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PRESTRESSED CONCRETE DURING AND AFTER FIRES. COMPARATIVE TESTS ON COMPOSITE FLOORS IN PRESTRESSED AND REINFORCED CONCRETE

by

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Abstract

Tests have been made under standardized furnace conditions to obtain information on the vertical deflections which occur when prestressed concrete floors are subjected to high temperatures, and on the recovery after cooling. The performance of a selected type of composite prestressed concrete floor during and after different heating periods was compared with that of a composite reinforced concrete construction designed for the same span and load conditions. It was found that, whereas for short heating periods, representing a fire of short duration, the maximum and the residual deflections were of the same order for both types of floor, in the longer heatings prestressed concrete appeared at a disadvantage in this respect.

Introduction

Fire-resistance as defined in B.S. 476 : 1932 is a measure of the time for which an element of structure will fulfil its normal functions when subjected to standard conditions of heat and load. While a fire-resistance grade implies satisfactory performance during a definite fire period and stability of the element of structure after cooling, no cognisance is taken of the fitness for use or repairability of a structure after a fire. These are important aspects of building fires which have not received the attention they merit, although the fire raids during the war lead to investigations being made into the repair of traditional buildings damaged by fire.

In concrete structures some spalling and deterioration of the concrete to a depth of 1 in. or 2 in. will not be obstacles in restoring an element to very nearly its original strength, but large deformations will be. Since prestressed concrete beams in cold loading tests may show practically complete recovery after overloads which cause substantial deflections, it has been suggested that they might display similar behaviour after the type of "overload" represented by exposure to high temperature. This suggestion assumes that heating causes no loss of prestress, either through loss of strength or shrinkage of the concrete, or reduction in strength or elongation of the steel. It was therefore decided to make comparative tests on prestressed concrete and reinforced concrete floors of the same span and load-carrying capacity to determine their ability to recover after fires of different durations. At the time the comparative tests were projected the investigations which had been made on the behaviour of prestressed concrete floors when exposed to high temperatures were concerned only with fire-resistance and since these tests were continued until collapse of the floor occurred or was imminent, there were no data on the condition of the specimens on cooling after a shorter heating.

The prestressed concrete floor selected consisted of a beam unit of the pre-tensioned type carrying precast concrete troughs serving as permanent shuttering for the in situ reinforced concrete topping. The floor for comparison was of a similar type with a reinforced concrete beam substituted for the prestressed unit. Both types of floor, which were tested with the ends simply supported, were known to have more than 2 hours fire-resistance. The method of construction was designed primarily for use with prestressed beams, or more accurately soffits, since they are uniformly stressed and form the tension zone of a beam which includes the in situ concrete. In practice, the soffits are on the grid lines of the building, at about 10 ft. centres, and the precast concrete trough units span between them. The feature of this design is the readiness with which it can be adapted to various spans by increasing its depth, i.e. having a greater thickness of concrete above the soffit. This is easily arranged by raising the troughs. A comparison of the prestressed with the reinforced concrete floor shows that, by using a broad, shallow soffit, a saving in depth of about 6 in. can be effected.

Three tests were carried out as follows. The first of ½-hour and the second of 1 hour were on the two different forms of construction tested together; the third test of 1 hour was on prestressed concrete only. The only design variable introduced for either type of floor was in the cover to the lower wires or the main bars in the beams.

Test conditions

In the tests for fire-resistance specified in B.S. 476 : 1932 standard furnace conditions are defined by a time-temperature curve (Fig. 1), the character of which for the first 2 hours is determined by the following points:-

At the end of the first	5 minutes	- 1,000°F	(or 538°C)
" " " " " "	10 "	- 1,300°F	(or 704°C)
" " " " " "	30 "	- 1,550°F	(or 843°C)
" " " " " "	1 hour	- 1,700°F	(or 927°C)
" " " " " "	2 hours	- 1,850°F	(or 1,010°C).

The furnace temperature obtained from the readings of a number of thermocouples, distributed so that they fairly represent the mean temperature, must conform to the standard curve within defined limits.

For the comparative tests on recovery after cooling it was necessary to adopt a time-temperature relationship recognized as valid and the standard furnace curve was the obvious choice. The test represents a floor exposed to fire on its soffit; it is considered that this is a more serious condition than a fire on top of the floor.

Description of tests

The furnace used for the tests is shown in Figs. 2 and 3. The floors were supported in a refractory concrete surround which was placed on the walls of the furnace when the specimens were ready for test. In order to ensure that the forms of construction which were being compared would be subjected to closely similar conditions, in each test one specimen of each type was included.

Cross-sections and longitudinal sections of the two types of floor tested are shown in Figs. 4 and 5. Each consisted of precast units and in situ concrete forming a Tee beam 5 ft. wide representing a section of floor centred on the main load-carrying member. The prestressed member, known as a "soffit", was uniformly prestressed by 126 wires of No. 12 S.W.G. It was 1 ft. 10¼ in. wide and its depth was 3¾ in. with a cover to the lower wires of 1½ in. The aggregate used for the concrete was flint gravel. For fire protection purposes this cover was altered for two of the tests to 1 in. of gravel aggregate with the addition of ½ in. of brick aggregate concrete to form the soffit. Castellations were provided on the upper surface of the soffit to ensure composite action with the concrete topping. The reinforced concrete beam of rectangular

section had a width of 10 in. and depth of $8^9/16$ in. to the centre of the reinforcement of four $\frac{1}{8}$ in. diameter bars. In the first test the concrete cover to the bars was 1 in. and in the second test $1\frac{1}{2}$ in. Stirrups of $\frac{1}{4}$ in. diameter rod at 9 in. centres projected 3 in. above the beam into the in situ concrete.

The design of the upper part of the floor was identical for the two types of specimen. Precast trough units which were supported at their ends on the reinforced concrete beam or on the prestressed soffit acted as shuttering for the in situ concrete which was $1\frac{1}{2}$ in. thick over the tops of the troughs, giving a flange 5 in. thick to the Tee beams. The in situ concrete was reinforced with $\frac{3}{8}$ in. diameter transverse rods at 3 in. centres and $\frac{1}{4}$ in. distribution bars at 12 in. centres. All the precast units, troughings, soffits and beams were supplied by a manufacturer of precast concrete products.

Details of the concrete mix and cube strengths for the topping are given in the Appendix with information relating to the manufacture of the prestressed soffits and the reinforced concrete beams.

Test procedure

In constructing the floors side by side in the refractory concrete surround a gap of 1 in. was allowed between them. A similar gap was provided between the outer edges of the floors and the surround. These gaps were sealed with asbestos rope lagging so that the specimens were free to deflect and heat leakage from the furnace prevented.

When the floors had matured sufficiently to reach an adequate strength as shown by cube tests, the floors were loaded and the fire tests carried out. In conformity with the test conditions of B.S. 476 : 1932, the load applied to each floor was $1\frac{1}{2}$ times the design load of 100 lb/ft.^{2} of slab and 450 lb/ft. run of beam. The load was in the form of cast iron weights standing on short legs so that the area in contact with the floor surface was reduced to a minimum.

Deflections were measured at the centre of the span and over the abutments by means of rods in contact at their lower ends with the floor surface and carrying a pointer which moved over a fixed scale at their upper ends. Observations of scale reading were made at intervals during a test to the nearest 0·02 in., and were continued during cooling at increasingly longer intervals until a maximum of 19 days had elapsed from the time of the test. The deflection rods were in place before loading so that the deflections due to application of the test load could be obtained.

Furnace temperatures were measured by nine No. 19 S.W.G. chromel/alumel thermocouples distributed to give a representative mean temperature. All thermocouples were located with the hot junction 3 in. from a surface, one group of three being adjacent to the prestressed soffit, another group of three adjacent to the reinforced concrete beam and the third group below the troughings in the gap between the adjacent specimens.

The fuel input to the furnace was controlled so that the mean temperature throughout the test corresponded to the values of the standard curve within the permitted tolerances. Heating in a test was terminated at a pre-determined time and the specimens allowed to cool slowly. When recovery appeared to be complete, the floors were unloaded and the final residual deflection noted. A typical curve of furnace temperature is shown in Fig. 1.

Results of tests

The tests were carried out in the following sequence, "A" denoting the prestressed and "B" the reinforced concrete floors:-

1) $\frac{1}{2}$ hour test on A and B (Concrete cover of 1 in. gravel with addition in A of $\frac{1}{2}$ in. brick).

2) 1 hour test on A and B (Both with $1\frac{1}{2}$ in. gravel aggregate concrete cover).

3) 1 hour test on A (Concrete cover of 1 in. gravel + $\frac{1}{2}$ in. brick). Fig. 6 shows a test in progress.

The results are given as a summary in Table 1 and shown in detail in Fig. 7 where deflections are plotted against time during the fire test and the subsequent cooling up to 6 days.

TABLE 1

Maximum and residual deflections of floors

Reference number of specimen	Bottom concrete cover to steel	Duration of fire test	Maximum deflection (inches)	Residual deflection after 6 days (inches)
A1	1 in. gravel + $\frac{1}{2}$ in. brick	$\frac{1}{2}$ hour	0·25	0·04
B1	1 in. gravel		0·24	0·07
A2	$1\frac{1}{2}$ in. gravel	1 hour	1·12	0·72
B2	$1\frac{1}{2}$ in. gravel		0·41	0·10
A3	1 in. gravel + $\frac{1}{2}$ in. brick	1 hour	1·03	0·92

The deflections of the floors due to the applied load were 0·1 in. for type A and 0·02 in. for type B. In the $\frac{1}{2}$ hour heating the prestressed floor compared favourably with the reinforced concrete having approximately the same increment over the initial deflection and showing better recovery. In the heatings of 1 hour duration the prestressed concrete constructions suffered greater distortion, whether the cover to the lowest row of wires in the soffit was wholly of gravel aggregate or partly brick and partly gravel. The extra insulation to the wires given by the brick had the effect of delaying their temperature rising to the point at which reduction in strength and loss of prestress become appreciable, so that at the end of the hour's heating there was a difference of 0·4 in. in the deflections measured on the specimens with and without the protective layer on the soffit. Since the temperature in the interior continued to rise after heating was stopped, the final deflections obtained for the two floors was of the same order.

There was little recovery beyond the figure obtained at 24 hours. For both types of floor in test 1, observations made up to 14 days after heating showed that the deflection only decreased 0·03 in. from the deflection at 24 hours. After test 2, readings of deflection were made at intervals for 8 days, when the recovery beyond the deflection at 28 hours was 0·06 in. for both prestressed and reinforced concrete specimens. The load was removed from the floors 6 days later and in the unloaded condition there were residual deflections of 0·53 in. for the prestressed floor and 0·10 in. for the reinforced concrete floor. Six days after the finish of test 3 the deflection (due to heating) was still 0·92 in. compared with 0·98 in. after 28 hours. There was a residual deflection of 0·56 in. after removal of the load.

In order to obtain information on the temperature at which prestress is lost in the steel, thermocouples were attached to selected wires during manufacture of the soffits. The results have not been included, since they were insufficient to form a basis for conclusions.

A feature of the tests was the consistent behaviour of the specimens, no spalling occurring in either the prestressed soffits or the reinforced concrete beams.

Discussion of results

With the ½ hour heating there was little difference in performance between prestressed and reinforced concrete. The maximum deflections were about the same, but the prestressed floor showed a more rapid recovery, indicating that there was no loss of prestress. After 24 hours the residual deflections were very small for both types of floor, decreasing to less than 1/2000 of the span after 6 days. These forms of construction are therefore adequate to withstand a fire of the severity of the ½ hour standard test without permanent damage.

The cover of 1 in. to the main bars in the precast beam of the reinforced concrete floor for the ½ hour test was increased to 1½ in. for the 1 hour test. This conforms to the requirements of the London County Council Byelaws for reinforced concrete beams, which specify 1 in. cover for ½ hour and 1½ in. for 1 hour fire-resistance. The results of the second test showed that the reinforced concrete floor could withstand the longer heating with little more permanent deflection than in the first test, whereas the prestressed concrete floor had a maximum deflection of over 1 in. and a residual deflection after 6 days of about 1/200 span. In this test the concrete cover to the lower wires in the prestressed soffit was the same as the cover to the bars in the reinforced concrete beam. If part of the cover in the prestressed soffit is replaced by a material giving slightly better thermal insulation as in the third test, the effect is merely to delay the deflection reaching its maximum, which after 1 hour's heating, was of the same order as that obtained in the second test with the homogenous cover, although the residual deflection after 6 days was greater. After removal of the imposed loads, the two floors had approximately ½ in. deflection, indicating the same loss of prestress.

The reinforced concrete beam after the hour test would probably require the renewal of the damaged concrete on its sides and soffit, but this presents no difficulty since the depth involved would be small. The structural properties of such a beam after repair would differ little from the original. Prestressed concrete members, however, which have suffered loss of prestress and show objectionable deflections after a fire are a more difficult problem. Loss of prestress is due partly to changes in the cold drawn wires when heated and partly to deformation and loss of strength of the concrete, both factors which would tend to make repair difficult.

The results obtained from the tests described in this note are strictly valid only for the particular type of floor described, that is, a combination of prestressed and precast units and in situ concrete, but it is considered probable that the behaviour is typical of prestressed concrete constructions generally, since the cause and effect of loss of prestress is common to all types under the conditions described. Greater or smaller deformations might well be obtained with different floors or beams of the same span, since prestressed concrete is characterized by its diversity of forms, but after certain temperatures have been reached at critical points within a member, loss of prestress with consequent permanent deflections must be expected. The establishing of these temperature conditions may be delayed by increasing the insulation to the steel. This can be done by providing extra concrete cover or by means of other protective encasements which are more effective for a given thickness.

Acknowledgements

The initiative for carrying out these tests came from the Architect to the London County Council and valuable assistance was received from his staff.

Thanks are due to H. Malhotra and R. Bigmore of the Fire Research Organization, who assisted with the work at all stages.

APPENDIX

Manufacturing data for the floors

(a) Typical prestressed concrete soffit:-

Mix: 1/1½/3 Portland cement/sand/gravel (maximum size ⅜ in.)
Water/cement ratio: 0·40
Mean cube strength at release: 5,660 lb/in.^{2} (at 2 days)
Initial prestress in wires: 75 tons/in.^{2}
0·1 per cent proof stress of wire: 118 tons/in.^{2}
Ultimate tensile strength: 130 tons/in.^{2}

(b) R.C. beams:- Concrete mix as for prestressed soffit.

(c) In situ concrete:-

Mix: 1/1½/3 Portland cement/sand/gravel (maximum size ¾ in.)
Water/cement ratio 0·45 to 0·47.

Specimen No.	Mean cube strength (lb/in.^{2})
A1	5,590 (3,820 at 7 days)
B1	5,320 (3,620 at 8 days)
A2	5,150
B2	4,430
A3	6,770.

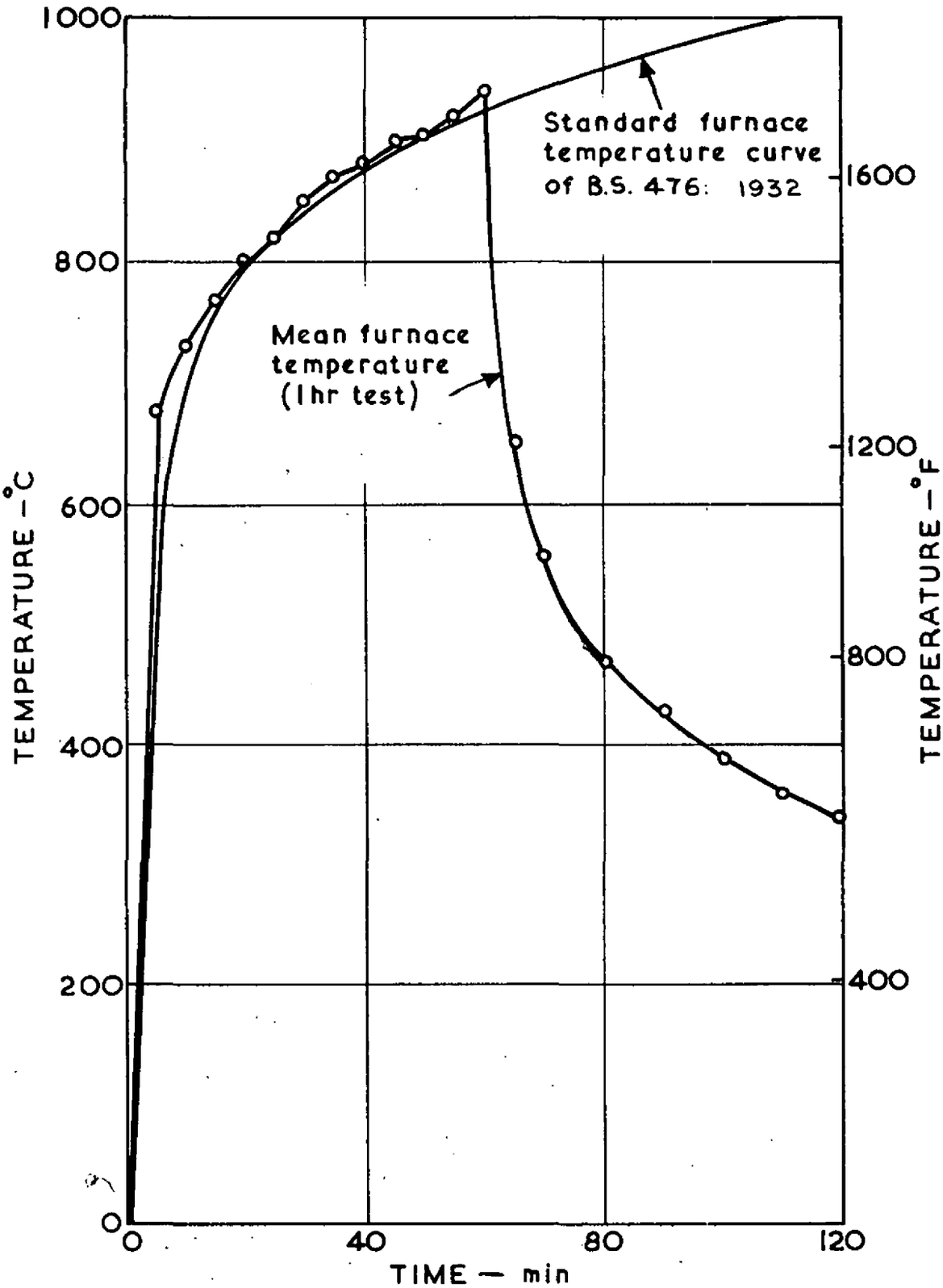

FIG. 1. FURNACE TEMPERATURES

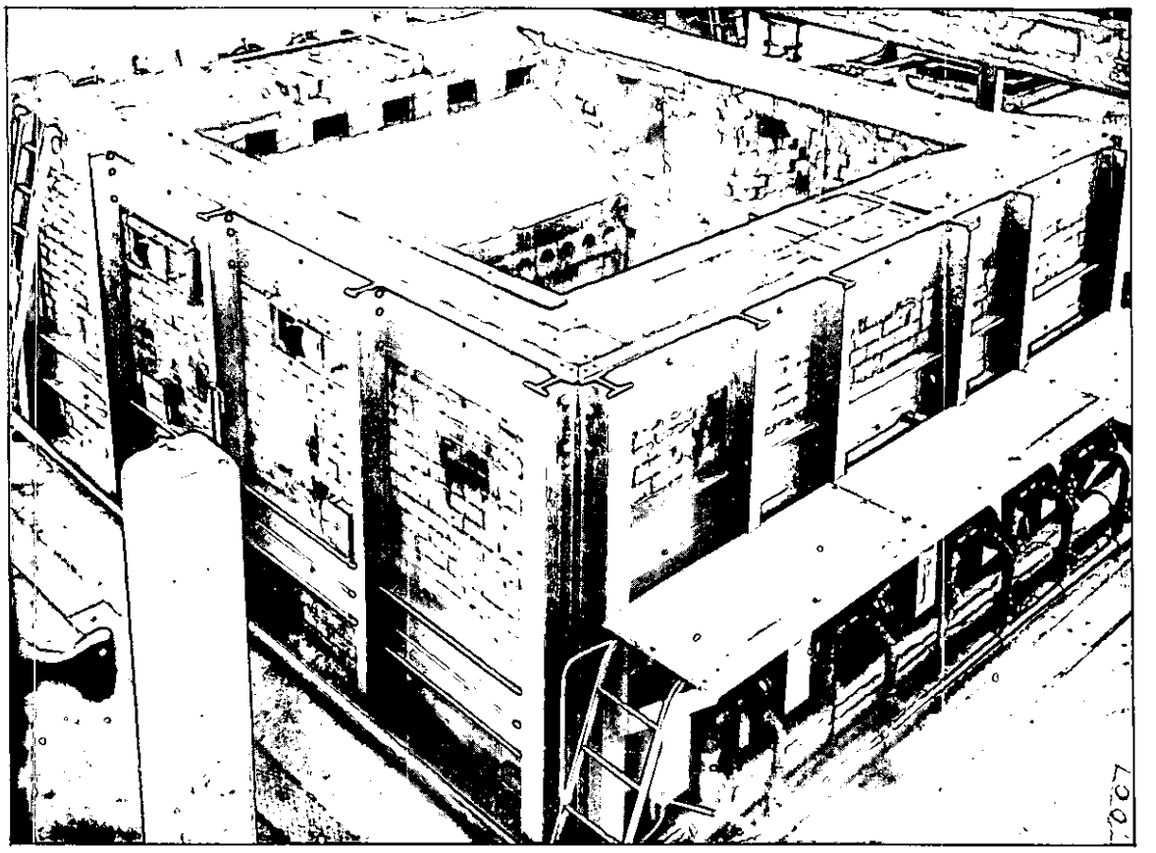

FIG. 2. GENERAL VIEW OF FLOOR FURNACE

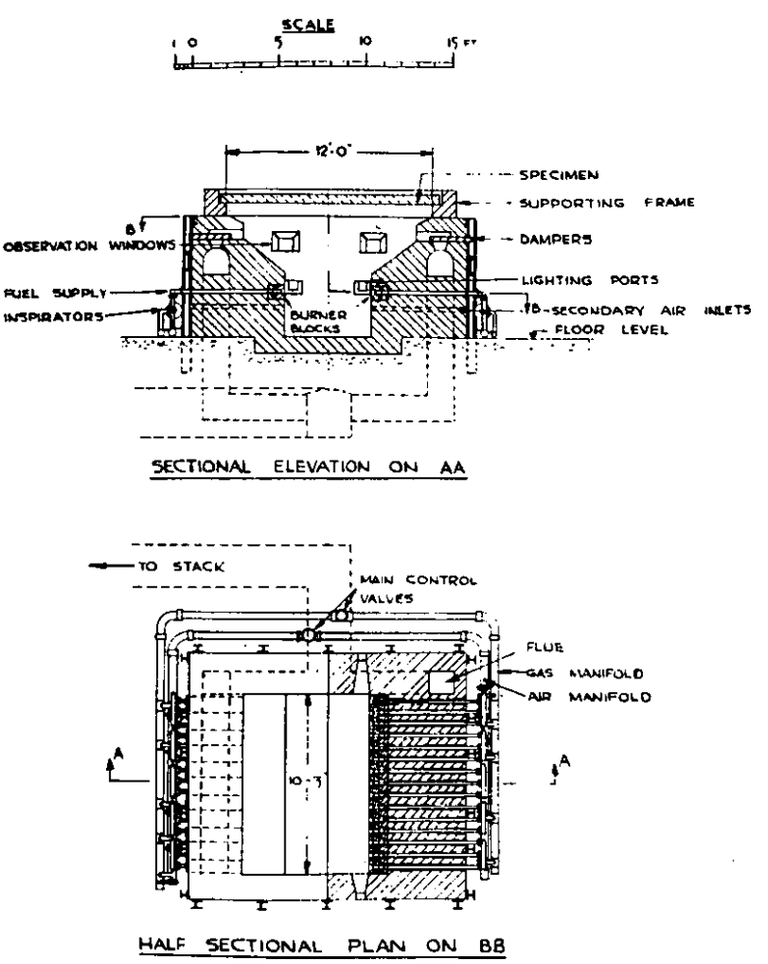

FIG. 3. FLOOR TESTING EQUIPMENT

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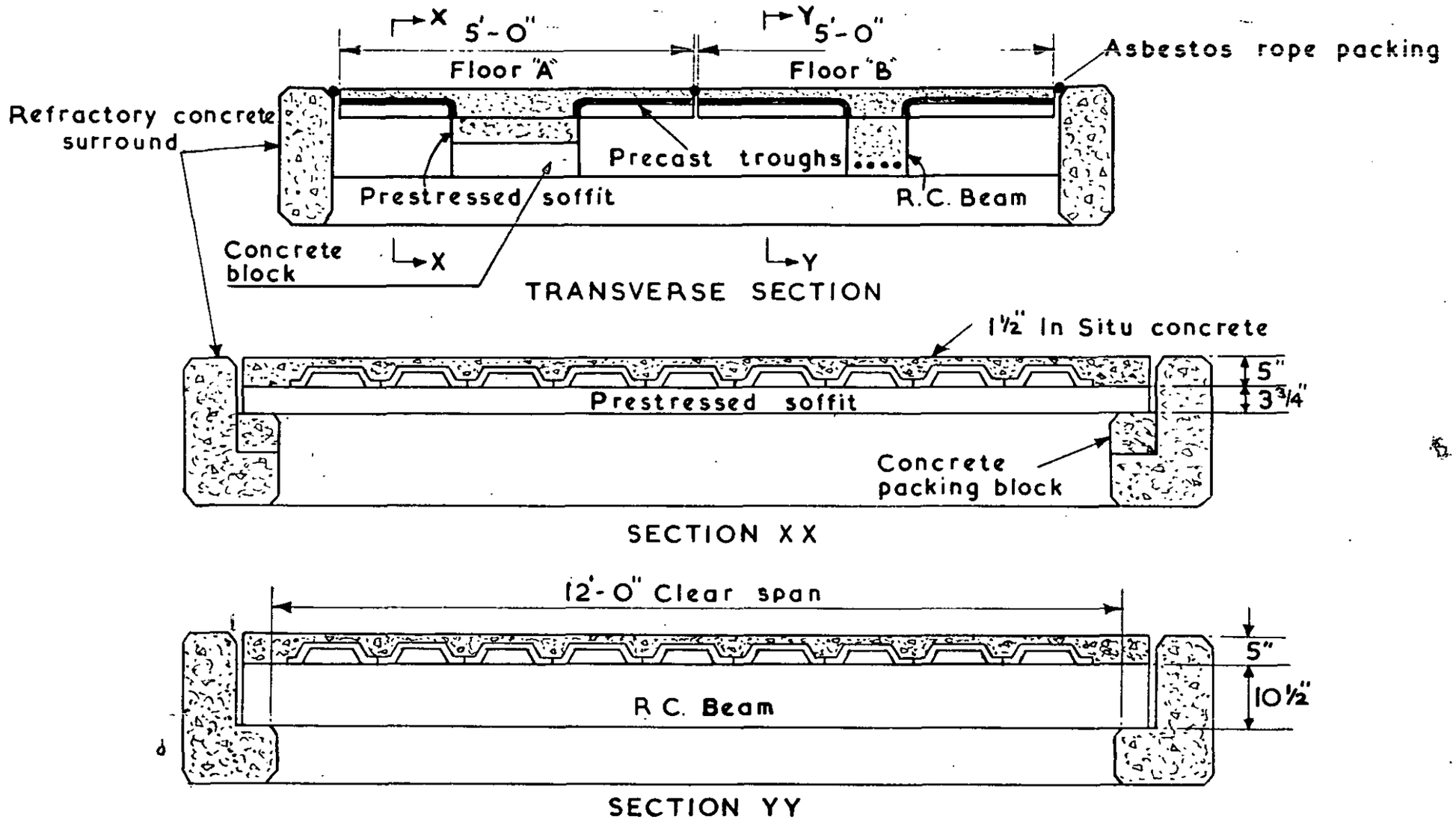
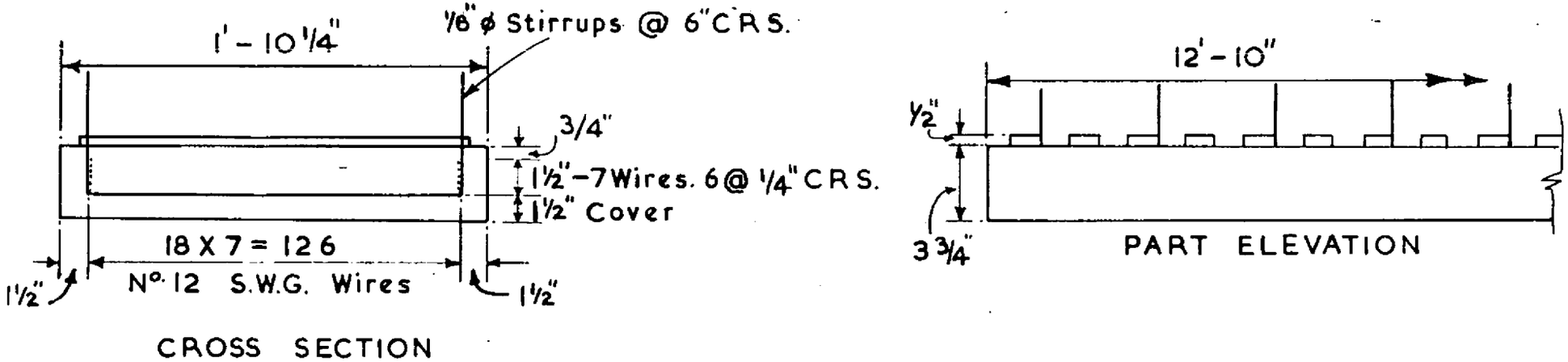
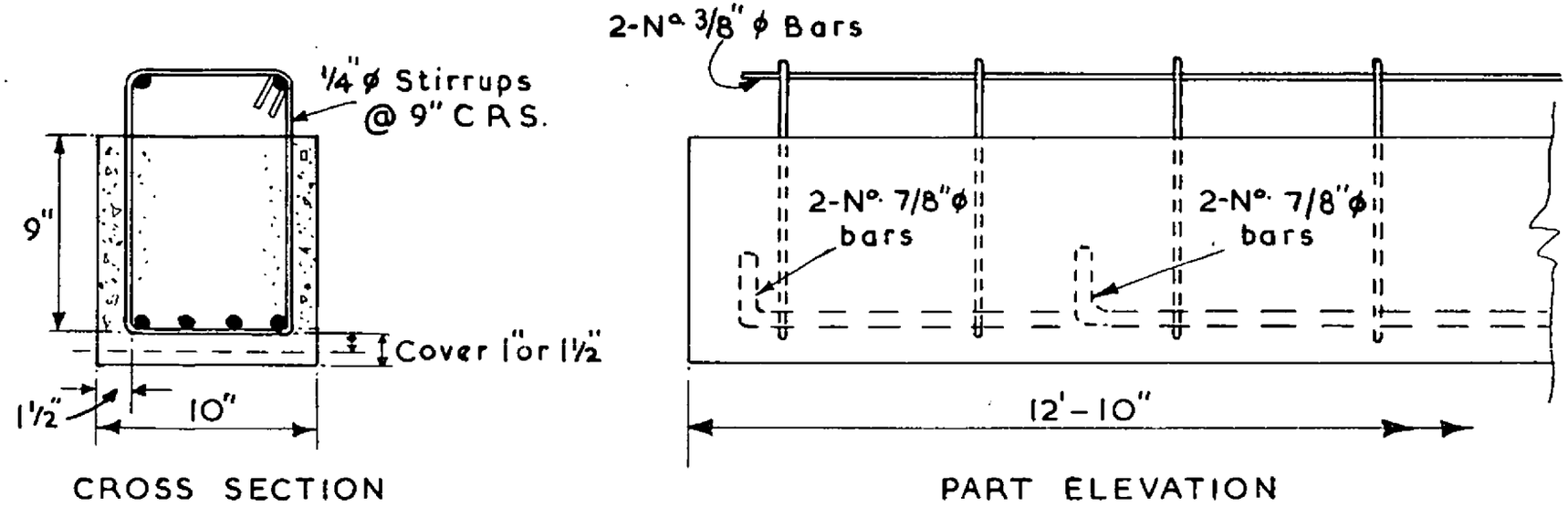


FIG. 4. ARRANGEMENT OF PRESTRESSED & R.C. FLOORS FOR TEST



(A) PRESTRESSED CONCRETE SOFFIT



(B) REINFORCED CONCRETE BEAM

FIG. 5. DETAILS OF R.C. BEAM & PRESTRESSED SOFFIT

FIG. 6. FIRE TEST IN PROGRESS

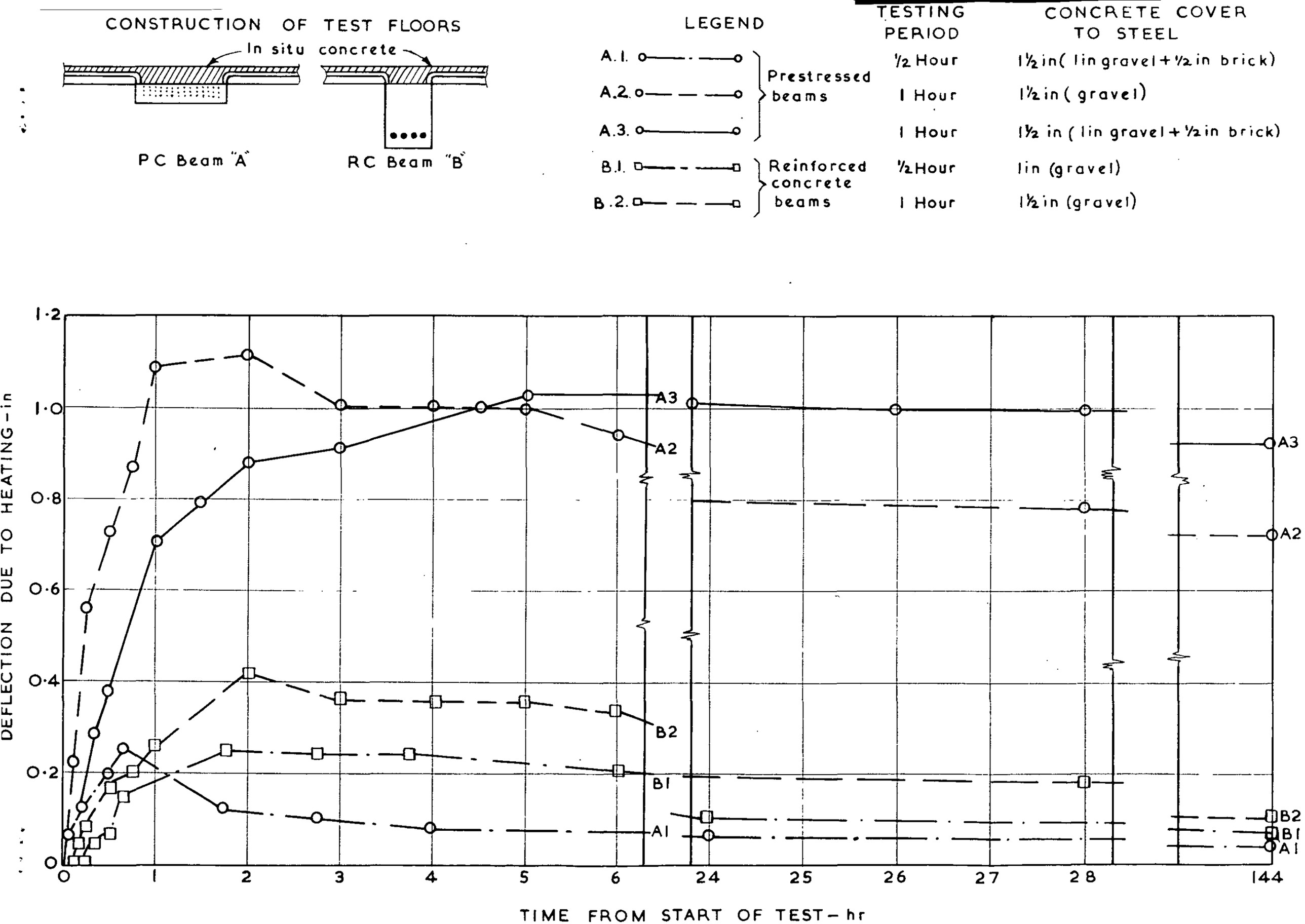


FIG. 7. DEFLECTION AND RECOVERY CURVES FOR PRESTRESSED AND REINFORCED CONCRETE BEAMS