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NATIONAL BUREAU OF STANDARDS REPORT

4920

FIRE TESTS OF PRECAST THIN-SHELL CONCRETE ROOF PANELS

by

J. V. Ryan

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FIRE TESTS OF PRECAST THIN-SHELL CONCRETE ROOF PANELS

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J. V. Ryan

to
Bureau of Yards and Docks
Department of the Navy

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NATIONAL BUREAU OF STANDARDS

FIRE TESTS OF PRECAST THIN-SHELL CONCRETE ROOF PANELS

ABSTRACT

Fourteen fire tests were made on precast thin-shell concrete roof panels. The panels' cross-sections were channel shape. Some had intermediate transverse ribs; others did not. The panels for the first two tests were reinforced conventionally, the remainder had prestressed reinforcement. The last four panels had insulating underfaces. The observed fire endurances ranged from 6 min to 31 min.

1. Introduction

The desirability of conservation of materials, reduction of weight, speed of erection, and other factors has lead to the investigation of new design techniques or new combinations of existing techniques in building construction. One such combination is represented by precast thin-shell prestressed concrete construction.

Precasting removes the fabrication of concrete building elements from the field to the factory and makes possible greater control of materials, mix proportions, curing conditions, and other factors tending to improve quality. The use of precision casting forms is essential to permit rapid erection of close fitting elements on the building site.

Thin-shell design makes use of efficient cross-sections thereby providing the necessary strength, or other characteristics, with the minimum amount of materials. This in turn leads to reduced weight for the building.

Prestressing involves putting a high tensile stress on the primary reinforcement and maintaining it by one of several methods, thereby producing compressive stresses in the concrete. The applied load on the structure in service must overcome these compressive stresses before tensile cracks can develop in the concrete.

A research program on the fire resistance of roof panels of this type was carried out under the sponsorship of the Bureau of Yards and Docks, U. S. Navy, Department of Defense. Fourteen fire tests were carried out in the National Bureau of Standards' large floor furnace. All the roof panels were precast thin shell concrete. Those for the first two tests were reinforced conventionally; the remainder were prestressed. The last four panels had insulating underfaces. The panels were tested without load or under one of various applied loads.

2. Materials and Specimens

In order to reduce the possibility of batch-to-batch variations, the concretes for the specimens were prepared and poured by the laboratory staff rather than by an outside contractor. The gravel aggregate was graded to size and the mix components weighed carefully. Therefore, the quality of the concrete and workmanship may have not been representative of that obtained ordinarily. Also, one of the insulating underfaces, a lightweight concrete, was a recent laboratory development not yet used extensively in the field.

2.1 Materials

Wire fabric, a 2 by 2 in. square mesh of 12 ga galvanized wires (SW ga), was used in all the panels. The longitudinal reinforcement was of 3/4 in. deformed steel bars for conventional and of 1/2 inch diameter smooth bars with threaded ends for prestressed construction. The transverse bars were 1/4 in. deformed in the conventional panels and 1/2 in. (No. 8) deformed for the prestressed panels. One inch hexagonal 13/16 in. long nuts tapped 1/2 - 20, 1 1/4 in. diameter washers, and 2 1/2 by 2 1/2 by 5/8 in. bearing plates were used with the prestressed bars.

The coarse aggregate was White Marsh gravel, a siliceous aggregate. All the gravel had passed through a 3/8 in. mesh sieve. The cement factor was seven bags per cu yd for all panels.

Glass fiber mats 1/2 in. thick were used as underface material on two panels. A perlite aggregate foamed concrete was used similarly on two other panels.

2.2 Specimens

The individual panels were in the form of long channels. For the conventionally reinforced construction, they were 17 ft 10 in. long, 4 ft 2 1/2 in. wide, 1 1/4 in. thick shell, with an 8 in. deep flange along each size plus 6 in. deep transverse flanges at each end and equally deep transverse ribs at center and quarter points, thereby dividing the panel into four thin-shelled bays. The reinforcement consisted of a single No. 6 deformed steel bar located 3/4 in. from the bottom of each longitudinal flange; two No. 2 deformed steel bars in each transverse rib or flange; and 2- by 2-in. mesh No. 12 ga welded wire fabric at the center of the 1 1/4 in. thick top shell. The wire fabric was turned down into each longitudinal flange. The panels were cast in a mold prepared for the purpose and the flanges, ribs, and shell were all cast at the same time. The concrete was mixed one part high early strength Portland cement, 2 1/2 parts clean bank sand, two parts clean White Marsh gravel. The concrete was vibrated in the mold to eliminate voids. The details of the panels, including locations of reinforcing bars, are given in figure 1.

The prestressed panels were 17 ft 7 3/8 in. long, 4 ft 2 1/2 in. wide, 1 in. thick shell, with a 6 in. deep flange along each side and 5 1/2 in. deep flanges across each end. For some of the panels transverse ribs 4 in. deep were located at the center and 4 ft 5 1/2 in. each side of center. The reinforcement consisted of a single 1/2 in. diameter prestressed bar in each longitudinal flange; single No. 4 deformed bars in each transverse rib or flange; and 2- by 2-in. mesh No. 12 ga welded wire fabric at the center of the 1 in. thick shell and turned down into the longitudinal and transverse flanges. The No. 4 bars were turned into the longitudinal flanges for a length of 8 in. The panels were cast in a mold prepared for the purpose. Before the concrete was poured, the mesh, deformed bars, and ducts for the prestressed bars were placed in the mold, the latter so that the center of the bars would be 3 in. from the bottom of each flange at each end and 2 in. at the center. The concrete was mixed in the same ratios as for the conventionally reinforced panels. The flanges, ribs, and shell were cast at the same time. The concrete was vibrated in the mold to eliminate voids. The same procedure and mold, with appropriate modifications of the latter, were used for the panels without intermediate transverse ribs and for the panels with insulating underface. The insulating material was placed in the mold to provide a 1/2 in. thick layer below the 1 in. thick shell but none on the flanges. The concrete was then poured onto the insulation. The details of the prestressed panels are shown in figure 2.

Each specimen was covered with burlap in the mold, and the burlap wet down periodically for several days. The prestressing bars were placed in the ducts after the sides of the molds had been stripped. The bearing plates, washers, and nuts were put on the ends of the rods and the nuts tightened sufficiently that the panel could be lifted and stored. Later in the aging period the bars were stressed by a jack and the nuts tightened against the plates and washers, holding the stress.

3. Test Method

3.1 Aging and Conditioning

The panels were aged for various periods of time in a large work room that was heated and ventilated according to the season and weather.

Three of the specimens were further conditioned by heating the furnace chamber to temperatures of about 125 to 150°F during the 10 days prior to test. The specific period of aging for each test specimen, as well as other information, is given in table 1.

3.2 Fire Test Procedures

For the two tests of conventionally reinforced construction, and the first test of prestressed construction, three of the panels were placed in the floor furnace as shown in figure 1. Thereafter only one panel was placed in the furnace, centered between the sides, and the remainder of the furnace opening closed with previously exposed panels or filler slabs. The panels were in close contact along their edges and the joints filled with grout. In the case of a single panel and filler slabs, a space of a few inches width was left between to permit deflection of the specimen. This space was filled with mineral wool or glass fiber insulation.

The conditions of loading varied. Some specimens were loaded by the dead weight of the hydraulic loading equipment; others by concrete cylinders as weights; and still others were not loaded. Table 1 gives the load applied and the number of panels in each test specimen.

The furnace fires were controlled to provide temperatures as near as possible to those defined in ASTM E-119, which include: 1000°F at 5 min, 1300°F at 10 min, 1550°F at 30 min, 1700°F at 1 hr, and 1850°F at 2 hr. The performances of the specimens were determined by the following end point criteria: 1) rise of the average temperature on the unexposed surface to 250 deg F above its initial value, 2) rise of the maximum temperature on the unexposed surface to 325 deg F above its initial value, 3) failure to sustain the applied load, 4) development of cracks or openings large enough to permit the passage of flames or gases hot enough to ignite cotton waste.

4. Results

The thin-shell or web sections of one of the conventionally reinforced panels and of two of the prestressed panels spalled explosively. The spalling involved the entire thicknesses of the webs. Otherwise, the results of the various tests were such that they could be separated into two representative groups, within each of which the results of the individual tests were similar. The ten tests of panels without insulating underfaces make up one group, the four tests of panels with such underfaces make up the other.

4.1 Non-insulated Panels

Cracks developed in the unexposed surfaces of all the panels. The pattern included cracks parallel to the edges, ends, and transverse ribs. Cracks also developed in the unexposed vertical surfaces of the longitudinal flanges and of the end transverse flanges. The unexposed surface cracks became as wide as 1/8 in. during tests of 1 hr or more duration. Very few cracks were observed in the exposed surfaces during the tests but were observed after cooling.

In three tests, one of a conventionally reinforced panel and two of prestressed panels, the thin-shell webs spalled through explosively. Prior to the spalling, which occurred at 10 min in two tests and 6 min in the other, there were a few fine cracks. Figures 3 and 4 show views of two of the spalled panels.

The deflections of the longitudinal flanges were upwards, initially, reaching individual maxima of 0.7 to about 8 in. An example is shown in figure 5. Except in the very short tests, the deflections decreased from these maxima and, with one additional exception, became downward with respect to the initial position of panel. The additional exception was one test (364) in which the thermal expansion of one of the prestressed bars was sufficient to jam against the furnace frame and hold the panel in an arched position. The downward deflections of the other panels reached values of 8 in. to 2 ft. In many instances these deflections represented the limit of slack in chains attached at mid-span to prevent complete collapse. The thin-shell webs of the panels with intermediate transverse ribs, and the ribs, sagged with respect to the longitudinal flanges. The deformations of the webs of the panels without transverse ribs were less consistant. In some cases they were upwards, in others downwards, and in still others upwards along part of the panels length and downwards along other parts at the same time. In general, the deformations of the webs became downward as the tests progressed.

The limiting temperature rises on the unexposed surfaces were reached in from 6 to 14 min; the test durations were from 7 min to 2 hr 3 min. Table 2 gives a summary of the observed results for the individual tests.

4.2 Insulated Panels

The cracks that developed in the unexposed surfaces of the four panels with insulating underfaces were less prominent and less extensive than those in the other panels. Cracks up to 6 in. in length were spaced every few inches across each end. These cracks extended down the end faces. In two panels single cracks developed in one longitudinal flange and in one panel a few short disconnected cracks parallel to the longitudinal flange developed in the unexposed surface.

The glass fiber insulation on the exposed surfaces of two of the panels fused and dropped off in pieces. By the end of an hour of exposure, most of the insulation appeared destroyed as shown in figure 6. The perlite-foam concrete underface did not show any signs of damage other than craze cracks. None of the exposed structural concrete of the panels spalled or sluffed off.

The deflections of the four panels were in the downward direction throughout and reached values of from 11 to 20 in. by the ends of the tests. The thin shell webs sagged with respect to the longitudinal flanges. The deflections of the panels and sag of the webs were so large that some of the concrete cylinders used as applied load on two panels were toppled over, as shown in figure 7.

The limiting temperature rises on the unexposed surfaces were reached in from 28 to 31 min. Corrections for fire exposure in accordance with the procedure given in ASTM E-119 reduces the time range to 29 to 31 min for the corrected fire endurance limits. Other data from the individual tests are given in table 2.

4.3 Load Failures

Although the fire endurances of the non-insulated panels were limited to not over 14 min and of the insulated panels to not over 31 min, all by temperature rise on the unexposed surface or passage of flames through openings resulting from spalling, most of the tests were continued in order to obtain as much information as possible. Five of the panels, as indicated in table 2, were considered to have failed under load. The times at which this occurred ranged from 1 hr to 1 hr 53 min. Of the five, two collapsed. In addition, three other panels had deflected to such an extent that they were supported by chains installed in several of the later tests to prevent collapse. The conditions of these three panels were such as to indicate that load failure was imminent.

5. Summary and Discussion

The cause of the violent spalling of the thin shell webs of three panels is not obvious. Possible causes include stresses set up by the very steep thermal gradient across the web, and superheating of trapped moisture with the resultant development of high pressure steam.

The high moisture content of freshly poured concrete decreases with age as the excess water moves to the surfaces and evaporates. This process continues until the concrete's moisture content reaches equilibrium with the surrounding air. The process is slow but may be accelerated by raising the temperature of the concrete. However, the temperature cannot be raised above the boiling point of water without the danger of damaging the concrete. A comparison of the various specimens that spalled with those that did not spall, in terms of age-at-test and heating to not above 150°F, is given in table 3. The data indicate that each of three specimens aged up to four months and not heated spalled whereas two specimens aged four months each and heated did not spall, and those aged 7 1/2 months or more did not spall, whether or not they were heated. Although it was not practical to make moisture content determinations of the specimens before test, it is reasonable to believe that the specimens that spalled had greater moisture contents than the specimens that had been heated or aged for a longer time. However, the strong possibility that the spalled specimens had comparatively high moisture contents does not prove that the latter caused the former. Had moisture content been the cause, spalling should have occurred in the transverse ribs and longitudinal flanges. These members were not spalled in any instance. Therefore, it appears that moisture content was not the sole cause of the spalling, but may have been a contributing factor.

The thermal gradient through a homogeneous material is not linear, ordinarily, when the temperature to which the hot surface is exposed is changing. The data from these tests, and published data from other standard fire tests of concrete slabs, show that the thermal gradient is steepest near the hot surface and lessens with increased depth from that surface during the first half hour of exposure. Comparison of the data from these tests with the published data at the end of 30 min indicates that the average gradient across the 1 in. thick web was not nearly as steep as that across the first 1 in. of thicker specimens. The expansion of the hot surface layer produces tensile stresses in deeper concrete. Even though the above comparison of gradients indicates that these stresses should be greater at 1/2- and 1-in. depths in thick specimens than at the center and back face of 1 in. thick webs, the former have the support of the additional depth to resist the formation of tension cracks and spalling. In addition, the presence of the wire mesh in the center of the thin webs might be expected to produce a slight discontinuity, similar to that between successive layers of laminated materials, at a depth where a steep thermal gradient would produce shear stresses parallel to the plane of the mesh. Therefore, it appears that the thermal gradient would be more likely to lead to spalling of the webs than of thicker sections such as the flanges and transverse ribs.

The foregoing discussion indicates that 1) high moisture content should be less likely to produce spalling in specimens having had long aging and heating than in those having had shorter aging and no heat, 2) moisture content should be more likely to produce spalling of the surface from thick sections than from thin sections having been aged under similar conditions, 3) that the stresses resulting from steep thermal gradient should be more likely to produce spalling of thin sections than of thick sections. Points 1 and 3 are in agreement with the observed results whereas point 2 disagrees. This tends to support the thermal gradient as the cause. However, further examination of the data weakens this support. The average temperatures of the furnace fires, the wire mesh at the centers of the thin webs, and on the unexposed surfaces of the three specimens that spalled were very nearly equal to the overall averages for all the non-insulated specimens and were slightly lower than those for two specimens, of the same age, that did not spall. These two specimens had been heated during aging. The thermal gradients, as indicated by graphs of temperature versus depth from the exposed face, were of the same order of magnitude for the several specimens.

From the above considerations it can be seen that there is some support and some contradiction for both thermal gradient and high moisture content as the cause of the spalling. In the absence of clear indications for one, it may be assumed that each was a contributing cause to an effect, spalling, that neither could produce alone.

The results of the several tests in the program indicate that thin shell concrete slabs of the type and size investigated will provide about 10 min fire endurance as determined by the methods given by ASTM E-119. However, the addition of 1/2 in. of either glass fiber or perlite concrete insulation to the underface of the thin-shell sections will lead to fire resistances of about 30 min. Well aged specimens can be expected to continue as effective barriers to the passage of flames for about 1 hr but panels may spall through if exposed to fire within the first four to seven months after casting unless heated to reduce moisture content.

Table 1. Details of Specimens and Test Conditions

Test No.	Date	No. of Panels	Reinforcing	Intermediate ribs	Conditioning Aging	Conditioning Other	Compr Strength $lb/in.^2$	Applied Load
325	6/30/53	3	Conventional	3	3-3 1/2 mo	None	6800	15.3 lb/ft^2
339	3/16/54	3	do	3	10 1/2-11 mo	do	6260	15.3 lb/ft^2
346	10/8/54	3	Prestressed	3	3-3 1/2 mo	do	6780	15.3 lb/ft^2
347	11/19/54	1	do	None	4 mo	do		None
348	12/16/54	1	do	do	4 1/2 mo	1 wk heat		15.3 lb/ft^2
349	12/28/54	1	do	do	4 mo	1 wk heat		None
362	3/5/56	1	do	do	7 1/2 mo	10 days heat	5190	28 lb/ft^2
363	3/8/56	1	do	do		None	3100	28 lb/ft^2
364	3/12/56	1	do	do	8 mo	do	3540	None
365	3/14/56	1	do	do	9 mo	do	4910	14 lb/ft^2
366	3/15/56	1	do	do	8 1/2 mo	do		None
367	3/16/56	1	do	do	8 mo	do	6260	14 lb/ft^2
368	3/19/56	1	do	do	7 1/2 to 8 mo	do		None
369	3/20/56	1	do	do	3 1/2 mo	do	4420	14 lb/ft^2

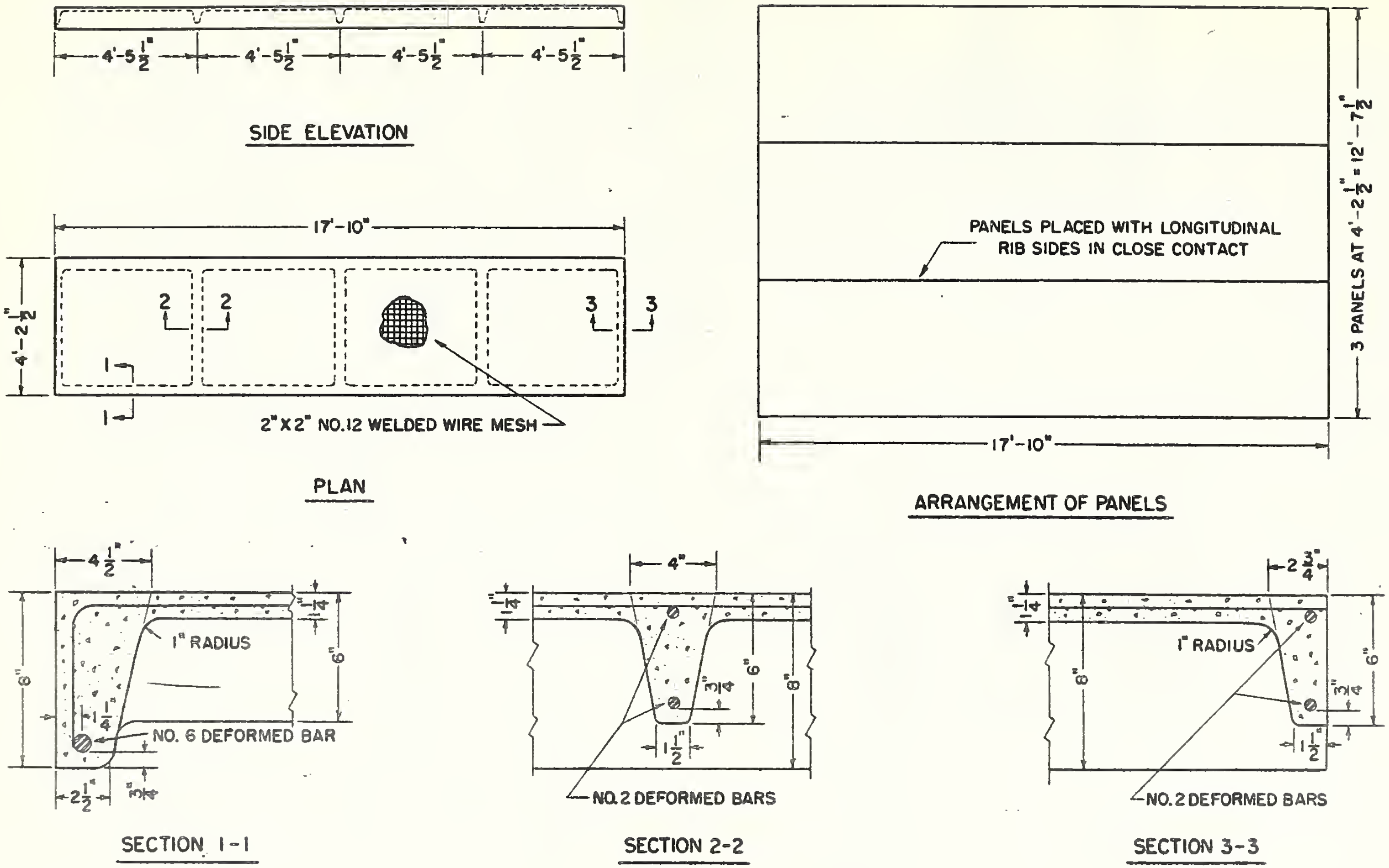
Table 2. Results

Test No.	Times at which end points reached: Temperature rise 250°F av	Temperature rise 325°F max	Load Failure	Flame Passage	Duration	Time at which main reinf. reached temp.: 1000°F av	1200°F max	Fire Exposure Severity %	Load lifted	Fire Endur. Corrected (where applicable)	Footnotes
325	0:10	0:10	-	0:10 & 0:15[a]	1:02	1:00	0:48	93.0	-	0:10	[a]spalled through explosively
339	0:10	0:12	1:53	-	2:03	1:25	1:33	92.9	1:52	0:10	
346	0:08	0:06	-	0:10[a]	0:13	-	-	105.1	-	0:06	
347	-	-	-	0:06[a]	0:07	-	-	117.8	-	0:06	
348	0:07	0:08	1:28[b]	-	1:28	1:06	1:11	98.4	-	0:07	
349	0:08	0:09	-	-	1:02	0:53	-	101.4	-	0:08	[b]collapse
362	0:09	0:11	-[c]	-	1:01	-	-	92.6	0.59[c]	0:09	[c]on support chains
363	0:11	0:12	-[c]	-	1:01	0:59 / 0:48[e]	0:53	94.3	0:54[c]	0:11	
364	0:14	0:16	-[d]	-	1:39½	1:06	1:04	91.7	-	0:14	[d]specimen jammed in arch
365	0:10	0:12	1:24[b,c]	-	1:25	0:59	0:56	102.3	-	0:10	
366	0:31	0:39	1:29[c]	-	1:29	1:27[e]	-	95.4	-	0:30	[e]one bar, only
367	0:28	0:32	-[c]	-	0:50	-	-	100.5	0:46[c]	0:29	
368	0:31	0:31	-	-	1:17	-	-	93.5	-	0:31	
369	0:28	0:32	1:00	-	1:03	-	-	98.0	-	0:29	

Table 3. Ages of Panels and Behavior as to Spalling

Condition	Spall, age	No spall, age
Conventional, no heat, 1/2 loaded	3 1/2 mo	10 1/2 mo
Prestressed, no heat, loaded,		8 mo
Prestressed, no heat, 1/2 loaded	3-3 1/2 mo	9 mo
Prestressed, no heat, no load	4 mo	8 mo
Prestressed, heated, loaded	-	7 1/2 mo
Prestressed, heated, 1/2 loaded	-	4 1/2 mo
Prestressed, heated, no load	-	4 mo
Insulated, prestressed, no heat, 1/2 load		3 1/2 mo*
Insulated, prestressed, no load, no heat		7 1/2-8 1/2 mo*

*Includes consideration of results from two tests.



NOTES

CEMENT FACTOR	7 BAGS/CU. YD.	INTERMEDIATE GRADE REINFORCING	24,000 PSI
MAXIMUM SIZE AGGREGATE	3/8 IN.	WIRE MESH	30,000 PSI

FIG. 1 CONSTRUCTION DETAILS OF PRECAST ROOF PANELS

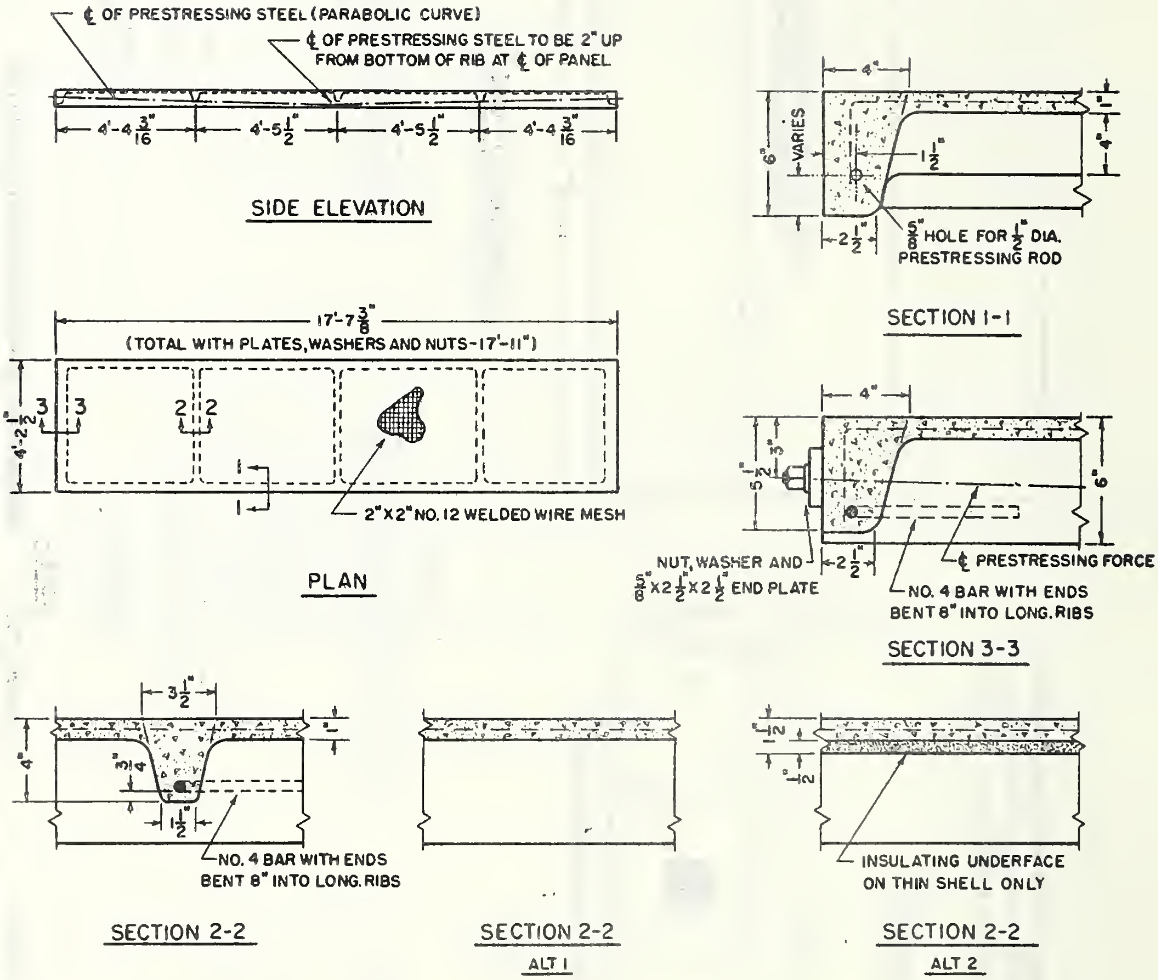


FIG. 2 CONSTRUCTION DETAILS OF PRECAST-PRESTRESSED ROOF PANELS

NOTES

CEMENT FACTOR	7 BAGS/CU YD.	INTERMEDIATE GRADE REINFORCING	24,000 PSI
MAXIMUM SIZE AGGREGATE	3/8"	WIRE MESH	30,000 PSI

Fig. 3. Exposed surface of center panel, test 346, showing spalled area of panel with transverse ribs.

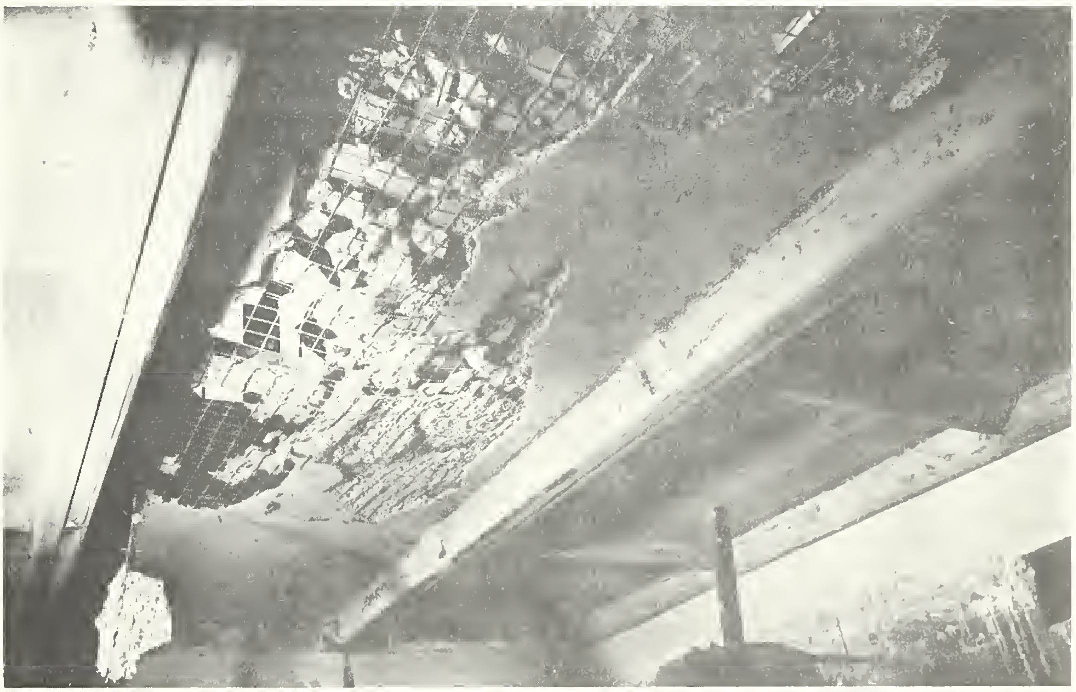


Fig. 4. Exposed surface of center panel, test 347, showing spalled area of panel without intermediate transverse ribs.

Fig. 5. Arched condition of panel, test 364, tested without applied load.

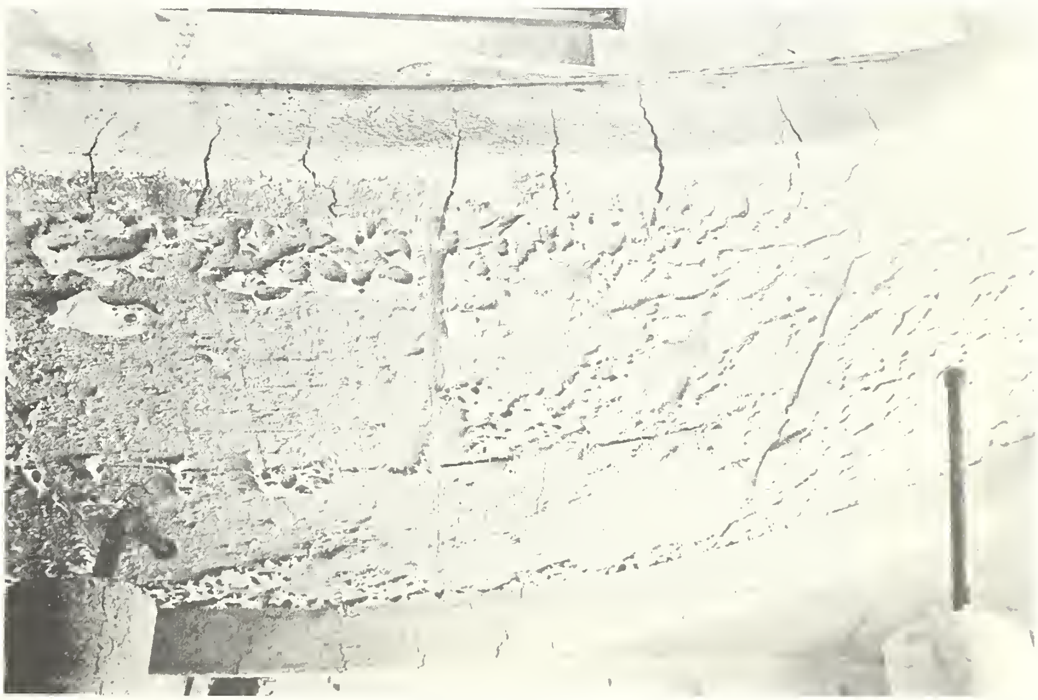


Fig. 6. Exposed surface of specimen having had glass fiber underface, showing remains of same and cracks in concrete.

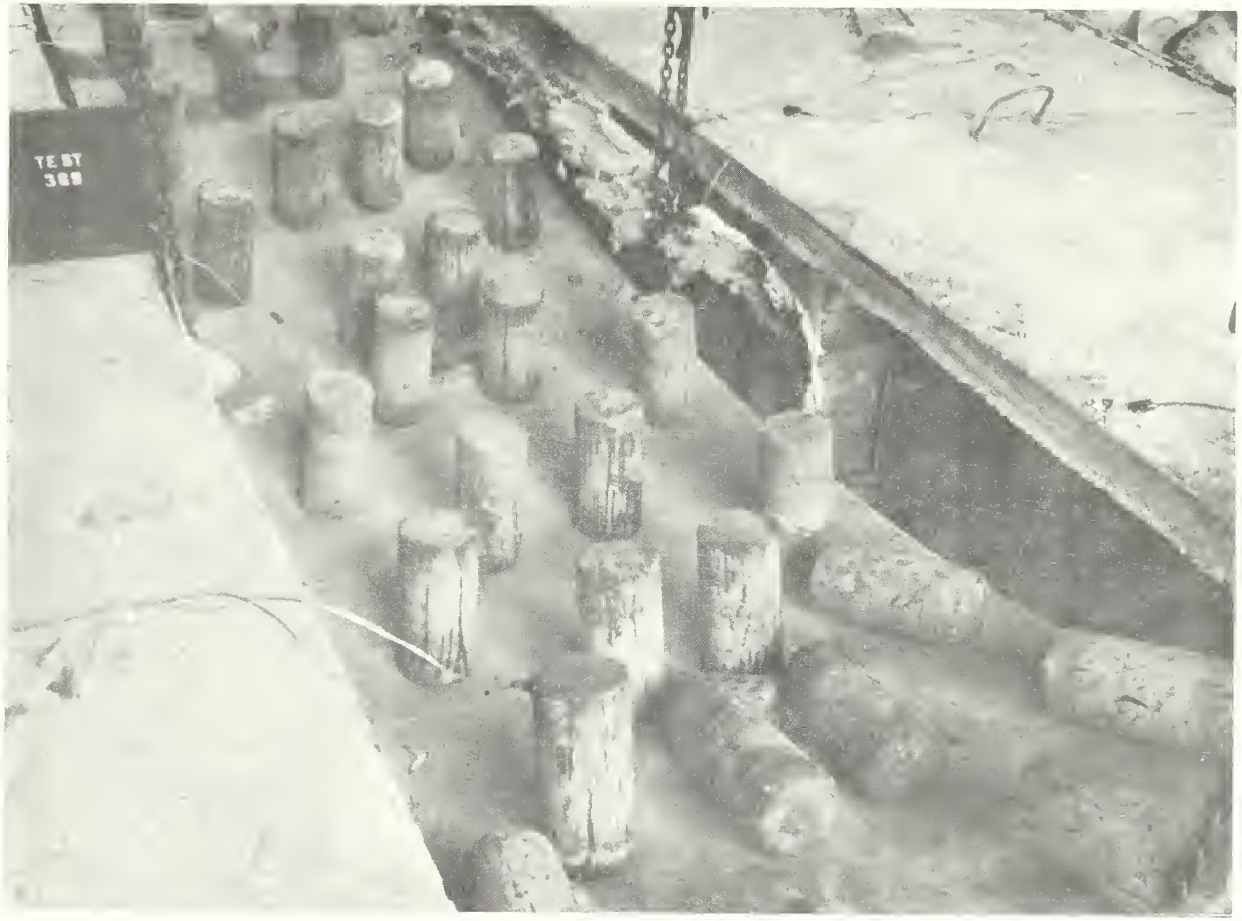


Fig. 7. Panel deflected about 20 in., beyond which further deflection or collapse prevented by chain suspension. Load (14 lb/ft^2) supplied by 6 in. diameter 12 in. long concrete cylinders.

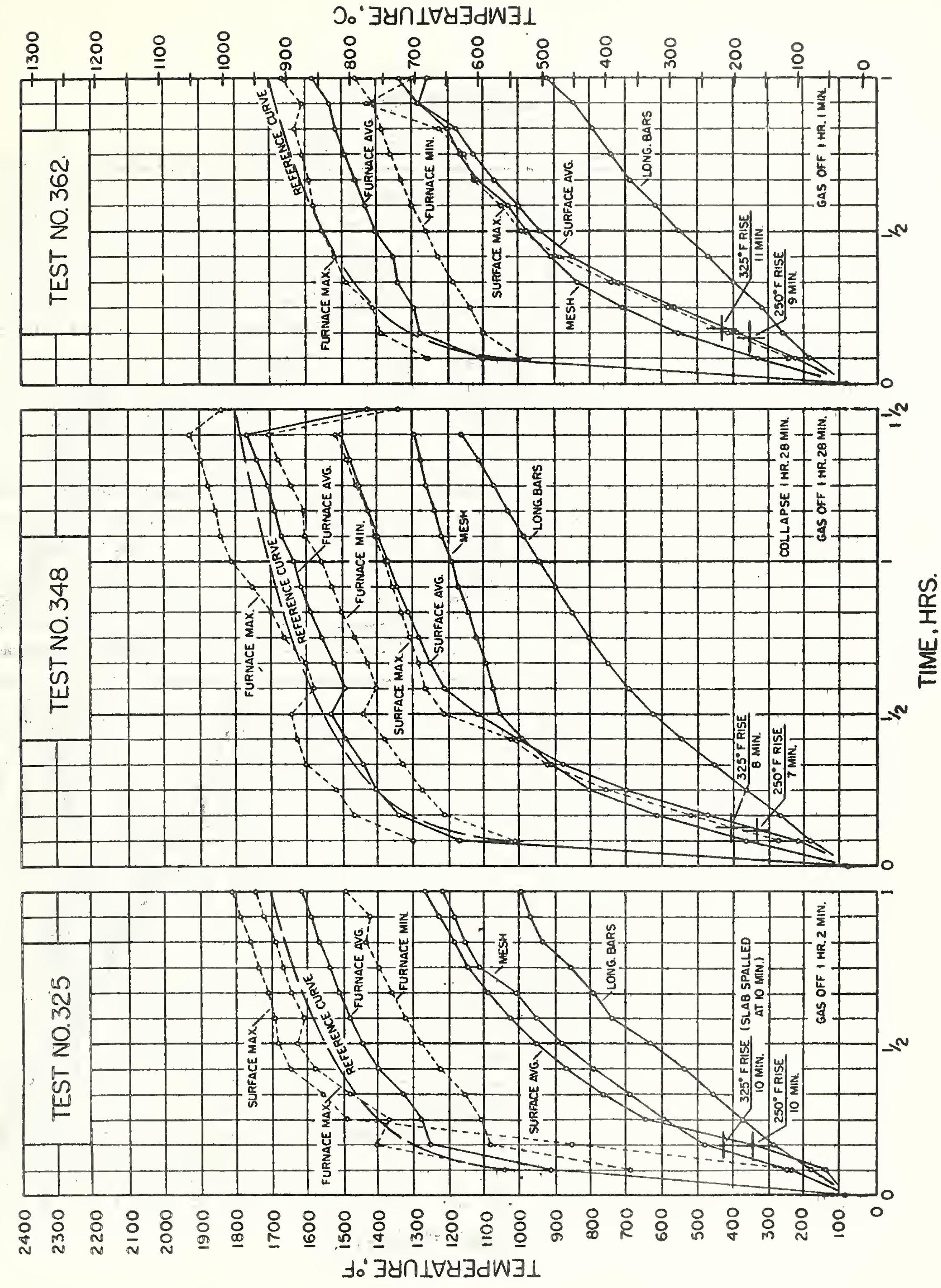


Fig. 8. Representative time-temperature curves of non-insulated panels. 325, spalled panel; 348, about same age as 325, heated, no spall; 362, heat, longer aging, no spall.

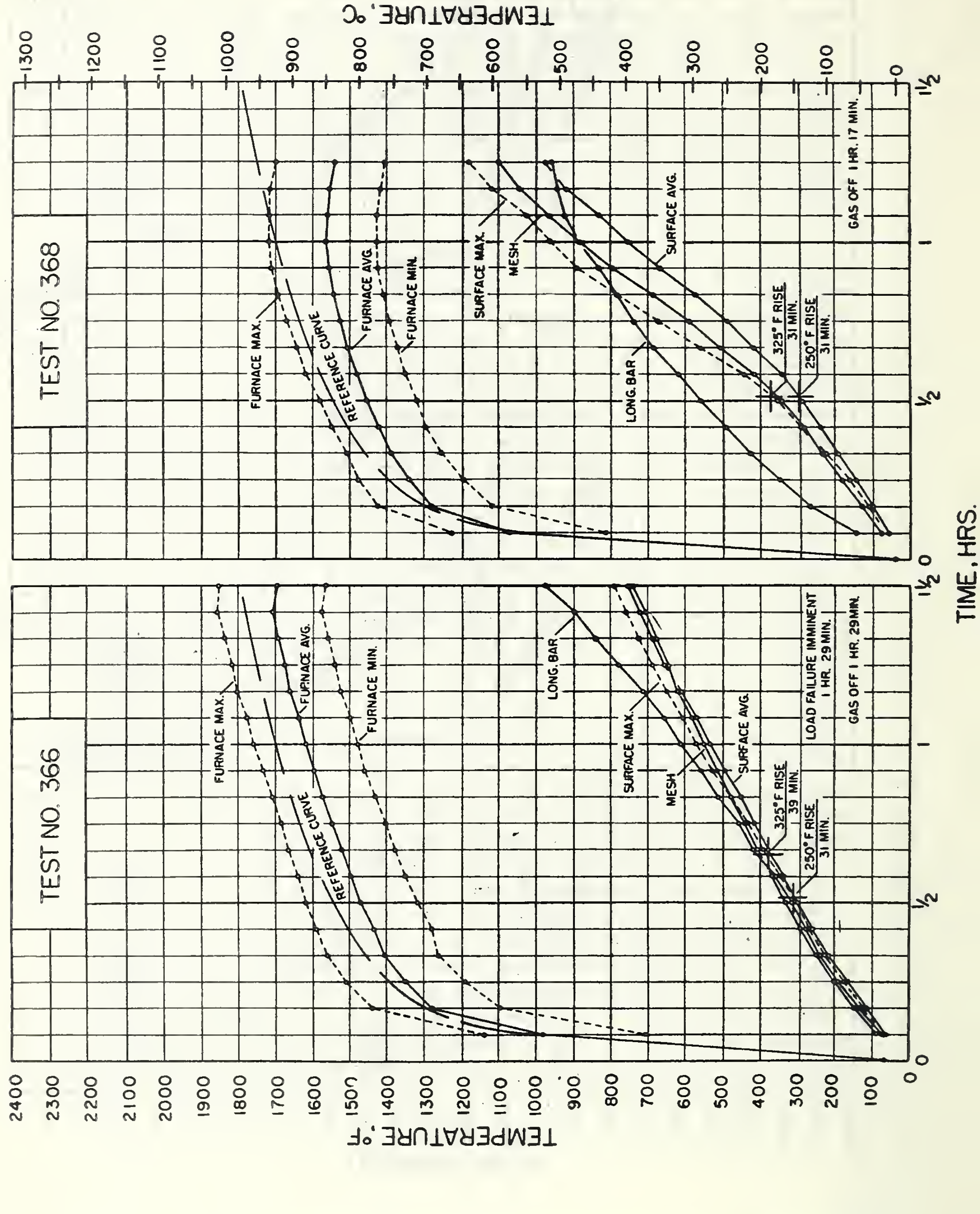


Fig. 9. Representative time-temperature curves of panels with insulating underfaces. 366, lightweight concrete insulation; 368, glass fiber insulation.

THE NATIONAL BUREAU OF STANDARDS

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