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Fire Endurance of Open-Web Steel-Joist Floors With Concrete Slabs and Gypsum Ceilings

United States Department of Commerce

National Bureau of Standards

Building Materials and Structures Report 141

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Fire Endurance of Open-Web Steel-Joist Floors With Concrete Slabs and Gypsum Ceilings

James V. Ryan and Edward W. Bender

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Fire Endurance of Open-Web Steel-Joist Floors With Concrete Slabs and Gypsum Ceilings

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The results presented were obtained in a program of 18 fire tests on open-web steel-joist floors, 16 of which were protected by ceilings of gypsum-perlite plaster on gypsum lath "furred" directly to the joists. Variables included plaster thickness, plaster mixes, spacing of furring channels, system of lath clips, reinforcing in the ceilings, and type of floor slab. An acoustical plaster finish was applied to one ceiling. The range of fire endurances obtained, from 1 hour to 4 hours 26 minutes, was sufficient to cover the requirements for floors in many building codes. The importance of the ceiling's protective function was demonstrated in two tests without ceilings, in each of which failure occurred at 7 minutes.

1. Introduction and Scope

The anticipated occupancy for which a building is designed predetermines the necessary strength of the whole structure and its various components, which fact frequently limits the designer's choice as to the type of construction to be used. This is especially true of the roof and floors upon which the "live load" rests directly. Floors and roofs of reinforced concrete slabs on open-web steel joists may be designed to provide load-bearing capacities within a wide range, including those adequate for houses, apartment buildings, stores, and office buildings. The Steel Joist Institute's tables of safe allowable loads [1][1] list total loads ranging from 28 to 530 lb/ft^2 of floor area for the various combinations of size, spacing, and clear span of open-web steel joists. This type of construction is widely used for roofs and floors in buildings of the types mentioned above.

Standard laboratory fire tests as well as actual fires in structures have shown that unprotected steel has a very low fire resistance in that it loses its strength at temperatures that are reached quickly in such fires. Therefore, the loadbearing capacity of a combination of a thin concrete slab on open-web steel joists would be "short lived" in a fire and its fire endurance correspondingly short. However, the joists may be protected with some type of ceiling and the fire resistance increased thereby. Such protection is provided by a ceiling of lightweight gypsum plaster on gypsum lath.

The "calcined" gypsum used to prepare gypsum plaster, or gypsum concrete, is identified by the chemical formula $CaSO_4 \cdot \frac{1}{2}H_2O$. When mixed with water, the powdery calcined gypsum takes up water into chemical combination and sets into a hard, strong substance, hydrated gypsum, changing from $CaSO_4 \cdot \frac{1}{2}H_2O$ to $CaSO_4 \cdot 2H_2O$. The latter form is that present in gypsum plasters, gypsum-fiber concretes, and the cores of laths, wallboards, and formboards. The calcined gypsum ($CaSO_4 \cdot \frac{1}{2}H_2O$) is 6.2 percent water by weight, and hydrated gypsum ($CaSO_4 \cdot 2H_2O$) is 20.9 percent water. Thus every 100 lb of calcined gypsum has about 3 qt of water in chemical combination, which increases to 12 qt as the gypsum "sets," or hydrates. When the gypsum plaster and lath are subjected to high temperatures, the gypsum calcines, or loses its combined water, at temperatures near the boiling point of the latter. Although gypsum calcines at temperatures that are low compared to those in a fire, test or otherwise, the high thermal capacity and heat of vaporization of water make the process slow. This change is accompanied by decrease in strength, shrinkage, cracks, and eventual breakage of plaster and lath. As the cracking of the lath and plaster progresses, the areas into which the ceiling is subdivided by the cracks become smaller and smaller until some of them are not supported by any component of the system by which the whole ceiling has been supported. As these unsupported areas of lath and plaster fall, the joists are exposed to the flames and soon lose their strength, resulting in load failure. Up to a limit, the fire endurance may be extended by increasing the amount of plaster applied, which lengthens the time required for the gypsum to calcine. However, after calcination, the gypsum serves as a good shield to protect the joists from radiant energy and from direct contact with the flames. Therefore, means of keeping the lath and plaster in place following calcination will contribute to greater fire resistance.

In order to determine the effects of added plaster thickness and of different means of reinforcing and retaining the lath and plaster, 2 exploratory tests

[1] Numbers in brackets indicate literature references at the end of this report.

and 16 standard fire-endurance tests were performed in the furnaces of the National Bureau of Standards. Two of the latter tests (324 and 329) were made on joists and slab without any ceiling. In the other tests, ceilings of gypsum-perlite plaster on ⅜-in. perforated gypsum lath were applied by 1 of 3 supporting systems. The plaster thicknesses ranged from ½ in. to 1¼ in. In 6 tests (311, 312, 313, 316, 318, and 326) an extra number of clips or 1 of 2 forms of supplementary reinforcing were employed. In test 326, an acoustical plaster was applied as the final coat, following gypsum-perlite plaster base coats.

2. Materials

Some of the materials were delivered from the manufacturer directly, some were purchased from distributors of building materials, and some were provided by local contractors. They were considered representative of the materials available on the market in the local area and in many other metropolitan areas, except for the plasters used, which set faster than those generally available on the East Coast. The details of the particular materials used in each test, and of the variation of materials from test to test, are given in table 4.

2.1. Steel Joists and Accessories

The steel joists were an open-web type, designated SJ103 under the system adopted by the Steel Joist Institute. The top chord consisted of two 1¼- by 1¼- by ⅛-in. angles; the bottom chord of two 9/16-in. rods; and the web of a combination of a single ½-in. rod near each end and a 7/16-in. rod in the center. The web was of a zigzag form and was welded between the angles at the top and the 9/16-in. rods at the bottom. Bearing plates of 3/16-in. steel were welded to each end. The joists were 10 in. deep and 13 ft 4 in. long for the large floors and 9 ft long for the small floors. They were finished by the manufacturer with a bituminous coating applied hot after the joist assembly was completed.

The bottom chords had been bent up near each end, and the 10-in. depth did not extend to the furnace wall. Therefore, formed ⅜- or 5/16-in. rods were provided to hang on each end of each joist and continue the line of the lower chords for the attachment of the ceiling. Lengths of ¾-in. cold-rolled channel, factory cut to the proper length, with a flat piece at each end to be bent around the joist chord were provided as bridging for the joists.

2.2. Materials for Floor Slabs

The bases for the portland-cement concrete floors were expanded metal laths with ⅜-in. V-ribs and ⅛-in. inverted V-ribs between the ⅜-in. ribs. Two varieties were used; one, nominally 4.0 lb/yd², came in sheets 96 by 24 in.; and the other, nominally 3.4 lb/yd², came in sheets 96 by 27 in. A check on one order of the latter showed an actual weight of 3.29 lb/yd². The formboard base for the gypsum-cement slabs was a ½-in. paper-faced gypsum board, which came in sheets 90 by 32 in. and weighed 2.2 lb/ft².

Except for tests 261 and 266, the portland-cement concretes were mixed 1 part by weight of portland cement, 2 parts of washed Potomac River (siliceous) sand, and 4 parts of pea gravel (siliceous). For tests 261 and 266 the mix was 1:2:3½ by weight. The concretes were machine-mixed on the job for tests 257 and 260, and delivered truck-mixed for the remainder.

The gypsum concrete was a mill mix of the gypsum plaster and aggregate, requiring only the addition of water. A chemical analysis indicated the major constituents were $CaSO_4 \cdot \frac{1}{2}H_2O$, 82.4 percent, and wood fiber (wood chips), 6.2 percent. A sample mixed 3 parts to 2 parts of water, by weight, in the laboratory and cast in 2-in. test cubes had a compressive strength of 720 lb/in.² after aging about 7 weeks.

Reinforcing in each concrete slab was provided by 1 of 3 types of welded wire fabric. Two types consisted of a 6-in. square mesh, one of 10 gage wires and the other of 8-gage wires, and the third type consisted of 14-gage wires spaced 8 in. and 12-gage wires spaced 4 in. at right angles to the former.

Accessories used in assembling the floor-slab forms included bulb-T rails in floor-length pieces for test 296, T-rails in 2- to 3-in. lengths for test 297, and galvanized 18-gage tie wire for the remaining tests. This wire was also used in all the ceiling assemblies.

2.3. Gypsum Lath

The laths used in these tests were ⅜-in. perforated gypsum lath in pieces 48 by 16 in. Each piece contained 48 perforations, each ¾-in. diameter, one for each 16 in.² The products of four manufacturers were used as representative of the materials available on the market. Ordinarily, sufficient lath was available to provide samples for the strength tests that were made on the 12- by 16-in. specimens. Table 1 gives the results obtained in these tests. It should be noted that the strengths of most of the samples tested parallel to the fiber were less than the minimum required by the test specification (ASTM C26–52).

2.4. Lathing Accessories

Furring for the placement of the gypsum lath was provided by ¾-in. steel channels. The channel came in 20-ft lengths and was cut on the job to the required size. The type of channels, either "hot-rolled" or "cold-rolled", used in each test specimen was determined by the system of clips to be used and is given in table 4.

Several different types of formed wire and sheet-metal clips were used in connection with the placement and support of the gypsum lath. These clips are shown in figure 3.

Table 1. *Results of tests on gypsum laths* [a]

Specimens 16 by 12 in. mounted on parallel 12-in.-long bearings, 14 in. apart and load applied from above through third 12-in.-long bearing parallel to and midway between first two. Samples tested to breaking with bearings parallel to paper fiber and other samples with bearings perpendicular to fiber. Bearings rounded to ⅛-in. radius.

Lot	Measured thickness	Breaking loads			
		Parallel to fiber		Perpendicular to fiber	
		Average	Minimum	Average	Minimum
	in.	*lb*	*lb*	*lb*	*lb*
1	0.353	26.6	----	84.4	----
2	.368	19.4	17.4	55.0	51.0
3	----------	23.3	21.6	75.2	72.0
4	----------	19.6	18.0	70.5	67.0
5	.359	24.0	22.2	77.5	75.4
6	.362	19.8	18.0	71.4	68.4
7	.360	22.4	22.0	78.0	74.8
8	.380	37.0	35.0	73.7	71.0
9	.357	23.8	22.4	80.6	79.8
10	.376	([b])	([b])	54.8	52.4
ASTM requirements [a]	.375 ± .031	27	----	60	----

[a] Tests under the provisions of ASTM C26–50 and –52 and C37–50.
[b] Not enough extra lath for all tests.

2.5. Wire Reinforcing

Additional support for the gypsum lath and reinforcing for the plaster were provided in two test specimens (311 and 312) by the use of 1-in. hexagonal-mesh galvanized 20-gage wire fabric, approximately 3 ft wide. For three test specimens (313, 318, and 326) lengths of galvanized 14-gage wire were used to provide support supplementary to that of the clips.

2.6. Plaster and Aggregate

The regular plasters used were extra-fibered gypsum plasters of well-known manufacturers and are commonly available in most parts of the country. The chemical compositions and physical properties were determined in accordance with the methods prescribed by Federal Specification SS–P–402 and met the requirements set forth therein. They also met the requirements set forth in ASTM Designation C28–50, except that

Table 2. *Results of chemical and physical tests of plasters* [a]

Chemical analysis	Maximum	Minimum
$CaSO_4.1/2H_2O$ (by ammonium acetate) %	93.7	74.1
$CaSO_4.1/2H_2O$ (by SO_3) %	92.7	73.9
$CaSO_4.1/2H_2O$ (by loss at 230° C) %	93.6	75.0
$CaSO_4.1/2H_2O$ (average) %	[b] 93.6	[b] 74.4
Physical tests		
Consistency	[c] 48	[c] 18
Time of set hr	11	4½
Tensile strength lb/in.²	245	160
Compressive strength lb/in.²	1,540	770

[a] Only maximum and minimum values for determinations of 10 samples.
[b] Maximum and minimum of averages of the three methods of determination.
[c] Consistency giving time of set on following line.

Table 3. *Sieve analyses of perlite aggregates*

Sieve	Proportion of material passing		
	Sample 1	Sample 2	Sample 3
	Percent	*Percent*	*Percent*
6	--------	--------	--------
8	100	99.9	98.6
10	--------	99	96
12	--------	--------	--------
14	--------	87	84
16	--------	78	75
20	--------	60	58
30	37	45	45
40	--------	--------	--------
50	21	24	23
70	--------	--------	--------
100	12	12	12
200	4.9	7.3	7.9

the mill-mixed plaster for test 266 had a longer time of set than the maximum allowed for such plasters. The results obtained from the prescribed tests are given in table 2. The plasters used for tests 257, 260, 261, and 266 were mixed with the aggregate at the manufacturer's plant.

The aggregate used for the regular plasters was expanded perlite, weighing 8 to 8½ lb/ft³. The sieve analyses of three shipments of perlite are given in table 3.

The acoustical plaster used in the specimen for test 326 was a proprietary mix that required only the addition of water. The particular acoustical plaster had been chosen as having shown the highest thermal conductivity in a group of comparison tests on samples of about 4 ft² exposed surface. The plaster appeared to be a mixture of gypsum and a lightweight aggregate in granules slightly larger than those of sand. However, its application characteristics were different from those of sanded or lightweight aggregate gypsum plasters.

3. Construction

The constructions of the test specimens were similar to those obtainable in regular building practice. The major part of the construction work was done by regular employees of various contractors, with general supervision by National Bureau of Standards personnel who have had considerable experience in the preparation of test specimens. The differences between the floors tested in the large furnace and those tested in the small furnace were made necessary by the sizes and designs of the furnaces and the provisions for mounting the test floors. They were not variations in the basic type of construction being tested. The variables in the construction of the individual test specimens are given in table 4. Typical constructions are shown in figures 1 and 2.

3.1. Placement of Joists

In the large furnace, nine of the 13-ft 4-in. joists were placed to span the short dimension of the furnace. They were spaced 24 in. on centers, which put each end joist approximately 7 in. from the furnace brickwork. The end of the joists

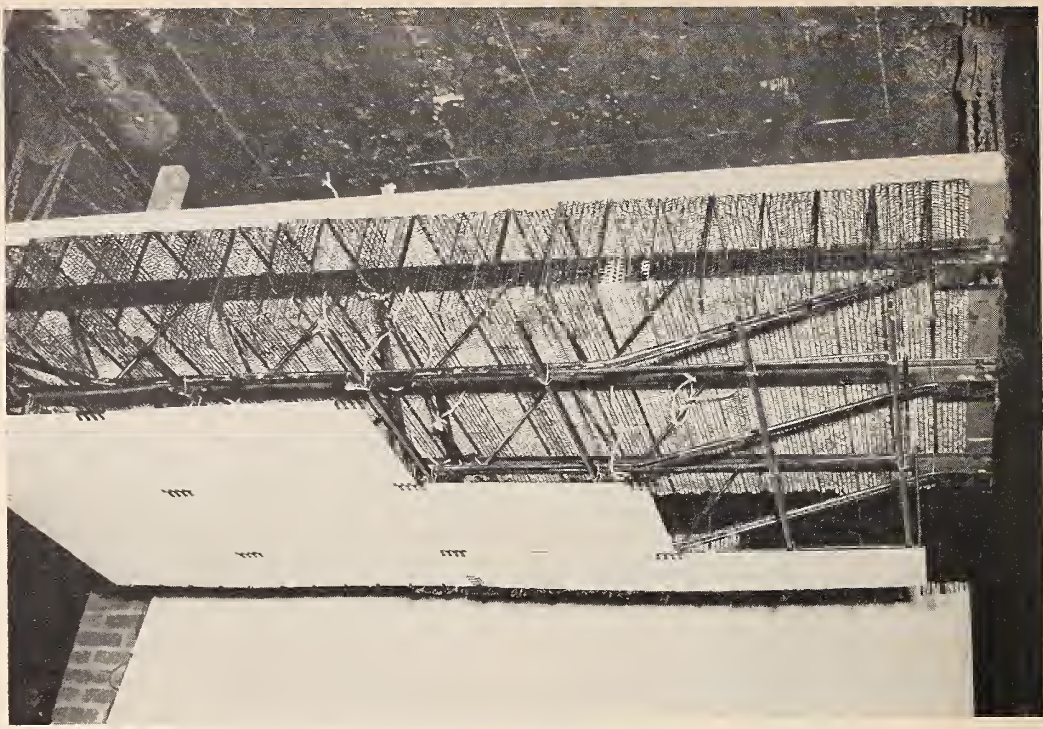

FIGURE 1. *Specimen for exploratory test during construction, showing joists and slab, furring, lathing, and clips.*

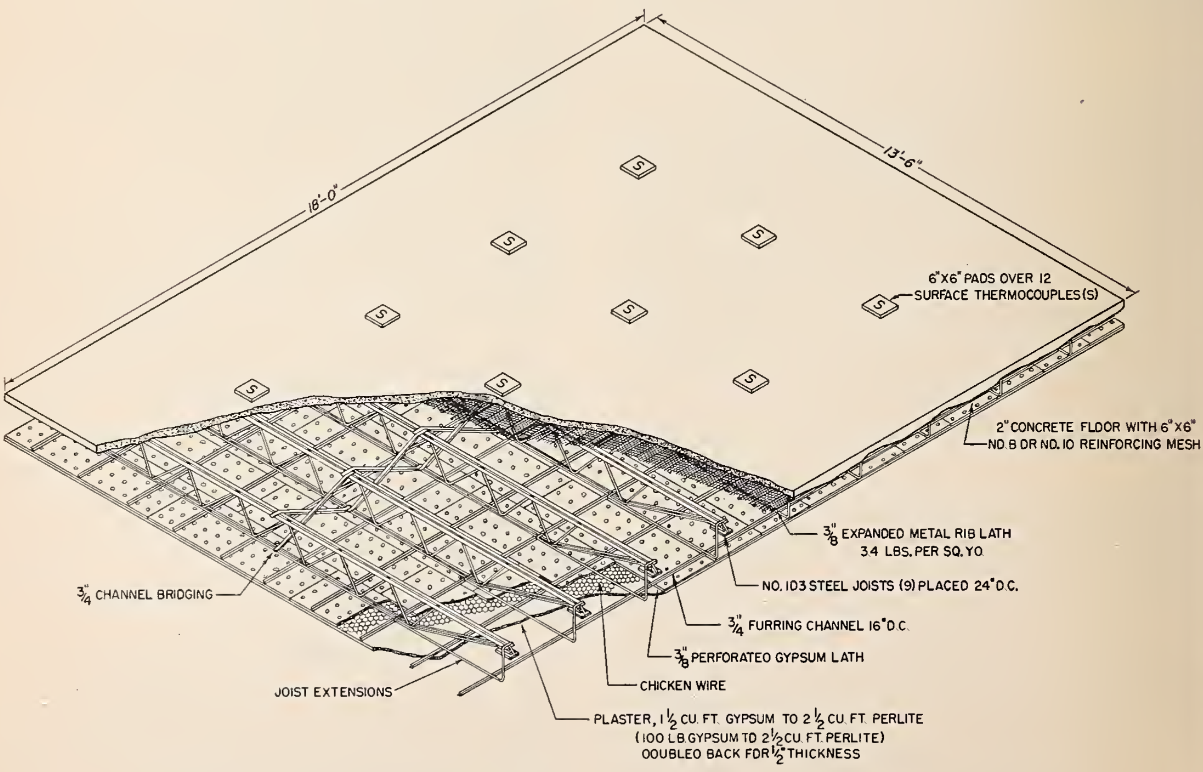

FIGURE 2. *Construction details of specimen for test 312 with hexagonal-mesh wire reinforcing.*

Table 4. *Summary of construction elements and fire endurance limits*

All specimens with No. SJ103 open-web steel joists; 18 in. on centers in tests 257 and 260, 24 in. on centers in all others. Plaster base was ⅜-in. perforated gypsum lath in each ceiling. Floor-slab dimensions were 9 ft by 4 ft 4 in. for tests 257 and 260; 18 ft by 13 ft 6 in. for all others.

Tests	Floor				Joist extension size
	Base	Reinforcing		Slab	
		in.	*Gage*		*in.*
Exploratory tests:					
257	4-lb rib lath	6×6	10×10	1:2:4 gravel concrete, 2 in. over joists	5/16
260	do	6×6	10×10	do	5/16
Standard tests:					
261	4-lb rib lath	6×6	10×10	1:2:3½ gravel concrete, 2 in. over joists	5/16
266	do	6×6	10×10	do	5/16
287	3.4-lb rib lath	6×6	10×10	1:2:4 gravel concrete, 2 in. over joists	⅜
295	do	6×6	10×10	do	⅜
296	½-in. gypsum board	8×4	14×12	Mill-mix gypsum concrete, 1½ in. over base	⅜
297	do	8×4	14×12	do	⅜
316	3.4-lb rib lath	6×6	8×8	1:2:4 gravel concrete, 2 in. over joists	5/16
317	do	6×6	8×8	do	5/16
319	do	6×6	8×8	do	5/16
313	do	6×6	8×8	do	⅜
318	do	6×6	8×8	do	5/16
326	do	6×6	8×8	do	5/16
311	do	6×6	8×8	do	⅜
312	do	6×6	8×8	do	⅜
324	do	6×6	8×8	do	5/16
329	do	6×6	8×8	do	None

Tests	Ceiling						Age at test [b]	Fire endurance limit [c]	
	Furring		Clip types [a]	Reinforcing	Plaster				
	Type	Spacing			Mix (by volume)	Thickness			
		in. on center				*in.*	*Days*	*hr*	*min*
Exploratory Tests:									
257	¾-in. cold-rolled	16	C, E	None	1½:2½ (mill)	½	47	1	10 [d]
260	do	16	do	do	do	¾	49	1	56 [d]
Standard tests:									
261	¾-in. cold-rolled	16	C, E	None	1½:2½ (mill)	⅝	30	1	24
266	do	16	do	do	do	½	28	0	55 [e]
287	do	16	D, E, F, G	do	1½:2½	⅝	36	1	00 [f]
295	do	16	do	do	1½:2; 1½:3	1	42	1	42
296	do	12	do	do	do	1¼	42	1	48
297	¾-in. hot-rolled	12	do	do	do	1⅛	43	1	43 [g]
316	¾-in. cold-rolled	12	A, B, G	Extra A clips	do	⅝	35	3	00 [f]
317	do	16	do	None	1½:2½	½	38	1	04
319	do	12	do	do	do	½	33	1	15
313	¾-in. hot-rolled	12	D, E, F, G	Diagonal wires	1½:2; ½:3	⅝	34	3	15
318	do	16	do	do	1½:2½	½	38	2	46
326	¾-in. cold-rolled	12	C, E, F, G	do	([h])	1⅛	31	2	44
311	¾-in. hot-rolled	12	D, E, F, G	Hexagonal mesh	1½:2; 1½:3	1	28	4	26
312	do	16	do	do	1½:2½	½	34	3	28
324	None		None	None	None		42	0	07
329	do		do	do	do		34	0	07

[a] Clip types shown in figure 3.
[b] Age of final base coat of plaster except when no ceiling, then age of concrete slab.
[c] The fire endurance limit was obtained by applying a correction formula, given in ASTM E119, to the time at which the first end point was reached (see table 5).
[d] Size less than minimum specified in Standard Test Methods (E119), hence does not represent standard fire endurance.
[e] Not loaded, estimated time at which specimen would have failed under load.
[f] No end point reached; load removed at this time and test discontinued to prevent damage to joists and slab and to permit reuse of same in next test.
[g] Power failure caused brief interruption of test; 3 min added to observed time.
[h] Base coat ½ in. of 1½:2½ gypsum-perlite plaster, acoustical finish of ⅝ in. of proprietary mill-mix plaster.

rested on the furnace shelf angles but were not attached thereto in any manner. A formed rod extension of the bottom chord was hooked to each end of each joist and a single row of X-bridging was placed transversely to the joists at centerspan. The end joists were anchored to the furnace wall in line with the bridging. In the small furnace, three of the 9-ft-long joists were placed to span the long dimension of the furnace and were spaced 18 in. on centers. Channel X-bridging at centerspan and formed rod extensions were attached in the same manner as in the larger constructions.

3.2. Floor Slabs

The expanded-metal rib lath was laid on the joists with the long dimension perpendicular thereto. The ends of successive sheets were overlapped from 4 in. to 1 ft, and the edges of adjoining sheets were overlapped from 3 to 9 in. The lath was tied to the top chords of the joists, with tie wire at each rib. The lapped joints between laths were secured with single-strand wire ties. Small holes were cut in the lath at the necessary locations over the joists to allow the passage of the leads from the thermocouples attached to the joists.

Above the metal lath, a welded wire fabric of 8- or 10-gage wires in a 6-in. square mesh was placed and the portland-cement concrete was poured and screeded to a depth of 2 in. above the joists.

In preparation for the gypsum floor slab of test 296, six bulb-T rails were fillet-welded to the joists, one at each end and the other four spaced 32⅝ in. They were perpendicular to the joists and extended the full length of the floor. The 32-in.-wide sheets of gypsum formboard were laid on the flanges of the rails and the top chords of the joists. The rectangular-mesh reinforcing was forced down between the rails to lie very close to the upper surface of the formboard, with the 12-gage wires, 4 in. on centers, parallel to the rails and the 14-gage wires, 8 in. on centers, transverse to the rails and parallel to the joists. The gypsum concrete was mixed with water to the desired consistency and poured to a depth of 1½ in. over the formboard.

For the other test specimen with gypsum concrete slab, test 297, the formboard was placed on the joists without the bulb-T rails. Short lengths of regular steel T-sections were welded to the top chords and transversely thereto in an inverted position, and the vertical leg of the T was put through the formboard. The same rectangular-mesh wire fabric as in the other gypsum-concrete slab was laid down, also with the 14-gage wires parallel to the joists. Gypsum concrete was poured to a depth of 1½ in. over the formboard.

Between the joists, the metal lath sagged under the concrete as much as 3 in., but the gypsum formboard did not sag noticeably under the gypsum concrete. The floor slabs and steel joists were not damaged excessively in tests 261, 287, 316, and 319 and were reused in tests 266, 295, 317, and 324, respectively.

3.3. Furring and Lathing

The initial step in the construction of each ceiling was the attachment of the furring channels. They were applied transversely below the bottom chords of the joists and extensions and secured thereto with double-strand wire ties. They were spaced at either 12 or 16 in. on centers. The use of either "hot-rolled" or "cold-rolled" steel furring channels was determined by the type of lath clips to be used in the particular test specimen (see table 4).

The gypsum lath was placed with the long dimension at right angles to the furring channels and was attached thereto by clips of one of the types illustrated in figure 3. Two of the types, C and D, provided continuous support across the width of the lath, hooking over the furring channel at one edge and joining with the adjacent clip at the other edge. A third type of clip, B, provided support only at the lath edges but was used with type A, which punctured the lath to hook over the furring at intermediate points. This combination was used in tests 316, 317, and 319 only. Still other clips (E, F, G) were used at the ends and edges of each piece of lath to keep it in alinement with the adjoining ones. These latter clips, some or all types of which were used in each ceiling, did not transmit any support from the furring channels to the lath. The lath was cut, where necessary, to carry the ceiling to the

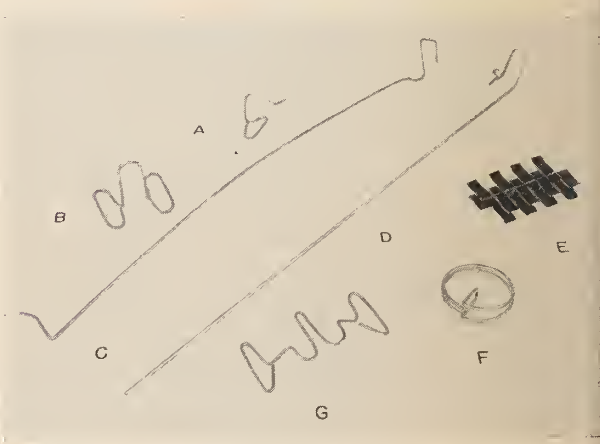

Figure 3. *Various clips used in applying ceiling laths for the test specimens.*

furnace wall and to make the ends fall between furring channels. Ordinarily, the cut pieces were long enough that they obtained support from at least two furring channels, whereas the full 48-in. length pieces were supported under 3 or 4 channels, depending on the spacing of the latter.

3.4. Reinforcing for Lath and Plaster

In five test specimens (311, 312, 313, 318, 326), following the lathing, 1 of 2 wire products was included in the construction to provide additional support and reinforcing to the lath and plaster. For tests 311 and 312, 1-in. hexagonal-mesh wire fabric—"chicken wire"—was stretched below the gypsum lath. It was tied to the lath clips during placement, but the main support was provided by double-strand wires tied between the edges of the lath to the furring channels. These wires were tied to each channel at each junction between laths. For tests 313 and 318, galvanized 14-gage wire was secured below the lath on the diagonal.

The wire passed under the lines of clips at the lath edges—the locations of clip connections—and hooked to the clips or was tied to them. In one half of the ceiling area, continuous lengths of wire extended from wall to wall and were tied to the clips with lathers' tie wire; in the other half, short lengths, approximately 2 ft long, were used and looped around the lower portions of the clips. The spacing of the diagonal wires was determined by the spacing of the lines-of-clips (furring channels); 12- and 16-in. spacings of the latter resulting, respectively, in 10- and 11.3-in. spacings of the wires.

Figure 4 shows the diagonal wire support in place below the lath during the construction of test floor 313.

type clips, shown in figure 3, one clip of type A was placed through the center of the 16-in. width of the lath along each furring channel, as in tests 317 and 319. However, in test 316 two A clips were used along each channel for each lath, one at each third point of the width.

3.5. Plastering

Wood strips of the proper size were tied to the gypsum lath to provide the temporary grounds for the plaster. They were removed after they had served their purpose, and the space left was filled with plaster. The depth of grounds, and thickness of plaster, was measured from the lower face of the gypsum lath. In each construction except

Figure 4. *Lathed ceiling with diagonal wire reinforcing.*

For test 326, 14-gage diagonal wires were also placed below the gypsum lath, but in a slightly different manner than described above. In one half of the ceiling, the short lengths bent around the clip junctions were used as described in the preceding paragraph. In the other half, 4-ft lengths were placed between the lath and supporting clips. They were neither bent around nor tied to any other component of the ceiling. The ends of successive lengths overlapped about 8 in.

In the five tests above, special reinforcings different from the other materials in the constructions were used. In test 316 additional support was provided to the ceiling by use of extra amounts of materials ordinarily a part of the construction. In usual building practice involving the A- and B-

the acoustical plastered ceiling (test 326), the grounds were set to $\frac{1}{16}$-in. less than the intended total plaster thickness so that the base coat or coats could be brought even with the grounds and the thickness completed with a $\frac{1}{16}$-in. white finish coat.

The base-coat plasters were applied by either the double-back process (tests 257, 260, 261, 266, 287, 312, 317, 318, 319), in which the full thickness of plaster is built up without waiting for part to set, or by the scratch- and brown-coat process (tests 295, 296, 297, 311, 313, 316, 326), in which the initial, or scratch, coat is applied, scratched to provide a better bond with the plaster to follow and allowed to set before the second, or brown, coat is applied to complete the base-coat thickness. The base-coat plasters were mixed in the ratio of 1½ ft^3 (equal to 100 lb) of gypsum plaster to 2½ ft^3 of expanded perlite for all double-back applications and in the ratio of 1½:2 (or 100 lb:2 ft^3) for the scratch coats and 1½:3 (or 100 lb:3 ft^3) for the brown coats. The plasters for all the white finish coats were mixed 3 parts of lime putty to 1 part of gaging plaster, also by volume.

3.6. Aging

Following the completion of the constructions, the test specimens were allowed to age for various periods before being subjected to test. These periods ranged from 28 to 49 days, as measured from the day on which the last of the base-coat plaster was applied to the day of the test, except for those test specimens (324 and 329) without ceilings, in which case aging was measured from the day the concrete was poured.

4. Test Method and Equipment

The tests of the larger floors were conducted in accordance with the provisions of the Standard Methods of Fire Tests of Building Construction and Materials of the American Standards Association and the American Society for Testing Materials (current ASTM Designation E119–53), but with certain exceptions. In most instances the tests were continued as long as practicable rather than being stopped as soon as the first end-point criterion was reached; therefore, the reloading test could not be made properly. The hose-stream test was also omitted. The reasons for and significance of these exceptions are discussed in section 6.1.

The tests were conducted in furnaces at the National Bureau of Standards designed for the fire tests of floors and roofs. Tests 257 and 260 were made in a small furnace, which would take a floor

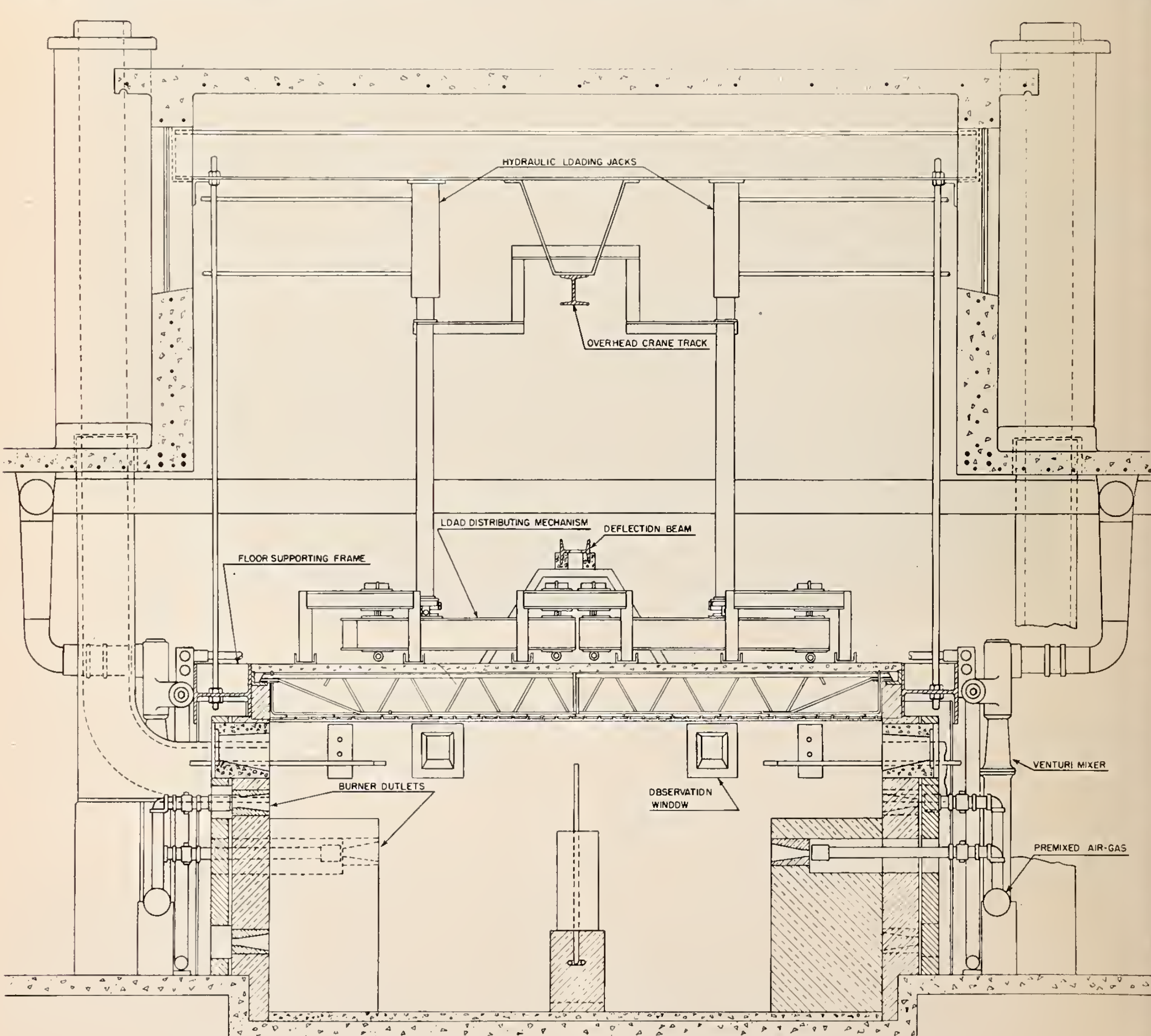

Figure 5. *Section of the large floor-test furnace at the National Bureau of Standards.*

9 ft by 4 ft 4 in., and the other tests were made in a large furnace, which took a floor 18 ft by 13 ft 6 in. The latter is shown in figure 5. Each furnace was in the form of a box open at the top, with gas burners along the sides. The test floor closed the open top, and the underside of the specimen was exposed to the furnace flames.

Six thermocouples were placed in the small furnace and 12 in the large to measure the temperature in the furnace chamber. They were encased in porcelain insulators and iron pipes closed at one end and placed so the thermocouple junctions were about 1 ft below the ceiling surface. The furnace fires for all tests were controlled to approximate closely the temperatures specified in the above mentioned standard test methods, which include: 1,000° F at 5 min, 1,300° F at 10 min, 1,550° F at 30 min, 1,700° F at 1 hr, 1,850° F at 2 hr, 2,000° F at 4 hr, and 2,300° F at 8 hr or over. The fire-exposure severity, defined as the ratio of the area under the curve of average furnace temperatures to the area under the standard time-temperature curve, is required to be between 90 and 110 percent for tests of 1-hr duration or less, between 92.5 and 107.5 percent for tests over 1 hr but not over 2 hr, and between 95 and 105 percent for tests over 2-hr duration.

The junctions of chromel-alumel thermocouples were placed on the upper surface of the floors. They were distributed over the surface in a symmetric pattern, with their junctions and short lengths of the thermocouple wires coiled under felted asbestos pads 6 in. square and 0.4 in. thick. A total of 6 such surface thermocouples were used on the small floors and 10 or 12 on the large floors.

The junctions of chromel-alumel thermocouples were placed on the joists at three levels; on the joist webs, the upper chords, and the lower chords. The individual thermocouple junctions on the top chords were approximately above those on the webs and bottom chords. Their locations on the various joists were such as to make a symmetrical distribution throughout the structure. They were attached to the joists by peening each wire into a separate drilled hole in the steel with a short distance between holes in each pair, so that the junction was completed through the steel. This was done to provide a more accurate determination of the temperature of the steel and to prevent false indications from thermocouples that might become detached from the joists. The thermocouple wires were encased in asbestos sleeving and brought up vertically above the anticipated level of the upper surface of the floor.

The loads applied to the large floors were computed on the basis of 145 to 150 lb/ft^2 of floor surface, the design load for No. SJ103 joists spaced 24 in. on center and having a 13-ft clear span. The loads for the small floors were computed on the basis of 3,900 lb per joist, uniformly distributed. These loads included the dead weight of the test specimen, the weight of the loading mechanism, and the applied load. The latter was provided by hydraulic jacks above the larger floors and distributed by the device illustrated in figure 5, and by a similar device for the smaller floors. The deflections were measured at regular intervals throughout the tests by a system of wires attached to the floor and passed over pulleys to a scale, where riders on the wires indicated the change from the initial level of the floor.

4.1. End-Point Criteria

The previously mentioned standard test methods specify that the performance of the specimen shall be determined as the time at which any of the following end-point criteria shall be reached or observed:

(*a*) The floor shall no longer sustain the design load.

(*b*) Cracks or openings shall develop, allowing the passage of flames or gas hot enough to ignite cotton waste.

(*c*) The average temperature, as measured at five or more points on the unexposed surface, shall rise 250 deg F above its initial temperature.

(*d*) The temperature as measured by one of the unexposed surface thermocouples shall rise by 325 deg F above its initial temperature.

Although not required by the ASTM Standard Test Methods, additional data were obtained relative to the following criteria, which have become common practice, apply to tests of ceilings, or were considered of known interest:

(*e*) The times at which the main steel structural members attained average temperatures of 925° F and 1,000° F at one level, or

(*f*) The time at which a main steel-structural member attained a temperature of 1,200° F at any one point.

The behavior of these steel-joist floors made the determination of a time at which they no longer sustained the load a difficult process. In the earlier tests, in which this end point was determined by a visual estimate of how rapidly the deflections were changing or of how the oil pressure fluctuated in the loading system, a survey of the data indicated deflections of about 3 in. at the time of load failure. Therefore, in the interests of consistency, criterion (a) was taken arbitrarily to be indicated by a 3-in. maximum deflection in the later tests.

5. Test Results

The results are presented as summaries of the test logs, including condition after test, and representative views of test specimens and graphs of the temperatures and deflections observed, as well as tabulations of the various end points and critical information, tables 4 and 5. The tests have been grouped in these summaries according to certain variables, mainly size and plaster reinforcing.

5.1. Group 1. Exploratory Tests

This group was established on size and includes the two specimens of smaller size than the mini-

Table 5. *Observed times of failures and other significant test data*

Test	Load failure	Unexposed surface temperature increase		Joist temperatures [a]			Fire-exposure severity	Unexposed surface-temperature increase at load-failure time	
		250° F (average)	325° F	925° F (average)	1,000° F (average)	1,200° F		Average	Maximum
	hr min	*hr min*	*hr min*	*hr min*	*hr min*	*hr min*	*Percent*	*° F*	*° F*
257	1 10	1 11	--------	--------	1 10	1 08	99.9	245	293
260	1 56	--------	--------	--------	1 51	1 53	103.3	--------	--------
261	1 25	--------	--------	--------	1 24	1 24	98.4	126	140
266	Not loaded	--------	--------	--------	--------	0 55	101.0	86	106
287	[b] 1 00	--------	--------	--------	--------	--------	97.7	76	86
295	1 43	--------	--------	1 45	1 46	1 40	99.4	106	142
296	1 48	--------	--------	1 50	--------	1 49	100.0	70	86
297	1 40	--------	--------	1 41	1 41	1 39	101.3	54	68
311	6 40	4 25	4 46	6 38	--------	6 39	100.2	457	488
312	6 26	3 27	3 46	6 11	6 19	6 15	100.4	500	562
313	4 12	3 14	3 19	4 04	4 18	4 12	100.6	362	490
316	[b] 3 00	--------	--------	--------	--------	--------	101.4	187	245
317	1 06	--------	--------	0 57	0 58	0 55	97.1	83	137
318	2 46	--------	--------	2 30	2 40	2 13	100.7	196	225
319	1 16	--------	--------	--------	--------	1 04	99.7	112	144
324	0 07	--------	--------	0 04	0 04	0 06	92.2	--------	--------
326	2 54	--------	2 44	2 58	--------	2 26	99.8	214	419
329	0 07	--------	--------	0 05	0 05	0 08	86.4	0	0

[a] These data do not represent end points specified in ASTM E119-53 but are known to be of interest to various building-code groups and to others.
[b] Test stopped before load failure, or any end point, to save joists and slab for use in following test.

mum required by the ASTM Standard Test Methods. They were tests 257 and 260.

Test 257. One-half in. of mill-mixed plaster on ⅜-in. lath. At 4 min, fine cracks outlined lath; 10 min, largest cracks under joists; 26 min, main cracks ⅛ in. or more wide, plaster along one edge of cracks offset below that along other edge; 40 min, offset as much as 1 in., plaster surface warped; 42½ min, approximately 3 ft^2 of lath and plaster fell; 55 min, more ceiling fell; 1 hr 10 min, deflections of floor increasing rapidly, concrete floor slab cracking, load removed; 1 hr 15 min gas to furnace fires turned off.

After the test, most of the lath and plaster had fallen, the slab was cracked, and the chords of two of the three joists were found to have been distorted.

Test 260. Three-quarter in. of mill-mixed plaster on ⅜-in. lath. At 4 min, first fine cracks; 15 min, more cracks up to ⅛ in. wide and full length along centerline; 40 min, ¼-in. offset along one crack; 1 hr 20 min, plaster warped, offset 1¼ in.; 1 hr 35 min, lath and plaster offset 4 in.; 1 hr 39½ min, first plaster fell; 1 hr 50 min, most of ceiling fell; deflections increasing rapidly, load off at 1 hr 56 min; gas off at same time.

After the test, nearly all the ceiling had fallen, the bottom chords of the joists were bowed, and the top chords buckled.

5.2. Group 2

This group included four large-size concrete slab floor tests in which no extra reinforcing was incorporated into the ceiling.

Test 261. Five-eighth in. of mill-mixed plaster on ⅜-in. lath. At 2 min, first small crack with a small local bulge in plaster; 6 min, bulged white-coat plaster flaked off spot 3 in. in diameter, cracks outlined lath; 19 min, crack in concrete slab; 34 min, large cracks and slight sag of ceiling at center; 1 hr, longitudinal centerline crack widest, some sag and offset; 1 hr 17 min, pronounced offset along cracks; 1 hr 22 min, half of ceiling fell; 1 hr 25 min, more of ceiling down, load off; 1 hr 27 min, gas off.

After test, the slab was intact but the joists had sagged somewhat, some of the top chords had buckled slightly, and the ceiling was nearly all down.

Test 266. Mill-mixed plaster, ½ in. on ⅜-in. lath. At 6 min, first cracks outlined lath; 15 min, slight sag along a crack; 27 min, smoke into furnace chamber from crack; 37 min, general sagging over ceiling plus local variations along cracks; 50 min, crack at center ¾ in. wide; 52 min, first portion of ceiling fell, additional portions fell until, at 1 hr 1 min about three-fourths of entire ceiling down; gas off 1 hr 1 min.

The floor slab and joists having been used in a previous test, no load was applied, and the deflections were small. Nearly all the ceiling was down by the end of the test.

Test 287. Plaster of ⅝ in. on ⅜-in. lath. At 10 min first cracks; 18 min, more cracks, with some sagging along them; 28 min, lath pattern beginning to show in cracks, some smoke in furnace; 34 min, flames into furnace from ceiling cracks; 49 min, offset of ⅛ in. along full-length crack ⅛ in. wide; 1 hr, several cracks ¼ in. wide, load removed to prevent damage to slab and joists; 1 hr 4 min, first fall of ceiling, about 4 ft^2; 1 hr 7 min, gas off, more of ceiling down.

After test, less than one-quarter of the ceiling had fallen, and both the slab and joists were undamaged. However, overnight most of the ceiling fell as it cooled.

Test 295. Ceiling of 1 in. of plaster on ⅜-in. lath, same slab and joists as in test 287. At 2 min, white-coat plaster peeling from over half ceiling; 18 min, spot about 6-in.-diameter sagging; 27 min, half of above spot fell, another sagging 1 in.; 34 min, cracks along lines of lath joints over most of ceiling; 48 min, slight sag along crack; 1 hr 3 min, several cracks ⅛ in. wide, others less; 1 hr 26 min, offset of ¼ in. along crack; 1 hr 36 min, sag of 2 in. at lath corner; 1 hr 36½ min, about 5 ft^2 of ceiling fell; 1 hr 43 min, load removed, floor continued to deflect under deadweight, about one third of ceiling down; 1 hr 49 min, nearly all ceiling down, joists buckling; 1 hr 53 min, gas off.

Most of the joists were buckled or bent, and only a few small pieces of plaster or lath remained after the test.

5.3. Group 3

This group consisted of the two gypsum concrete-slab floors. The ceilings were job-mixed gypsum-perlite plasters on perforated ⅜-in. gypsum lath. No extra reinforcing was incorporated in the ceiling.

Test 296. Plaster 1¼ in. thick on ⅜-in. lath. At 22 min, first crack; by 1 hr, only 5 cracks, each 2 to 8 ft long but not over ⅟₁₆ in. wide; 1 hr 10 min, very slight general sag of ceiling; 1 hr 35 min, flames into furnace from ceiling crack; 1 hr 46 min, offset of ¼ in. at crack across lath joint; 1 hr 47½ min, about 35 ft² of ceiling fell, exposing joists; 1 hr 48 min, more of ceiling sagging badly, load off, floor continued to deflect under dead load; 1 hr 53 min, gas off, most of ceiling down.

After the test, most of the plaster and lath had fallen, but the clips that held the lath to the furring channels were in place. Several of the joists were buckled slightly.

Test 297. Plaster 1⅛ in. thick on ⅜-in. lath. At 9 min, first crack; by 23 min, several cracks, which outlined some of the lath; 51 min, power failure for 4 to 5 min stopped operation of air blower and other equipment, such as loading pump, clocks, potentiometers; 1 hr 10 min, maximum crack width ⅛ in., slight sag along some cracks; 1 hr 28 min, sag of ¼ in. along ⅜ in. wide crack; 1 hr 31 min, flames into furnace from same crack; 1 hr 34 min, about 12 ft² of ceiling fell; 1 hr 40½ min, more ceiling down, load off; 1 hr 45 min, gas off.

The times after 51 min do not include the period of power failure, during which the clocks were stopped and the furnace fires were greatly reduced by lack of air pressure. At the end of the test, nearly all the ceiling was down, but the lath clips were still in place. The joists were bent somewhat, as were the cross-bridging members.

5.4. Group 4

This group consisted of the three tests of floors in the ceilings of which the laths were secured to the furring by one type of clip, which provided support at the edges only, and by other related clips through the laths across their width (types A and B, fig. 3).

Test 316. Plaster ⅝ in. on ⅜-in. lath, extra clips. At 8 min, white-coat plaster flaking off in pieces about 2-in. diameter; 31 min, crack about half length of ceiling; 1 hr 12 min, maximum crack width ⅜ in.; 1 hr 21 min, slight sag near center; 2 hr, sag of 3 in. along centerline crack, offset of at least ⅝ in. on one side; 2 hr 42 min, offset of 3 in. or more; 2 hr 52 min, some cracks 1 in. wide, others offset 4 to 5 in.; 3 hr, test stopped, gas and load off.

The test was stopped before an end point was reached in order that the joists and slab might not be damaged and could be used for another test. At the end of the test, no significant amount of the ceiling had fallen but some pieces were sagging about 1 ft and left openings. Upon cooling, a few square feet of the ceiling fell, but the remainder did not.

Test 317. Same joists and slab as in test 316. Plaster ½ in. on ⅜-in. lath. At 13 min, several cracks in two straight lines, apparently across lath ends; 19 min, cracks outlined all laths, also two full-length cracks; 43 min, maximum crack width ¼ in., slight offset; 46 min, distinct wave in ceiling surface; 48 min, ceiling fell from area of one lath, much larger area very irregular; 1 hr 2 min, about half of ceiling down, 1 hr 6 min, load off; 1 hr 7 min, gas off.

During cooling the remainder of the ceiling fell. Several of the joists were buckled slightly.

Test 319. Plaster of ½ in. on ⅜-in. lath. At 8 min, first crack with local peeling of white coat; 17 min, 3 full-length cracks; 24 min, 6 full-length cracks, some ⅛ in. wide; 39 min, cracks outlined all laths and divided some, slight sag and ⅛-in. offset; 55 min, offset of 1 to 2 in.; 59½ min, section of ceiling about 5 ft² fell; 1 hr 4 min, more ceiling down; 1 hr 16 min, load and gas off.

The joists were bent slightly, but the slab was not cracked. About one-quarter of the ceiling fell during the test and as much again during cooling. The remainder was badly cracked.

5.5. Group 5

This group was composed of the tests in which diagonal wire was used as additional reinforcement below the lath, in addition to the wire clips.

Test 313. Diagonal wires 10 in. apart, plaster ⅝ in. on ⅜-in. lath. At 13 min, first cracks along each side; 17 min, thin black smoke into furnace from some cracks; 30 min, cracks over most of ceiling without sharp outlining of lath, ¼-in. sag; 50 min, sag ½ to ¾ in. at several places; 1 hr, cracks along lath joints had become prominent, about ⅛ in. wide, offset of ¼ to ½ in.; 1 hr 30 min, general sag over ceiling, local variations nearly all disappeared; 1 hr 50 min, offset 1½ in., cracks ¼ in. wide near center of ceiling; 2 hr 21 min, two small strips of plaster hanging down 4 to 5 in. where previously offset; 2 hr 46 min, plaster fell from 1-ft² area; 3 hr 20 min, small pieces of plaster hanging or offset at additional locations; 4 hr 7 min, sag of ceiling at least 12 in., overall cracks; 4 hr 24 min, gas and load off.

After the test, very little plaster and lath had fallen, but both fell from over half the ceiling during the following 2 days. Instead of having been buckled, the joists were bent in smooth arcs.

Test 318. Diagonal wires 11.3 in. apart, plaster ½ in. on ⅜-in. lath. At 8 min, first crack; 15 min, smoke from single crack; 19 min, cracks partially outlined laths; 24 min, slight sagging along two cracks; 31 min, offset of ¼ in., some peeling of white coat; 35 min, entire ceiling surface had wavy appearance; 50 min, wavy appearance lessening except for 3-in. sag along two cracks; 1 hr 15 min, corner of lath and plaster sagging 1¾ in.; 1 hr 35 min, maximum crack width 1½ in., local sag as much as 4 in.; 2 hr 6 min, many cracks ½ to 2 in. wide, corners of lath and plaster hanging down 3 to 8 in., leaving openings about 6 and 10 in. square; 2 hr 27 min, about 2½ ft² of ceiling fell; 2 hr 47 min, load off; 2 hr 53 min, gas off.

Less than one-quarter of the ceiling fell during the test and subsequent cooling. Most of the joists were bent, a few buckled slightly, and the floor slab showed no appreciable cracking.

Test 326. Diagonal wires 10 in. apart, regular base-coat plaster ½ in. thick, plus ⅝ in. of acoustical plaster on ⅜-in. lath. At 2 min, plaster surface blackened; by 25 min the blackening was burned off, and a 3-in.-diameter hole ¼ in. deep had appeared in plaster; 33 min, a second hole about same size but ⅝ in. deep popped open; 43 min, first observable crack; 47 min, acoustical plaster down from 1½-ft-diameter area, exposing base coat; 1 hr 1 min, plaster of depth to expose diagonal reinforcing wire down from 4- to 5-ft² area, scaling of acoustical plaster from other areas; 1 hr 23 min, more plaster down, ceiling had a ragged appearance, some laths exposed in offsets; 1 hr 57 min, general sag of ceiling; 2 hr 38 min, deflections increasing rapidly, pieces of plaster hanging 1 to 2 ft below ceiling on wires; 2 hr 46 min, large area of ceiling fell; 2 hr 54½ min, load off, crack across center of slab; 3 hr 4 min, gas off.

A single area of about one third of the ceiling and some other small areas had fallen. Nearly all the acoustical plaster was down, mostly as small granules. The joists were bent and buckled. The floor slab was cracked across the middle, one end having sagged excessively.

5.6. Group 6

This group consisted of the two tests of floors with 1-in. hexagonal-mesh galvanized 20-gage wire fabric secured below the lath before plastering.

Test 311. Plaster 1 in. on ⅜-in. lath. At 15 min, first crack; 19 min, small blister in white coat popped; 41 min, thin smoke from crack, maximum crack width ¹⁄₁₆ in.; 1 hr 29 min, slight sag at junction of cracks in center of ceiling, cracks nearly full length and full width; 1 hr 32 min, flames into furnace from center; 1 hr 42 min, offset of ⅛ in. at center, cracks not over ³⁄₁₆ in. wide; 4 hr, no noticeable change in cracks, sag, or offset since about 1¾ to 2 hr; 4 hr 50 min, sag at center about ¾ in.; 5 hr 40 min, local sag at center 1½ in., widest crack ½ to 1 in.; 6 hr, the whole ceiling had settled slowly into a curve whose depth at the center was about 1 ft, local offset of 2 in., local sag about same; 6 hr 25 min, oily burlap bag that had been on top of floor ignited, some cracks 1 in. wide, others offset up to 6 in.; 6 hr 34 min, opening 6 to 8 in. wide due to sag and offset through which some lath had fallen but no plaster; 6 hr 40 min, load off; 6 hr 43 min, gas off.

At the end of the test no plaster had fallen, but it was thoroughly cracked. The joists were bent but not buckled. No appreciable amount of plaster fell after the test.

Test 312. Plaster ½ in. on ⅜-in. lath. At 13 min, first crack; 27 min, short cracks outlined laths over part of ceiling; 1 hr, maximum crack width $\frac{1}{16}$ in., length 3 ft, 1 hr 45 min, several parallel transverse bulges or sags of small depth, probably between lines of support for wire mesh; 2 hr 43 min, small edge cracks in floor slab, little change in ceiling; 3 hr, maximum crack width ⅛ in., length 6 ft; 4 hr, ceiling had developed 1 to 2 in. general sag; 5 hr, general sag of ceiling had developed into curve of 9-in. depth at center; 5 hr 20 min, local sag of ½ in. over area 3 ft in diameter; 6 hr 15 min, ceiling fell from 4-ft^2 area near center; 6 hr 27 min, load off; 6 hr 34 min, gas off, more ceiling down.

A total of about 24 ft^2 of the ceiling fell by the end of the test. The remainder stayed up through cooling and several days after. The joists were bent in smooth curves but were not buckled.

5.7. Group 7

This group was made up of the tests of two floors without ceilings. One was the same slab and joists from a previous test. This floor had withstood loading to twice the live load before the retest. The other test floor consisted of all new materials.

Test 324. Same slab and joists as in test 319. By 4 min the channel bridging was a dull red and the deflections were as much as ½ in.; 7 min, the maximum deflection reached 3 in. and all were increasing rapidly, load off; 8 min, the joists were bright red and the gas turned off.

The joists recovered about one fourth of the total deflection after the cooling and removal of load.

Test 329. All new materials, no ceiling. Some difficulty was encountered with the burners in the first 4 min, during which time some smoke came out above the slab, and the deflections became about 1 in.; at 7 min 15 sec the maximum deflection reached 3 in. and the load was removed; by about 13 min, when the gas was turned off, the joists and bridging gave off a bright glow.

The joists upon cooling recovered about ¼ in. of the more than 3-in. deflection. There was a thin diagonal crack across each corner of the slab. Because of the trouble with the burners, the fire-exposure severity was quite low (86.4%) and outside the limits set by the test specification. However, the behavior and endurance were essentially the same as those of the reused floor and joists in test 324.

Figures 6, 7, 8, 9, 10, and 11 show the after-test conditions of some representative specimens and representative graphs of the temperatures observed in the tests.

FIGURE 6. *Condition of joists after test 295 of specimen with unreinforced ceiling showing buckled joists.*

FIGURE 7. *Condition of ceiling after test 318 of specimen with diagonal wire reinforcing.*

One or two smoothly bent joists may be seen through the opening in the ceiling.

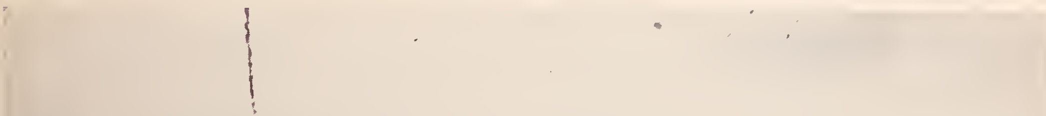

FIGURE 8. *Condition of ceiling in test 312, having hexagonal-mesh wire fabric, after 6½-hour exposure.*

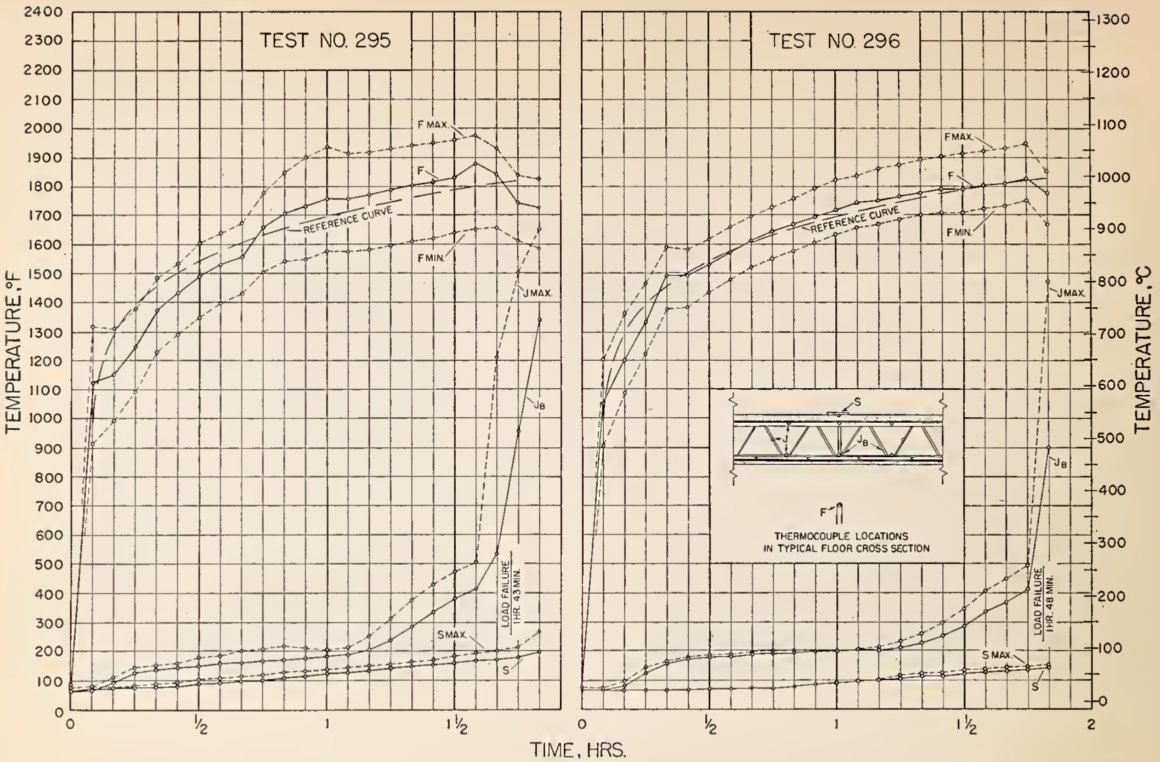

FIGURE 9. *Time-temperature curves from tests 295 and 296, unreinforced ceilings.*

Sketch indicates thermocouple locations. Curves labeled as follows: Standard exposure curve of E119, Reference curve; furnace temperatures, average, maximum, and minimum, F, F_{max}, F_{min}, respectively; average of bottom chords of joists, J_B; maximum on joists, J_{max}; unexposed surface, average and maximum, S and S_{max}.

6. Discussion

6.1. Deviation from Standard Test Methods

Ordinarily, fire-endurance tests at the National Bureau of Standards have been continued until as many as possible of the end points defined by the applicable test criteria (those for floor tests are given in 4.1) were reached, so that all possible information could be obtained from each test. This practice is at variance with the standard test methods, under which tests are ended as soon as the first end point is reached and immediately followed by the hose-stream test. Although the fire endurances of the floors were determined by the initial end point in each test, so that these results were equivalent to those under strict compliance with the standard test methods, the total fire exposures were usually much greater by the end of the fire exposure period. Consequently, the conditions of the test specimens were not equivalent at the times the hose-stream tests and the double-reloading tests would have been made. For this reason, these portions of the standard test methods for floors were omitted. The observations of the temperatures of the various components and the conditions of the floors and ceilings indicated that alternate specimens would have withstood hose-stream and reloading tests where required.

6.2. Nature of Failures

Table 5 shows that the determining end points in the tests were usually either load failure in comparatively short tests or temperature rise on the unexposed surface in the longer tests. This may be related to the behavior of the ceiling and the joists.

In the tests of floors with ceilings in which the lath-clip systems were not supplemented by other reinforcing, progress from the end of the calcination period to load failure was rapid, with little difference noted for ceilings of the thicker plaster coats. Once the gypsum calcined, the lath and plaster cracked extensively and soon lost the strength necessary to support themselves. Portions of the ceilings fell, exposing the joists above directly to the hot flames and gases. These exposures resulted in high steel temperatures, loss of strength, and load failures.

In contrast to the previously mentioned tests involving rapid load failure, the tests in which means were taken to prevent the breakup and fall of the ceiling indicated a slow rate of heat transfer through the ceilings and floors until the temperatures on top of the latter had been raised by the limiting 250 deg F average, or 325 deg F at one point. The means utilized to prevent the fall of the ceiling consisted of extra, more closely spaced supports for the lath so that much more

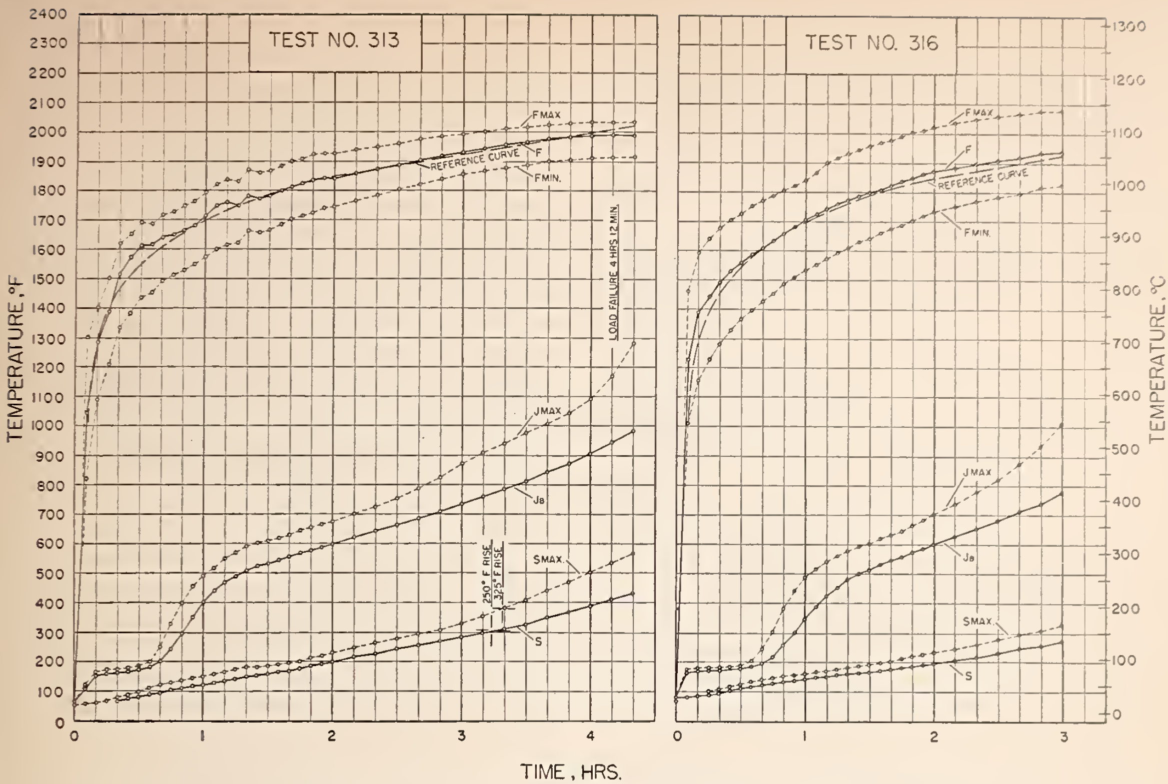

FIGURE 10. *Time-temperature curves from tests 313 and 316, the former having a ceiling with diagonal wires and the latter one with extra clips.*

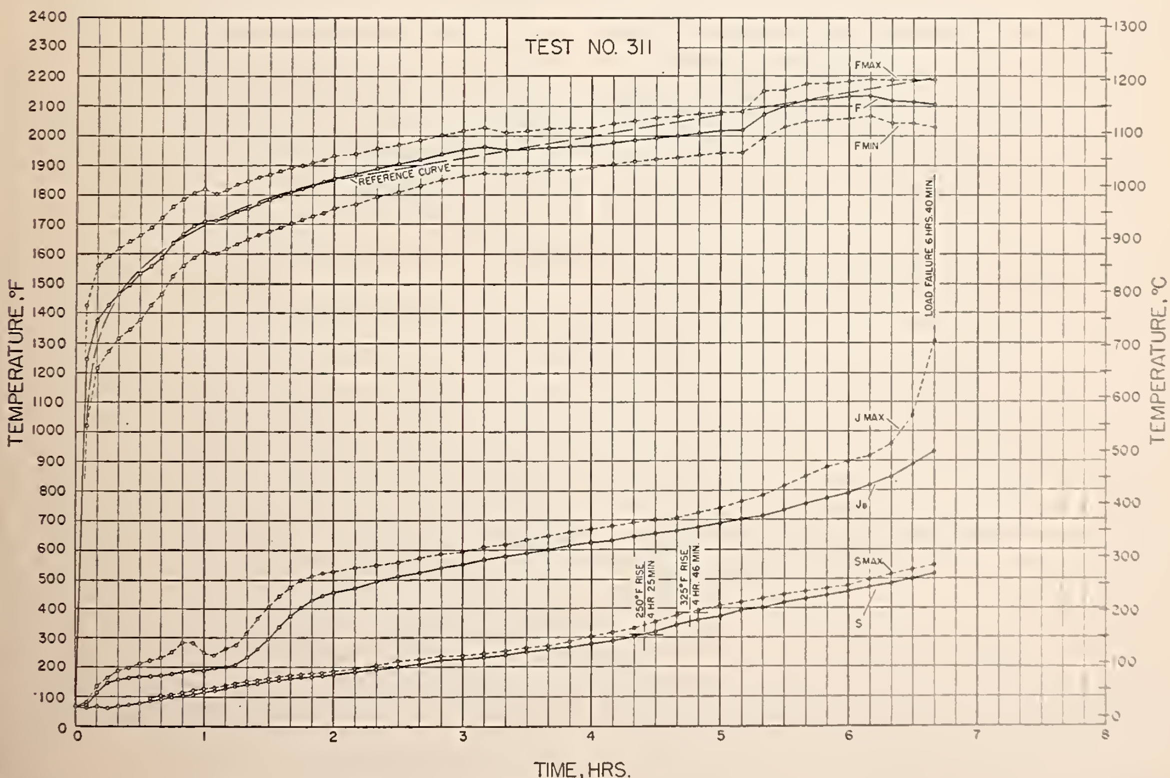

FIGURE 11. *Time-temperature curves from test 311 having a ceiling with 1-in. hexagonal-mesh wire-fabric reinforcing.*

breakup would be necessary before any pieces of lath and plaster were small enough to be unsupported. As long as the ceiling was kept in place, it continued to protect the joists and floor slab, even after the gypsum calcined. The joists were heated slowly and uniformly, yielding gradually into smooth curves rather than sharp buckles. In some cases, the joists were acting as suspension members by the ends of the tests.

6.3. Effectiveness of Reinforcing or Extra Support

The various means of providing extra support for the ceiling were: closer spacing of furring channels and clips, use of additional intermediate clips, wires laid in or tied in on the diagonal, and 1-in. hexagonal-mesh wire fabric ("chicken wire"). The effectiveness of these added reinforcements, as well as the regular supporting clips, is due not only to the fact that they pass under the lath but to the direct support given to the whole ceiling because they become at least partly embedded in the plaster. The change in spacing of the furring channels, and therefore of the supporting clips, from 16 to 12 in. gave an increase of 11 min from a test of 1 hr 4 min on a comparatively thin (⅞ in. total) ceiling. This increase amounted to about 17 percent, or one-sixth. The addition of diagonal wires to an equally thin ceiling on furring at 16-in. centers gave triple the resistance obtained without reinforcing. The use of hexagonal-mesh wire fabric in a ⅞-in. ceiling gave almost four times the resistance obtained without. The results of tests on moderate (1 in. total) ceilings, one with diagonal wire and one with extra intermediate clips, were essentially equal. The combination of the closer (12-in.) furring and either extra intermediate clips or diagonal wires gave about 2½ to 3 times the resistance of a moderate ceiling on the wider (16-in.) furring with no reinforcement. With a 1⅜-in. ceiling, the use of closer furring and hexagonal-mesh wire fabric increased the fire resistance to about 2½ times that of an equally thick ceiling without reinforcing. This increase in time was 2 hr 44 min. The greatest increases, both in time and percentage wise, were obtained with the hexagonal-mesh wire fabric. The use of the various reinforcements was especially valuable to thick and comparatively heavy ceilings. The results of test 326 did not indicate a significant difference between the effectiveness of the short diagonal wires with each end bent around the clip junctions and that of the 4-ft. lengths neither bent not tied.

6.4. Plasters

The various plasters and mixes employed in the tests seem to have been of about equal value. The mill-mixed and job-mixed plasters gave approximately the same results when in equal thicknesses. However, not enough tests were made with the mill-mixed plasters to draw definite conclusions. A research program consisting of tests in different thicknesses, including representative floor, wall, or column constructions, would be necessary to evaluate the relative merits of mill-mixed and job-mixed plasters.

The plasters of ½-in. and ⅝-in. thickness on unreinforced ceilings, were mixed 1½ parts of gypsum to 2½ parts of aggregate, by volume (100 lb of gypsum to 2½ ft^3 of perlite), and those of 1-in. or greater thickness were in two coats, the first, or scratch, mixed 1½:2 (100 lb:2 ft^3) and the second, or brown, 1½:3 (100 lb:3 ft^3). As the different mix ratios were not used in equal thicknesses, no comparison was attempted. In the scratch and brown-coat work, the two coats were of approximately equal thicknesses. As mentioned in the preceding section, the thicker plasters were most effective when given additional support.

Comparison of the results of test 326 with those of test 318 indicated that the acoustical plaster as applied to the former contributed nothing to the fire resistance of the test specimen. During construction of this specimen numerous drop-outs occurred on application of the acoustical plaster, which at the time were blamed on improper drying of the base coat. Later experience with the same type of acoustical plaster has, however, indicated that the difficulties were caused by segregation of the components during shipment and that the additional ⅝ in. of acoustical plaster should have considerably increased the fire resistance of the specimen.

6.5. Balance of Designs

It is of importance to economical construction that no more materials be used than necessary to achieve the desired results, with appropriate margins or factors of safety. Therefore, the design and construction should be such that the materials are employed in the most efficient manner. The design must be "balanced" with all considerations in mind, including fire resistance. Much information on the fire resistances of various building components has been obtained and published. Some of these publications are listed in section 8. In the majority of the tests, load failure occurred and the high temperatures were reached in the joists, but the limiting temperature rise on the unexposed surface was not reached (see table 5), indicating that the floor slab still had considerable insulating value some time after the joists had failed. It was considered necessary to stop most of these tests before the limiting temperature rise was reached in order to prevent the collapse of the test specimens. However, in three tests, the limiting temperature rise on the unexposed surface was reached from 1 to 3 hr before load failure, indicating that the protection for the joists was much greater than needed. In each case the designs may be said to be unbalanced in that some part of the assembly had an unused reserve of fire resistance compared with the other parts. As this represented costly materials that were not contributing to the fire resistance, it is of interest to the architect and the builder to use a balanced design. It is important to realize that it is not a simple problem of adding or substracting the correct amount of material but, frequently, the difficulty of keeping the materials in place as long as they have any fire resistive value. This is shown by comparison of tests 295 and 311, in which the same types and amounts of lath and plaster were used—⅜ in. of lath plus 1 in. of plaster. In the former, this ceiling protected the joists for only 1 hr 43 min, whereas in the latter the same ceiling, kept in place and nearly intact on more closely spaced furring by wire-fabric reinforcing, protected the joists against load failure for 6 hr 40 min, although the fire endurance was limited to 4 hr 26 min by temperature rise on the unexposed surface. Subsequently, in test 312 only ½ in. of plaster was applied to the lath and wire fabric, but the joists were still protected for over 6 hr. The fire endurance of this assembly was limited to 3 hr 28 min by temperature rise. Thus ½-in. thickness of plaster on ⅜-in. lath, which was the thinnest ceiling in the test series (tests 257, 266, 312, 317, 318, 319), gave the second longest fire endurance when sufficiently reinforced.

7. Conclusions

On the basis of the tests reported in this paper, and comparison with those in other BMS reports [2, 3], several conclusions may be drawn.

1. Open-web steel-joist floors with ceilings of perforated gypsum lath and gypsum-perlite plaster will provide fire resistances up to 1¾ hr and those with adequate reinforcement to more than 4 hr, covering the range of requirements in many building codes.

2. Even relatively thin coats of plaster and lath as normally applied without reinforcing lose strength to the point they can no longer support their own weight while still of considerable fire protection value.

3. The use of some form of reinforcing to reduce the span of lath and plaster between supports and thereby keep the ceiling in place and functioning as protection to the joists and slab is essential for fire resistances of 2 hr, or longer.

The authors acknowledge the contribution of N. D. Mitchell under whose direction the work reported herein was initiated.

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