Paper No. 6444

The fire-resistance of prestressed concrete beams†

by

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and

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Discussion

Mr A. W. Hill (Deputy Technical Director, Cement & Concrete Association) felt that the Paper was of considerable value to the development of prestressed concrete. The information had fortunately been available for some time and had been of particular value in preparing the Code of Practice, B.S.C.P. 115:1959.

55. It was important to realize that the Paper was limited to beams. Slabs generally gave a much better performance, at least judging by the results of tests which had been carried out at the Fire Research Station on various types of prestressed concrete flooring. He thought that this might in some respects be due to the better distribution of wires which Dr Bate had referred to, but also to the fact that the fire on slabs only got at one face instead of three, as in a beam.

56. He had been rather disappointed to see, in § 28, which summed up the discussion on model testing, that the early hopes in this respect had not been justified. There would obviously be considerable difficulties with prestressed concrete work, since it dealt with structures of very long span, if it was always essential to insist on having full-sized members tested. Some of the results showed that the least that could be said was that the model testing had been extremely encouraging and that the reasons for the various differences which occurred with the larger members needed further exploration.

57. What were the Authors' views on scaling down the concrete aggregate? In some beams ⅜-in. aggregate had been used but in most of them ¾-in. He thought it was possible that if further attention had been given to the scaling down of the aggregate there might have been better correlation between scale and fire-resistance.

58. The results seemed to indicate a further restriction to the development of continuous structures in prestressed concrete. There had been considerable difficulties in regard to structural design as compared with reinforced concrete, and it was difficult in some cases to see the advantages of continuity. Any plans for a further investigation into the fire-resistance of continuous structures would be of considerable interest. He believed that the new furnace at Boreham Wood now gave those facilities.

59. In § 50, referring to aggregates, the Authors seemed to indicate that there would be no advantage with other aggregates. All the tests had, of course, been carried out with gravel aggregate, which was possibly the worst type of aggregate for fire-resistance. With other forms of construction, particularly reinforced concrete, there was some advantage in fire-resistance clauses for the use of limestone, and he thought that there might also be some advantages with blast-furnace slag aggregate which in its manufacture had been subjected to considerable heat. Why did the Authors think that there would be no advantage with other aggregates?

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† Proc. Instn civ. Engrs, vol. 17, pp. 15–38 (Sept. 1960).

60. In dealing with composite construction, in § 51, the Authors showed that for full resistance it was necessary to have projecting stirrups from the top of the beam into the in-situ concrete. This was an important consideration, since for normal structural testing it had been found that even the ordinary roughening of the concrete properly carried out was sufficient to get a complete bond. It would therefore seem that if the Authors' conclusions were correct some slight modification of the Code of Practice might be necessary in this respect, and he would like to have their further views on that matter.

Mr A. J. Harris (Partner, A. J. & J. D. Harris, Consulting Engineers) felt that it was interesting to put the subject into its historical perspective. Mr Ashton had mentioned the tests on a very early thin-walled beam. The story of the failure of that thin-walled beam had gone round the world at a very high speed. He recollected, in 1948, being in the United States discussing a bridge, and in the middle of the proceedings news had reached the clients of that test, and they had said, "What about fire-resistance?" The fact that the bridge was over an arm of the sea had apparently not been thought pertinent.

62. To what extent were the Authors' results consistent? Had there been enough repeats of tests to produce several readings on the same thing which agreed with one another?

63. Dr Bate had mentioned the subject of redundancy, and this had in fact reminded him of a test which was a trifle incongruous. It was a test on a very light triangulated beam structure in the form of a grillage. He did not think that anyone had been particularly hopeful as to the results of it. Some had expected 10 min, and some 15 min. In fact they had got 50 min. Since the size had been 2 in. × 2 in. and there had been very little cover indeed, this had been an exceedingly difficult result to account for. It might conceivably have a bearing on the aspect of redundancy; it might, on the other hand, have been a completely freak result. He thought that the scale effect was probably to blame for the fact that almost the whole of the screed had remained in position still supporting the load after the beam had collapsed beneath it.

64. As a result of the admirable enterprise and industry of the Fire Research Station, he thought they were now in the very curious position that much more was known about fire-resistance of prestressed concrete, which was a relatively new and novel material, than was known about that of steelwork or reinforced concrete. This was occasionally reflected in regulations which included pretty well tested characteristics of prestressed concrete alongside figures for other materials which had grown up over the years. How did the Authors think prestressed concrete would compare with the more classic materials if the latter were to be subjected to anything like the same degree of testing?

65. Mr Harris emphasized Mr Hill's point that the particulars given in the Paper applied to beams and not to slabs, because on many occasions it happened that people who had not read the code in which these figures were reproduced quite as carefully as they ought to have done tended to require 1½-in. cover everywhere for 1-hour fire-resistance.

66. Had the Authors learned of any fires in prestressed concrete buildings? Fires were singularly difficult things to estimate. Had any results been found in actual fires which conflicted with or confirmed the experimental results?

Mr D. J. G. Shennan (Senior Civil Engineer, John Mowlem and Co. Ltd) said that his remarks were not strictly to be concerned with prestressed beams, but he hoped, nevertheless, that they might be of interest. About 3 months before, a serious fire had taken place underneath an ocean tanker berth which his firm had constructed. This had been caused by the spilling of oil while a tanker was unloading. The oil had flowed on the surface of the water under the berth, it had been retained by the tanker and an oil-retaining boom, and had burned furiously for 2½ hours before being extinguished.

68. The construction of the berth consisted of an in-situ slab about 350 ft × 50 ft

cast on 6-in.-thick precast soffit slabs. This deck was in turn supported on prestressed hollow-core piles about 120 ft long and 27½ in. dia.

69. Mr Shennan then showed a number of slides. They showed that apart from the top 6 ft or so, the piles were undamaged and that the edges of the precast soffit slabs had apparently suffered very little damage.

70. At the time of the fire the water had been near its highest level, say 6 ft below the deck of the berth, which had been providential, because had the fire occurred at low water the repairs to the piles would have been extremely difficult.

71. The effect of the fire on the soffit had been that about two-thirds of the width of each slab, i.e. about 4 ft out of 6 ft, had spalled away to a depth of about 2 in. It appeared that this damaged section had been held in place for some appreciable time by the mesh reinforcement, so that considerable fire-protection had been afforded to the rest of the slab, and to the in-situ concrete above, which had been completely undamaged. Cores taken from the deck and subsequently tested had proved this, and incidentally, confirmed the Authors' point that mesh protection of that nature would afford protection.

72. So far as the piles were concerned, the damage had consisted of spalling which, commencing at water level, had been negligible, and had tended to taper up to the point where the pile met the soffit and there reached a maximum, generally speaking, of about 2 in. At that point the main high-tensile wires were, of course, exposed, and there was little doubt that, probably for the top 3 ft of the pile at least, the high-tensile wires had been subjected to annealing; but fortunately the piles had been plugged internally to a depth of 5 or 6 ft, so that even in the worst instances some connexion was still left between the original pile and the deck.

73. He need not dwell on the question of repairs, but basically the loose concrete had been removed, and the sections had been built up to something more than their original dimensions by gunite application. The berth had been in use for the past month, the repairs having taken about 6 weeks.

74. It appeared from this incident that there was a fire liability risk in the use of prestressed concrete where the main high-tensile wires were close to a surface which was liable to be exposed to excessive heat. The indications were that, as stated by the Authors, as the thickness of cover was increased so was the resistance to fire. He thought that if on some future occasion it was required to make piles resistant to fire damage, a solution would possibly be to have fairly close to the surface a layer of small, close-knit mesh—say ¾-in.—which would in effect form a wrapping that could contain the concrete should it be affected by heat, and would thereby form a protection to the main high-tensile reinforcement.

Mr Francis Walley (Senior Structural Engineer, Structural Engineering Branch, Ministry of Works) agreed with Mr Ashton's comment in his introduction that the reason prestressed concrete had received so much attention from the fire aspect was partly that the material had been developed for use in building just after the war, when the effects of fire on structures were in everybody's mind. He also agreed that still more information was needed. Indeed, recently an architect had assured him that he had used timber instead of prestressed concrete for a hangar because of the low fire-resistance of that material. Thus, although all this information was available, it still was not getting through to the appropriate quarters.

76. Would the Authors elaborate a little more on their scaling technique (§ 6)? He appreciated that in § 28 they had some doubts about it, but it did not seem to be a similar technique to normal structural scaling. There were far too many variables which could not be scaled along with every other factor; the furnace-temperature/time relation and the stress/strain relation at varying temperatures were just two of them, and since the furnace temperature/time had not been altered, the cover over the wires would be of more importance than any other factor.

77. Fig. 10 illustrated that if cover was plotted against time this would probably be just as relevant as Fig. 5 which the Authors had drawn. He realized, of course, that if

the results which the Authors gave in conclusion were plotted, the result would not be a straight line but a curve.

78. Had the Authors any explanation of the relatively rapid increase in deflexion during the first few minutes, mentioned in § 26? The drying shrinkage in the lower fibres would tend to hog the beam as described in § 31. He knew the difference between the two tests, one loaded and one unloaded, but he would have thought that the same phenomena would have taken place.

79. In § 32, which dealt with scale and end-restraint, if the figures given were plotted on a semi-logarithmic scale, the points would lie on a straight line, and if extrapolated to full scale, it would be found that there was no fire-resistance at all. This result would,

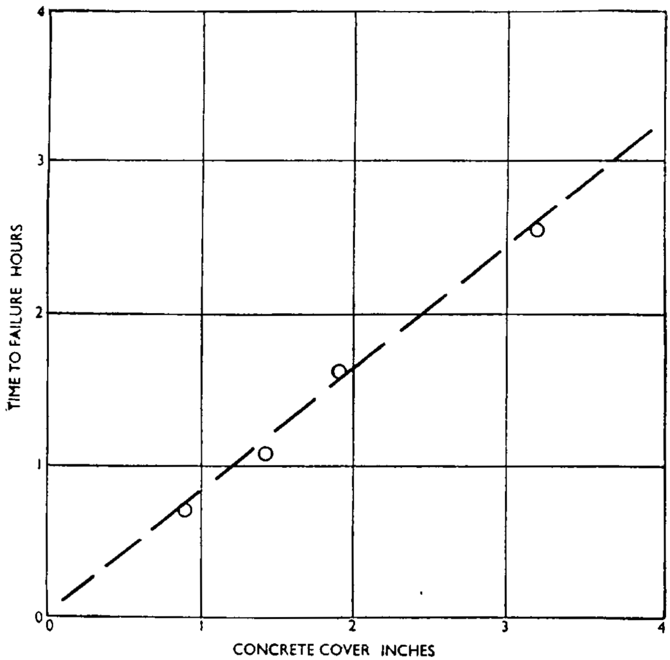


FIG. 10

of course, be quite absurd. He felt that the Authors had put the worst face on this, perhaps deliberately, by choosing results which gave the best results for the increase and the worst results for the decrease; but if the procedure was reversed, rather different figures were obtained—20, 27, and 10%. Had the Authors been deliberate in this, or had they any other reason for being pessimistic rather than optimistic on this point?

80. In § 33 it was stated that the wires lost half their strength at 400°C. It would be more accurate to say that a wire stressed to 50% of its ultimate strength would fail at 400°C. Had the Authors any information or any results which showed whether the temperature would be different if the wire were stressed to, say, 40 or 60% of its ultimate load? If, in fact, there was a significant difference in the results, there could perhaps be a case for reducing the initial stress during prestressing if the fire hazard was important.

81. In § 44 the question was raised of partial damage in a fire. Could it be concluded from this test whether at 300°C the ultimate strength of the wire was reduced by 25%, or was the low result solely due to a premature shear failure?

82. In § 47 the results with different wires were discussed. His reading of this paragraph led him to the conclusion that the similarity of the results of the test after heating to 200°C might be caused by the fact that the wires had been tensioned while under heat, which was in fact the same treatment which wire E received in its normal processing. Since all the wires had been given the same treatment, they would be expected to behave similarly on second reloading. Would the Authors agree with that interpretation of their results?

83. Were there not any better aggregates? He understood that there were certain limestone aggregates which should give better results than gravel.

84. Finally, dealing with the conclusions in § 52 (ii), what degree of confidence did the Authors have in their 4-hours fire-resistance figure? There were very few results, and he appreciated the reasons for that, but it was the only figure which was out of step with the figures that had been accepted for reinforced concrete. Those figures were consistently ½ in. less than for prestressed concrete, except for 4-hours fire-resistance, when the increase was 1½ in. Were the Authors again being pessimistic rather than optimistic?

Mr O. J. Masterman (Technical Director, The Unit Construction Co. Ltd) said that he had been concerned in the making of some of the prestressed units which had been tested, and in particular some of those which had been referred to earlier in the discussion and which had caused some alarm.

86. He had been responsible for making a number of very small floor joists which had been among the first prestressed units to be tested at the Fire Research Station—with disastrous results.

87. There was more information available now concerning size and cover, but probably very few people realized that if he had made exactly the same sized units in normal reinforced concrete and put them into the furnace the result would have been much the same.

88. The Paper was clear and concise as far as it went, which was on beams, with certain limitations—post-tensioned, free-ended—but a lot more of this kind of codification was needed for slabs and joists—and floor joists in particular.

89. Table 7 showed the cover required by different authorities for fire periods of

TABLE 7.—COVER REQUIRED BY DIFFERENT AUTHORITIES FOR FIRE PERIODS SHOWN: INCHES

Authority	Construction	1 hour	2 hours	4 hours
Model By-laws	Reinforced concrete beams	1½	2	2½
	Reinforced concrete floors	½	½	1
B.S. Code 114:1957 and L.C.C.	Reinforced concrete beams	1	2	2½
	Reinforced concrete floors	½	½	1
Fire Research Station	Prestressed concrete post-tensioned beams	1½	2½ + secondary reinforcement	4 + secondary reinforcement
B.S. Code 115:1959	Prestressed concrete unspecified	1½	2½ + secondary reinforcement	4 + secondary reinforcement

1, 2, and 4 hours. For beams the fire requirements were rather more onerous for prestressed than for reinforced construction, especially for the 4-hour fire period. Where floors were concerned the difference was much more marked.

90. Tables 8 and 9 showed details of some of the *ad hoc* tests carried out on prestressed floor constructions in Britain and America which showed that very much smaller covers were sufficient for these cases than for beams.

91. Table 8 showed two floor constructions with ½-in. and ⅔-in. cover respectively, each of which gave more than 2 hours' fire-resistance with ½ in. of plaster on the soffit. The third example was a thin prestressed plank with only ⅓-in. cover and ½ in. of plaster; this lasted nearly 1 hour and did not fail on account of the cover.

92. Table 9 showed examples of nine tests to the A.S.T.M. Standard E119–58, which corresponded to the standard fire test in Britain. There were five places where 1½-in. cover or less had given fire periods of 2 hours or more, and there was no plaster over any of them. Two points worth noting from these results were:

(i) that some tests were made with full end-restraint and some free, the restrained cases giving longer fire periods;
(ii) that temperatures of the tendons recorded ranged from 482°C (900°F) to 815°C (1,498°F).

93. A further point to note was that a 3-ft-deep girder which had only 1¾-in. cover gave a fire period of 4½ hours, whereas the proposal in the Paper for a 4-hour period was 4 in. of cover with steel mesh to keep it in place.

94. Table 10 showed tentative standards set up by the American Prestressed Concrete Institute in their standard code for prestressed concrete, published in November 1959. The two points to note here were, first, that the Americans had proposed different covers for beams, joists, and slabs, recognizing that floor joists and slabs did not require such large cover as independent beams and columns; secondly, that the covers proposed for light-weight concrete were less than those for normal-weight concrete.

95. Did the Authors think that the position revealed in the present codes and bylaws did justice to prestressed concrete?

96. Was it possible to look forward to an early codification of the cover requirements for floor joists and slabs so that *ad hoc* tests were not required for every small change in design and so that prestressed concrete constructions would not be unfairly restricted in comparison with reinforced concrete?

Mr Jan Bobrowski (Chief Engineer, Pierhead Limited) said that Fig. 11 showed certain anomalies in a direct comparison between reinforced concrete construction and prestressed concrete. To comply strictly with the present Code of Practice for reinforced concrete a construction of the kind shown, with 3-in. thickness of rib, ½-in. cover, and 4-in. minimum thickness occurring at the crown only, was recognized for 2-hour fire-resistance. To get a corresponding resistance with prestressed concrete would mean increasing the 3-in. dimension to 7 in., providing 2½-in. cover, and 5-in.-thick flange.

98. Which of those cases did the Authors think was nearer the truth? Had the one had too optimistic treatment and the other one too pessimistic treatment, or was the truth somewhere in between the two? He felt that there could not possibly be that kind of difference between the two in view of the tests on the beams, where the figures corresponded, except in the case of the 4-hour fire-resistance. Here the ratio for covers was as high as 5 (½-in. cover for reinforced concrete and 2½-in. cover for the corresponding prestressed concrete).

Mr R. J. M. Sutherland (Partner, A. J. & J. D. Harris, Consulting Engineers) wished to pursue a little further the question of consistency. He understood that prestressed columns were much more consistent in their behaviour than reinforced columns. He would have expected this to be due to the fact that little if any binding reinforcement was used in prestressed columns. He would then expect prestressed beams without

TABLE 8.—CONSTRUCTION AND TEST DATA

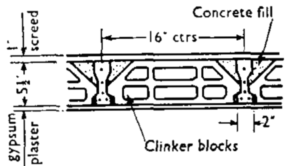
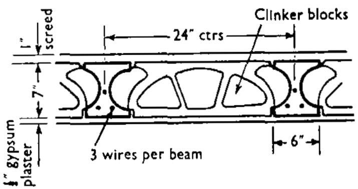
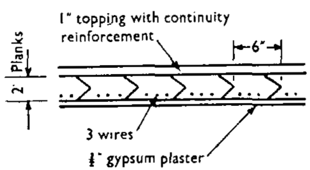
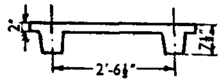
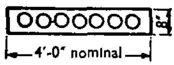
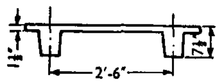
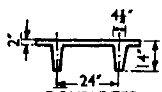
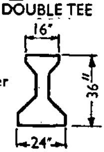
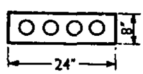
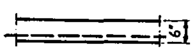
Dimensioned section	Casting data for prestressed units	Mean cube strength: lb/sq. in.	Concrete cover: inch	Wire size and prestress (initial)	Test load: lb/sq. ft.	Time to failure or test duration: hr min	Mode of failure	Approx. steel temperature at end of test or at failure	Central deflexion: inches
	Mix: 1:1½:3 (by wt) Rapid-hardening Portland cement; sand; gravel. Max. size ⅜ in. Water/cement ratio: 0·45	At release: 4,970 At 28 days: 7,000	0·5	No. 12 S.W.G. 1,573 lb/wire	30	2 09	Collapse	Central wire in web 300°C approx.	At 30 min 1·25 At 1 hour 2·4 At 2 hours 4·8
	Mix: 1:1½:3 (by vol.). Portland cement; sand; gravel. Max. size ¾ in.	At release: 5,000 At 28 days: 7,000	0·66	0·2 in. dia. (indented) 169,000 lb/sq. in.	80+50%	2 0	Did not fail		At 30 min 0·7 At 1 hour 1·2 At 2 hours 2·45
	Mix: 1:1½:2. Portland cement; sand; granite	At release: 3,000 At 28 days: 6,500	0·2	0·2 in. 148,000 lb/sq. in.	40+50% +5 for omitted floor finish	0 54	Formation of hole through floor		Max. (at 15 min) 0·15

TABLE 9.—SUMMARY OF U.S. FIRE TESTS

Duration of test	Section	Concrete cover: inches	Bearing condition	Steel temperature	Test sponsor
A 2 hours 1 min		2	Full end-restraint	1,260°F	P.C.I.*
B 4 hours 1 min		1½	Full end-restraint	1,200°F	Spancrete
C 2 hours 10 min		¾		Not available	
D 2 hours 1 min		1½	Full end-restraint	1,498°F	Rockwin
1 hour 1 min	 DOUBLE TEE	1½	Roller end bearings without restraint	1,170°F	P.C.A.*
1 hour 16 min				1,230°F	
4 hours 31 min	36"girder 	1¾	Roller support	Not available	P.C.A.*
2 hours 10 min		1½	Full end-restraint	max. 900°F min. 775°F	Prestcrete
E 4 hours		1½	Full end-restraint	920°F	Western Concrete Structures

The first column indicates time until furnace fire was extinguished. Structural failure did not occur in any of these tests.

A—3-in. concrete topping required for heat transmission (2 hours).
B—1½-in. concrete topping required for heat transmission (4 hours).
C—No concrete topping required for heat transmission (2 hours).
D—2½-in. concrete topping required for heat transmission (1 hour 51 min).
E—No concrete topping required for heat transmission (3 hours 51 min).

* P.C.I. = Prestressed Concrete Institute, Chicago, Illinois.
P.C.A. = Portland Cement Association, Skokie, Illinois.

secondary reinforcement to be more inconsistent in their behaviour than those with secondary reinforcement.

100. The data in Table 4 did not support this. In the only case shown with four beams of the same size, the results were remarkably consistent; he would be glad if the Authors could throw some light on this matter.

101. For the future he thought that cables in grooves could be checked on a small scale. He did not know whether any tests had been done on them or on entirely separate cables, if so he would have thought that there was some future in developing high-performance insulation better than concrete and testing this on a small scale.

TABLE 10.—FIRE RESISTANCE. PRESTRESSED CONCRETE INSTITUTE TENTATIVE STANDARD (NOVEMBER 1959)

Rating: hours		1	2	3	4
		Concrete cover: inches			
Normal-weight concrete	Beams, columns	1½	2½	3	4
	Joists	1¼	2	2½	
	Slabs	1	1½	2	
Light-weight concrete	Beams, columns	1¼	2	2½	3
	Joists	1	1½	2	
	Slabs	¾	1¼	1½	

Mr A. B. Harman (Secretary, The Reinforced Concrete Association) said that at the present time light-weight prestressed concrete was talked about but not very much used. However, useful research on the subject had been done by Professor Evans[10]. Perhaps in reply to the discussion the Authors would mention what work they knew of in this sphere, for it was to be hoped that due attention would be paid to the effects on fire-resistance of using light-weight concrete in prestressed work.

Mr O. J. Masterman, commenting on Mr Harman's remarks, said that there was a tentative standard drawn up by the Prestressed Concrete Institute for light-weight concrete beams, columns, joists, and slabs; the covers were all less than for normal-weight concrete. To give two cases: 2-hour fire-resistance for beams and columns required 2½ in., and in light-weight concrete, 2 in.; for 1-hour fire-resistance, for slabs 1 in., and for light-weight slabs, ¾ in. These figures had been published in the P.C.I. (tentative) code which had been issued in November 1959.

The following contributions were received in writing.

Mr G. W. Shorter and **Mr T. Z. Harmathy** (National Research Council of Canada, Division of Building Research), in a joint contribution, observed that a series of tests performed on some concrete walls in the Fire Research Laboratory of the Division of Building Research (National Research Council of Canada) had provided evidence that the presence of moisture was the primary cause of explosive spalling during the fire tests of these particular walls. They described the probable mechanism of spalling.

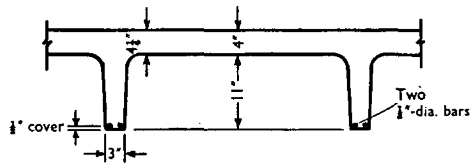
105. As the temperature of the surface of the specimen exposed to fire reached and exceeded 100°C and the rate of desorption of moisture in a thin layer adjoining the surface increased, some of the desorbed vapours proceeded towards the cold surface and condensed in neighbouring layers where the temperature was lower. The pores in the direction of the unexposed surface thus gradually filled with free water which moved slowly towards the colder regions, especially along cracks where the resistance to liquid flow was the lowest.

106. Since flow through the passages towards the cold surface became restricted by liquid water an increasingly higher portion of the vapour tried to escape in the direction of the furnace. As the thickness of the dry layer increased, however, the vapour met more and more resistance, partly because of an increase in volume during migration

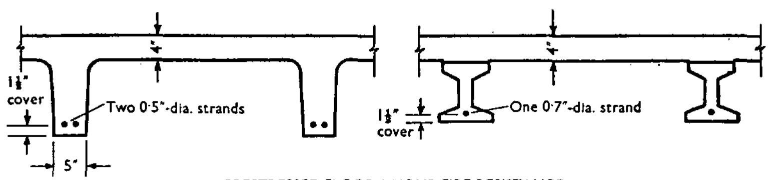
[10] R. H. Evans and T. R. Hardwick, "Lightweight concrete with sintered clay aggregate". Reinf. Concr. Rev., vol. 6 (June 1960), pp. 369–400.

through hotter layers owing to absorption of sensible heat, and partly because of the extended length of the pore passages.

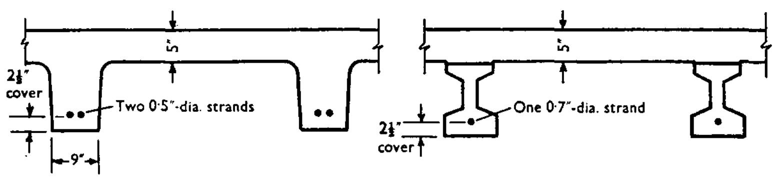
107. In the meantime, a very sharp temperature gradient developed across this still relatively thin dry layer. While the surface temperature at this stage of the test might already be greater than 500°C, at about ½ in. from the surface where the region of accumulated free water began, the temperature could not rise much higher than the boiling point. The effect of this sharp temperature gradient was twofold: (i) the rate of heat flow through the dry layer was extremely high, which in turn influenced the rate of vaporization at the interface of the dry and wet regions, and induced high vapour pressures in the region of the interface, and (ii) the thermal stresses also attained high values.



REINFORCED CONCRETE FLOOR 2-HOUR FIRE RESISTANCE IN ACCORDANCE WITH C.P.114 (1957)



PRESTRESSED FLOOR 1-HOUR FIRE RESISTANCE IN ACCORDANCE WITH C.P.115 (1959)



PRESTRESSED FLOOR 2-HOUR FIRE RESISTANCE

FIG. 11

108. It must be accepted that appreciable vapour pressures could be developed only if the temperature was raised considerably above 100°C, a temperature of 138°C being necessary, for example, to produce a pressure of 50 lb/sq. in. absolute over free water. At a stage when the dry layer became thick enough to offer a very high resistance to the vapour flow towards the hot surface, but was still thin enough to bring about a sharp temperature gradient, the stresses might rise beyond the limit tolerable by the material. If this condition occurred, a layer of thickness approximately equal to that of the dry layer separated from the material. In this way new sections completely saturated with water became suddenly exposed to high temperatures and the rapidly developing vaporization resulted in progressive deterioration of the construction.

109. It was not necessary to assume that the explosive release of energy came from expanding water vapour alone, since the dry surface layer was already highly stressed by the thermal conditions and this energy was released when spalling occurred. It seemed reasonable to assume that the presence of water contributed in two ways to the explosive

spalling; it led to sharp temperature gradients and it provided through the development of vapour pressure a force at right angles to the surface which, in combination with the high thermal stresses, caused a layer of material to be dislodged. It might even be possible that sharp temperature gradients alone could cause spalling. If so, it should be possible to find some materials which would spall when dry, but in the case of the tests to which reference had been made there had been evidence that explosive spalling had occurred only when water was present.

110. According to these observations, the critical thickness was about 1 in. Some concretes which had exhibited explosive spalling when wet had not spalled when pre-dried to produce a dry layer of 2–2½-in. thickness adjoining the exposed surface.

111. If, as had been proposed, the presence of water was responsible for explosive spalling, it seemed reasonable to suppose that for every concrete a critical moisture content could be found below which explosive spalling would not take place. The value of this critical moisture content or perhaps moisture-content distribution was likely to be a function of the permeability. For materials of high permeability it might even correspond to the condition of the pores being completely filled with free water. It seemed very probable that the moisture content of concrete constructions aged several years was below the critical level.

112. When explosive spalling did not take place, the moisture content had a marked effect on the time of fire endurance. Numerical heat-flow analyses showed that with brick walls the increase in fire endurance might be as high as 7·5% for each per cent (by weight) of moisture.

Mr D. C. Gatenby (Division Engineer Construction, Geocon Ltd, Montreal) wondered if the figures for thicknesses of concrete cover which would be required to ensure a given fire endurance for a prestressed concrete beam should not be qualified. The Authors stated in § 24 that the fire-resistance of a beam was affected to a marked extent by the quantity of free water in the concrete, but affected in what way? It was fairly well known that the more moisture that had to be evaporated from a concrete section the slower the heat transfered and the greater the endurance. However, it seemed also that some concretes with high humidity were susceptible to explosive spalling which could rapidly blow off all cover and gave a poor endurance. The Authors did not make the distinction as to which cause they referred. Had they fire-tested beams with a high humidity and if so what had been the results? Could they give figures for the relative humidity and the absolute humidity of the concrete in the beams tested? They gave the storage conditions and approximate length of time but it seemed impossible to deduce from these figures the conditions obtaining in the concrete, especially those protected with vermiculite.

114. The concrete used for prestressed work was normally a low water/cement ratio product with often a fairly high cement content and as such was a relatively impermeable product. It was thought to be much less permeable than the concrete that had been used in normal reinforced concrete construction, and on the tests of which most of the ideas on the fire endurance of concrete structures were based.

115. Many fire tests had been carried out at 60–90% relative humidity range and this had seldom resulted in explosive spalling because, in Mr Gatenby's view, the permeability had been adequately high, so the idea had developed that concrete structures had good fire-resistance practically from the time the forms were stripped, and this to a degree was true. The net effect had only been to give the construction a greater rating than it deserved or could obtain had it been tested in a state of dryness similar to that it would attain in several years.

116. However, it was felt that the same did not hold good for the high-grade concrete used in prestressed concrete work and that until it became dry it would be extremely sensitive to explosive spalling. Such spalling appeared to be governed by the total volume of water in the concrete and the rate at which it could escape.

117. The rate of escape would depend principally on the permeability of the concrete and this property was much decreased in no-slump, low water/cement ratio concretes.

Obviously some concretes still were permeable, but at a much reduced rate, and if under fire test the volume of steam produced, which depended on the quantity of free water, was greater than the permeability could handle, an explosion would result when the pressure had built up to a point exceeding the tensile strength of the concrete.

118. For instance, recent fire tests on no-slump expanded-slag concrete (5,000 lb/sq. in. at 28 days, density 124 lb/cu. ft), an expanded-shale concrete (5,700 lb/sq. in. at 28 days, density 113 lb/cu. ft) and an expanded-shale vermiculite concrete (3,200 lb/sq. in. at 28 days, density 106 lb/cu. ft) had given the following results for a 5-in.-thick wall section when tested in accordance with the time/temperature curve set out in ASTM E119–58. The expanded-slag concrete had been fire tested at 84% and an endurance of 4½ hours had been obtained. The concrete had not spalled in any manner throughout the whole test. The expanded-shale concrete and expanded-shale vermiculite concrete had been tested at 85 and 80% relative humidity—the absolute humidity being approximately 7 and 12% respectively. The most resounding general explosive spalling followed by continuous local spalling forced discontinuation of the tests in less than 45 min. However, the expanded-shale concrete when tested at 55% relative humidity had suffered no spalling whatsoever and had proved to have an endurance of 4 hours. The expanded-shale vermiculite concrete when tested at 75 and 34% relative humidity had also behaved perfectly throughout the tests, the endurance being 5 hours 20 min and 4 hours 40 min respectively.

119. Although these concretes had been made with artificial aggregates and perhaps could not be directly compared with the concrete described in the Paper because the free-water content might be greater, it was felt that the results indicated a distinct trend.

120. These tests illustrated a humidity line above which two concretes were found to be unstable in fire and below which they were stable. The tests also indicated that reducing the relative humidity from 75 to 30% gave approximately 20% reduction in the fire endurance for the particular concrete tested.

121. Fire could occur in a building during construction when the concrete had 100% relative humidity or at any time to the last day of its expected life. Buildings could be wet, dry, hot, or cold and the humidity of the concrete in the structure would adjust fairly slowly according to these conditions. It might take a year or more under some conditions to get below 90% relative humidity in the concrete, in which case was a prestressed concrete member in danger of losing all cover in less than 1 hour? Had the Authors any data which would indicate that explosive spalling was not a more important factor in high-grade concrete and had they established any maximum humidity or permeability/humidity ratio which might fix a limit? Also, in view of the fact that fire endurance varied with the humidity of the concrete, was it not desirable when quoting various thicknesses of cover to obtain a given fire endurance to specify the relative and absolute humidities at which the endurance could be expected?

The Authors, in reply, confirmed that the results given in the Paper related only to beams, as had been emphasized by some speakers. The Authors were aware that a better performance would be likely with a floor constructed of units with a given cover to the wires, where the units formed a continuous soffit, or where filler blocks spanned between units in such a way that the underside only of the members was exposed to the fire. The difficulty in giving requirements for cover, in examples of this kind, was the large diversity in the types of units used and in defining the cover where the wires were distributed throughout the section. On the question of modelling, the Authors agreed with Mr Hill and Mr Walley that there were many factors to be taken into account and that the technique was not the same as that for structural models. It should be realized that this was the first attempt at making model tests for fire-resistance, and it had not been preceded by any fundamental work. On that account it would be wrong to be disappointed if the early hopes had not been fulfilled. A large programme was in hand at the Fire Research Station on using models to solve some of the problems in connexion with fires in buildings and it was hoped that this basic work would provide a better foundation for future developments. One aspect of scaling, which was not considered of great importance in determining behaviour, was that of the maximum size of aggregate.

123. In reply to the speakers who had raised the question of continuity, the Authors agreed that there were a number of factors to be considered and that it was difficult to forecast what the effects might be in specific circumstances. A research programme into the effect of continuity on the fire-resistance of beams and floors had, however, been formulated and testing would commence during the summer of 1962. The programme was comprehensive and would include not only prestressed concrete, but also normal reinforced concrete and protected structural steel construction.

124. The Authors had confined their experiments to prestressed concrete made with the type of aggregate in most common use. To have extended the programme to investigate the use of light-weight aggregates would have entailed a prohibitive amount of extra work, but a study of their use was now being considered. It was known from other fire-resistance tests that the light-weight aggregates often gave superior performance to natural aggregates other than limestone. In prestressed concrete beams with post-tensioned steel, however, the insulation provided by light-weight aggregates was likely to result in only a small reduction in the thickness of concrete cover required, and in the opinion of the Authors, secondary reinforcement would still be necessary to retain light-weight concrete in place for the 4-hour period. It should also be noted that in achieving a high strength for concretes made with light-weight aggregates, their fire-resisting qualities might be lowered. The Authors had experience of one type of unit sent for test by a manufacturer, in which light-weight aggregate concrete was used, where the behaviour in the fire test had probably been worse than anything experienced with gravel aggregate units of the same type. On the general question of aggregates, it was thought that § 50 summarized the present position adequately.

125. Mr Hill had asked whether for full fire-resistance it was necessary to have stirrups projecting from the beam into the slab. Investigation had shown that these stirrups were necessary only for the largest sizes of beam, which were likely to have secondary reinforcement to meet the requirements of the B.S. Code of Practice, CP 115:1959, the structural use of prestressed concrete in buildings.

126. On the question of consistency, mentioned by Mr Harris, Table 4 showed that good repeatability had been obtained. The number of repeated tests was small, but this appeared to be justified in view of experience with fire tests on other forms of construction where manufacture was very carefully controlled. For example, a large programme had been carried out some years before on reinforced concrete columns in which repeat tests had been made and the results had agreed within 10% for quite a range of column sizes. Table 4 gave the results for two 4/5 scale beams, which, although having different secondary reinforcement, could be regarded as identical for the purpose of this discussion; the times to collapse for these beams were 3 hours 22 min and 3 hours 23 min.

127. Mr Harris had asked whether anything was known of fires in prestressed concrete buildings. To the knowledge of the Authors, the number of fires which had occurred in prestressed concrete buildings was extremely small. Although the Fire Research Station obtained reports of all fires attended by the fire brigades, there was no means of ascertaining whether the buildings were of prestressed or reinforced concrete. It was only if the fire had some unusual feature and a further investigation was made that the type of construction could be identified. The very scanty data available on fires in actual buildings, where prestressed concrete was used, confirmed the behaviour observed in fire-resistance tests.

128. Mr Shennan's remarks were very interesting particularly on the matter of spalling. It was unfortunately true that little was known about the nature and causes of spalling, but the fire to which Mr Shennan referred was consistent in its effects with experience. Spalling would be expected to be less severe near the waterline where the moisture content of the concrete was probably high, since where concrete was saturated, spalling was less likely. The use of embedded steel mesh near the surface of members

could reduce the effects of spalling, but such a measure would not necessarily be useful for axially loaded members in general.

129. Mr Walley had asked for an explanation of the relatively rapid increase in deflexion during the first few minutes of heating. The Authors attributed this to the combination of several effects—thermal expansion and creep of the steel offset by shrinkage of the concrete. The tests which Mr Walley quoted were not really relevant as examples; the unloaded model beams were not tested realistically, since they did not support the full design deadload corresponding to that for full-scale beams and, therefore, extrapolation was unrealistic. Reference had also been made to partial damage in fire and Mr Walley had referred to Fig. 9 where failure was aggravated ultimately by shear, but collapse occurred primarily through the excessive deformation because in fact the whole of the prestress had been lost. It had been found, however, that wires removed from a cable which had been heated to 300°C showed no loss in strength when compared with the original cold strength of the material. On the question of confidence in the results for the 4-hour period, the Authors agreed that the data were few, but were confident that for normal design a fire-resistance of 4 hours would be obtained with a concrete cover to the prestressing tendons of 4 in. In fact, 4 in. was probably a little on the conservative side. Mr Walley's comparison with reinforced concrete was not valid, since the factors determining the fire-resistance of reinforced concrete were not the same as those affecting prestressed concrete. In prestressed concrete, it was essential to avoid the steel reaching a temperature of 400°C, whereas in reinforced concrete the reinforcement could reach a much higher temperature without failure occurring. Comparisons between reinforced concrete and prestressed concrete in terms of concrete cover could not, therefore, be made. This critical temperature of 400°C corresponded to the temperature at which the steel would fail when stressed to half its strength at normal temperatures. Since the loading on the beams largely controlled the stress in the tendons at failure, an increase in the loading would reduce the temperature at which failure occurred, and a reduction in loading would increase this temperature and so prolong the fire-resistance. If a change in the initial prestress in the tendons led, therefore, to a reduction in the design load for a member then this fire-resistance would be increased as Mr Walley supposed. In the fire tests on beams with different makes of wires in the cables but otherwise of similar dimensions (see Table 6), to which Mr Walley referred, it was possible to identify differences in behaviour in subsequent loading tests attributable to the different characteristics of the wires at high temperature. Thus, the loss of prestress in the beam stressed with wire E after the cable had been heated to about 200°C was appreciably less than that for beams stressed with other makes of wire which had been similarly heated. This was expected from the fundamental study on the properties of these wires at high temperatures[6]. Nevertheless, all the beams had ceased to be serviceable as a result of damage to the concrete during the period of test of about 2 hours necessary to raise the temperature of the cable to about 200°C. During this period the concrete surface had become friable and the concrete had lost all its tensile resistance. Thus, the similarity in the condition of these beams was due not to the performance of the steel but to damage caused to the concrete.

130. The data presented by Mr Masterman in Table 7, relating to the requirements of different authorities for concrete cover in various reinforced concrete and prestressed concrete constructions for different periods of fire-resistance, suffered from the drawback mentioned earlier of not being a valid comparison. With regard to Table 8, the results shown emphasized the point made earlier about the difficulty in assessing performance on account of the large differences in construction. For example, the last floor shown in the table had a topping with continuity reinforcement which affected significantly the performance in the test. Early in the heating period, spalling started and eventually exposed the prestressing wires and, although the wires were red hot, the floor was able to support the test load for 54 min, because the top reinforcement was relatively cool. It was difficult to judge the validity of the results given in Table 9, since these probably represented only some successful tests and there was no detail of the distribution of the wires in the various sections or of the load factors used. With

regard to the fire-resistance ratings given in Table 10, the Authors wished to emphasize that their figures applied only to beams and that much more work was needed before information could be given on columns or on the effect of using light-weight concrete. In the light of the information available, the present Codes and Byelaws did not appear to be unfair to prestressed concrete; some restrictions might be attributable to limitations in knowledge but these would not seem to be unduly severe. It might be possible in the near future to give general guidance on cover requirements for floor units, but in the light of what had already been said, it was apparent that these figures must be conservative. Small changes in design of such units, however, should not call for new fire tests.

131. Mr Bobrowski showed in Fig. 11 examples of different types of floor construction. The Authors wished to point out that he had adopted the thickness for the reinforced concrete floor given by CP 114 for inverted U-sections, whereas in fact his drawing showed a construction which would be regarded as a slab and should therefore have a thickness of 5 in. in order to achieve a fire-resistance of 2 hours. He had again raised the question of comparison between requirements for reinforced concrete and prestressed concrete constructions and the Authors could only repeat their statement that in prestressed concrete the steel was a much more sensitive element than in reinforced concrete. Mr Sutherland suggested that the results of fire tests on prestressed concrete columns had shown greater consistency than those on reinforced concrete columns. The information on prestressed concrete columns, available at present, was confined to relatively slender members of one particular type. Without a planned investigation it would be unwise to make categorical statements, but the results so far did not give the same consistency as the tests on reinforced concrete columns. In fact, apparent paradoxes had been obtained in that decreasing the test load on a given size of column did not always give an increase in fire-resistance. Spalling in all the columns had been negligible and on that account the inclusion of a light mesh would not necessarily have affected the performance, although the use of secondary reinforcement would probably have been of assistance.

132. Mr Shorter and Mr Harmathy had given their explanation of explosive spalling of concrete exposed to high temperatures. The Authors were grateful for the contribution, which attempted to elucidate the problem of spalling, but they did not regard the explanation as complete. In their experience, moisture was only one factor in a complex phenomenon. Research into the nature and causes of spalling had been started in the United States, and the Fire Research Station were now undertaking a detailed investigation.

133. The most striking feature of the fire tests made at the Fire Research Station on prestressed concrete beams and columns had been the virtual absence of explosive spalling, except where floor units of relatively thin section had been involved. Such behaviour had been unexpected in view of the severe spalling experienced with many types of reinforced concrete members. With the large-scale beams the feature which affected performance was a different type of spalling generally called "sloughing off" of the concrete cover, a phenomenon having no less influence on the performance of a beam than the more spectacular explosive spalling. There were then these two types of spalling which should be distinguished—explosive spalling which tended to occur at an early stage in the exposure of a member to high temperatures and the more gradual spalling where large portions became detached, generally at the plane of the reinforcement, and which might happen at any time during heating.

134. In reply to Mr Gattenby, the Authors wished to draw attention to two ways in which the moisture in concrete would affect behaviour in a fire test. Within a certain moisture-content range conditions would be favourable for spalling. If spalling did not occur, however, the moisture in the concrete would affect the heat transfer to critical sections such as prestressing wires and, as pointed out by Mr Shorter and Mr Harmathy, a significant increase in fire-resistance could arise from even small changes in moisture content.

135. The Authors had referred to the investigation which was being made by the Fire Research Station on the nature and causes of spalling and in this research the effect

of moisture content, to which Mr Gattenby referred, would be covered. They had already mentioned that their tests on high-grade concrete, as used in prestressed members, did not always show explosive spalling. Mr Gattenby had emphasized the importance of moisture in concrete on its performance in fire, and all those concerned with research in this field were aware of its importance. How to measure the moisture content of a concrete member at any given time after manufacture, and how to decide when it was appropriate to test it, were matters which were now engaging the attention of those working in this field.

CORRIGENDA

Proceedings, August 1961:

Vernon Harcourt Lecture,

page 433, *below* Ainsley Marshall Rendall Montagu, C.I.E., M.I.C.E. *insert*
Consultant, Sir M. MacDonald & Partners

Minutes of Proceedings (Pippard),
page 610, § 5, line 5, *for* Not *read* Now

Proceedings, September 1961:

Paper No. 6515 (Richmond),

page 143, § 8 and § 9
Throughout (in three instances), for a_{in} *read* a_{1n}
At the end of Equation (4), insert $=0$

page 144, Equation 8
Throughout, D_3 *should be followed by* α'^2.