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NEW FACILITY TO DETERMINE FIRE RESISTANCE OF COLUMNS

by T. T. Lie

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New facility to determine fire resistance of columns

T. T. LIE

Fire Research Section, Division of Building Research, National Research Council of Canada, Ottawa, Ont., Canada K1A 0R6

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The new Division of Building Research (DBR) column testing furnace is described and an outline given of the proposed studies that this facility makes possible. ✓

Le four de mise à l'essai des poteaux de la Division des recherches en bâtiment (DRB) est décrit et les différentes études que cette installation peut permettre sont énumérées. ✓

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Introduction

One of the safety requirements for buildings today is the provision of appropriate fire resistance. Until fairly recently, the fire resistance of building components could only be determined by costly and time-consuming tests. Now it can be determined by calculation, thanks to the development of mathematical models. Because these models only partially represent reality, however, their validity must be verified.

A versatile column testing furnace has recently been installed at the Division of Building Research of the National Research Council of Canada. The new facility will enable the Division to test the validity of mathematical models to predict fire resistance, and to obtain a better understanding of the many problems for which there are yet no theoretical solutions. Although designed for research purposes, the furnace is also capable of performing standard tests on specimens in accordance with most international standards.

Calculation Procedure

Predicting the fire behaviour of structural members involves the specification of fire temperatures and the calculation of temperatures, deformations, and strength of structural members. Because all these quantities vary with time the calculation procedure is complex, but it has been simplified by the development of numerical calculation techniques and the use of high-speed computers. The various steps in calculating the fire resistance of a member and determining the appropriate protection are shown in Fig. 1.

Fire Load

First is the determination of the fire load, i.e., the combustible contents, which should form the basis for the fire resistance design of a building. Several surveys have been carried out recently to obtain information on fire loads in buildings (Bryl *et al.* 1974; National Academy of Sciences 1977).

Fire Temperature

Assuming that the design fire load is known, the next step is to determine time-dependence of the fire temperature. Calculation of the fire temperature course of compartment fires has been the subject of several studies (Kawagoe and Sekine 1963; Ödeen 1963; Magnusson and Thelandersson 1970; Tsuchiya and Sumi 1971; Harmathy 1972). The fire temperature course can be determined from a heat balance for the compartment, taking into account the heat produced and the heat losses to walls and openings. The most important factors are fire load and the dimensions of the openings through which air,

FIG. 1. Calculation procedure for fire-resistant design.

necessary for combustion of the fire load, can enter. How fire load affects fire temperature is shown in Fig. 2, the influence of openings in Fig. 3. Fire load determines the duration of the fire, whereas the openings influence both intensity and duration. The calculated fire temperature course or, eventually, a standard fire temperature curve is used as exposure temperatures for the calculation of the temperatures in structural members.

Temperature of Members

Temperatures of fire-exposed structural members can be calculated; the most common procedures are the finite difference and finite element methods. In these, the dependence of material properties on temperature is taken into account and, in some cases, a high accuracy can be obtained. For example, the accuracy with which temperatures in protected steel can be predicted is better than 1% if the material properties of the protection are known precisely (Lie 1977). In practice this is usually not the case, but an accuracy of 15–20% is possible, which in the field of fire is regarded as fairly accurate.

Although, in principle, it should be possible to

FIG. 2. Influence of fire load on fire temperature course.

obtain for concrete the same accuracy as for steel, it is in fact more difficult to predict concrete temperatures. The main reason is that the thermal properties of concrete depend strongly on the properties of the aggregate, which may vary over a wide range and are difficult to determine accurately. In addition, moisture in concrete will have considerable influence on its internal temperatures.

Strength of Members

When the temperature rises in fire-exposed members, their strength lessens. If the fire load is sufficient and the duration of the fire long enough, a stage will be reached at which the strength of the member will no longer be adequate to support the structural load. The fire load that is just sufficient to reduce the strength to this critical point is defined as the critical fire load. The aim is to make the critical fire load for a member sufficiently high to allow it to withstand the burn-out of the design fire load. In general, this can be achieved by selecting for the member appropriate protective materials of adequate thickness and appropriate dimensions.

Test Furnace

The test furnace was designed so that it could produce the conditions to which a member might be exposed during a fire, such as fire temperatures, structural loads, and heat transfer. It consists of a steel framework supported by four columns with the furnace chamber inside the framework (Fig. 4; Table 1 gives details of furnace characteristics).

Loading Device

Three hydraulic jacks produce forces along the three principal axes. The jack acting along the axis of the test column is designed for a maximum load of 2200 kips (9790 kN). This capacity is sufficient to subject concrete columns of approximately 30 in. $\times$ 30 in. (760 mm $\times$ 760 mm) to their design load.

This jack can also be used to restrain the thermal

FIG. 3. Influence of openings on fire temperature course.

expansion of a column and thus simulate the conditions in fires where column expansion is restrained by upper floors. The other two jacks exert lateral forces at the top of the column, to simulate the forces and displacements due to floor expansion during a fire. Loads and movements of the jacks can be controlled manually or by computer, and can be programmed to follow a predetermined course, making it possible to simulate a wide range of practical conditions.

Furnace Chamber

There are 32 propane gas burners in the furnace chamber arranged in eight columns of burners containing four burners each. The total capacity is 16 000 000 Btu/h (4700 kW), which should be sufficient to simulate any fire severity encountered in practice.

The pressure in the furnace chamber is controlled automatically. It is usually set somewhat lower than atmospheric pressure to avoid a flow of gases from the chamber to outside. If necessary, for example to meet ISO¹ standards, the furnace can be run at an overpressure.

It is possible to test both columns and walls with a fire-exposed length of between 10 and 14 ft (3.1 and 4.3 m) in the furnace. Heating can be controlled in such a way that one or more sides of the specimen are exposed to fire.

The furnace chamber, whose floor area is 8 ft 8 in. (2.6 m) square, is made of an insulating material that will produce high heat transfer to the specimen. The roof can move freely upwards and functions as a blow-out panel as a safety measure against explosion.

Safety against explosion is provided by various other measures. Before ignition of the pilot burners there is a purge period in which an amount of air about three times the volume of the furnace chamber is blown through it. In each burner there is an ultra-

¹International Organization for Standardization.

FIG. 4. Test furnace and specimens.

violet sensor that can detect failure of a burner. If this happens, the gas supply to the column of burners in which the failure occurred will shut off automatically. It is possible, however, to restart the burners manually, without purging, provided the furnace temperature has reached a level at which there is no danger of explosion. A temperature of 1000°F (588°C) was selected as being safe. This temperature is usually reached after 5 min in a

standard test. Being able to restart the burners without purging prevents the loss of a test in an advanced stage.

Instrumentation

Furnace temperatures are measured with the aid of Chromel-Alumel thermocouples installed 1 ft (0.3 m) from the test specimen at various heights. There are two thermocouples placed opposite each

TABLE 1. Furnace characteristics

Loading device	
Capacity axial load [kips (kN)]	2200 (9790)
Capacity lateral load (x-axis) [kips (kN)]	70 (310)
Capacity lateral load (y-axis) [kips (kN)]	25 (110)
Maximum movement of axial jack [in. (mm)]	12 (305)
Maximum movement of lateral jacks [in. (mm)]	6 (152)
Maximum speed of jacks [in./min (mm/min)]	3 (76)
Accuracy of controlling and measuring loads (% at low loads)	Approx. ± 5
Accuracy of measuring displacements [in. (mm)]	± 0.004 (0.1)
Furnace chamber	
Inner height of chamber [ft (m)]	Up to 14 (4.3)
Floor area [in. (m)]	104 (2.6)
Capacity of 32 burners [Btu/h (kW)]	16 000 000 (4700)
Temperature uniformity (% deviation from average temperature after 5 min)	Less than 2
Pressure in chamber at 9 ft (2.7 m) height	Adjustable between -0.2 and $+0.2$ in. (-5 and $+5$ mm) H_2O
Properties of material of floor, ceiling, and doors (ceramic blanket)	
At 932°F (773 K)	
Density [lb/ft ³ (kg/m ³)]	6 (96)
Specific heat [Btu/lb·°F (J/kg·K)]	0.26 (1090)
Thermal conductivity [Btu/ft·h·°F (W/m·K)]	0.007 (0.12)
At 2000°F (1352 K)	
Density [lb/ft ³ (kg/m ³)]	6 (96)
Specific heat [Btu/lb·°F (J/kg·K)]	0.27 (1130)
Thermal conductivity [Btu/ft·h·°F (W/m·K)]	0.24 (0.42)
Properties of material of walls (insulating fire brick)	
At 932°F (773 K)	
Density [lb/ft ³ (kg/m ³)]	45 (720)
Specific heat [Btu/lb·°F (J/kg·K)]	0.24 (1000)
Thermal conductivity [Btu/ft·h·°F (W/m·K)]	0.15 (0.26)
At 2000°F (1352 K)	
Density [lb/ft ³ (kg/m ³)]	45 (720)
Specific heat [Btu/lb·°F (J/kg·K)]	0.31 (1300)
Thermal conductivity [Btu/ft·h·°F (W/m·K)]	0.28 (0.48)

other every 2 ft (0.6 m) along the height of the furnace chamber, starting from the floor. The temperatures measured by the thermocouples are averaged automatically and the average temperature used as the criterion for controlling the furnace temperature.

As every burner can be adjusted individually a high temperature uniformity can be obtained. At present the uniformity is such that after 5 min the deviation of temperature at the various measuring points from the average furnace temperature is less than 2%.

Triaxial loads are measured by pressure transducers that supply an electrical signal to recorders.

Axial deformations of test specimens and lateral displacements at the top of the specimen are measured with linear potentiometers. In testing restrained specimens, the deformations of the steel framework of the furnace are measured with strain gauges.

All electrical signals, i.e., those from temperature, load, and deformation sensors, can be used to

control these quantities. A computerized control and data acquisition system is used for this purpose and for measuring the important variables that determine the performance of test specimens during exposure to fire.

A problem of long standing is how to measure accurately the deflection of a specimen in a furnace: the temperature is too high to use conventional methods. A method that has been developed recently by the Division of Physics, NRCC, is used to measure deflections in this furnace. In this method (Chapman and Green 1977), whose general purpose is to measure movements in a hostile environment (Fig. 5), a laser beam is split into two beams with the aid of a beam doubler. The beams are focused on a target, in this case the centre of the column. Thus two spots are formed on the target. If the target moves, the distance between the two spots changes. With the aid of lenses and mirrors an image is formed of the two spots. The image of each point is reflected,

FIG. 5. Device for measuring deflections (Division of Physics, National Research Council of Canada).

TABLE 2. Information on test columns

Number of columns	Cross section, [in. $\times$ in. (mm $\times$ mm)]	Load	Moisture condition	Aggregate	Purpose of test
3	12 $\times$ 12 (305 $\times$ 305)	0	Atmospheric	Siliceous	Repeatability
1	8 $\times$ 8 (203 $\times$ 203)	0	Dry	Siliceous	Heat transfer
1	12 $\times$ 12 (305 $\times$ 305)	0	Dry	Siliceous	Heat transfer
1	16 $\times$ 16 (406 $\times$ 406)	0	Dry	Siliceous	Heat transfer
1	12 $\times$ 12 (305 $\times$ 305)	Design load	Dry	Siliceous	Loaded model
2	12 $\times$ 12 (305 $\times$ 305)	To be selected	Atmospheric	Siliceous	Influence load
1	12 $\times$ 12 (305 $\times$ 305)	0	Atmospheric	Carbonate	Influence aggregate
2	12 $\times$ 12 (305 $\times$ 305)	To be selected	Atmospheric	Carbonate	Influence aggregate

NOTE: Column lengths are all 12.5 ft (3.8 m).

one after the other, on a photocell with the aid of a rotating mirror. In this way, pulses are generated by the cell. Because the time interval between two pulses is proportional to the displacement of the column, the deflection of the column can be determined by measuring this time interval.

The deflections of a column are measured along the two orthogonal axes perpendicular to the column axis. Tests in an existing furnace show that the device is capable of measuring displacements with an accuracy of ± 0.004 in. (0.1 mm) at a distance of 61 in. (1550 mm).

Test Program

Concrete Columns

The first series of columns intended for testing, as a part of a joint study, are reinforced concrete columns constructed by the Portland Cement Association. Mathematical models for calculating

the temperature distribution in square columns and their strength during exposure to fire were developed a few years ago (Lie and Allen 1972; Allen and Lie 1974). By subjecting the columns to the fire conditions and loads assumed in the models it will be possible to verify the validity of these models.

Figure 4 shows one column installed in the furnace and two, awaiting tests, on the right. In total 12 columns were constructed for the first series of tests; information on these columns is given in Table 2. Three columns of 12 in. $\times$ 12 in. (305 mm $\times$ 305 mm) cross section were constructed to examine the repeatability of the tests. Three columns 8 in. $\times$ 8 in. (203 mm $\times$ 203 mm), 12 in. $\times$ 12 in. (305 mm $\times$ 305 mm), and 16 in. $\times$ 16 in. (406 mm $\times$ 406 mm), will be tested unloaded to verify the heat transfer model. One column will be tested under the design load to compare the calculated with measured fire resistance. Two columns will be tested under lower

FIG. 6. Temperatures at various depths along centre line in 12 in. $\times$ 12 in. (305 mm $\times$ 305 mm) column as a function of time.

load to obtain information on the influence of over-design. The other columns were made with carbonate aggregate to determine the influence of the aggregate on the fire resistance of the columns.

Tests on a second series are planned. The columns will be larger and the influence of the steel reinforcement cover thickness on the fire resistance of the column will be examined. It is also intended to test more columns made with carbonate aggregate, to see if they have a higher fire resistance than those made with siliceous aggregate.

Figure 6 shows the results of the first test of the series. This was carried out on a column of 12 in. $\times$ 12 in. (305 mm $\times$ 305 mm) to examine the temperature distribution in the column. In Fig. 6 calculated temperatures are compared with temperatures measured at the following depths: 1, 2½, and 6 in. (25, 63, and 152 mm). Calculated temperatures are higher than most measured temperatures, but the differences are relatively small. The results indicate that the heat transfer model is reasonably accurate, although it is somewhat conservative. More tests under various conditions must be carried out, however, to establish a mathematical model that can be used with confidence for such calculations.

Steel

One of the mathematical models that has been validated is for heat transfer in protected steel (Lie 1977). Often a critical temperature of the steel can be specified for use as a criterion of failure. In this case the calculation of failure can be reduced to the calculation of the temperature of the steel. North American standards, for example, assume an average steel temperature of 1000°F (538°C) as the failure

temperature of steel columns. Although accurate prediction of steel temperatures is possible this assumption creates an uncertainty in the prediction of failure. It is probable that factors such as load and slenderness of the column play an important role in determining the failure temperature. With the aid of the new column furnace it will be possible to investigate this.

Another project now under study is the fire resistance of concrete-filled steel columns. These columns have several advantages, one of which is that concrete filling can be provided at a lower cost than conventional protection. In addition, by designing the column so that the steel carries the load at room temperature and the concrete carries it at fire temperatures when the steel has lost most of its strength, a fire resistance of more than 2 h can be obtained. This resistance is obtained without added protection; unfilled the fire resistance of the steel would be not more than about 10 min. Another advantage of fire protection by concrete filling is that some floor space is gained because there is no outside protection.

The concrete filling also substantially increases the strength of the column but there must be enough concrete to obtain sufficient fire resistance, which may be more than is needed for structural loads.

The construction of mathematical models for the calculation of the fire resistance of concrete-filled columns is at an advanced stage. It is anticipated that the new column test furnace can soon be used to study the performance of these columns.

Conclusion

Development of numerical techniques and the introduction of powerful computers have accelerated the transition from testing to calculation of fire resistance. Few facilities exist, however, that are capable of producing the conditions necessary to determine the adequacy of the mathematical models used for the prediction of fire resistance. NRCC's Division of Building Research has now installed a versatile testing furnace that can test full-scale columns and walls under various load and fire conditions.

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