NATIONAL BUREAU OF STANDARDS REPORT

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THE FIRE RESISTANCE OF PRESTRESSED CONCRETE BEAMS

by

J. V. Ryan

Report to

Bureau of Yards and Docks
Department of the Navy

NBS

U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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To

Bureau of Yards and Docks
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NATIONAL BUREAU OF STANDARDS

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Abstract

Six fire-endurance tests of prestressed concrete beams were made to supplement the results from an extensive program in England which was designed to investigate the fire resistances of large beams by determining the fire resistance of geometrically similar scale models at various scales. Of the six beams tested here, five were at 4/5 scale and the sixth at 1/2 scale. Variables included beam section, concrete cover to the prestressed cable, and the use of lightweight insulating concrete as an outer shell. The test results reported provide the information on the behavior of prestressed concrete during fire exposure and tend to confirm the scale relationship previously observed with smaller specimens during fire tests in England.

1. INTRODUCTION

The use of prestressed concrete construction has become increasingly popular during recent years, largely because of the reduction in the amount of steel and concrete necessary to provide the required design strength and load capacity. This results in lower dead loads and conservation of building materials.

With the more frequent use of prestressed construction the fire resistance behavior of such constructions became important. A research program to study this behavior was therefore started at the British Fire Research Station, Elstree, in cooperation with the Building Research Station. A survey of prestressed concrete applications in large buildings led to the selection of a 20 ft span beam as the basic unit to be investigated. Because the size of the floor testing furnace would not permit tests of 20 ft long beams, the program was

carried out on geometrically similar small scale beams in the belief that a relationship between fire resistance and scale would be established by which the fire resistances of larger scale beams could be predicted. Tests were made on beams of three different design types at scales of 1/4, 3/8, and 1/2 of the 20 ft basic unit under various conditions of loading and restraint.

The results of the tests seemed to indicate a linear relationship between geometric scale and fire resistance for T-section beams with a single cable of prestressed wires, designated type A, and it appeared desirable to extend the range of information by obtaining data on such beams at larger scales. The National Bureau of Standards offered to perform tests on a series of beams of larger size because of its interest both in prestressed concrete construction and information on the value of tests of small models for determining what performance may be expected from large structures. The six tests described herein were undertaken in cooperation with the Bureau of Yards and Docks, U. S. Navy. The test specimens were built at the Building Research Station in England and shipped to this country by the Fire Research Station.

2. TEST SPECIMENS

Each of the six test specimens was different from all the others in some respect, but they had points of similarity. Three were type A beams (T-section, single cable) one of 1/2 scale, for the purpose of correlation with the tests at the British Fire Research Station, one of 4/5 scale, and the third 4/5 scale with 1-in. protection of reinforced vermiculite concrete on bottom and sides of the beam and the underside of the top slab. A fourth beam was type D, 4/5 scale, similar to type A, but having a greater concrete cover to the cable. The fifth and sixth beams were type E, 4/5 scale, identical to type A except that type E had no top slab. The maximum compressive stresses in a fully loaded T-section beam (types A and D) occur at the slab's upper surface, which is not exposed to the fire. The E type beam was introduced in order that the zone of maximum compressive stresses, located at the top of the rectangular section, would be within the furnace and therefore experience more severe fire exposure. One of the type E beams had 1 in. of vermiculite concrete on bottom and sides.

The beams were designated by National Bureau of Standards fire test numbers and by a three-part system of notation used by the British, which consisted of type letter, scale fraction, and thickness of vermiculite concrete protection in inches. For example, A:1/2:0 indicated an A type beam of 1/2 scale with no (0-in.) vermiculite concrete protection. The test numbers and beam notations are given in table 1.

Each of the beams was of uniform cross section over the center half of the span, increased in depth by bottom haunches to near each end, increased in width immediately beyond the haunches, and were of constant depth and width at each end bearing. The haunches were incorporated in the design to allow the use of straight prestressed cable cavities and still provide the greater bottom cover near the ends that would be found in beams in which a curved cable and cavity were used.

The ends of the prestressed cable and their anchorages, which extended beyond the ends of the beam proper, were encased in concrete. The dimensions of the various test specimens are given in figure 1. The prestressed cable in the 1/2 scale beam consisted of 32 steel wires of 0.103 in. diameter (12 ga British Standard Gage) while the cables in the 4/5 scale beams each consisted of 24 steel wires of 0.2 in. diameter. The wires were of cold drawn steel having tensile strengths as shown in table 3. The vermiculite concrete protection had been cast in 1-in. thick slabs with 1 1/2-in. hexagonal mesh 0.040 in. diam (No. 19 B.S. Ga) wire fabric at the mid-thickness, cut to the desired sizes and shapes, and placed to line the molds of the beams to be so protected. The gravel aggregate concrete for the beam proper was then cast into the lined mold, forming a direct bond with the vermiculite concrete slabs. The pattern of protective slabs, and the joints between, is shown in figure 2.

The concrete aggregate for the beams, including the top slabs of the T-sections, was a river gravel from the Thames valley. The mix proportions and water cement ratio were selected to give a compressive strength of 6000 lb/in.^{2} at 28 days, when tested in the form of 6-in. cubes. (The strengths of 6- by 12-in. cylinders may be estimated by multiplying these values by 0.85, giving about 5100 lb/in.^{2}). For the A:1/2:0 beam the proportions by weight were approximately 1 part of rapid hardening portland cement, 1 3/4 parts of sand (3/16 in. max size), 2 5/8 parts of gravel (3/16 to 3/8-in. size). For the 4/5 scale specimens, the proportions by weight were 1 part of rapid hardening portland cement, 1 1/2 parts of sand (3/16 in. max), 1 part of gravel (3/16 to 3/8 in. size), and 2 parts of coarser gravel (3/8 to 3/4 in. size). The water-cement ratio by weight was 0.48 for all specimens. A

petrographic survey of a sample of gravel recovered from one beam after test indicated the composition to be 95 to 98 percent chert (or flint). This gravel is one of the most common concrete aggregates in use in Britain; the particular gravel selected was a fair representative of its class.

The rectangular portions of the T-beams were cast first, with castellations along the top. The rectangular element was stressed seven or eight days after casting, when the cube strength of the concrete was at least 4500 lb/in.^{2}, the initial stress in the cable being 145,600 lb/in.^{2} (65 long tons/in.^{2}). A grout of rapid hardening portland cement and water, in the ratio of 0.4/1 by weight, was injected into the cable duct when tensioning was completed. The slabs for the A and D type beams were then cast on the castellated upper faces of the beams. During the period between completion of manufacture and shipment from England the specimens were stored in the open. During the 2 1/2 to 3 1/2 month period between arrival at the National Bureau of Standards and testing, they were stored indoors at approximately 70° F and 50 percent relative humidity.

3. TEST METHOD AND EQUIPMENT

The beams were subjected to tests under the provisions of British Standard 476, Fire Tests of Building Materials and Structures, with additional data taken to provide the basis for comparison with ASTM E119-50, Standard Methods of Fire Tests of Building Construction and Materials. The former requires that a beam continue to support the test load (representing the assumed dead load plus 1 1/2 times the design load) while exposed to furnace fires controlled to produce temperatures as close as possible to: 1000° F (538° C) at 5 min, 1300° F (704° C) at 10 min, 1550° F (843° C) at 30 min, 1700° F (927° C) at 1 hr, 1850° F (1010° C) at 2 hr, 2050° F (1121° C) at 4 hr, and 2200° F (1204° C) at 6 hr. The furnace temperatures were measured by 12 chromel-alumel thermocouples of 18 ga wire encased in ceramic insulators but with the junctions and about 1 in. of the wires bare. Six other thermocouples were located in the concrete and six on the wires of the prestressed cable. The former were 19 ga chromel-alumel while the latter were steel-constantan, employing an individual wire of the cable as half of each thermocouple. For those beams (tests 334 and 336) with vermiculite concrete protection, other thermocouples of 19 ga chromel-alumel wire were located at the inner face of the vermiculite concrete. In addition, 12 thermocouples in wrought iron pipes (per ASTM E119-50) were distributed throughout the furnace to

provide comparative data. However, the temperatures measured by the bare thermocouples were used as the indication of proper furnace control in each test. The locations of the various thermocouples in the beams are indicated in figure 3.

Each beam was placed in the floor test furnace, in special supports prepared to receive it. The beam was located mid-way between the furnace sides with the underside of the top slab level with the undersides of the other concrete slabs used to fill out the remainder of the furnace opening. A gap of about 1 in. was left between these slabs and the test specimen, which gap was filled with mineral wool insulation. Separate slabs were cast to be placed on the type E beams. These slabs were made about 5-in. deep except at the center and quarter points where glass fiber inserts, 2- by 5- by 32 in. kept the top slabs from being rigid and continuous. Full length reinforcing bars tied the slab sections and inserts together without rigidity. This was done to provide a flexible method of loading the beam and closing the furnace opening. The beams were loaded at four points, the 1/8, 3/8, 5/8 and 7/8 points of span, by means of the mechanism shown in figure 4. The loads applied to the various beams, as well as other data, are given in table 1. The computed stresses in the concrete, before and after loading, were as given in table 2. The beams were tested under conditions described as loaded and unrestrained against longitudinal expansion.

4. RESULTS

The results of the tests are given as logs of test observations, plots of the temperatures recorded, and representative photographs.

4.1 Test 331-A:1/2:0 beam

During the first 1 hr 10 min the beam showed no heat effects other than reddening of the edges and some deflection; at 1 hr 25 min, cracks across the beam were observed near center span and the deflections were increasing rapidly; 1 hr 29 min, crack across soffit, deflection nearly 4 in., load removed; 1 hr 37 min, gas off.

The temperatures indicated by the steel cable thermocouples changed rather erratically during the test. However, the furnace temperature control was fairly good, and the temperatures at the various locations in the beam rose in smooth curves, as shown in figure 5.

Table 1. Summary of Results

NBS Test No.	Symbol for beam 1/	B.R.S. Marking	Age at test	Load	Duration of test	Type of failure	Cable Temp at failure		Fire Exposure severity 2/	Remarks
							Av	Max		
			da	lb	hr:min		°F	°F	percent	
331	A:1/2:0	BP28	238	24,400	1:29	Deflections	610	716	97.7	Reloaded cold, failed under original applied load
332	D:4/5:0	BP34	223	58,200	3:40	Beam & cable broke	1069	1072	103.3	
333	A:4/5:0	BP29	256	59,600	2:36	Cable exposed	788	1652	101.6	
334	A:4/5:1	BP30	262	59,600	6:02	none	698	793	99.5	Loaded to failure cold, 68,910 lb live load
335	E:4/5:0	BP32	262	26,200	1:55½	Beam broke	761	1371	99.0	
336	E:4/5:1	BP33	267	26,200	4:39½	Beam broke	511	610	99.7	

1/ System of notation introduced by B.R.S.: Letter refers to beam type; fraction to scale, final number to thickness of vermiculite concrete in inches.

2/ Defined as ratio of area under curve of average furnace temperatures to area under Standard Time-Temperature Curve, each area above 20°C (68°F) base line.

Table 2. Applied loads for the different beams and estimated stresses in the concrete

Type of section	Scale	Applied load	Estimated compressive stresses in the concrete at age of test: lb/in.^{2}							
			Before test load is applied				After test load is applied			
			At top of slab	Under-side of slab	At top of rec-tangular slab	At soffit of beam	At top of slab	Under-side of slab	At top of rec-tangular slab	At soffit of beam
		lb								
A	1/2	24,400	60	10	10	1630	1220	330	330	-580
A	4/5	59,600	90	20	-80	1590	1200	320	220	-580
D	4/5	58,200	90	40	120	760	980	390	490	-600
E	4/5	26,200	--	--	70	1700	---	---	2340	-580

The day after the test, the beam had recovered some of the deflection and a reloading test was made. The beam failed under a load of 10.4 long tons, almost the same as the test load. Following the reloading test, when the specimen was broken up, it was found that all of the wires in the prestressed cable were unbroken but the steel-constantan junctions were rusty, possibly accounting for the observed variations in cable temperatures. The conditions of the beam after the fire test and after the reloading test are shown in figures 6 and 7.

4.2 Test 332-D:4/5:0

During the first hour the beam showed no heat effects other than reddening, some deflection and emission of steam; at 1 hr 10 min, two small pop-outs and four short cracks in beam; 1 hr 13 min, crack 1 to 3-in. from bottom of beam runs full length, about 1/8-in. wide; 1 hr 30 min, cracks wider; 1 hr 43 min, considerable concrete fell from bottom and one side of south haunch, about 2-in. deep; 1 hr 54 min, cracks along beam up to 2-in. wide, fall of concrete from north haunch; 1 hr 56 min, concrete down from 3 to 4 ft of south haunch and beam, 2- to 3-in. deep; 3 hr 31 min, considerable concrete fell from west face of beam near center of span; 3 hr 38 min, concrete fell from full width of beam, north half, 3-in. deep, pressure in loading system unsteady; 3 hr 40 min, beam broke and collapsed; 3 hr 41 min, gas off.

The furnace control was fairly good, the average temperature having been near or slightly above the Standard curve throughout the test. The temperatures at the various locations in the beam rose to about 212° F (100°C) and leveled off for periods ranging from 10 min to 1 hr 10 min before continuing upward, apparently indicating time required to eliminate moisture. The cable temperatures behaved in a similar manner but remained near 212° F about 1 3/4 hr. The temperature curves are shown in figure 8.

After the test, the beam and slab were found to have broken in the middle, and the bottom concrete had broken off to expose the prestressed wires from haunch to haunch. The breaks in the broken wires were not all in one location but were divided into two locations, as shown in figure 9. All the wires were broken.

4.3 Test 333-A:4/5:0

At 12 min, water was dripping from the beam at center span; 15 min, four or five puddles of water, each 3 to 10 in. across, on top of slab near each quarter point; 20 min, two transverse hairline cracks in top slab near each quarter point, water or steam therefrom bubbling into covering puddle; 34 min, water from beneath steel plates on top slab at two loading points; 53 min, short longitudinal crack 1 in. from bottom of east side of south haunch; 1 hr 23 min, eight transverse cracks in top slab ranged from hairline to 1/16-in. wide; 1 hr 32 min, 1 ft long crack 1 in. from bottom of east face near center span; 2 hrs, cracks in beam 1/8- to 1/4-in. wide; 2 hr 4 min, momentary drop of oil pressure in loading system; 2 hr 9 min, concrete fell from bottom of beam along north half, including most of haunch, in depth of 2- to 3-in. over full width, temporary large drop in oil pressure; 2 hr 27 min, some wires of prestressed cable exposed, apparently since 2 hr 9 min, concrete fallen from bottom edges in south half; 2 hr 36 min, load failure as beam settled down quickly; 2 hr 38 min, gas off.

The furnace control was good, the average temperature having been near that specified in the Standard Time-Temperature Curve throughout the test. The temperatures indicated by the six thermocouples in the concrete rose smoothly during the first 2 hr but those by two jumped quickly thereafter. The temperatures in the prestressed cable behaved in a similar manner, as shown in figure 10.

On the day following the test the beam had recovered partially from the maximum deflection and the beam and slab were cracked in several locations. They were cracked through or broken at center span. Concrete had fallen from the bottom to expose the lower side of the grouted cable duct over the north half including most of the haunch, and to expose much of the cable in the south, again including most of the haunch. Fifteen of the 24 wires in the cable were broken. Their locations are shown in figure 11. The condition of the beam is shown in figure 12.

4.4 Test 334-A:4/5:1

At 11 min there appeared to be a 4-in. diam pop-out in the vermiculite concrete; 47 min, a piece of vermiculite concrete, 4-in. long by 1/2-in. wide. hanging down near south end; 1 hr 49 min, full thickness of vermiculite concrete fell from bottom of beam at south end for 2 ft; 1 hr 59 min to 2 hr 1 min, repeated loud popping as concrete spalled

violently along 1 to 2 ft of beam and haunch in north, dislodging the vermiculite concrete; 2 hr 30 min, a few moist spots on top of slab, each 10 to 12-in. diam; 4 hr, loud thump and repeated popping as slab spalls away all but top 1 1/2 in. of depth along 2 ft of east edge north of center; 5 hr 39 min, loud metallic sound; 6 hr 2 min, test stopped, gas off.

The furnace control was good, the average temperatures being a little low only near the end of the test, and the temperatures in the beam and cable rose gradually and smoothly throughout the test, as shown in figure 13. Thermocouple P_1 became inoperative at about 4 1/4 hr and P_4 had been found to be inoperative in a pre-test check.

Upon being unloaded and cooling over the weekend, the beam recovered about one-third of the total deflection. The vermiculite concrete slabs were thoroughly cracked and the joints between had opened. The beam had spalled at each end and the slab in the north half on the east side, as shown in figure 14. The spalling had involved, or been caused by, splitting of the aggregate rather than loss of bond between aggregate and cement. This is shown in figure 15. The beam was subjected to a reloading test and failed under a load of about 65,180 lb (29.1 long tons), exclusive of the weight of the beam and slab. The beam and slab broke at the worst of the spall in the slab, about 2 ft north of center, exposing the cable from that location to the north end of the exposed length, as shown in figure 16. After the reloading test it was found that none of the prestressed wires was broken.

4.5 Test 335-E:4/5:0

During the first hour, the beam showed no fire effects other than reddening and some deflection; 1 hr 19 min, two full length cracks on east side of the beam, each about 1/8-in. wide, one 1 in. and the other 2 1/2 in. from bottom; 1 hr 24 min, at least 1 in. of concrete fell from bottom of beam, full width along central 8 ft; 1 hr 43 min, more concrete fell from north end; 1 hr 46 min, more concrete fell from south; 1 hr 55 min, pressure in loading system fell; 1 hr 55 1/2 min, beam collapsed; 1 hr 56 min, gas off.

The furnace control was fairly good, the average temperature being a little low during most of the test. The temperatures in the concrete and cable rose smoothly at first but jumped after 1 1/2 hr as shown in figure 17, probably due to cracking. Three of the thermocouples in the concrete became inoperative before the end of the test.

The beam had broken at three places, roughly the center and the quarter points. The cable was exposed over the central 14 to 15 ft but only two wires were broken, as indicated in figure 11. The concrete of the beam was much more "burned out" than in previous tests, and could be crumbled in the hand except that from the ends which had been in the protected supports.

4.6 Test 336-E:4/5:1

No fire effects other than reddening and deflection were observed until 51 min, when the joints between vermiculite concrete slabs appeared to have opened about 1/4 in.; 1 hr 28 min, joints slightly wider, possibly 1/2 in.; 1 hr 50 1/2 min to 1 hr 55 min, repeated loud popping and spalling of beam in north until vermiculite concrete slabs and some of beam down from bottom of north haunch and adjoining 1 ft of central section; 3 hr 30 min, no change since 2 hr except some loosened vermiculite concrete fell; 4 hr 29 min, loud thump, temporary drop in oil pressure; 4 hr 39 1/2 min, beam "sat down" in slow collapse; 4 hr 41 min, gas off.

The furnace control was good, the average temperature having been very near that specified by the Standard Time-Temperature Curve throughout the test. The temperatures in the concrete and cable rose smoothly and gradually, except that indicated by thermocouple P_1 which jumped at about 4 hr, as shown in figure 18.

After test, the beam was found to have broken at the center of the span and a considerable amount of concrete was off the north half, exposing the cable. Twelve of the 24 wires in the cable were broken, the breaks having been about 4 ft north of where the beam broke. A large piece of concrete had sheared off the top, as shown in figure 19. The spalled areas showed shearing of the aggregate, as in the test of the A:4/5:1 beam.

5. DISCUSSION

5.1 Size of Beam

The fire endurance of the A:1/2:0 beam (test 331) observed in this series of tests was about 91 percent of that of a similar beam in the previous British tests, the latter beam having been aged about one month longer, and was about 93 percent of that of a duplicate beam made and tested in England at the same time as the beam in test 331. This agreement was considered to be close enough to permit comparisons between the results obtained in this series and

those from the British Fire Research Station. The slight differences between the fire endurances may have resulted from differences in temperature and humidity conditions during aging.

The results obtained for the A:4/5:0 beam (test 333) were about 10 percent lower than those anticipated from an extension of the linear relationship tentatively based on the results from England. As the beams tested by the Fire Research Station were of 1/4, 3/8 and 1/2 scales and those tested at the National Bureau of Standards of 1/2 and 4/5 scales (A:1/2:0 and A:4/5:0), predictions of the fire endurance of a full scale beam involve an extrapolation equal to 36 percent of the total range of available test data. If it is assumed that the fire endurance is proportional to a linear dimension of the geometrically similar beams, the predicted value for a full-scale beam A:1:0 would depend somewhat upon the data used in making the extrapolation. Considering the data for the beams A:1/4:0, A:3/8:0 and A:1/2:0 originally tested by the Fire Research Station in England, the predicted value is about 3 hr 42 min; using only the data for the beams A:1/2:0 and A:4/5:0 tested in Washington, it is 3 hr 20 min; and by giving equal weight to all available data, it is about 3 hr 24 min.

5.2 Concrete Cover to Cable

On the A and E type beams, the thickness of concrete on each side of the cable cavity was slightly less than that below, the difference having been 1/8 in. on the 1/2 scale and about 1/10 in. on the 4/5 scale. However, on the 4/5 scale D type beam, the concrete thickness was about 1/10 in. greater on the sides than the bottom. This leaves some question as to which thickness to consider; the bottom in all cases, the side, or whichever is least on each specimen. The orientation of the cable in the beam requires consideration of how extensive a "face" it presents to the heat penetrating the concrete. Since both sides of each beam were exposed, the sum of the two sides of the cable made a greater "face" than the bottom in all cases. However, the bottom concrete was subject to exposure from three sides and often showed evidence of greater heat damage than the sides, as evidenced by cracks, crumbling, and spalling. Therefore, the thickness of concrete below the cable appears to have been more significant than that on each side, so long as they were as nearly equal as in these test beams. The results obtained in the three tests of unprotected T-section beams (tests 331, 332, 333), when plotted as fire resistance vs thickness of concrete below the cable, gave points approximating a straight line. Interpolation on this line for the 4-in. thickness expected on a full scale type A beam gives 3 hr 20 min as the

predicted fire resistance for such a beam. Extrapolation along a line based on the results of the two A type beams, alone, would predict a resistance more nearly 3 3/4 hr. However, the lower value of 3 hr 20 min, having been determined by consideration of one more data point and by interpolation rather than extrapolation, should be more nearly correct.

The cracking and crumbling of the concrete mentioned above would become increasingly important at the larger scales. It would appear desirable and might prove necessary to incorporate some reinforcement in the concrete, such as a cage or basket of wire mesh located about 1 in. beneath the concrete surface. Such reinforcement should prevent loss of concrete.

5.3 Insulation

The 1-in. thick reinforced vermiculite concrete insulation used in two tests proved very effective in extending the period of fire resistance. The unprotected A:4/5:0 beam had failed at 2 hr 36 min whereas the insulated A:4/5:1 beam withstood the fire exposure during the maximum period defined in BS476, 6 hours, without failure and, after cooling, retained strength to support a load up to 13,000 lb greater than that applied during the fire test. The ratio of fire resistance periods for the protected beam compared to the unprotected was 2.32/1. However, since the A:4/5:1 beam had not failed at the end of the test, this ratio would have been higher if the beam could have been tested to failure. Very similar results were obtained in the tests of the E:4/5:0 and E:4/5:1 beams (tests 335 and 336), respectively. In this case, however, both beams broke. The fire resistance of the former was 1 hr 56 min and of the latter was 4 hr 40 min. The ratio of fire resistance for the E:4/5:1 to that for the E:4/5:0 was 2.42/1 of the same order as that for the A beams. It is believed that about 1 1/4-in. thick vermiculite concrete would be required on full scale beams in order to give the same ratio between the fire resistances of protected and unprotected beams.

The only violent spalling observed in this series of tests occurred in the two tests of beams with insulation of 1-in. reinforced vermiculite concrete. Each of these beams spalled explosively along the haunches and ends of the central section. Spalling near one end occurred in two of the four British tests of A-type beams with 1 in. of vermiculite concrete insulation but did not occur in any other tests, either with greater thicknesses of the same type of insulation or with no insulation. The spalling might have

been caused by stresses resulting from excessive local heating through cracks along the joints between adjacent vermiculite-concrete slabs at the transition from central section to haunch. It is also possible that the vermiculite concrete may have retarded the escape of excess moisture from the beams during curing. Previous observations during fire tests of dense concrete having high moisture content have indicated greater spalling than that observed during tests of more thoroughly dried specimens. Neither of the foregoing possible explanations is considered completely satisfactory; they are suggested, however, as possibilities.

5.4 Shape of Section

The difference between A and D type beams was largely one of thickness of concrete around the cable, as discussed in section 5.2. That between the A and E beams, however, was in the top slab's contact with the beam. Since the cover to the prestressed cable was the same in each type, this factor should not enter into any difference in fire resistance. The intimate contact between beam and slab in the A type was such that the top slab would dissipate heat from the concrete and assist in supporting the load. This assisting effect was of greatest importance late in the fire exposure as the concrete at the bottom of the beam lost strength. Loss of strength to a given depth in the concrete should require about the same time in each type but would represent a larger fraction of the total load bearing section in the type E beam than in the type A, thereby leading to the earlier failure of the former.

5.5 Cable Temperature

Of the six thermocouples in the prestressed cable, four were located at the center of the span. Although the temperatures of the prestressed wires measured during the tests may not have been the maxima over the full spans of the wires due to the small number of thermocouples and their concentration, the wire temperatures at which failure should be expected can be predicted from the results of a study made in England. The English data on the strength-temperature relationship for prestressed wire used in their beams indicates a 50 percent loss of strength at about 750° F (about 400° C). Similar data 1/ on steel for conventionally reinforced concrete

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1/ Mechanical Properties of Metals and Alloys, National Bureau of Standards Circular C447, Dec. 1,1943, pp.252-254.

shows a 50 percent loss of strength at 1000 to 1060°F (about 540 to 570° C). Thus if beams of the two types of construction are fabricated using a factor of safety of two in their designs and equal concrete cover, it would be expected that failure would occur in the prestressed beam at an earlier time during fire tests of the two beams.

The average and median temperatures of the prestressed wires measured at the time of failure in each test are given in table 3 as degrees F above the predicted 750° F.

Table 3. Temperatures at Failure, degrees F above 750° F

Beam	Average	Median
A:1/2:0	-140	-142
A:4/5:0	+ 38	-124
D:4/5:0	+319	+322
E:4/5:0	+ 11	-277
A:4/5:1	-52*	- 95*
E:4/5:1	-239	-248

* Temperature at end of 6 hr exposure without failure.

The fact that these temperatures were lower than expected in most cases indicates that the wires in the prestressed cables were heated to failure at locations somewhat removed from the central location of the thermocouples. Examination of the beams after the tests showed that most of the breaks and drawnout sections in the wires were at least 1 ft from the thermocouple junctions.

5.6 Deflections

The curves of deflections versus time in figure 20 show large early deflections followed by a steady state period for the unprotected beams, but a slow more or less uniform increase of deflection for the insulated beams. This effect is believed to be one of differential thermal expansion. As the concrete at the beam soffit, and the bottom of the slab of an A or D beam, is heated rapidly at the start of the fire exposure it expands while the concrete in the interior of the beam and the top of the slab remains cool and does not expand. In these beams of high strength concrete, a bowing toward the hot surface resulted. For the E:4/5:0

beam, the effect was of reduced magnitude since the separate top slab would not offer much restraint against the expansion of the upper surface of the beam. The vermiculite-concrete insulation prevented the rapid heating of the beam soffit, thereby diminishing the tendency for large deflections after the initial fire exposure.

6. SUMMARY

These tests provide data which, coupled with the data from tests at the British Fire Research Station, provide the basis for a linear relationship between fire resistance and scale of geometrically similar A type beams by which the fire resistance of full scale A beams may be predicted. This relationship may be expressed as:

$$R_F = 218\ S - 14$$

where R_F is fire resistance in minutes and S is scale. For an A:1:0 beam (S = 1), this formula gives a predicted R_F of 3 hr 24 min. In view of the range of data, S should not be taken greater than unity. The D and E type beams were tested only at 4/5 scale so no relationship may be proposed.

The thickness of the concrete cover over the reinforcing cable is one of the several variables which affect the fire resistances of prestressed beams. The results of these tests indicate it may be one of the most important. The D:4/5:0 beam had 4.4 in. cover and a fire resistance of 3 hr 40 min, the A:4/5:0 beam with 3.0 in. cover had a fire resistance of 2 hr 36 min, and the A:1/2:0 beam with 2 in. cover had a fire resistance of 1 hr 29 min. An A:1:0 beam, with 4-in. cover would be between the first two and would be expected to have a fire resistance of 3 hr 20 min on the basis of cover thickness. With the thick covers of 3 in. and more it would appear advisable to include some light reinforcement such as wire mesh not more than 1 in. from the concrete surface to prevent the loss of concrete during fire exposure.

The use of vermiculite concrete well bonded to the structural concrete, as when used as a form liner for the latter, will greatly increase the fire resistance which may be expected from a given size beam. The use of 1 in. of vermiculite concrete on 4/5 scale A and E beams gave 2 1/3 to 2 1/2 times the fire resistance of the unprotected beams and might be expected to give at least 2 times the fire resistance when used on A:1 and E:1 beams. Although beams so protected showed a tendency to spall violently, which was not shown by the other beams, this tendency is more than offset by the increased fire resistance.

Table 4. Physical Data for Construction Materials.

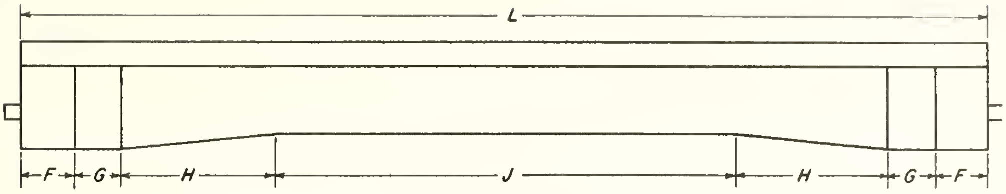
Symbol	Compressive strength of 6-in. cubes at 28 days		Compressive strength of 6-in. cubes at test age		Age at test	Tensile strength of wires
	Beam	Slab	Beam	Slab		
	lb/in.^{2}		lb/in.^{2}		da	lb/in.^{2}
A:1/2:0	6810	5980			238	284,500
D:4/5:0	6390	6460	8630	7980	223	255,400
A:4/5:0	7070	6940	9240	9020	256	250,900
A:4/5:1	7000	7010	9350	9310	262	255,400
E:4/5:0	6070	--	7410	--	262	248,600
E:4/5:1	7210	--	8790	--	267	255,400

Table 5. Results of Cold Loading Tests on Beams.

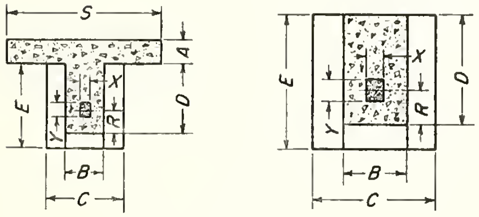
The following results were obtained in tests of beams similar to those subjected to fire tests. The data were obtained in England

Symbol for beam	Age at test	Total load* in pounds at occurrence of		Compressive strength of 6-in. cubes at test		Tensile strength of wires in cable
		First crack	Failure	Beam	Slab	
	da			$lb/in.^2$		$lb/in.^2$
A:1/2	108	27,600	48,200	9100	9100	284,500
A:4/5	40	65,900	112,700	6690	5980	253,100
D:4/5	39	62,300	115,400	7280	6100	257,600
E:4/5	210	31,600	51,500	7630	--	253,100
E:4/5	48	29,800	47,000	6510	--	255,400

* Includes weight of beam



SIDE ELEVATION



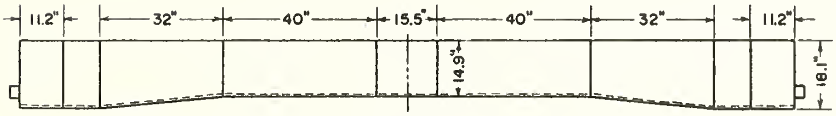
TYPES A&D   TYPE E

SECTIONS THROUGH CENTER OF SPANS

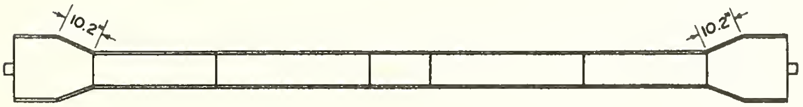
DIMENSIONS OF TEST SPECIMENS IN INCHES

TYPE -	A	A	D	E
SCALE -	$\frac{1}{2}$	$\frac{4}{5}$	$\frac{4}{5}$	$\frac{4}{5}$
L -	126	201.6	201.6	201.6
F -	7	11.2	11.2	11.2
G -	6	9.6	9.6	9.6
H -	20	32	32	32
J -	60	96	96	96
S -	20	32	32	—
A -	3	4.8	4.8	—
B -	5	8	12	8
C -	10	16	16	16
D -	9	14.4	15.4	14.4
E -	11	17.6	17.6	17.6
R -	3	4.5	5.5	4.5
X -	1.25	2.16	2.95	2.16
Y -	2	2.95	2.16	2.95

FIG. 1 DIMENSIONS OF TEST BEAMS



SIDE

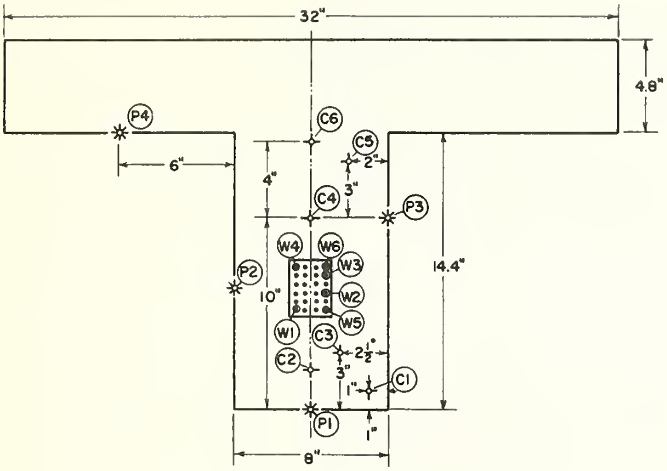


BOTTOM

DIMENSIONS FOR INSULATION ON PROTECTED BEAMS

JOINTS BETWEEN $\frac{1}{2}$" VERMICULITE CONCRETE SLABS WERE $\frac{1}{4}$" TO $\frac{1}{2}$" WIDE-GROUT FILLED

FIG. 2 ARRANGEMENT OF VERMICULITE-CONCRETE SLABS ON INSULATED BEAM (E:4/5:1)

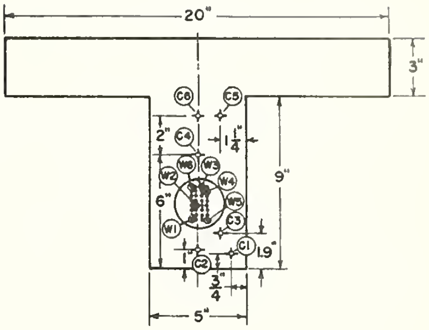


TYPES A&E $\frac{4}{5}$ BEAMS

⌖ CONCRETE – C1 TO C6 AT CENTER OF BEAM

◎ CABLE – W1 TO W4 AT CENTER OF BEAM
W5 & W6 4 FT. FROM CENTER OF BEAM

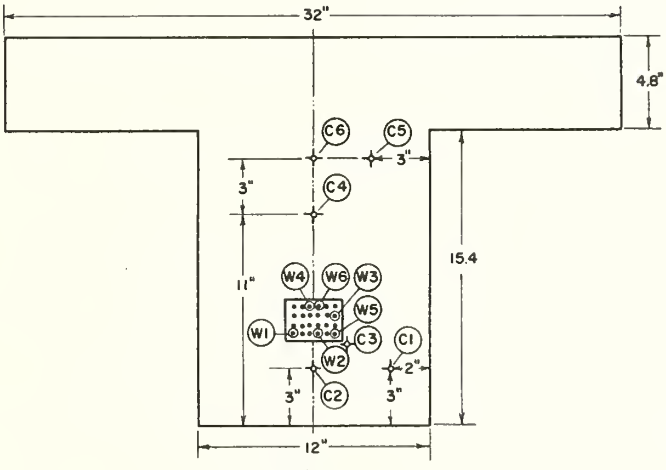
✳ INSULATION – P1 TO P4 FOR TYPE "A" P1 TO P3
FOR TYPE "E" ALL AT CENTER OF BEAM



TYPE A $\frac{1}{2}$ BEAM

⌖ CONCRETE – C1 TO C6 AT CENTER OF BEAM

● CABLE – W1 TO W4 AT CENTER OF BEAM
W5 & W6 $2\frac{1}{2}$ FT. FROM CENTER OF BEAM



TYPE D $\frac{4}{5}$ BEAM

⌖ CONCRETE – C1 TO C6 AT CENTER OF BEAM

◎ CABLE – W1 TO W4 AT CENTER OF BEAM
W5 & W6 4 FT. FROM CENTER OF BEAM

FIG. 3 THERMOCOUPLE LOCATIONS IN BEAMS

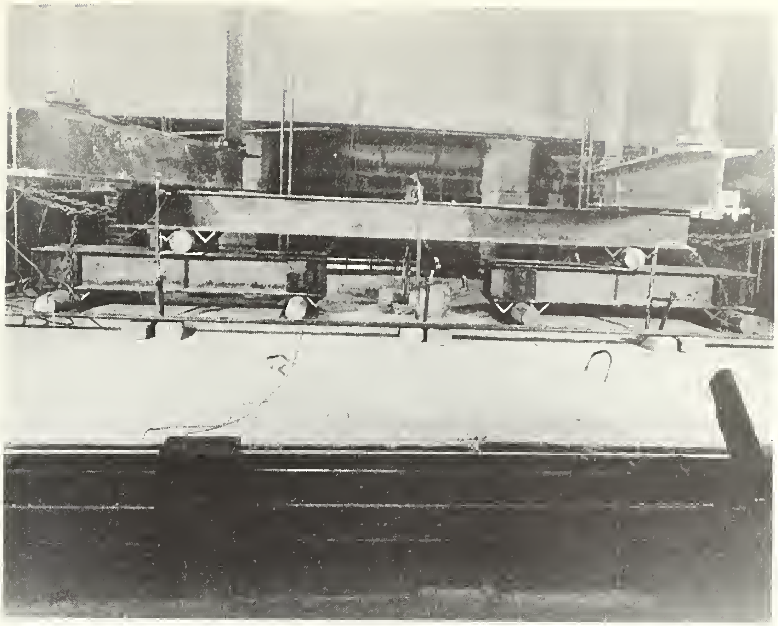


FIG.4 LOADING APPARATUS IN PLACE BEFORE TEST

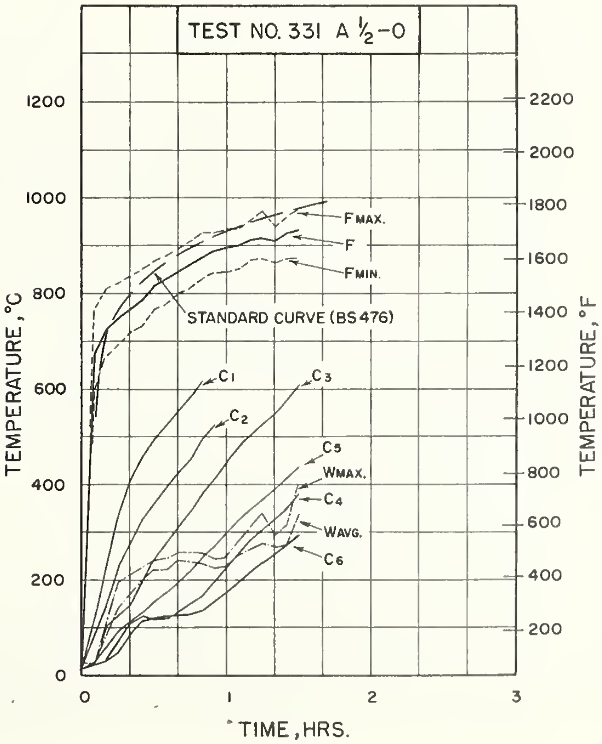


FIG. 5 TEMPERATURES OBSERVED DURING TEST 331

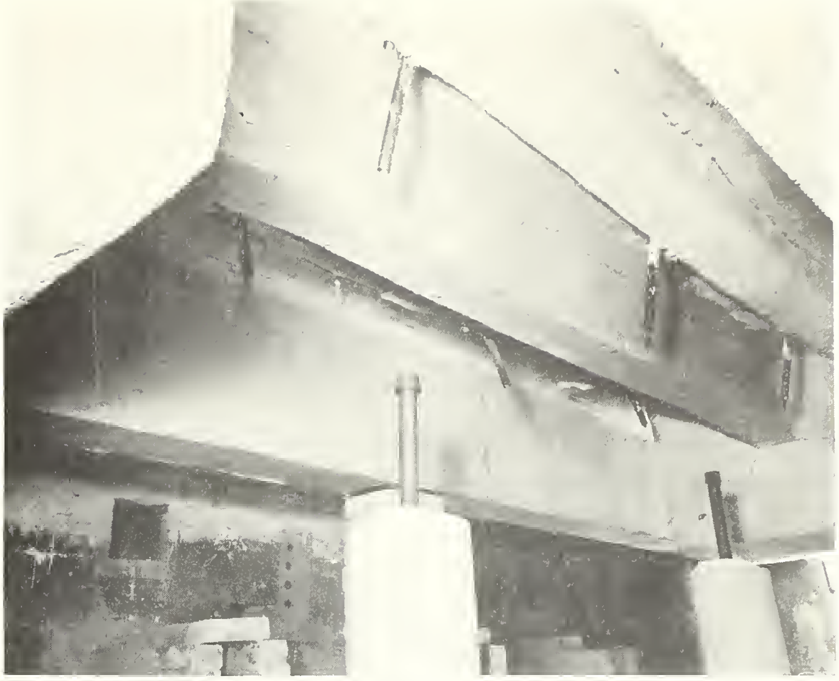


FIG.6 A:1/2:0 BEAM AFTER FIRE TEST 331

FIG.7 A:1/2:0 BEAM AFTER FIRE TEST 331 AND RELOADING TEST

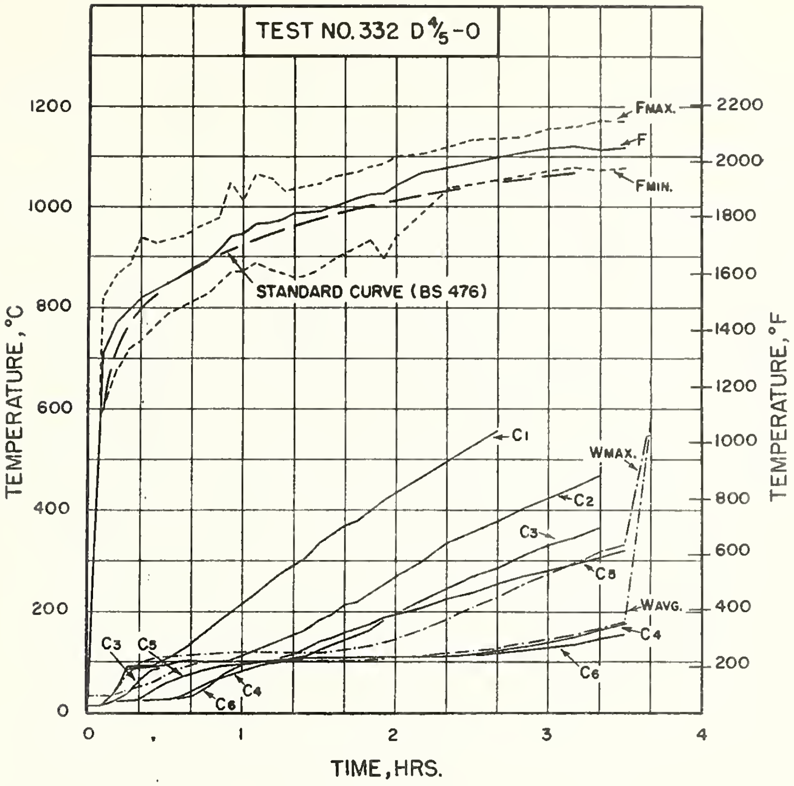


FIG. 8 TEMPERATURES OBSERVED DURING TEST 332. TEST STOPPED BEFORE ALL 3 HR. 40 MIN. TEMPERATURE OBSERVATIONS COMPLETED

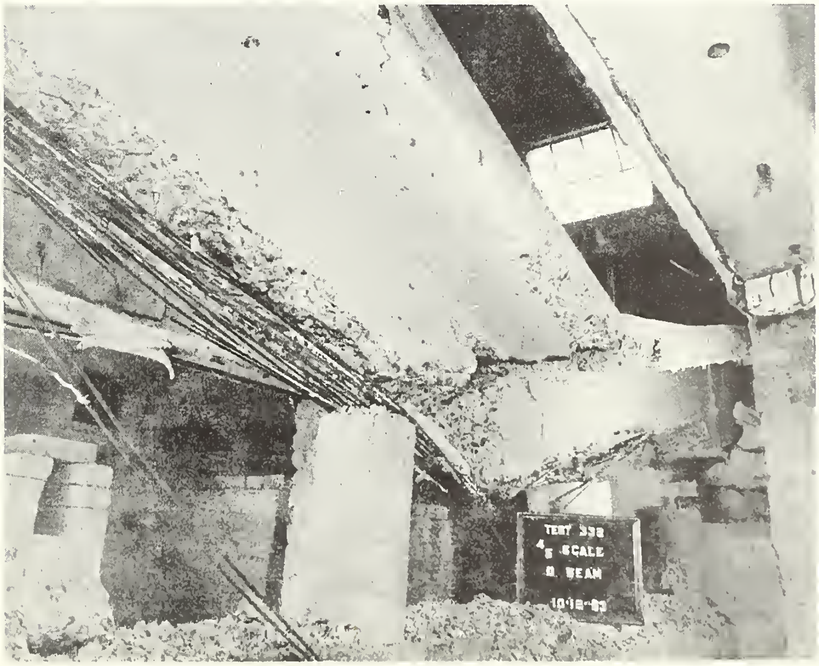


FIG. 9, D-4/5-0 BEAM AFTER FIRE TEST 332, SHOWING BREAKS IN SLAB, BEAM, AND CABLE, THE LATTER GROUPED IN TWO LOCATIONS.

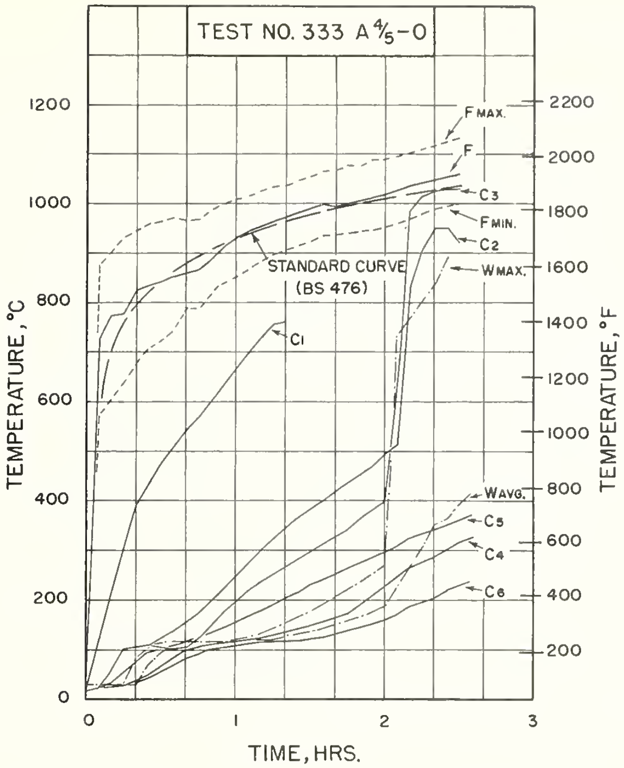


FIG. 10 TEMPERATURES OBSERVED DURING TEST 333

TEST 331 - 1/2 SCALE TYPE A - NONE BROKEN
TEST 332 - 4/5 SCALE TYPE D - ALL BROKEN
TEST 334 - 4/5 SCALE TYPE A WITH VERMICULITE CONCRETE - NONE BROKEN

X - BROKEN
O - UNBROKEN

333 4/5 SCALE TYPE A	335 4/5 SCALE TYPE E
O O O O	X O O O
X O O O	O O O O
X X X X	O O O O
X X X X	O O O O
X O X X	O O O O
X X O X	O O O X

336
4/5 SCALE TYPE E
WITH
VERMICULITE CONCRETE

X O O O
X X O X
X X O X
X X X X
O O O O
O O O X

FIG. 11 LOCATIONS OF BROKEN AND UNBROKEN PRESTRESSED WIRES

FIG. 12 A:4/5:0 BEAM AFTER FIRE TEST 333

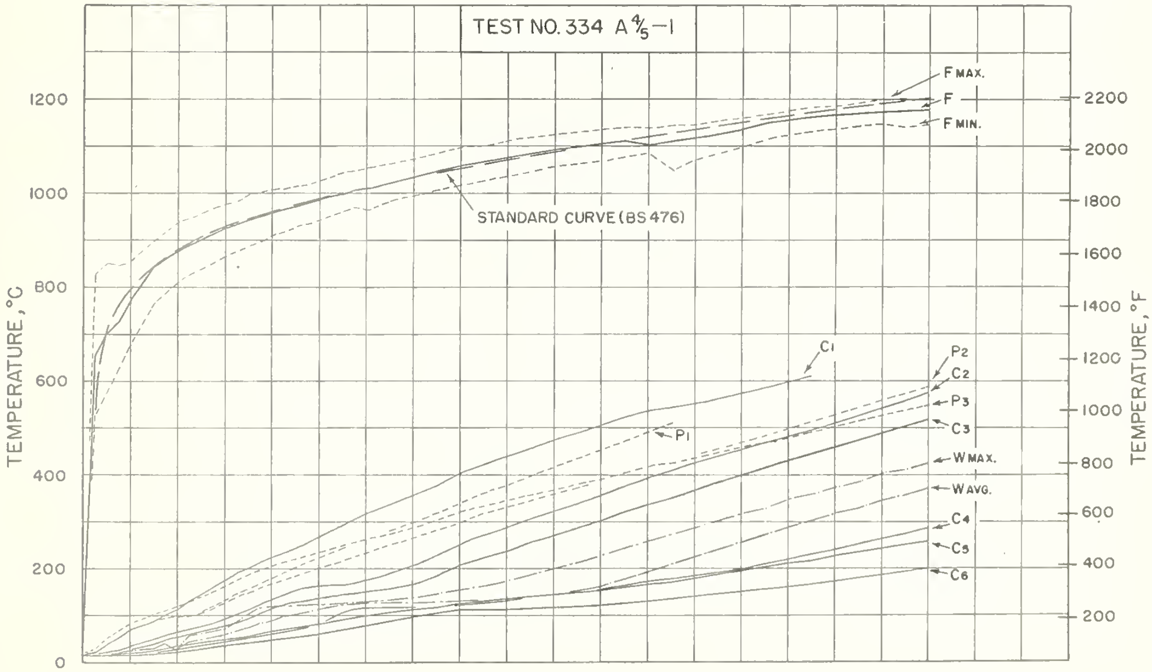


FIG. 13 TEMPERATURES OBSERVED DURING FIRE TEST 334

FIG. 14 A:4/5:1 BEAM AFTER FIRE TEST 334

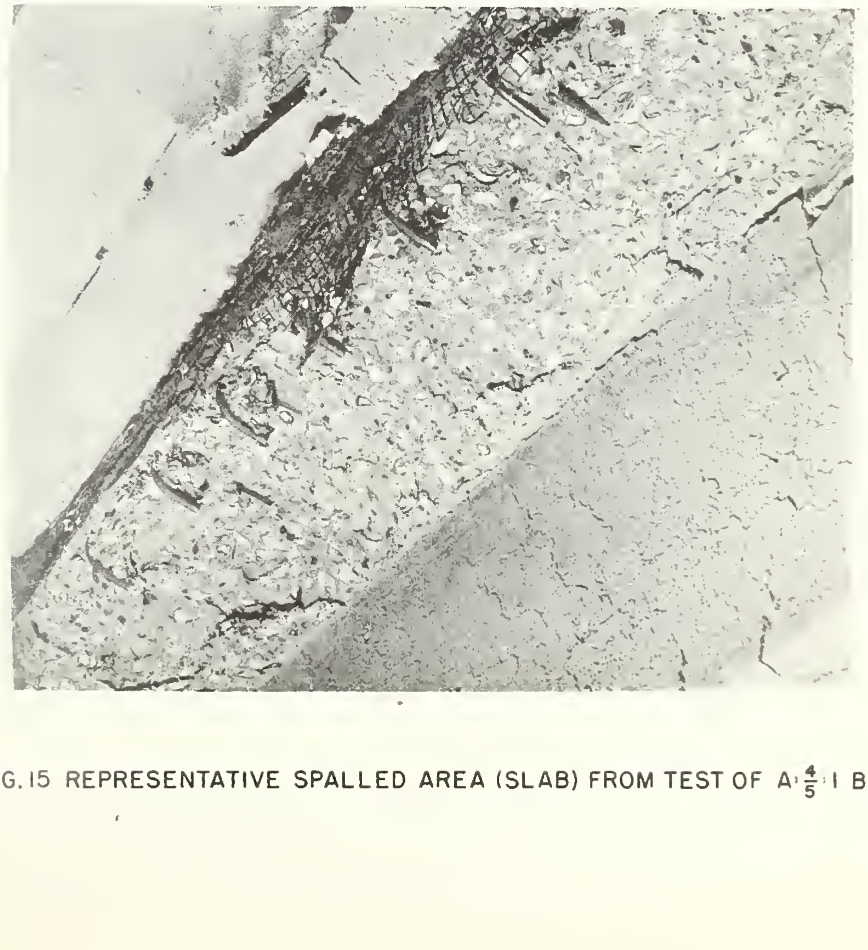


FIG. 15 REPRESENTATIVE SPALLED AREA (SLAB) FROM TEST OF A:$\frac{4}{5}$:1 BEAM

FIG. 16 NORTH HALF OF A:4/5:1 BEAM AFTER FIRE TEST 334 AND RELOADING TEST

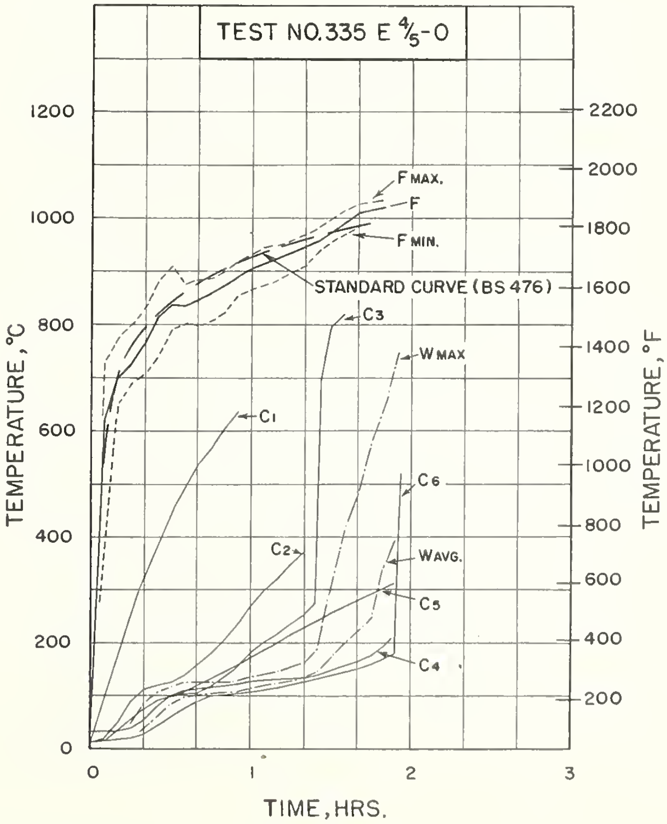


FIG. 17 TEMPERATURES OBSERVED DURING TEST 335

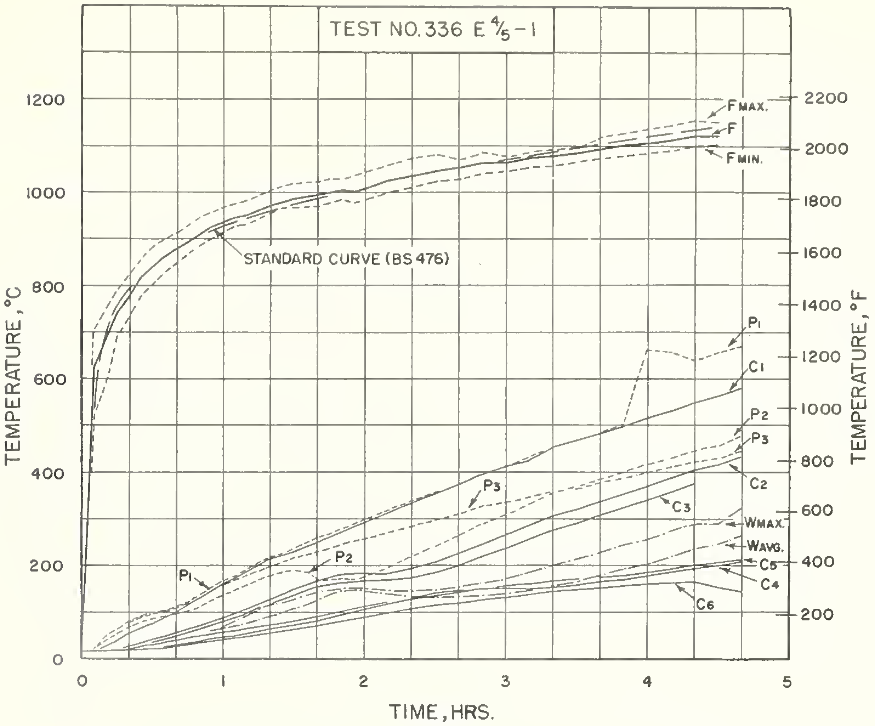


FIG. 18 TEMPERATURES OBSERVED DURING TEST 336

FIG. 19 E·4/5·1 BEAM FROM ABOVE AFTER FIRE TEST 336
SHOWING SHEAR FAILURE AT TOP

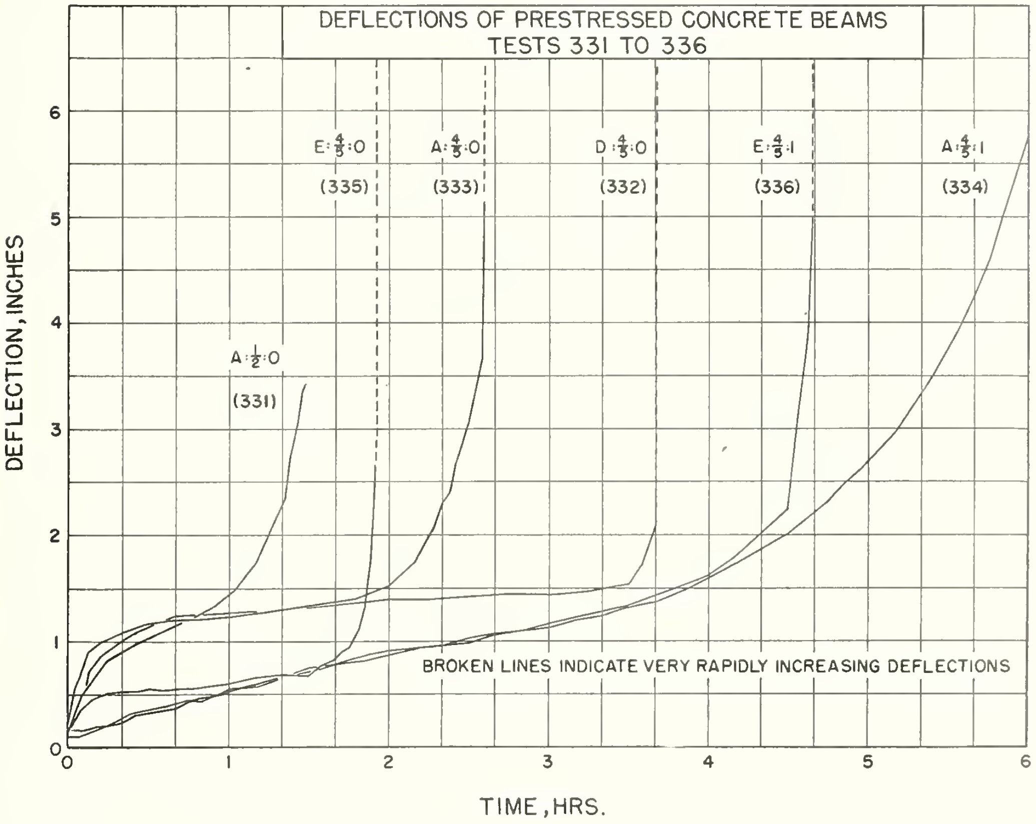


FIG. 20 DEFLECTIONS AT CENTERS OF BEAMS OBSERVED DURING TESTS, ALL DEFLECTIONS DOWNWARD

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