SP 80-1

Simulation of Realistic Thermal Restraint During Fire Tests of Floors and Roofs

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Synopsis:

This report describes a five-phase test program. In Phase I, 13 small size specimens were tested. Included were flat plates, flat plates with edge beams, and ribbed slabs. Horizontal and vertical temperature distributions, expansions, and deflections were measured during heating periods.

In Phases II and III, computer programs for heat flow calculations and stress analysis were developed. Subsequently, six 14x18-ft floor slabs were fire tested. During the tests, slab expansions in both directions were controlled to follow computed time-expansion relationships.

Four more 14x18-ft specimens were fire tested in Phases IV and V to verify results of studies to develop methods of simulating realistic restraints in a fixed frame furnace through the use of pads made with compressible materials. Expansions and restraining forces measured when compressible pads were used were compared with those obtained for companion slabs tested in a furnace with hydraulically controlled restraining frames. The comparisons show reasonable agreement indicating that it is possible to use fixed frame furnaces to simulate realistic thermal restraints during fire tests of floor slabs.

Keywords: computer programs; concrete slabs; deflection; expansion; finite element method; fire resistance; fire tests; flat concrete plates; floors; furnaces; high temperature; measuring instruments; restraints; roofs; thermocouples.

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BACKGROUND

Results of fire tests of floors and roofs are influenced significantly by the degree to which thermal expansion is restricted (or restrained). Floors and roofs in buildings are seldom completely free of thermal restraint and consequently, most fire tests have been conducted with restraint although the amount of such restraint is not known. To obtain results that realistically define the true behavior of the test specimen in the structure, the restraint forces must be known and controlled during the fire test. A simple way to accomplish this in fixed frame furnaces was required.

A research program to develop such a method was undertaken. This research program, entitled "Simulation of Realistic Thermal Restraint During Fire Tests of Floor and Roof Assemblies," was divided into five phases:

Phase I	Experimental Studies of Small Specimens Subjected to an Isolated Fire.
Phase II	Analytical Studies Toward Developing Computer Simulations to Extend Results of Phase I.
Phase III	Fire Tests of Full-Scale Floor Specimens Applying Programmed Restraint Determined by Use of Computer Program of Phase II.
Phase IV	Analytical Studies to Develop Methods of Simulating Realistic Restraint through Use of Fixed Restraining Frames.
Phase V	Fire Tests of Full-Size Floor Specimens in Fixed Restraining Frames to Verify Results of Phase IV.

Table 1 lists the major tasks of the five-phase program.

PHASE I

The objectives of Phase I were:

1. To measure dilations in slab specimens subjected to an isolated fire.

2. To study the effect on the dilation and displacements of such variables as concrete type, amount of reinforcing steel, ratio of total to heated areas, eccentric heating, and amount of additional restraint supplied by surrounding beams, columns and structural members.

During Phase I, 13 slab specimens 3x3 ft, 6x6 ft, or 9x9 ft in plan were designed, fabricated, and tested. Included were flat plates with and without edge beams, and ribbed slabs. Table 2 gives specimen and fire-test details. All specimens were exposed to ASTM Designation: E119 (1) fire exposure for 4 hr 3 min.

Test Procedure

Figure 1 shows the system used for measuring slab expansions during fire exposure. Expansions of the heated portion of the slab were measured in both horizontal directions. Telescopes equipped with slide micrometer cathetometers that sighted on vertical wires were used. Figure 2 shows equipment used for measurement of expansion during the test.

Summary of Test Results

Results of the 13 fire tests were analyzed to evaluate the effect of the following factors on expansion of slabs during exposure to fire:

1. Amount of reinforcing steel,
2. Location of heated area,
3. Ratio of total to heated areas,
4. Geometry of specimen,
5. Edge beam,
6. Aggregate, and
7. Out-of-plane load

Figures 3 to 11 show results of this analysis.

Based on results of experimental fire tests, the following observations and remarks are made:

1. Doubling reinforcing steel had only a minor effect in restraining the specimen. Expansions measured in two

slabs, one with twice the reinforcement of the other, were nearly equal (Fig. 3).

2. Location of the heated area had a major effect on expansion and consequent restraining forces. Much smaller expansions occurred in the specimen that was centrally heated than in those heated along an edge or corner (Fig. 4).

3. The ratio of total area to heated area affected measured expansions. A decrease in this ratio was accompanied by an increase in horizontal displacement (Figs. 5 and 6).

4. For the same ratio of total to heated areas, greater expansions occurred in ribbed slabs than in flat slabs (Fig. 7).

5. Effect of edge-beam constraint on the expansion of the central heated area of a flat plate was insignificant (Fig. 8) for the case where the ratio of total to heated areas was nine.

6. Expansions measured in a lightweight concrete slab were considerably smaller than those measured in a companion normal weight concrete slab (Fig. 9).

7. Somewhat greater horizontal displacements were measured in slabs where vertical edge loads were applied to simulate column action than in companion slabs without out-of-plane loads (Figs. 10 and 11).

8. Temperature measurements indicated that at any horizontal plane, the temperature distribution was uniform over the heated area. Practically no temperature rise occurred in the unexposed portion of the specimen.

9. In most tests, practically all vertical deformations occurred during the first hour of tests.

10. Radial cracks were detected about 5 minutes after start of test. Circular cracks around the heated area were also observed, at various times after start of test in the edge and corner heated specimens and those with out-of-plane edge forces.

Temperature Distribution

In addition to expansion data, temperature information is required for the development of an analytical solution for calculating in-plane forces. Temperature distributions were developed from information obtained during tests of Phase I. Example distributions are shown in Figs. 12 and 13.

PHASE II

The objectives of Phase II were:

1. To develop a computer program for calculating in-plane forces. Experimental results obtained in Phase I were used to verify the program.

2. To extend work of Phase I to other fire situations.

Analytical Study of Problem

Temperature and expansion data obtained in Phase I were used to verify assumptions required in the analytical solution. Temperature data shown in Figs. 12 and 13 provided a basis for two important assumptions: (a) the temperature of the exposed area was assumed uniform so that use of a one-dimensional heat flow equation was possible, and (b) the sharp decrease of temperature in the horizontal plane outside of the heated area, shown in Fig. 13, indicated that the adjacent element to the heated area could be considered to remain at room temperature throughout the test.

A rational method of dividing heated from unheated areas of the slab was developed by using a scaling factor derived from basic compatibility and equilibrium conditions. Use of the scaling factor simplified the analytical solution.

With these assumptions, the slab assembly during the fire test was divided into a heated area that tended to expand, and an unheated surrounding area that restrained the expansion of heated area. The heated part of the specimen was considered to be a plate subject to stresses due to a thermal gradient through the thickness and to the in-plane compressive forces. The unheated restraining area was considered as elements subjected to stresses due only to in-plane forces, a primary factor affecting the fire endurance of slabs.

Structural behavior of reinforced concrete slabs exposed to fire can be characterized as follows: (a) under certain conditions of load and temperature, concrete and steel behave elastically in tension and compression, and (b) beyond these conditions, plastic deformations occur in steel and concrete, and concrete cracks in tension. The cracked concrete is considered continuous and capable of resisting only normal stress parallel to the crack direction. Table 3 outlines the structural behavior problem.

The finite element method (2) was used to compute in-plane stresses due to the thermal gradient. Expressions for the material stiffness of cracked and uncracked elements were developed to form the matrix equations for the elastic and plastic solutions of the problem. The thermal and material properties of steel and concrete needed for the computation were taken from reference (3).

Computer Program Development

Subsequently, a computer program was developed using equations obtained in the analytical study. The program was written in Fortran language for the elasto-plastic solution of a reinforced concrete slab subjected to an isolated fire. It contains one main program, 12 subroutines, and three linking programs that generate temperature data and store these data on disk files. The program was developed on an IBM 1130 Computing System consisting of the 1131 Central Processing Unit Model 2C (internal disk drive and 16K core storage capacity), the 1442 Card Read Punch, and 1132 Line Printer.

Organization of the overall program is presented in Fig. 14. A brief explanation of the main program and subroutines is given in Table 4. The output includes echo print of input data, element numbering sequence, nodal displacements (two at each nodal point), element stresses, crack directions, and restraining forces. Output data are given at a test time of 1 minute, at 10-minute intervals for the first hour, and at 30-minute intervals from 1 hr to the end of the 4-hr test.

Comparison of Results

Calculations of displacements, stresses, forces and cracks were made for eight of the thirteen specimens of Phase I. Property values determined by a number of investigators on concrete similar to that used in the fire tests were used in the calculations. For all specimens in which the central area was heated, good agreement was obtained between computed and measured horizontal displacements at the center of edges of the heated area. For edge and corner heated areas, computed displacements were 10 to 20% smaller than those measured. Calculated restraining forces were consistent with the horizontal displacement. Computed and observed radial crack development were in good agreement.

Computed horizontal expansion, expansion profiles, restraining force, and crack pattern for a flat slab are given in Figs. 15 to 18. Good agreement was obtained between calculated and measured horizontal displacements at the center of edges of heated areas for specimens with center-heated areas. However, there were differences of 10 to 20% between computed and measured expansions for edge and corner heated specimens.

Calculated restraining forces appeared to be consistent with horizontal displacement information. Greater forces were calculated for center-heated specimens, where resistance to expansion was generally greater, than for edge and corner heated specimens. Figures 19 and 20 show crack patterns on top and bottom surfaces of a slab after fire test. Cracks in one quarter of slab were highlighted. Computed results shown in Fig. 18 compare well with test results shown in Figs. 19 and 20. There was good agreement between computed and observed radial crack develpment in the eight specimens for which computations were made.

PHASE III

The objectives of Phase III were:

1. To design full-size tests in terms of allowed expansions or restraining forces for the case of typical interior and exterior spans of a structure exposed to fire.

2. To conduct full-scale fire tests on flat plates and ribbed floors in which expansions are controlled to simulate realistic peformance in a structure. Time-expansion relationships in these tests are based on expansions calculated by use of the computer program developed in Phase II.

3. To measure restraint developed under the programmed expansions for comparison with calculated forces.

The major work in Phase III involved design, fabrication, and fire tests of six 14x18-ft floor slabs. Slabs included were: 2 flat, 2 waffle, and 2 pan-joist, all 14x18 ft in plan. Each floor type was tested to simulate behavior when exposed to fire at an interior or exterior slab of a continuous multi-bay concrete floor system.

Description of Specimens

Specimens were 13 ft-10-1/2 in. x 17 ft-9 in. in plan. Flat plates were 7 in. thick and had a 7-in. wide by 14-in. thick perimeter beam cast integrally with the slab.

Waffle slabs were 11-1/2 in. thick with a 3-1/2-in. thick deck and 8-in. deep joists. Joists were 6 in. wide at the bottom with a 1-1/2:12 side draft. Most joist spacings were 3 ft on center. Three dome sizes were used to obtain desired joist configuration. Included were twelve 30x30-in., six 20x30-in. and eight 14-1/2x30-in. domes. In addition, 14 partial domes were used around the perimeter of each waffle specimen. All domes were 8 in. deep.

Pan-joist specimens had a 3-1/2-in. thick deck. Joists spanning the long direction, spaced 35-in. on center, extended 10-in. below the slab giving an overall thickness of 13-1/2 in. Joists were 5-in. wide at the bottom with a 1:12 side draft. Transverse beams, 6-in. wide were cast integrally at specimen ends to facilitate handling.

Reinforcement--All reinforcing bars were ASTM Designation: A615 Grade 60 with a minimum yield of 60,000 psi. Number 4 bars generally were used for major reinforcement. Minimum bottom, side, and top concrete cover to reinforcing bars was 3/4 in. Welded wire fabric, 6x6-6/6, was in the deck slabs of waffle and pan-joist specimens.

For flat plates, top bars were 10 in. on center in column strips and 16 in. on center in the middle strip in the long direction. For the short direction, column-strip bars were 17 in. on center and middle-strip bars 26 in. on center. Bottom reinforcing bars were spaced 14 in. on center in both directions.

For waffle slabs, each joist was reinforced with two straight and one bent No. 4 bars. Bars in the transverse joists were supported by longitudinal bars and had 1-1/4-in. clear cover. Welded wire fabric, 6x6-6/6, supported on No. 3 bars had a 3/4-in. clear cover from the slab top.

Pan-joist specimens had two longitudinal bars in each joist; a No. 5 straight bar, and a No. 4 bent truss bar. These specimens also contained 6x6-6/6 welded wire fabric having 3/4-in. clear cover from the slab top.

Thermocouples--Each test specimen contained a number of chromel-alumel thermocouples for measuring temperatures of main reinforcing steel. All thermocouples were positioned at mid-height of bars. Thermocouples also were attached to welded wire fabric of waffle and pan-joist slabs. Flat-plate specimens contained a thermocouple tree for measuring the vertical temperature distribution in the concrete. Thermocouple locations are given in Fig. 21.

All specimens contained Monfore-type wells (4) for monitoring the relative humidity of concrete specimens.

Concrete--Ready-mixed concrete was used for all specimens. Tests were made for slump, unit weight, and air content from each cubic yard of concrete. Batch quantities, properties of plastic concrete, and strength information are given in Table 5.

Concrete was made with carbonate sand and gravel from McHenry, Illinois. Maximum size of coarse aggregate was 1 in. Physical properties of aggregates are given in Table 6.

Fabrication and conditioning of specimens--Forms for flat plates were fabricated from polyester-coated plywood, positioned in a heavy metal frame. Metal chairs were used in all slabs to hold bars in place, and to maintain cover beneath reinforcement. As previously described, three sizes of metal domes were used to fabricate waffle slabs. For pan-joist floors, forms were made from 30-in. wide x 10-in. high metal pans, with plywood used elsewhere.

Concrete was distributed into the form with an overhead dump bucket and consolidated with internal vibrators. The top surface was leveled with a screed. Specimens were finished with magnesium floats.

Concrete was cured in the forms under damp burlap for seven days. Specimens were then lifted from the casting deck and forms were removed. Specimens were stored in air maintained at 70-75F and 30 to 40% relative humidity to dry to proper moisture condition for test. Concrete cylinders 6-in. in diameter by 12-in. high were made at the time each slab was cast for determining compressive strength.

Computer Programs

To conduct fire tests of Phase III, it was necessary to develop computer programs in three main areas: (a) calculation of temperature distribution in a joist slab, (b) stress analysis of joisted floor slabs, and (c) development of programs for use with a Hewlett Packard 9100B Computer. For temperature distribution work, a two-dimensional heat-flow computer program that was developed using nonlinear thermal properties (5) for another project was modified. Figure 22(a) shows a typical computed temperature distribution in a joisted slab at 2-hr fire exposure. To relate this two-dimensional temperature distribution to the plane-stress computer program, it was necessary to convert it to an equivalent one-dimensional temperature distribution through the thickness of the joisted floor slab. This was accomplished by averaging the temperature at nodal points at the same elevation across the joisted slab cross section. Figure 22(b) represents this equivalent one-dimensional temperature distribution.

The plane-stress computer program used for flat plates was expanded to generate element stiffness of joisted slabs. Figure 23(a) shows a triangular element that represents joist members in both directions. A hypothetical grid system was used to replace joist members to form the basic stiffness matrix. Figure 23(b) displays two orthogonal line elements, equivalent to joists in each direction, running through nodal points of a triangular element. In this manner, a two-way joisted slab was treated as a composite assembly of a flat-plate and a grid system.

Finally, three more programs were developed for use with a Hewlett Packard 9100B Computer and a HP 9125B plotter. The functions of these programs were: (a) to optimize specimen position in the floor furnace, (b) to compute restraining forces from hydraulic ram pressures, and (c) to compare moment capacity of the test floor during fire tests with actual moments due to loads. With these programs, it was possible to monitor and predict structural behavior of a floor slab during a fire test.

Fire tests of two flat-plate, two waffle, and two pan-joist floor specimens were conducted. Each floor type was tested to simulate an interior and exterior span of a multi-bay concrete structure.

Expansion of each of the specimens during fire tests was controlled to conform to a computed time-expansion relationship. Relationships were calculated by use of a computer program developed for this purpose in Phase II of this study. Expansion of specimen during fire tests was controlled by varying horizontal forces applied to the four sides of the specimen.

Summary of Test Results

Specimen details and fire test results are given in Table 7. Expansions, restraining forces, deflection, and moment-capacity information was obtained for all six specimens. This information for flat-plate Specimen S-55 is plotted in Figs. 24 to 29.

Major findings were:

1. It was possible to follow the computed time-expansion relationship for the first 1-1/2 hours of test periods. After this time, actual expansions were less than computed values. Differences between actual and measured expansions after 1-1/2 hours are probably due to neglect of creep strain in the computed time-expansion relationships.

2. Restraining forces applied to specimen edges to control expansion increased rapidly for the first 45 minutes of test periods and reached maximum or near maximum values at that time. For the remainder of test periods, restraining forces remained fairly constant or increased slightly at a much slower rate.

3. Measured restraining forces were less than those computed. Since computed forces were larger than those developed during tests, the computer program can be considered to give a conservative estimate of behavior of floor systems exposed to fire. Even with effects of creep strain neglected, the computer program yields values of restraining forces accurate enough for engineering analysis of the structure.

4. In this series of fire tests, exterior as well as interior bays performed as restrained floor systems in a structure. Tests were stopped after 4 to 4-1/2 hours of exposure with no visible signs of structural failure.