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PRESTRESSED CONCRETE AND HIGH TEMPERATURES

by

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Introduction

In Great Britain the study of prestressed concrete at high temperatures has been concerned solely with its behaviour in fires. This aspect is being covered by means of standard laboratory tests which measure the fire-resistance of elements of construction. The work started in 1949 with a number of tests on light types of pretensioned floor unit, which did not form part of a planned programme. A systematic investigation of post-tensioned beams followed, which was designed to show the effect on fire-resistance of the most important variables. Research of a more fundamental nature is now in hand, dealing with some of the properties of concrete and cold-drawn steel wire at high temperatures. The question of residual strength and repairability of prestressed concrete after fires of much shorter duration than would lead to failure is also receiving attention.

Fire-resistance and the standard test

The term "fire-resistance" is applicable strictly to elements of construction only and not to the constituent materials. It denotes the capacity of an element to withstand heating of specified severity while performing its normal functions, thus restricting the spread of fire in a building for a definite time. Since fire-resistance can be expressed only in terms of performance in a standard test it is necessarily relative and does not imply that the same result would be obtained in an actual fire. It is implicit, however, that elements of construction having the same fire-resistance as measured by the standard test, would behave the same under similar fire conditions in service.

The methods for measuring fire-resistance are the subject of a British Standard (No.476). The test is of the full scale type since it is required that the test specimen shall be full size if possible or a representative portion not less than 10 ft. long for columns and beams or 10 ft. x 10 ft. for floors and walls shall be taken. Elements which are designed to carry loads are loaded in the test and the specimen is subjected to restraints simulating those present in a building. The heating conditions to which the specimens are subjected in the test furnaces are defined by a time-temperature relationship shown by the curve of Figure 1. A characteristic of actual fires, which is reproduced in the test, is the rapid rise of temperature in the first few minutes. Fires of varying severity can be represented by tests of different duration, since a relationship has been established between the amount of heat which would be liberated by complete combustion of the contents of a compartment of a building and the corresponding test period.

Observations are made continuously throughout the test to determine when the first critical point is reached denoting failure of the specimen to act as a barrier to spread of fire. In elements of structure, such as floors, which have a separating function in a building, failure may occur in three ways:- (1) by excessive heat conduction sufficient to ignite inflammable material in contact with the surface remote from the fire: (2) by the formation of cracks and holes which would allow flames and hot gases to pass from one side of the floor to the other: (3) by excessive deflection or collapse. Beams have only a load-bearing function in a building and their fire-resistance is given by the time from the start of the test at which failure under criterion (3) occurs.

Testing equipment

The furnace used for the tests of prestressed concrete constructions is the floor furnace shown in Figure 2. It is esentially a rectangular box of firebrick built into the floor of the test building and having an opening at the top approximately 12 ft. x 10 ft. Floors are mounted on the furnace walls over the opening so that the soffit is exposed to heat, this in general being a more severe condition than application of fire to the upper surface. The furnace is gas-fired, but there is no actual flame contact with the specimen.

Simply supported floors are built in a refractory concrete surround: restrained floors are constructed in a frame of steel beams encased in concrete. Loading of the floors is most easily effected by means of cast iron weights uniformly distributed on the upper surface.

Beams are supported for test on brackets in a steel bridge (Figure 3) which is mounted centrally on the furnace walls. The opening on either side of the beam is closed with concrete covers. The specimens can be loaded by means of hydraulic jacks at one, two or four points.

Methods of test

Floor specimens are allowed to mature naturally until they reach a state of strength and moisture content representative of possible conditions in a building. For floors, which may consist of precast units, in situ concrete and plaster, this may involve some weeks delay between completion of construction and testing. Bean being transportable, can be conditioned if required in a constant temperature and humidity room.

During a test the fuel supply is controlled so that the mean furnace temperatu as obtained from thermocouples symmetrically distributed in the furnace, conforms t the time-temperature curve within the permitted tolerances of B.S.No.476. Wheneve possible thermocouples are placed within elements of structure during manufacture t obtain the temperature at points which are considered to be critical in determining the behaviour in the fire test, for example on the high tensile steel wires of prestressed concrete members. In a floor specimen thermocouples are necessary on its upper surface to obtain the mean temperature, which must not exceed a defined limit if failure is not to occur under criterion (1). Vertical deflections are measured at several points on floors and beams.

Results of tests

(a) Pretensioned members

Floor units of the bonded wire type, used as joists or as part of a composite construction, were first tested. The majority were intended for relatively light loads and, with one exception, were made of gravel aggregate concrete. There was a great variety in the design of unit but only two were without a plaster finish. All but one were tested simply supported and unrestrained.

The floors made with the units can be divided into four main types:-

(1) Isolated joists requiring a decking of precast concrete or timber and a ceiling of building boards or plaster on metal lath.

(2) Joists having hollow infilling blocks of clay or clinker, a concrete topping and a plastered soffit.

(3) Planks or hollow beams placed side by side to form continuous surfaces for top screed and plaster

(4) Beams of heavy section exposed to the furnace on sides and soffit and supporting secondary members with an in situ concrete topping. The beams of this type were unplastered.

The specimens of each type were reasonably consistent in behaviour under the test conditions.

Type (1) was relatively unaffected until the ceiling fell. When the joists were exposed to furnace temperatures between 700°C and 800°C violent spalling soon occurred, leading to almost complete disintegration.

The floors of Type (2) had the advantage of the protection given to the sides of the joists by the infilling blocks and to the soffits of the joists by the plaster. The key given to the plaster by the blocks ensured that it would remain in place until collapse of the floor occurred. No spalling was observed on floors of this type and failure by collapse, rather than by heat transmission, would be expected since the constructions were usually thick and of low thermal conductivity.

The planks and slabs of Type (3) did not provide a good key for plaster and, therefore, the time the plaster stayed in place during a test was variable. Early falls of plaster might occur leading to spalling of the exposed concrete. If, however, these areas were small and the spalling not persistent the stability of the floor would not be affected, but extensive spalling might hasten collapse or be of sufficient severity to form holes through units and top screed.

A number of tests on Type (4) constructions showed that spalling of prestressed units of substantial section (not less than about 4 in. in any part) did not occur. Members in which a large number of wires are used distributed in rows at different depths will be at an advantage in so far as collapse is determined by loss of strength in the wires through rise of temperature, compared with units having only one row of wires with a small concrete cover.

It appeared from these tests that pretensioned floor units of small section (about 2 in. or less minimum thickness) made with gravel aggregate concrete were likely to spall when exposed directly to the temperatures encountered in fires. Where protective ceiling finishes were used, no instance of spalling occurred as long as the protection remained in place. Usually a mean temperature of the wires exceeding 350°C indicated that collapse was imminent but temperature was not a reliable guide in some composite constructions where the <u>in situ</u> concrete had some influence in delaying failure. In the only specimen having units made with granite aggregate concrete extensive and continuous spalling occurred in all areas from which the plaster fell.

Deflection of floors heated on one face is due at first to the temperature difference between the upper and lower surfaces. With continued heating and increase in temperature of the wires loss of prestress accounts for further deflection and a marked sag is observable shortly before failure. The deflections obtained with a prestressed floor of Type (2) with simply supported ends are of the same order at corresponding times as those of a hollow clay tile floor of the same overall thickness tested with the same end conditions. Restraint at the edges considerably reduces the deflections.

Fire-resistances between one and two hours were obtained without special measures for floors of all the types listed above except (1). This type, however, would be suitable for small domestic buildings, in which a fire-resistance of half an hour is required if a ceiling is used having a resistance to flame penetration of at least 25 minutes. By using a suspended ceiling of vermiculite/gypsum plaster on metal lath it should be possible to raise the fire-resistance of most of the floors of types (2) - (4) to four hours.

(b) Post-tensioned beams

Whereas in the pretensioned constructions the tests did not form a connected series, post-tensioned beams were tested in a systematic programme designed to investigate the most important factors affecting fire-resistance. The constant factors were concrete composition and strength, the type of wire and its initial stress. The variables were the concrete cover to the cable, load, end conditions, shape of cross-section and effect of protective encasements. Owing to the limitations of the equipment available post-tensioned beams representative in span and cross-section of those used in buildings could not be tested. Working from an assumed full size beam of 20 ft. span, linearly scaled beams of 1/4, 3/8 and 1/2 size were made and tested with the object of obtaining the fire-resistance of the full scale beams by extrapolation of the appropriate plotted results. An opportunity to check the validity of the extrapolations in the tests which were considered most important has been afforded by the co-operation of the National Bureau of Standards, Washington, in offering to test 4/5 scale beams sent from this country.

From the results of these tests certain tentative conclusions have been drawn for the types of beam covered:-

(1) Spalling is unlikely to occur in unprotected beams having a minimum thickness of about 2 in. in any part of the section.

(2) Failure of a beam is likely when the mean cable temperature exceeds 400°C.

(3) A fire-resistance of two hours can be obtained with a concrete cover to the cable of not less than $2\frac{1}{2}$ in. Increasing the cover would raise the fire-resistance but it is desirable to include light mesh reinforcement round the cable if the thickness of cover exceeds 3 in.

(4) Collapse is likely to be gradual and will be preceded by visible signs. Warning of failure is given by the development of a marked sag which may increase visibly just before the end. Cracks form well before failure and extend and open as collapse approaches.

(5) The greater the applied load, the earlier will failure occur. The compressive stresses present in the lower portion of a beam when carrying the dead load only do not lead to disintegration of the concrete.

(6) There is little difference in performance between beams of rectangular section and beams of I-section designed for the same load and having the same cover to the cable.

(7) A full size beam longitudinally restrained may have a lower fire-resistance than when simply supported.

(8) Even after a heating of about one half of that necessary to cause collapse a beam will show an appreciable loss of prestress on cooling. A marked permanent deflection will be present even after removal of the superimposed load, but the ultimate strength may still be a high proportion of its original value.

Prestressed concrete after fires

The fire-resistance of an element of structure was defined earlier. It is a measure of performance during a fire and gives no indication of fitness for service or repairability after a fire of less severity than that which would cause failure. This is an important aspect of the performance in fires of any form of construction and so far a small amount of attention has been directed to it. For post-tensioned beams the results of some observations are outlined in Conclusion (8) above.

A useful method of assessing the merits of prestressed concrete in fires is to compare the deflections of a given construction with those of a similar construction in normal reinforced concrete during cooling after various times of heating. Tests have been made on composite floors to compare recovery and residual deflections when prestressed or normal reinforced concrete members were included in the construction. For short heating periods (about one quarter of the time to failure in the standard test) there was little to choose between the two systems and the residual deflections were extremely small. On doubling the heating period it was found that, whereas the residual deflection of the reinforced concrete floor differed little from that obtained after the shorter heating, the prestressed concrete floor had a much higher deflection during heating and showed little recovery even after about a week.

Present work

An analytical approach is being made to the problem of the fire-resistance of prestressed concrete by linking the results of the tests carried out so far with data concerning the properties of the constituent materials. Investigations are in hand on the properties of both cold-drawn wire and concrete at high temperatures and after cooling. An electrical analogue is being used to predict the temperatures at any point in the cross-section of a beam after exposure to the standard furnace heating for a given time. When the critical factors which determine the behaviour of prestressed concrete during and after fires have been established, the means will be available to assess the performance of beams with dimensions exceeding the capacity of the testing equipment.

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