Fire endurance of continuous reinforced concrete beams

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Endurance au feu de poutres continues en béton armé

Feuerwiderstand durchlaufender Stahlbetonträger

M.S. ABRAMS
Manager Fire Research Section
Portland Cement Association
Skokie, Illinois, USA

A.H. GUSTAFERRO
Consulting Engineer
The Consulting Engineers Group Inc.
Glenview, Illinois, USA

T.D. LIN
Senior Research Engineer
Portland Cement Association
Skokie, Illinois, USA

1. SYNOPSIS

Results of fire tests of eleven full-scale rectangular reinforced concrete beams are presented. The specimens represented simple spans and interior and exterior spans of multi-bay structures. Test results indicate that full redistribution of moments occurs when statically indeterminate structures are exposed to fire. This redistribution substantially increases fire endurance.

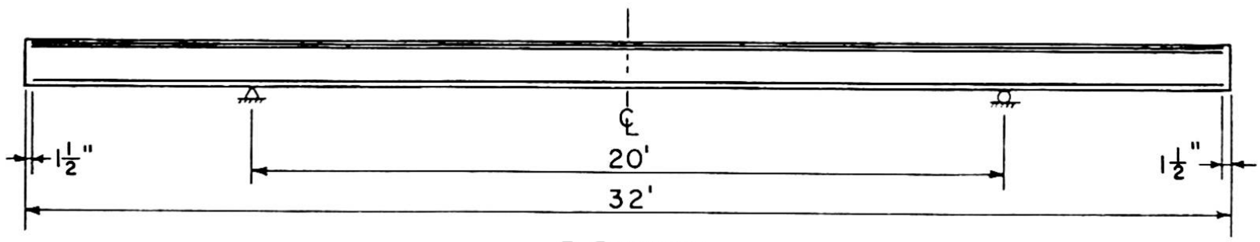
2. DESCRIPTION OF SPECIMENS

Specimen Design - Test beams 12-in. (305 mm) wide by 14-in. (356 mm) high and 32-ft (9.76 m) long were tested. Figure 1 shows the important features of the five designs used in the test program.

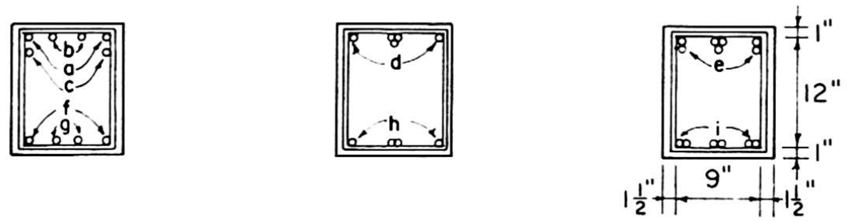
Ten beams were made with normal weight concrete containing a carbonate aggregate. One specimen was made with sanded lightweight aggregate concrete.

Thermocouples were attached to most of the top and bottom reinforcing bars at midspan and at four other locations between midspan and the support.

*Manager, Fire Research Section, Portland Cement Association, Research and Development, Construction Technology Laboratories, Skokie, Illinois, USA; Consulting Engineer, The Consulting Engineers Group, Inc., Glenview, Illinois, USA; and Senior Research Engineer, Fire Research Section, Portland Cement Association, Research and Development, Construction Technology Laboratories, Skokie, Illinois, USA.



ELEVATION



SECTIONS

SPECIMEN TYPE and DESIGNATION[1]	TOP BAR[3] (Beginning 1½" from each end)						BOTTOM BAR[3] (Symmetric about ℄)					STIRRUPS (Beginning 3" from each end)						
	DESIGN[1]	a	b	c	d	e	DESIGN	f	g	h	i	DESIGN	SIZE	SPACES				
I AAA	A	2 #6 31'-9"	2 #6 9'-2½"	2 #6 7'-11½"	–	–	A	2 #6 31'-9"	2 #6 11'-8"	–	–	A	3	19 @ 6" = 9'-6"	5 @ 12" = 5'-0"			
II ABA	A	2 #6 31'-9"	2 #6 9'-2½"	2 #6 7'-11½"	–	–	B	2 #6 31'-9"	2 #6 31'-9"	–	–	A	3	19 @ 6" = 9'-6"	5 @ 12" = 5'-0"			
III AAB	A	2 #6 31'-9"	2 #6 9'-2½"	2 #6 7'-11½"	–	–	A	2 #6 31'-9"	2 #6 11'-8"	–	–	B	3 & 4	10 @ 4½"[2] = 3'-9"	19 @ 2½"[2] = 3'-11½"	7 @ 3" = 1'-9"	7 @ 6" = 3'-6"	2 @ 12" = 2'-0"
IV ABC	A	2 #6 31'-9"	2 #6 9'-2½"	2 #6 7'-11½"	–	–	B	2 #6 31'-9"	2 #6 31'-9"	–	–	C	3	7 @ 6" = 3'-6"	18 @ 3" = 4'-6"	3 @ 6" = 1'-6"	6 @ 12" = 6'-0"	
V BCD	B	–	–	–	5 #8 31'-6"	2 #8 13'-0"	C	–	–	4 #6 31'-6"	2 #6 10'-11"	D	3 & 4	10 @ 4½"[2] = 3'-9"	16 @ 3"[2] = 4'-0"	5 @ 4" = 1'-8"	6 @ 6" = 3'-0"	3 @ 12" = 3'-0"

1 Roman numeral designates type, first letter refers to top steel, second to bottom steel and third to stirrups
2 # 4 bar stirrups, all other stirrups # 3
3 All bars Grade 60 = 60 ksi or 4,218 kg/cm^2

NOTE: 1 in = 2.54 cm; 1 ft = .305 m.

Fig. 1 - Specimen Design Details

Fire Testing Procedure and Data - Fire tests were conducted in the Portland Cement Association beam furnace, Fig. 2, using procedures described elsewhere.(1) Each specimen was mounted in the furnace with a 20-ft (6.1 m) span between 6-ft (1.83 m) cantilevers, as shown in Fig.3. Specimens were supported on steel roller bearings to provide free rotation and longitudinal expansion.

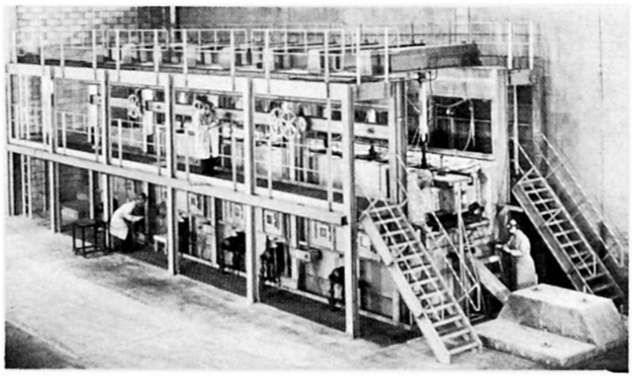


Fig. 2 - Beam Furnace

Four equally spaced hydraulic rams applied loads, P_3 shown in Fig. 3, to the interior span. Cantilever loads, P_1, P_2, were applied through hydraulic rams positioned 1-ft (0.305 m) from each end of the beam.

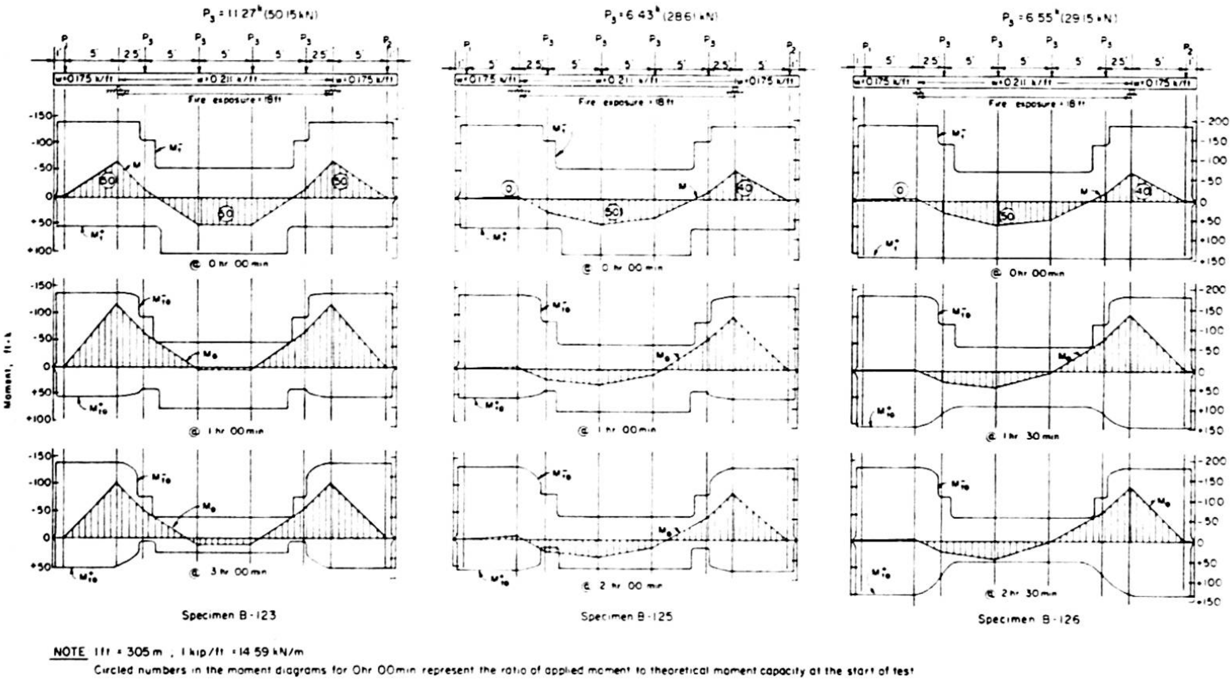


Fig. 3 - Loading and Moment Diagrams Before and During Tests

Each specimen was loaded to develop applied moments at mid-span and over the supports equal to a predetermined percentage of the calculated ultimate moment. Strain hardening was not considered in these calculations. The magnitudes of the applied moments as percentages of the calculated capacities are shown in Table 1.

TABLE 1 - TEST DATA

Speci-men No.	Speci-men Type	Moment Intensity, M/M_t at Start of Test: West Support	Midspan	East Support	Span Loads P_3	Cantilever Loads West, P_1: 0 Hr	Maximum	End of Test	East, P_2: 0 Hr	Maximum	End of Test	Avg. Temp. Bottom Reinforcement End of Test		Midspan Deflection End of Test	Test Duration
		%	%	%	Kips		Kips			Kips		F	C	in.	Hr:Min.
B-123	I	50	50	50	11.2	12.9	23.0	20.7	13.6	21.3	22.0	1315	712	6.3	3:30
B-124	I	0	50	0	4.5	0	0	0	0	0	0	952	511	6.4	1:20
B-125	I	0	50	40	6.4	0	0	0	10.4	20.1	18.1	1123	606	3.5	2:00
B-126	II	0	50	40	6.6	0	0	0	10.6	21.4	21.4	1213	655	5.4	2:33
B-127	III	55	50	40	10.5	14.9	23.1	19.1	10.2	22.7	20.0	1360	737	6.1	4:03
B-128	III	40	40	40	8.8	10.4	19.7	17.4	10.8	19.5	16.7	1450	787	4.0	4:31
B-129	III	50	50	50	11.2	13.2	21.6	20.0	13.3	23.3	20.8	1315	712	4.8	3:36
B-130	III	60	60	60	13.5	16.1	24.6	24.6	16.1	24.2	24.4	1293	700	5.3	3:03
B-131	IV	0	50	40	6.4	0	0	0	11.2	21.6	21.2	1280	693	7.0	3:01
B-132	V	0	60	60	11.3	0	0	0	33.0	53.1	46.5	1088	586	4.5	2:03
B-136[1]	I	55	55	55	13.4	16.2	27.7	24.1	16.0	27.3	22.9	818	436	3.0	1:30

[1]Lightweight aggregate concrete; all other specimens were of normal weight concrete.

Note: 1 in. = 25.4 mm; 1 kip = 4.45 kN.

With the exception of Specimen B-124, all beams were loaded to simulate continuous beam action. This was accomplished by varying loads P_1 and P_2 to maintain a constant elevation at the free end of one or both cantilevers. The cantilever loads generally increased sharply during the first 15 minutes of the fire test, reached a maximum value at 30 to 45 minutes, and then remained about the same for the rest of the test.

Furnace atmosphere temperatures were programmed to follow the time-temperature relationship specified in ASTM Designation: E119.(2) Reinforcing bar temperatures were monitored throughout each test.

3. ANALYSIS OF TEST RESULTS

General - Figure 3 shows applied moments and moment capacities at the beginning of and during three of the fire tests. The applied moments were calculated from the measured applied loads. The moment capacity, M_t, at the beginning of each test was calculated using the measured strengths of the reinforcement and concrete. Moment capacity during the test was calculated using the strength-temperature relationships for hot-rolled steel(3) and for concrete.(4)

Simple Support - One test, B-124, was loaded to simulate a simple support condition. During the test, no cantilever loads were applied, and no attempt was made to keep the ends at constant elevation.

The fire endurance of 1 hr 20 min. was reached when the moment capacity was reduced to the applied moment. The behavior of simply supported members is covered in another publication.(5)

Interior Spans - Six specimens were loaded to simulate continuity at both ends. Specimens B-123 and B-129 were loaded to induce moments at midspan and over each support equal to 50% of the calculated moment capacities. Both tests were terminated when it appeared that the flexural capacity was about to be reached. The test was stopped at 3 hr 30 min. for B-123 and 3 hr 36 min. for B-129.

Specimens B-128, B-129, and B-130 were loaded to moment intensities of 40, 50 and 60%, respectively, of calculated capacities over the supports and at midspan. Observed fire endurances were 4 hr 31 min., 3 hr 36 min., and 3 hr 03 min. Fire endurance decreased as the applied loading increased.

Specimen B-127 was loaded so that the midspan applied moment was 50% of the calculated capacity and the moments over the supports were 55% and 40%, respectively. The resulting fire endurance was 4 hr 03 min.

Specimen B-136 failed in shear. From Table 1 and Fig. 1, data show that B-136 was more vulnerable to shear failure than were the others.

Initial loading of B-136 was greater than that of other specimens with similar shear reinforcement. In addition, it was made of lightweight aggregate concrete.

The crack that precipitated the shear failure was located between two stirrups spaced 12-in. (305 mm)on center.Calculations indicated that shear reinforcement was required. Although the area provided was adequate, the spacing was nearly twice that permitted by ACI 318-71.[6]

End Spans - Four specimens, B-125, B-126, B-131, and B-132, were loaded to simulate end spans of continuous beams. No provisions were made to restrict rotation or movement at one end. At the other end, the cantilever was maintained at a constant elevation to provide continuity.

The flexural capacity of Specimen B-125 in the region near the bottom cut-off bars was reached at 2 hr 00 min.

Specimens B-126 and B-131 were similar in design except for shear reinforcement. Fire endurances of 2 hr 33 min. and 3 hr 01 min. were observed for these specimens.

Specimen B-132 was of a significantly different design. The top reinforcement consisted of bundled No. 8 bars. During the test, the top bars yielded over the support due to thermal deformation of the beam. This provided full redistribution of moment. The redistribution was not limited by cut-off bars.

4. CONCLUSIONS

1. For simply supported concrete beams exposed to fire, the flexural end point is reached when the positive moment capacity is reduced to a value that equals the applied moment. The positive moment capacity can be accurately calculated by taking into account the heat-reduced strengths of steel and concrete.

2. Continuous concrete flexural members undergo a redistribution of moments during fire exposure. Negative moments at supports increase causing a reduction in positive moments. Such redistribution occurred early during the fire tests reported here. In all cases, full redistribution was obtained.

3. Redistribution of shear was observed in several of the specimens tested. A failure attributed to redistribution of shear was observed in one specimen. However, the shear reinforcement for this beam was inadequate even at normal temperatures.

4. From the data obtained, it appears possible to develop design procedures for calculating fire endurance of continuous concrete flexural members.

5. REFERENCES

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SUMMARY

The redistribution of moments that occurred in a fire test of continuous flexural members resulted in an increase in moments over the supports and a decrease in moment at midspan. This redistribution of moment increases the fire endurance of concrete structural members. The results of tests of eleven concrete beams are reported in this paper.

RESUME

La redistribution des moments qui s'est effectuée durant des essais à l'incendie sur membres fléchissants continus a résulté en l'augmentation des moments aux appuis et en la diminution des moments au milieu de la portée. Cette redistribution des moments augmente l'endurance au feu d'éléments en béton. Les résultats d'essais sur onze poutres en béton sont présentés.

ZUSAMMENFASSUNG

Bei Versuchen an brandbeanspruchten durchlaufenden Stahlbetonträgern ergab sich eine neue Verteilung der Biegemomente. Die Stützmomente wurden grösser, die Feldmomente dagegen kleiner. Die neue Momentenverteilung erhöht den Widerstand der Betonträger. Die Versuchsergebnisse für 11 Betonträger werden in diesem Aufsatz beschrieben.