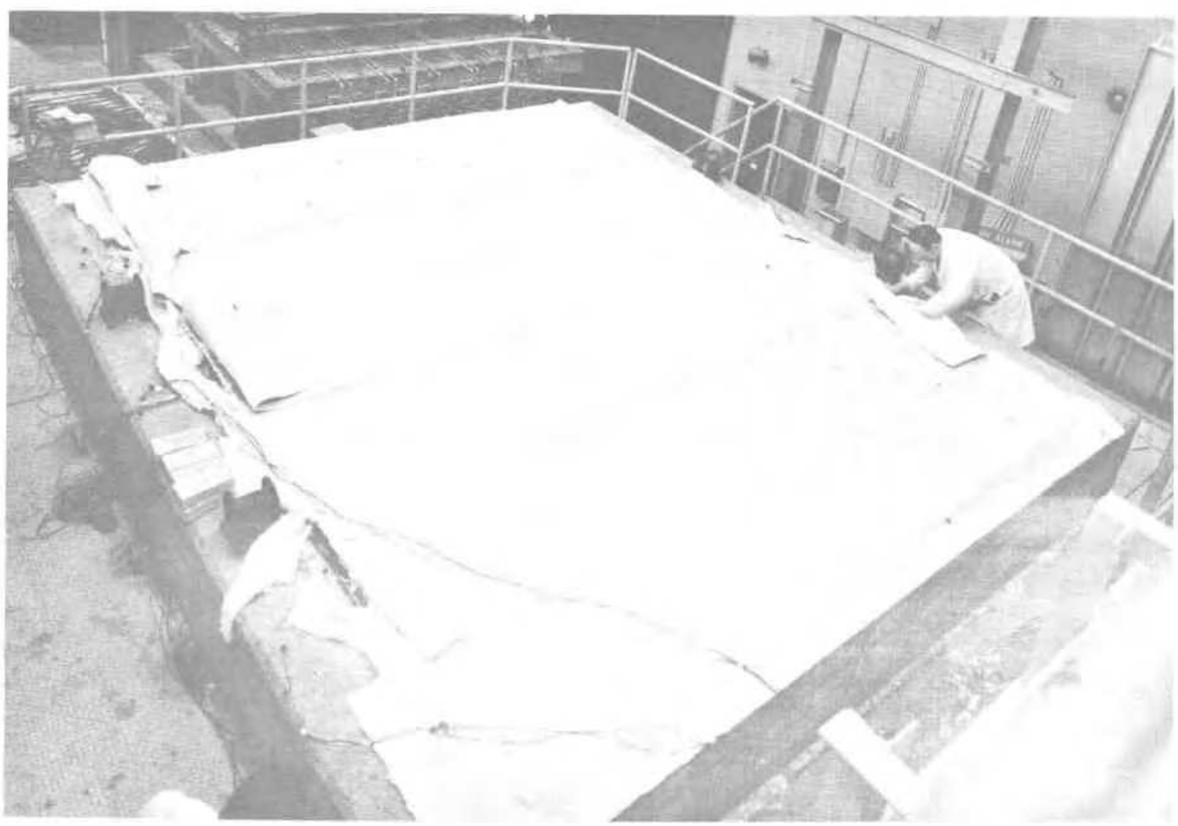
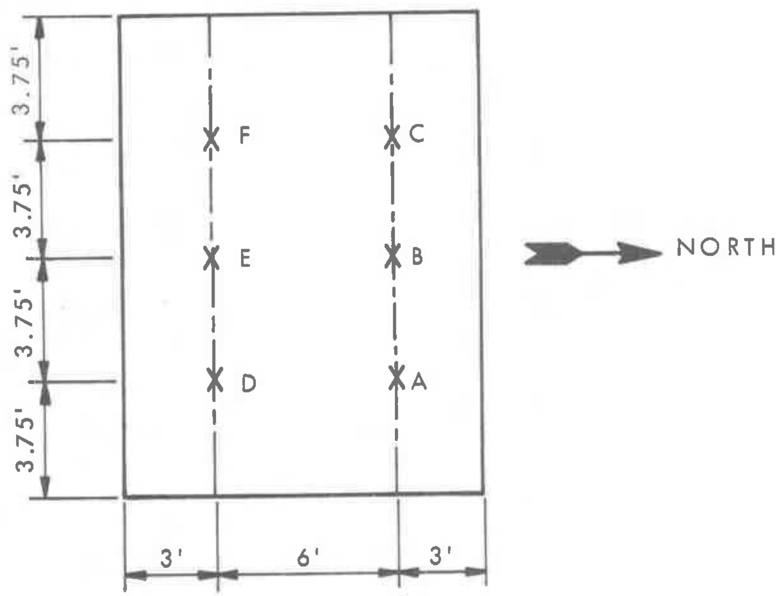


Fig. 5 Completed construction of roof assembly

PLAN OF THE ROOF ASSEMBLY - TEMPERATURE IN LOCATIONS A-F WERE RECORDED



CROSS - SECTION A-F WITH THERMOCOUPLES 1 - 4

FIGURE 6

TEMPERATURE MEASUREMENT ON STEEL JOIST. LOCATION OF THERMOCOUPLES

PLAN OF THE ROOF ASSEMBLY

STEEL ROOF DECK CROSS SECTION

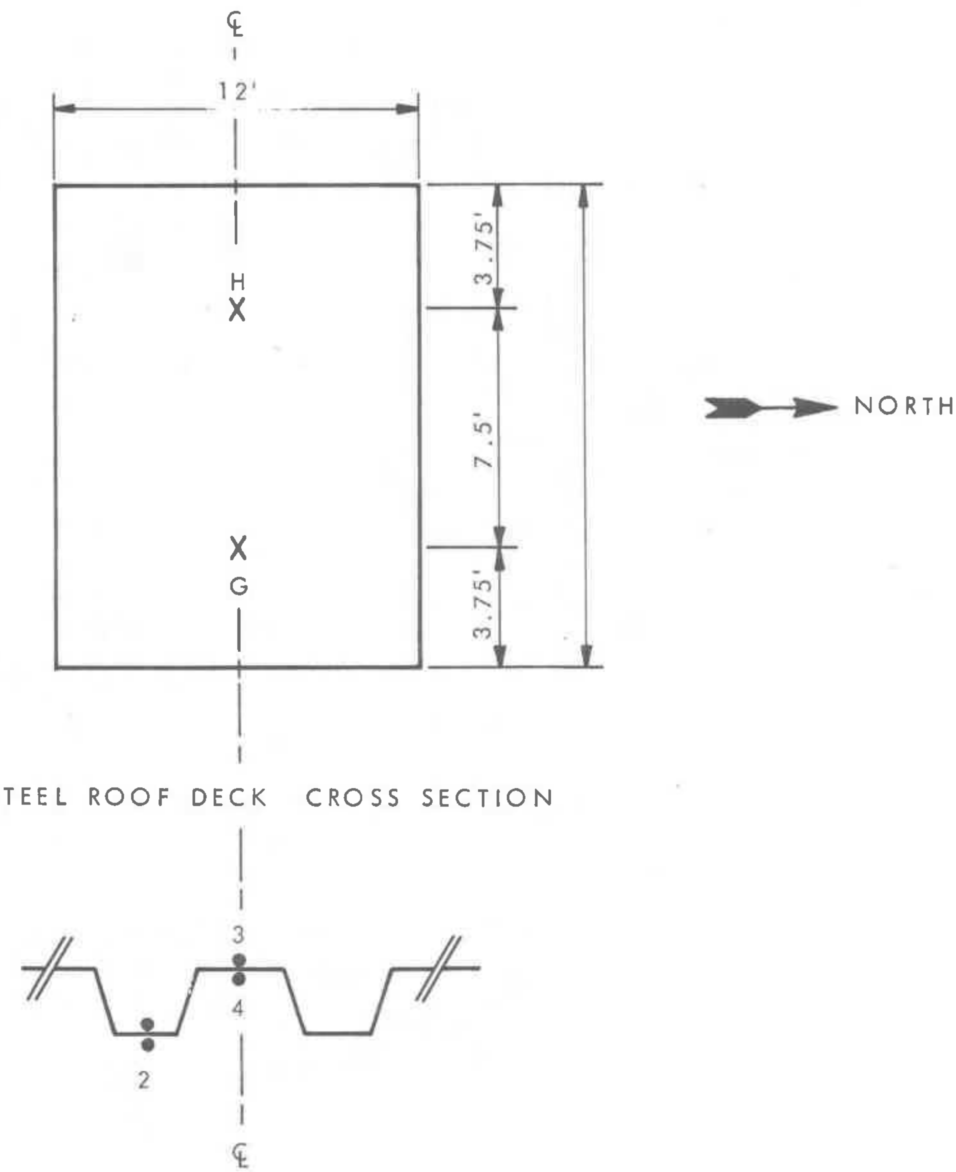


FIGURE 7
LOCATION OF THERMOCOUPLES ON STEEL ROOF DECK

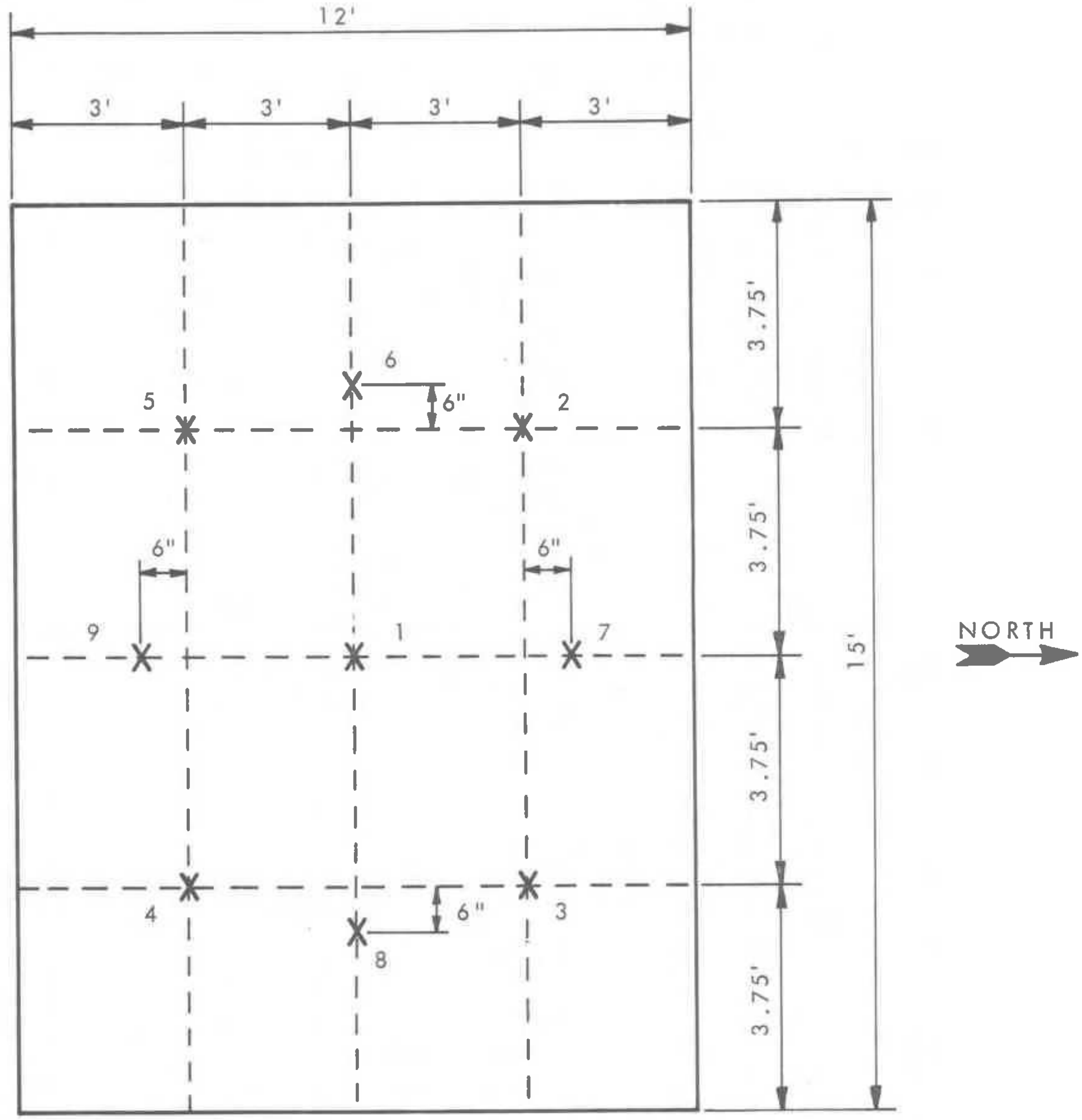


FIGURE 8
LOCATION OF THERMOCOUPLES ON UNEXPOSED SURFACE

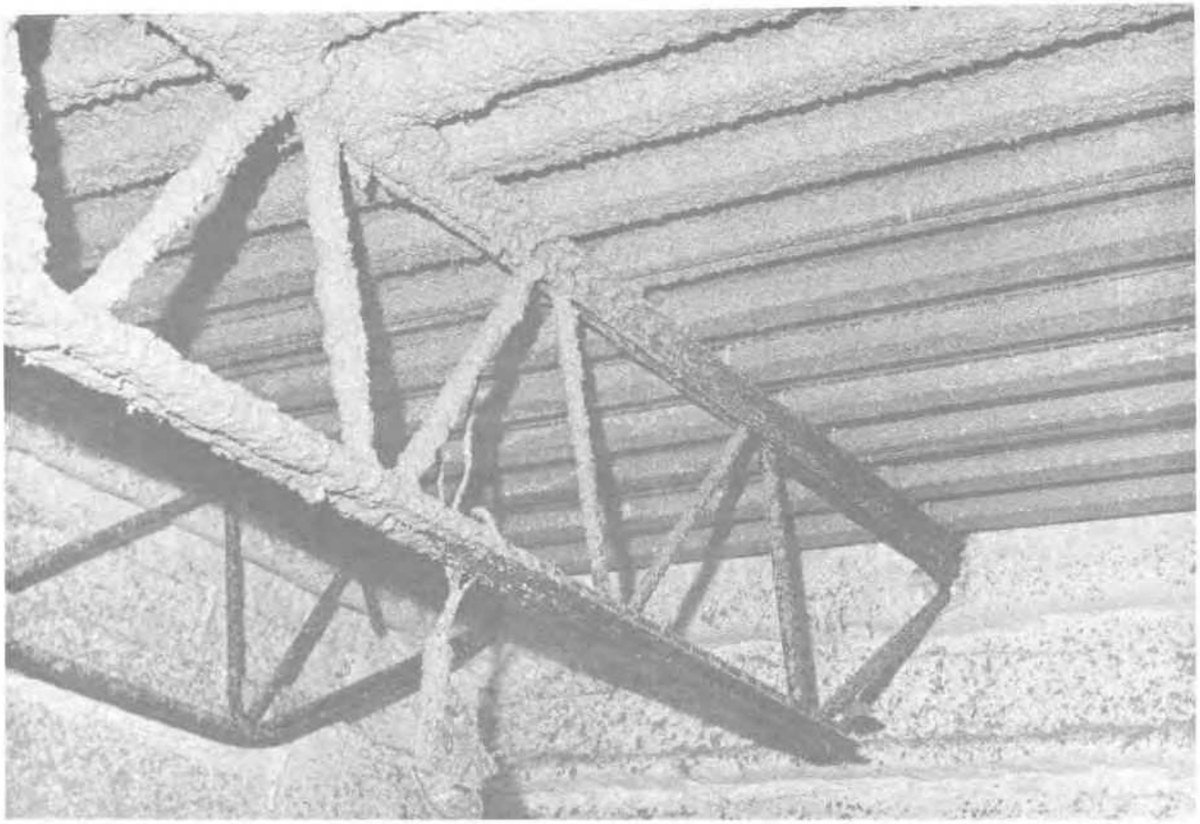


Fig. 9 Uncompleted sprayed fire protection of roof assembly

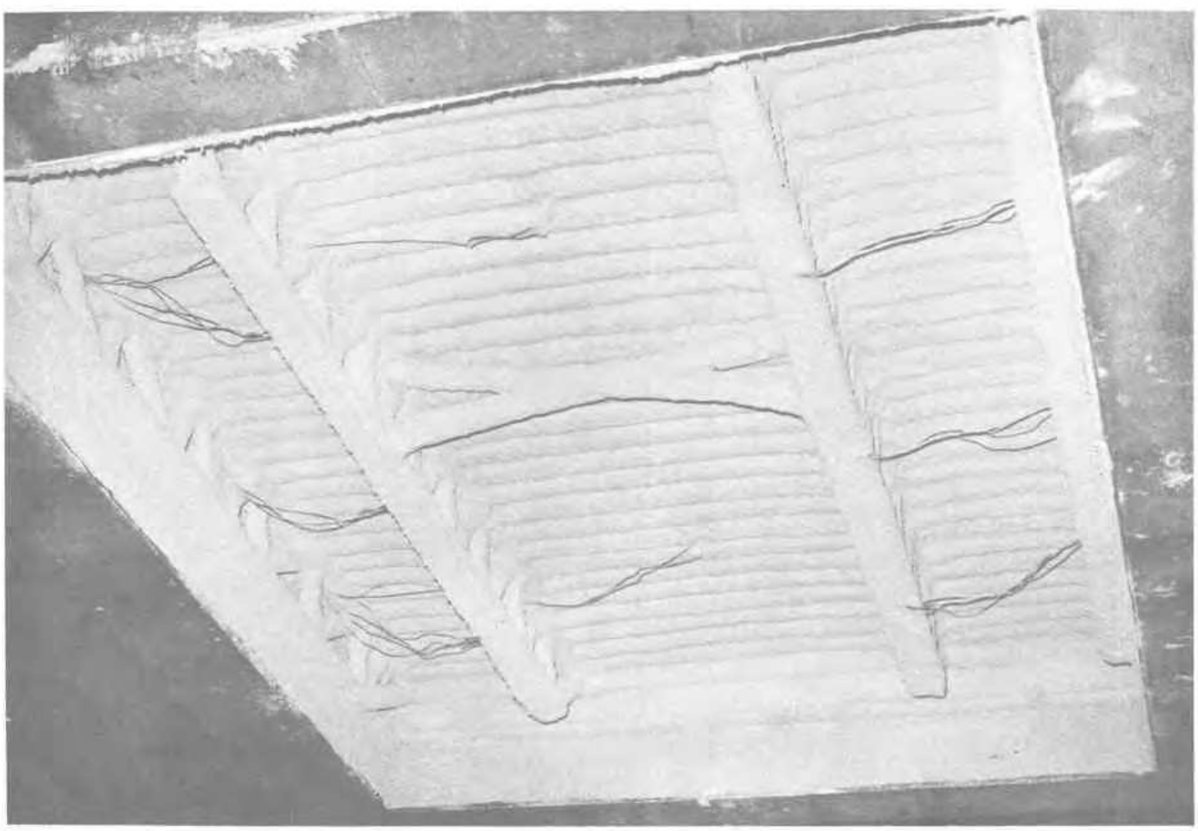


Fig. 10 Completed fire protection of roof assembly

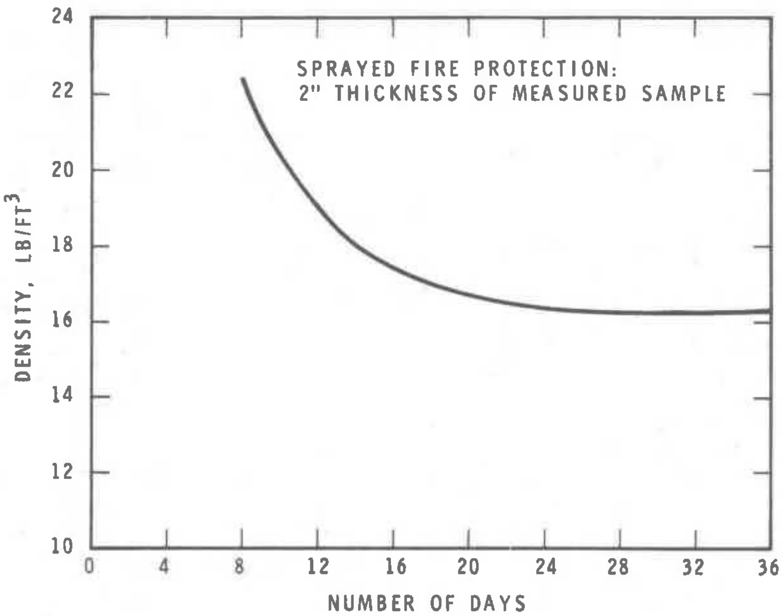


FIGURE 11

CHANGE IN DENSITY OF SPRAYED MATERIAL WITH RELATION TO TIME

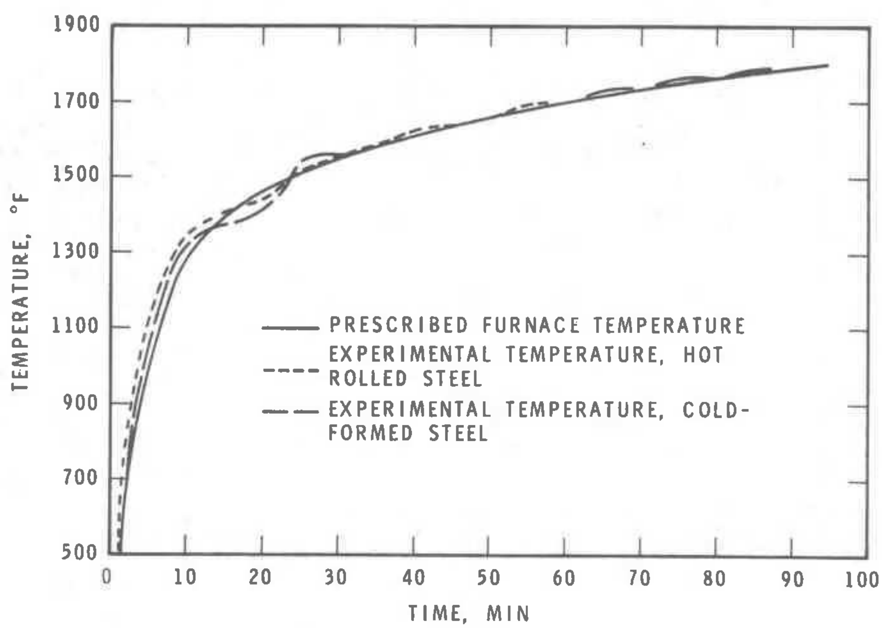


FIGURE 12

FURNACE TEMPERATURES, PRESCRIBED AND EXPERIMENTAL

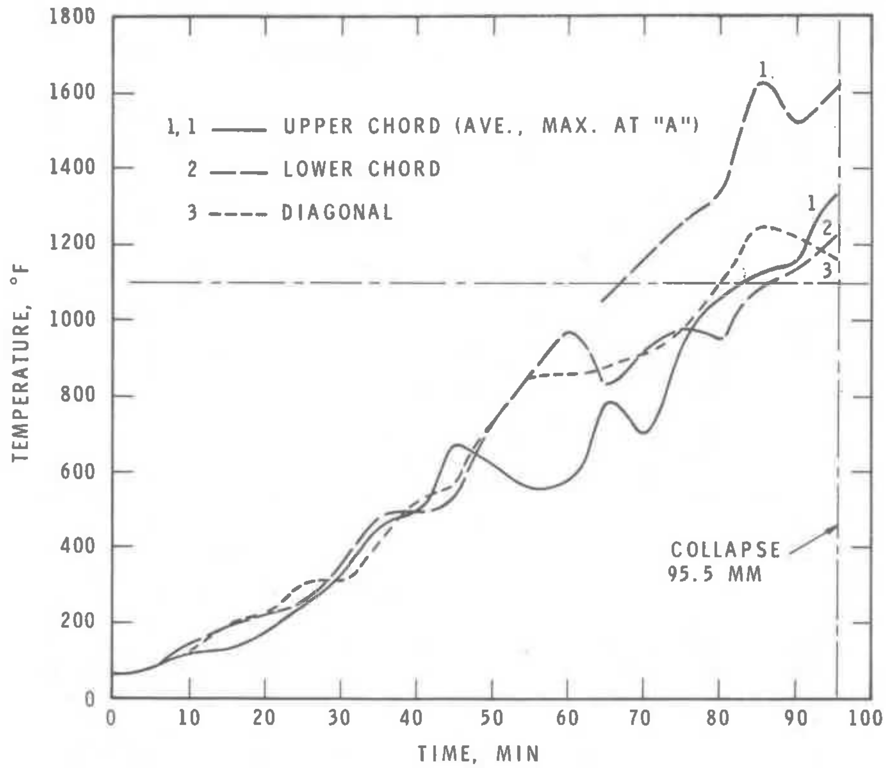


FIGURE 13

TEMPERATURE MEASURED ON NORTH OPEN-WEB STEEL JOIST (HOT-ROLLED STEEL)

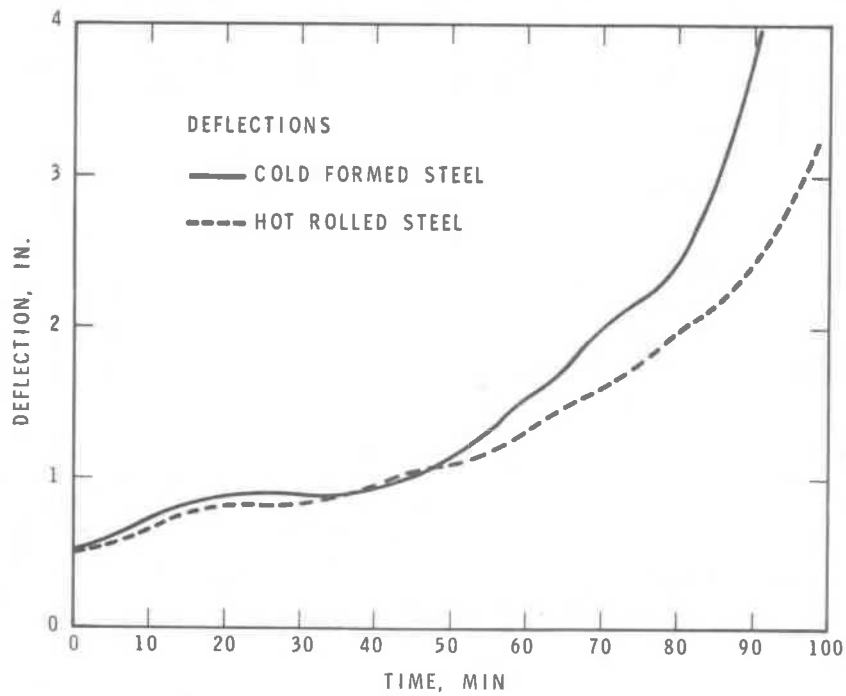


FIGURE 14

DIAGRAM COMPARING THE DEFLECTIONS OF COLD-FORMED AND HOT-ROLLED OPEN-WEB STEEL JOISTS

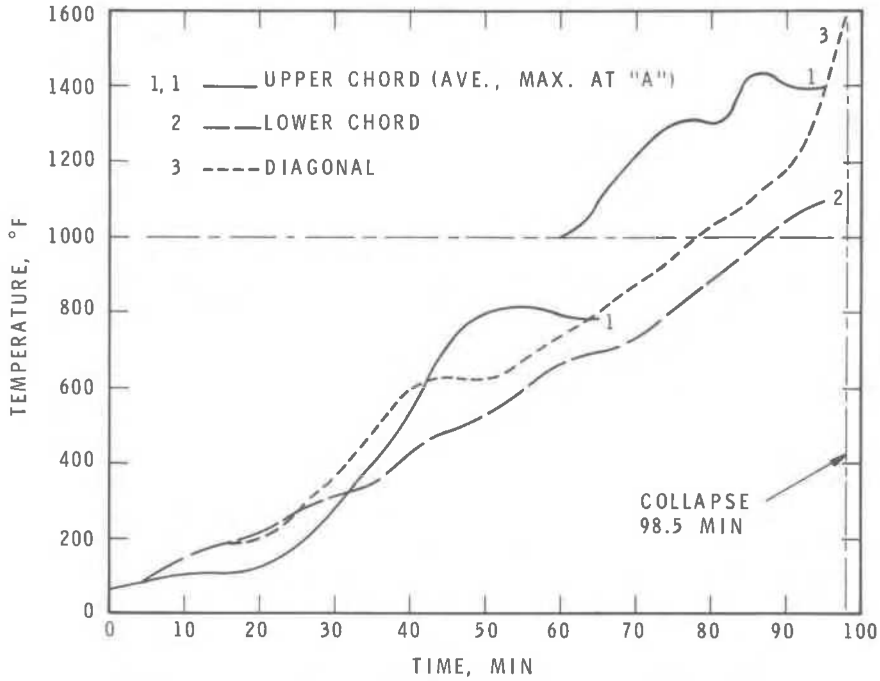
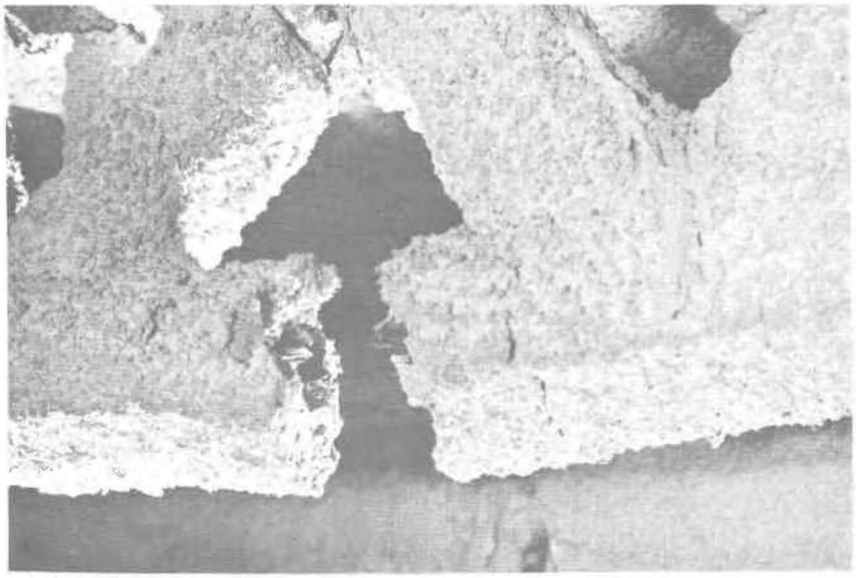


FIGURE 15

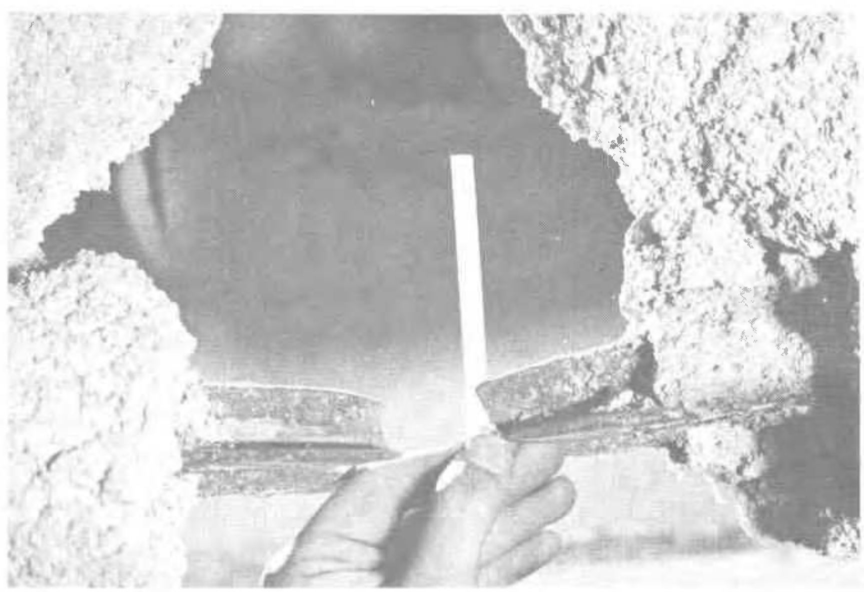
TEMPERATURE MEASURED ON NORTH COLD-FORMED STEEL OPEN WEB JOIST

(a) Exposed surface of the assembly after fire test

Fig. 16 Roof assembly after fire test

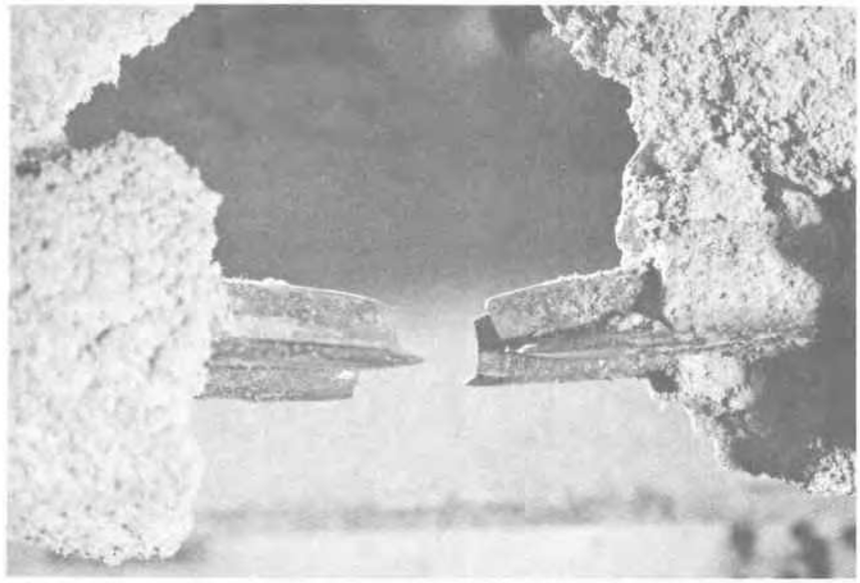


(b) Detail of ruptured lower chord of steel joist

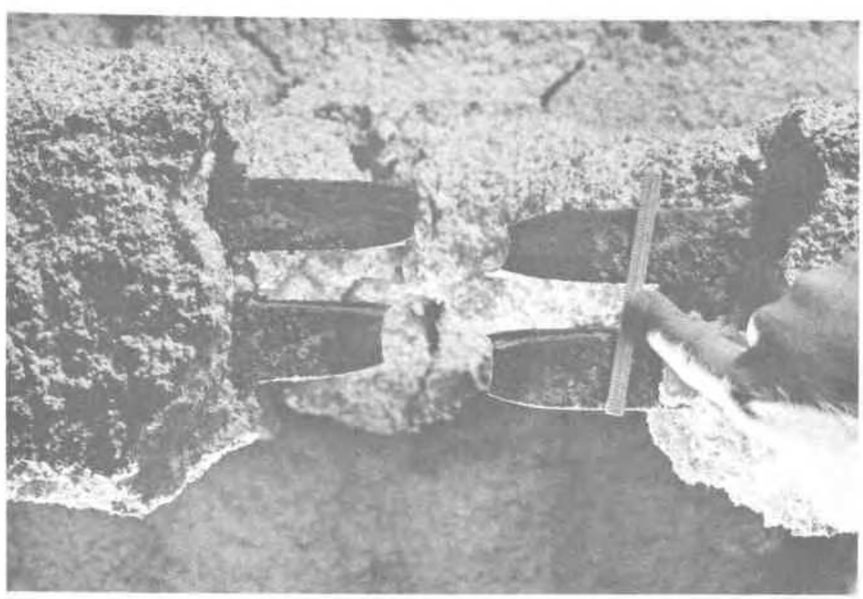


(c) Details of ruptured lower chord of open-web steel joist

Fig. 16 Roof assembly after fire test



(d) Change in dimensions of lower chord cross-section after fire test



(e) Detail of ruptured lower chord of open-web steel joist

Fig. 16 Roof assembly after fire test

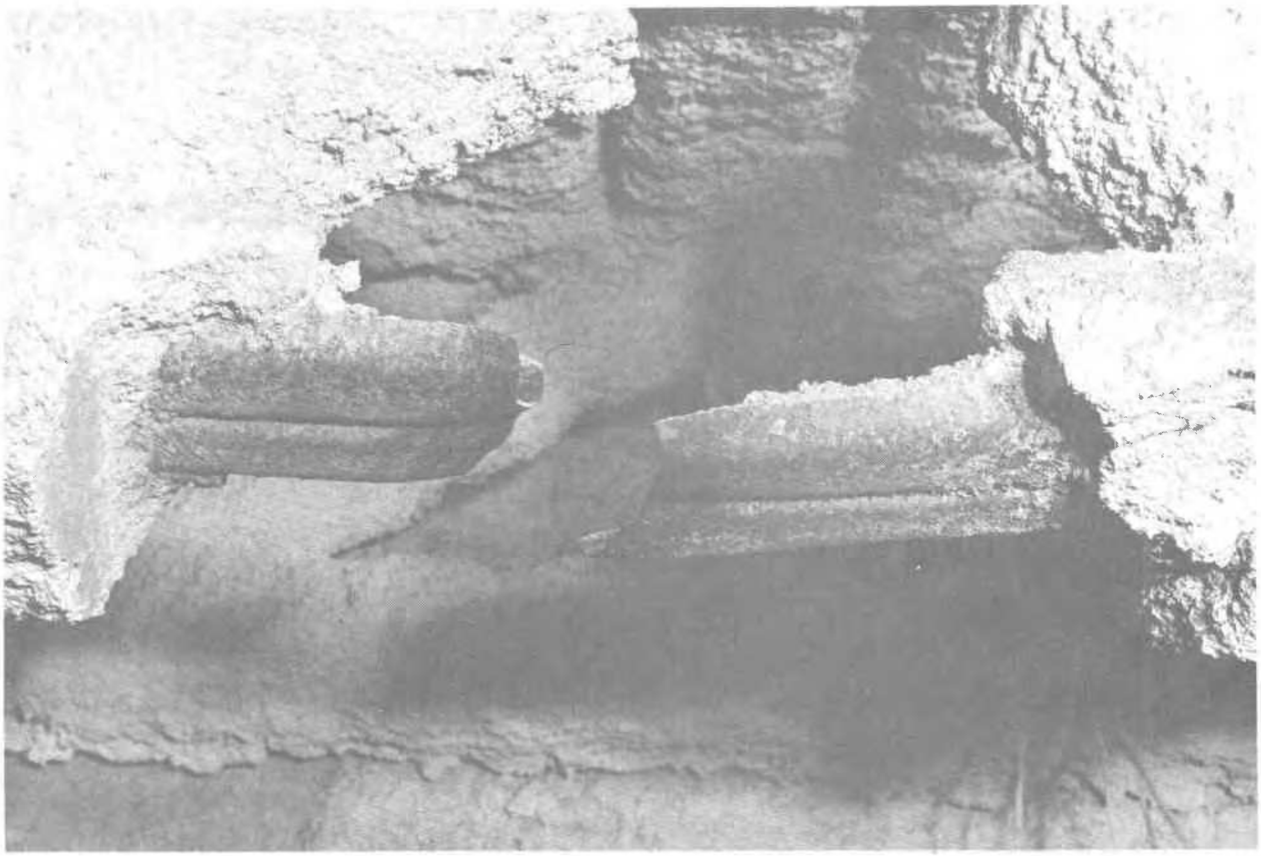


Fig. 17 Deformation and rupture of open-web steel joint made of cold-formed steel

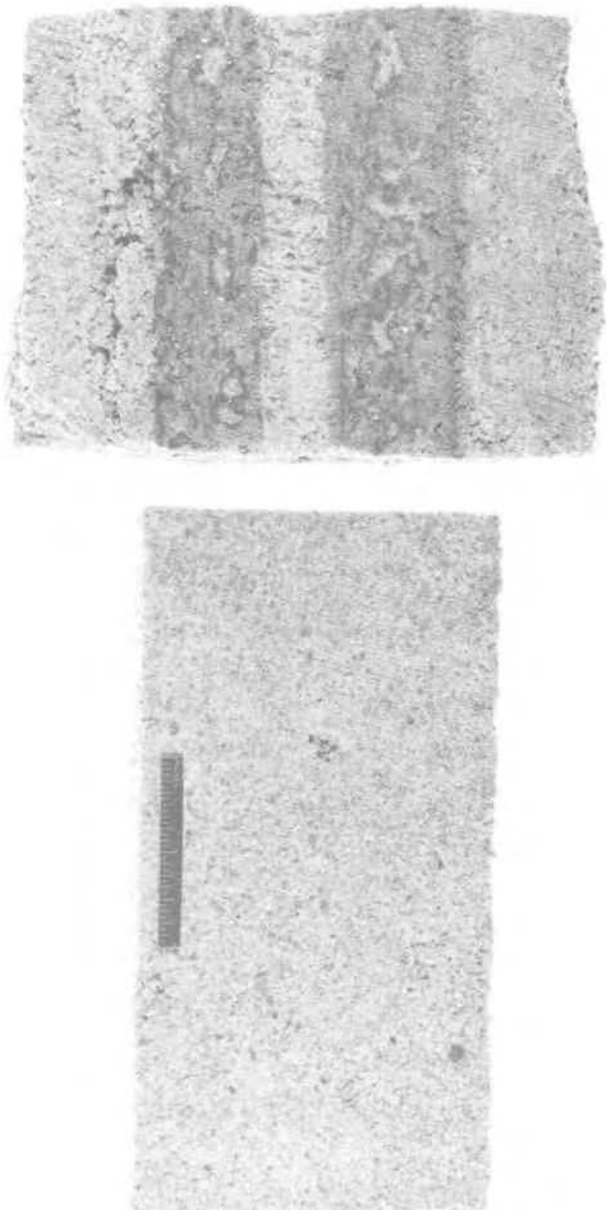


Fig. 18 Corrosion of steel joist, hot-rolled steel. Fire protection with visible mark of corrosion, where in contact with steel (top picture). Fire protection not exposed to fire (lower picture)

Fig. 19 Corrosion of steel joist - cold-formed steel. Fire protection with visible mark of corrosion, where in contact with steel (top picture). Fire protection not exposed to fire (lower picture).