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**Applicability of Temperature Predicting Models to
Building Elements Exposed to Room Fires**

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APPLICABILITY OF TEMPERATURE PREDICTING MODELS TO BUILDING ELEMENTS EXPOSED TO ROOM FIRES

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ABSTRACT

The validity of mathematical models for the prediction of temperatures attained in a clay brick wall and a protected steel column is examined. For this purpose, test specimens consisting of a clay brick wall and a square hollow steel column, protected with vermiculite board, were exposed to fire in two full scale room burns and the temperatures measured in the specimens. Using existing mathematical models and published thermal properties of the materials of which the test specimens were composed, the temperatures in the specimens were calculated. A comparison between measured and calculated temperatures showed that it is possible to predict the temperatures of the test specimens with relatively high accuracy, in spite of the large temperature fluctuations that occurred during the room burns.

INTRODUCTION

Over the years, a large number of mathematical models have been developed to predict the temperatures and structural behavior of fire-exposed building elements. These are commonly referred to as fire resistance models. In general, the validity of these models is verified by comparing calculated results with those obtained during exposure of a test specimen to a well-controlled fire in a test furnace. Such fires can usually be controlled to follow a predetermined fire

temperature course; the heat transfer from the furnace to the test specimen is also controllable and the temperatures in the furnace chamber are reasonably uniform.

This is not the case in actual compartment fires. The temperatures in these fires are generally not uniform and the heat transfer to exposed objects, as well as the fire temperature course itself, are more erratic than in test furnaces.

As a part of a project to investigate the influence of the properties of the bounding walls on the severity of room fires, studies were conducted to verify the accuracy of mathematical models for the prediction of the temperatures of building elements exposed to room fires. For this purpose, two mathematical models of building elements with known thermal properties were selected. The models, which were developed at the National Fire Laboratory (NFL) of the Institute for Research in Construction, National Research Council of Canada, comprised of a model for the prediction of the temperatures of clay brick walls [1, 2] and another for the prediction of the temperatures of hollow steel sections protected with vermiculite board [1, 3]. Specimens of these building elements were constructed and their temperatures measured during exposure to fire in full scale room burn experiments.

FULL SCALE ROOM BURN EXPERIMENT

Two full scale room burn experiments were carried out in a test room designed to withstand the severity of post-flashover fires.

Test Room

The test room, built of 200 mm thick masonry blocks, had inside dimensions of 5.0 m by 2.54 m and a height of 2.44 m (Figure 1). In each experiment, the test room was separated by partitions into two compartments of equal size, one of which was the burn room and the other a room to which the fire eventually could spread through the partition. Spread of fire will not be considered in this study, however.

All construction and instrumentation details for the two experiments were identical except that, in the first test, a wood stud frame with one layer of gypsum board on each side was used as a dividing partition; and, in the second test, a steel stud frame covered by one layer of gypsum board on each side was used for the same purpose.

Wood cribs were used to simulate office furniture to ensure repeatability of test conditions. The cribs in both tests were equivalent to a fire load of 60.3 kg/m^2 of floor area. All cribs were ignited simultaneously to simulate a rapidly developing fire leading to flashover conditions. A ventilation opening, 0.584 m in width and 0.66 m in height, was provided in each room at an elevation of 1.32 m from the floor level. The walls and floor of the burn room were covered with gypsum

Figure 1. Schematic diagram of test room.

board. The ceiling was protected with ceramic fiber insulation to enable it to withstand the complete burnout of the two compartment fires.

Burn room temperatures were measured with eight thermocouples. Four were attached, at equal vertical distance of approximately 500 mm between floor and ceiling, on each of two trees at different locations (Figure 1).

Test Specimens

Two test specimens, namely, a clay brick wall and a protected square hollow steel column were simultaneously exposed to fire in each of the two burn rooms.

The clay brick wall was 1220 mm in width by 1830 mm in height and had a thickness of 200 mm. It was insulated at the non fire-exposed face with ceramic fiber blanket and placed with this side against the concrete wall of the room (Figure 1). To measure the temperatures of the clay brick wall, five thermocouples were installed at various depths, namely one at the center of the exposed surface and the other four at respectively 33 mm, 66 mm, 99 mm, and 198 mm distance from the exposed surface.

The square hollow steel column had a height of 1830 mm and a cross section with 150×150 mm outside dimensions. It was protected at all sides by a 25 mm thick vermiculite board. The steel temperatures were measured at the mid-height

with eight thermocouples, two on each side of the column, peened in the steel at a distance of 50 mm from the corners of the column.

MATHEMATICAL MODEL

The mathematical model for the calculation of the temperatures of the wall are described in detail in [2] and for the calculation of the temperatures of the protected steel column in [3]. In this article these models will not be discussed further. Only an outline of the calculation procedure will be given.

The calculation of the temperatures of the specimens was carried out using a finite difference method. In this method, the cross-section of the specimens is divided in elementary regions, which are elementary layers for the wall and elementary squares for the protected steel column. For each element its temperature is calculated at selected time intervals during exposure to fire. In this way, the temperature history of the specimens can be determined.

The temperatures of the specimens, reached during exposure to fire, depend on the fire temperature course. This temperature course, which is used as input data in the mathematical model, can be a standard temperature course, a calculated temperature course or a measured temperature course. In this study, the measured average temperature course, obtained by averaging the temperatures measured at the eight thermocouple locations in the burn room, was used as input data. The average temperature courses, measured during the two room burns, are shown in Figure 2. Burn No. 1 was with a wood stud partition and Burn No. 2 with a steel stud partition.

Because of the fluctuations in temperatures, which made the use of these temperatures as input data more complicated, the temperature courses of the two room burns were approximated by a number of straight lines, which can easily be used as input for the mathematical model. These lines, representing the temperature courses of the two room burns, are shown in Figure 3. They can be given for Burn No. 1 by the following equations:

$$\begin{array}{lll} T = 9.4 t + 175.4 & \text{for} & 0 \leq t \leq 23 \\ T = 35.6 t - 415.1 & \text{for} & 23 < t \leq 27 \\ T = 7.9 t + 310.3 & \text{for} & 27 < t \leq 44.5 \\ T = 2.5 t + 554.8 & \text{for} & 44.5 < t \leq 115 \\ T = -12 t + 2212.6 & \text{for} & 115 < t \leq 149.5 \end{array}$$

and for Burn No. 2:

$$\begin{array}{lll} T = 8.8 t + 199.2 & \text{for} & 0 \leq t \leq 16.5 \\ T = 14.8 t + 156.2 & \text{for} & 16.5 < t \leq 32 \\ T = 0.98 t + 660.9 & \text{for} & 32 < t \leq 100 \\ T = 6.1 t + 139.8 & \text{for} & 100 < t \leq 120 \\ T = -3.3 t + 1267.7 & \text{for} & 120 < t \leq 149.5 \end{array}$$

Figure 2. Average room burn temperatures as a function of time.

Figure 3. Representative room burn temperatures as a function of time.

where:

T = the fire temperature in $^{\circ}\text{C}$

and t = the time in minutes.

With the approximate temperature courses as input data, the temperatures of the wall and the protected steel specimens were calculated, using the mathematical models described in [2, 3] and the relevant thermal properties given in the Appendix. The calculated results, which will be further discussed, are given below.

RESULTS AND DISCUSSION

In Figures 4 and 5, calculated steel temperatures for the protected steel columns are compared with those measured during the two room burns. Because the emissivities of the fires were not known precisely, the calculations were made for two emissivities; namely, one for a reasonably high emissivity of 0.6 and the other for the extremely high emissivity of 1.0. It can be seen that, for high emissivities which are normally the case for the luminous flames produced by wood fires, there is almost no influence of the emissivity on the steel temperatures.

The comparison for Burn No. 1 (Figure 4) showed a good agreement between calculated and measured temperatures up to about 100 minutes. After this time,

Figure 4. Measured and calculated steel temperatures as a function of time for Burn No. 1.

Figure 5. Measured and calculated steel temperatures as a function of time for Burn No. 2.

the measured temperatures rose considerably faster than those calculated. This sudden rise in steel temperature can be attributed to the formation of openings in the joints at the corners of the protective vermiculite boards. Therefore, calculated and measured temperatures could no longer be compared. For Burn No. 2 (Figure 5), the comparison showed good agreement between calculated and measured steel temperatures for the whole duration of the experiment.

The results for the clay brick wall are shown in Figures 6 and 7, where calculated wall temperatures are compared with those measured at various depths in the wall. The comparisons are made for two times during exposure to fire, namely, for sixty and 120 minutes after the start of the fire.

The results show that there is good agreement between the temperatures measured at various depths in the walls and those calculated. The maximum difference between measured and calculated temperatures is approximately 20 percent, which is small taking into account the several factors that determine the results, such as, accuracy of the thermal properties used, location of the thermocouples in the walls and the approximation of the fire temperature course used as input data.

The results indicate that it is possible, using existing methods, to predict the temperatures in building elements exposed to real world fires with relatively high accuracy, provided the temperatures of the fire, to which the building element will be exposed, are known. Unfortunately, this is not the case at the design stage of a

Figure 6. Measured and calculated clay brick temperatures as a function of depth for Burn No. 1.

Figure 7. Measured and calculated clay brick temperatures as a function of depth for Burn No. 2.

building. It is possible, however, to indicate fire temperature courses, representing a severity which will likely not be exceeded in the event of fire in the building under consideration [1, 4-9]. Using these temperature courses as input data in the mathematical models, the thermal behavior of building elements can be evaluated with relatively high accuracy.

CONCLUSIONS

The results of this study indicate that, in spite of the erratic temperature fluctuations met within room fires, the prediction of the thermal behavior in such fires for clay brick walls and protected steel can be made with relatively high accuracy. Given the excellent correlation that exists between thermal behavior and fire resistance ratings, designers can thus be provided with flexible and reliable modeling tools.

In order to be able to make such fire resistance predictions, at the design stage of a building, it is necessary to know the maximum likely temperature course of the fire to which the building elements will be exposed in the event of fire. Although the intensity and duration of the fire are not predictable, it is possible, using existing data, to indicate a fire whose severity will likely not be exceeded during the service life of the building. This enables the selection, at the design stage, of appropriate measures, such as, wall thickness, steel size and shape or thickness of steel protection, that will provide adequate fire protection for the building. It is expected that, using existing models, similar predictions can be made for other building elements, such as, beams, floors, and columns.

APPENDIX: THERMAL PROPERTIES

The thermal properties used in this study were derived from various publications. The thermal properties for clay brick were published in [3], those for ceramic fiber in [10], those for steel in [1, 3] and those for vermiculite board in [11]. The moisture content of vermiculite board was 5 percent by volume. That of the other materials, which normally do not contain a significant amount of water, was assumed to be negligible.

Clay Brick

Thermal conductivity

$$k = 5.07 \times 10^{-4} T + 0.935$$

Thermal capacity

$$pc = 4.80 \times 10^2 T + 1.64$$

Ceramic Fibre

Thermal conductivity

$$k = 2.91 \times 10^{-2} + 6.54 \times 10^{-5} T + 2.52 \times 10^{-7} T^2$$

Thermal capacity

$$pc = 96 \times 10^3$$

Steel

Thermal conductivity

Perfect conductor

Specific heat

$$c = 0.478 T + 440$$

Vermiculite Board

Thermal conductivity

$k = 0.000192 T + 0.135$	for	$0 \leq T \leq 1000^\circ\text{C}$
$k = 0.327$	for	$T > 1000^\circ\text{C}$

Thermal capacity

$pc = 4200 T + 425000$	for	$0 \leq T \leq 50^\circ\text{C}$
$pc = -4250 T + 847500$	for	$50 < T \leq 100^\circ\text{C}$
$pc = 335 T + 389000$	for	$100 < T \leq 1000^\circ\text{C}$
$pc = 724000$	for	$T > 1000^\circ\text{C}$

where:

T = the temperature in $^\circ\text{C}$ k = the thermal conductivity in $\text{J}/(\text{m}^\circ\text{C})$ pc = the thermal capacity in $\text{W}/(\text{m}^3^\circ\text{C})$ c = the specific heat in $\text{J}/(\text{kg } ^\circ\text{C})$ **REFERENCES**

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