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Assessment of the Fire Resistance of Steel Hollow Structural Section Columns Filled with Plain Concrete

by T.T. Lie and D.C. Stringer

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ASSESSMENT OF THE FIRE RESISTANCE OF STEEL HOLLOW STRUCTURAL SECTION COLUMNS FILLED WITH PLAIN CONCRETE

ABSTRACT

Experimental studies were conducted to determine the fire resistance of circular and square hollow structural section columns filled with plain concrete. Mathematical models were developed and used to investigate the influence of important parameters that determine the fire resistance of these columns. The experimental and parametric studies provide information for the development of formulas for the calculation of the fire resistance of circular and square concentrically loaded columns filled with plain carbonate or siliceous aggregate concrete. Such formulas are suitable for incorporation in building codes.

ASSESSMENT OF THE FIRE RESISTANCE OF STEEL HOLLOW STRUCTURAL SECTION COLUMNS FILLED WITH PLAIN CONCRETE

1 INTRODUCTION

For a number of years, the National Research Council of Canada (NRC) has carried out research on the fire resistance of concrete-filled steel columns. Both experimental and theoretical studies to develop methods for the prediction of the fire resistance of these columns have been conducted.

As part of these studies, mathematical models were developed for the calculation of the fire resistance of hollow structural sections (HSS) filled with concrete. Columns of various steel sizes and shapes filled with various concrete types were studied. Full scale tests for the validation of the models were carried out. Similar studies were carried out by several organizations around the world. [1-8]

At present, the research at NRC has reached a stage at which sufficient data, suitable for release, have been produced for concentrically loaded HSS columns filled with plain concrete. Experimental results of 44 full-scale fire resistance tests were reported in Reference 9. Mathematical models for the calculation of the fire resistance of such circular and rectangular concrete-filled HSS columns are described in References 10 and 11.

Using these models, a large number of computer runs were made to investigate the influence of the important parameters that determine the fire resistance of the columns [12, 13]. The computer runs also provided information for the development of formulas, suitable for incorporation in building codes, for the calculation of the fire resistance of the columns. In this report, such formulas are presented for the calculation of the fire resistance of circular and square columns filled with carbonate and siliceous aggregate concrete.

The development of the formulas was carried out at the National Fire Laboratory of the Institute for Research in Construction, NRC, with the support of the Canadian Steel Construction Council and the American Iron and Steel Institute.

2 PROCEDURE DEVELOPMENT OF FORMULAS

2.1 Comparison between Calculated and Experimental Results

Using the mathematical model and the material properties described in Reference 10, calculations were made of the fire resistance of a large number of circular plain concrete filled steel columns, that were tested at NRC. Some of the columns were filled with siliceous aggregate concrete and others with carbonate aggregate concrete. The test results established that the type of concrete has an effect on the fire resistance. For example, a column with carbonate aggregate concrete has a higher fire resistance than one with siliceous aggregate. This occurs mainly because carbonate aggregate has a substantially higher heat capacity than siliceous due to an endothermic reaction that takes place in carbonate aggregate around 700 °C. In Chapter 2, Section 1.4 of the Supplement to the National Building Code of Canada 1990, concrete with predominantly carbonate aggregate is identified as Type N, whereas concrete with predominantly siliceous aggregate is identified as Type S.

The calculated results are compared in Fig.1 with experimental results. The comparison shows that, for long durations of fire exposure, high applied loads and high concrete strengths, there may be substantial differences between calculated and experimental results. Several reasons may be proposed to explain these differences between actual and predicted fire resistance, including:

1. In the case of long duration of fire exposure, steadily increasing temperature causes the propagation of local cracks resulting eventually in the total degradation of the core and in the loss of concrete strength.

2. If the applied load on the column exceeds the factored resistance [14] of the concrete core, sudden failure can occur due to the loss in strength of the steel section during the fire.

3. In the case of concrete fillings with high strengths, increased concrete brittleness associated with the high strength, may be a contributing factor to sudden and premature failure.

Since the fire resistance cannot be accurately predicated for conditions of high fire duration, high loads and high concrete strength, it is necessary to set limits of applicability on these parameters. In addition, because the experimental studies have been conducted on Class 1, 2 and 3 Sections [14] with effective lengths between 2000 and 4000mm and with outside diameters between 140 and 410 mm, the theoretical model is also confined to stay within these limits.

In summary, the theoretical model is deemed to be applicable when limits are set on the following parameters:

1. Fire resistance (R): $\leq$ 120 minutes
2. Load on column (C): $\leq$ factored compressive resistance of concrete core according to CAN/CSA-S16.1-M89 [14]
3. Specified 28-day concrete strength (f'_c): 20 to 40 MPa
4. Effective length of column (KL): 2000 to 4000 mm
5. Outside diameter or outside width of column (D): 140 to 410 mm.
6. Width/thickness ratio not to exceed Class 3 Section [14]

Within these limits, it is evident from Fig. 2, that predicted fire resistances are generally conservative in comparison to the experimental values for circular columns tested at NRC.

2.2 Important Parameters

The experimental results [9] and the computer runs [12,13] show that the most important parameters that determine the fire resistance of hollow steel columns filled with plain concrete are:

1. The load on the columns
2. The outside diameter or the outside width of the column
3. The effective length of the column
4. Concrete strength
5. Type of aggregate.

2.3 Fire Resistance Formula for Circular Columns

The results of the computer runs [12] also show how the fire resistance of the columns varies with the important parameters noted above. Using the relations between the fire resistance and the various parameters that determine it, the following formula for the fire resistance of circular hollow steel columns, filled with plain concrete, was empirically established.

$$R=f_1 \frac{(f'_c+20)}{(KL-1000)} D^2 \sqrt{\frac{D}{C}} \qquad (1)$$

where:

R = fire resistance (min)
f_1 = 0.07 for siliceous aggregate concrete filling (Type S)
0.08 for carbonate aggregate concrete filling (Type N)
f'_c = specified 28-day concrete strength (MPa)
K = effective length factor
L = unsupported length of the column (mm)
D = outside diameter of the column (mm)
C = applied load (KN)

with validity limits:

R $\leq$ 120 min
f'_c 20 to 40 MPa
KL 2000 to 4000 mm
D 140 to 410 mm (with $D/t \leq$ Class 3 section [14])
C $\leq$ factored compressive resistance of concrete core according to CAN/CSA-S16.1-M89 [14]

To verify the validity of the formulas, the fire resistances calculated with the formula were compared with those calculated with the mathematical model, which as shown in Fig. 2, predicts experimental fire resistances with reasonable accuracy. The comparison is shown in Fig. 3 for those circular columns tested at NRC, which satisfied the limitations with regard to load, concrete strength, and duration of fire exposure, mentioned earlier. Because the fire resistances, predicted by the model, lie with a few exceptions on the safe side, values of the factor "f" in equation (1) were selected that produced slightly higher fire resistances than those calculated by the model. In Fig. 4, the fire resistances calculated with the formula are compared with experimental fire resistances. The accuracy with which the formula predicted the experimental fire resistances is better than that of the model. Almost all predictions, however, are still somewhat conservative.

2.4 Fire Resistance Formula for Square Columns

The material discussed thus far deals only with circular columns which comprise most of the studies carried out at NRC. These studies complement the studies carried out by other laboratories [2-7], which were dominantly on columns with square cross section.

Unfortunately, there is a lack of information on the thermal properties and on the type of aggregate for the tests conducted at other laboratories. Due to these missing data, it is not possible to compare those test results with the NRC mathematical model.

Results of computers runs [13] indicate that the fire resistance of square columns is influenced by similar parameters to those of circular columns. In addition, to achieve correlation between theoretical and experimental results, validity limits on parameters are also similar to those of the circular columns.

For square hollow structural columns filled with plain concrete the following empirical formula conservatively fits the experimental data:

$$R=f_2 \frac{(f'_c+20)}{(KL-1000)} D^2 \sqrt{\frac{D}{C}} \qquad (2)$$

where:

R	= fire resistance (min)
f_2	= 0.06 for siliceous aggregate concrete filling (Type S) 0.07 for carbonate aggregate concrete filling (Type N)
f'_c	= specified 28-day concrete strength (MPa)
K	= effective length factor
L	= unsupported length of column (mm)
D	= outside width of column (mm)
C	= applied load (kN)

with validity limits:

R	$\leq$ 120 min
f'_c	20 to 40 MPa
KL	2000 to 4000 mm
D	140 to 305 mm (with D/t $\leq$ Class 3 section [14])
C	$\leq$ factored compressive resistance of concrete core according to CAN/CSA-S16.1-M89 [14]

In Fig. 5, the fire resistances, calculated with the formula, are compared to experimental resistances from tests largely conducted at other laboratories [2-7]. Only those tests which satisfied the validity limits are included in the sample. It is evident that there is considerable variation between calculated and experimental values. This occurs due to the large scatter of experimental results. For example, tests on nominally identical columns carrying identical loads, sometimes show significant differences in fire resistance when tested at different laboratories. The discrepancy has been mainly attributed to variations in end fixity of the various testing machines. The coefficients are selected, such that the formula predicts fire resistance generally conservatively.

3 DISCUSSION AND CONCLUSION

In terms of cross-sectional area required to support a given load in a fire situation, circular columns can be seen to be more efficient than square columns. Several reasons may be proposed to explain the relative efficiencies of circular and square columns. For example, the steel shell of square columns is more prone to local buckling than that of circular columns, thus reducing the containment of the concrete and allowing spalling to occur. In addition, due to the shape of square columns, an unequal temperature field develops during a fire and generates large internal stresses in the concrete compared with those in a circular column. These internal stresses reduce the relative load-bearing capacity of the square column.

In this report, formulas, suitable for incorporation in building codes, for the calculation of fire resistance of circular and square hollow structural sections with plain concrete filling, are presented. Fig. 6 shows a comparison between fire resistances calculated with the formulas and experimental fire resistances for circular and square columns. It is evident that the formulas predict the fire resistance conservatively, provided that the column design parameters stay within the validity limits noted in this report.

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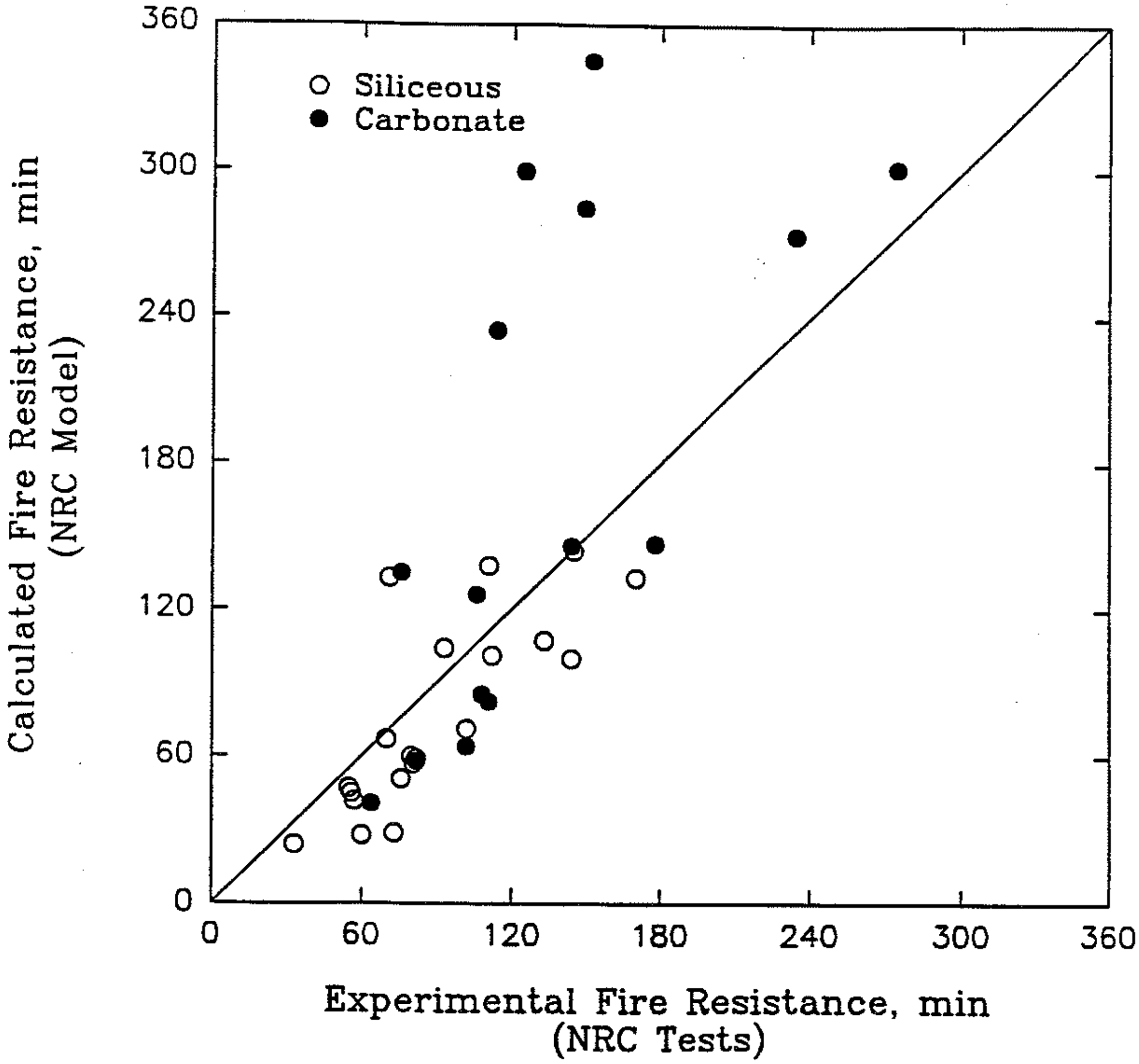

Figure 1. Comparison between the Fire Resistances Calculated with the NRC Mathematical Model and Experimental Fire Resistances for Circular Columns Filled with Plain Concrete.

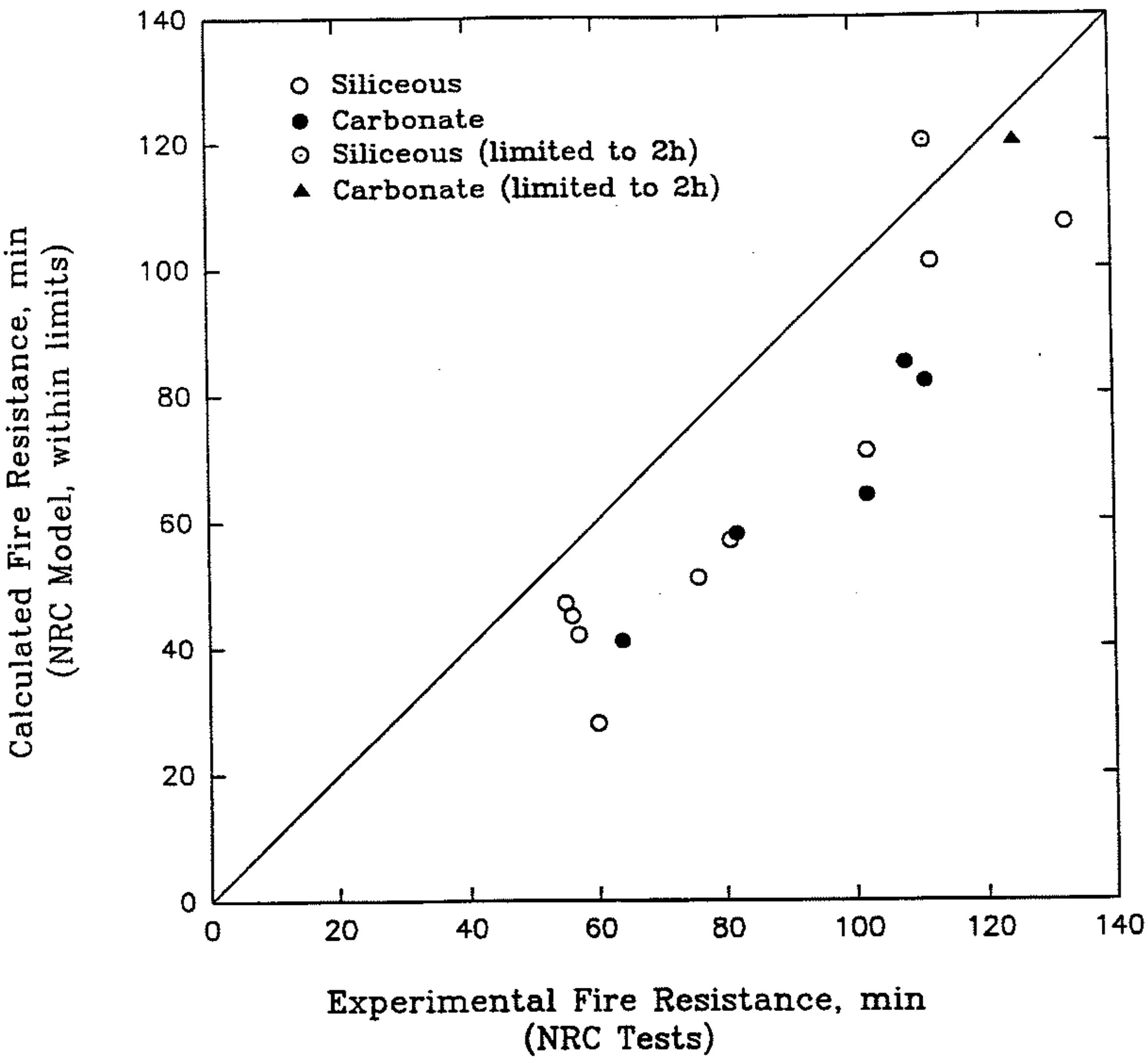

Figure 2. Comparison Between the Fire Resistances Calculated with the NRC Mathematical Model (within limits) and Experimental Fire Resistances for Circular Columns filled with Plain Concrete

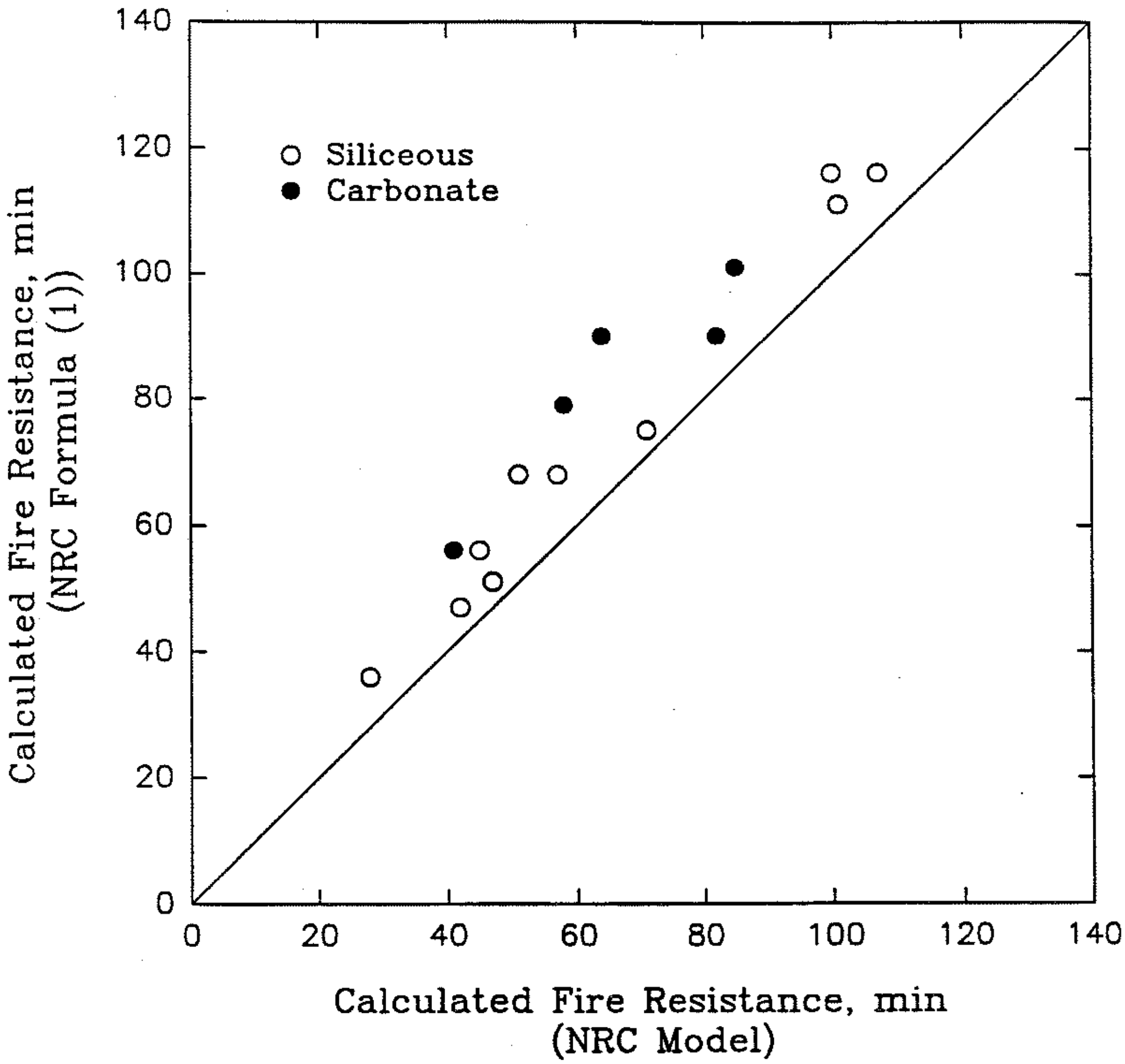

Figure 3. Comparison of Calculated Fire Resistances Between NRC Formula (1) and NRC Mathematical Model for Circular Columns filled with Plain Concrete

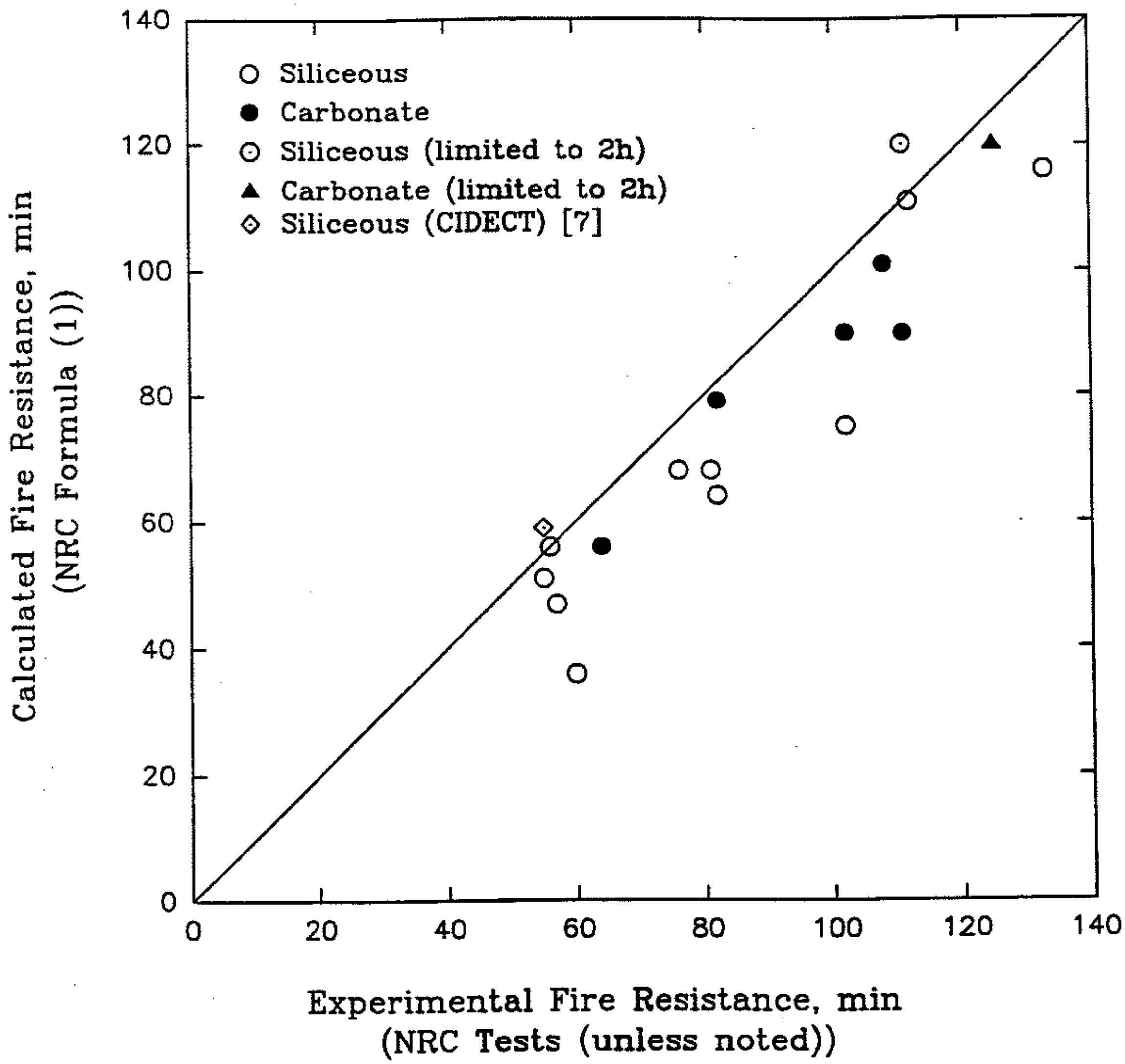

Figure 4. Comparison between the Fire Resistances Calculated with the NRC Formula (1) and Experimental Fire Resistances for Circular Columns filled with Plain Concrete

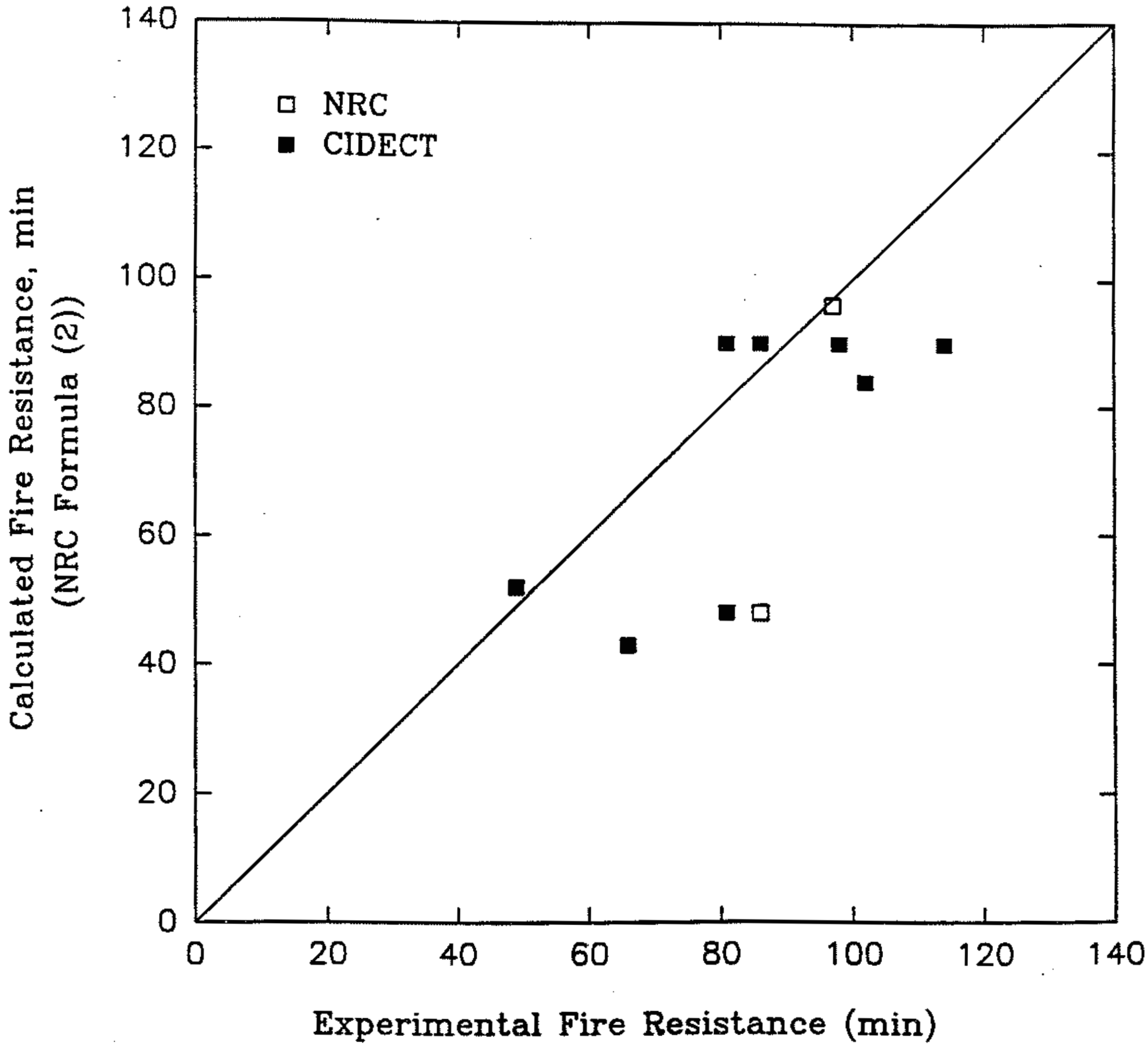

Figure 5. Comparison between the Fire Resistances Calculated with the NRC Formula (2) and Experimental Fire Resistances for Square Columns filled with Plain Concrete

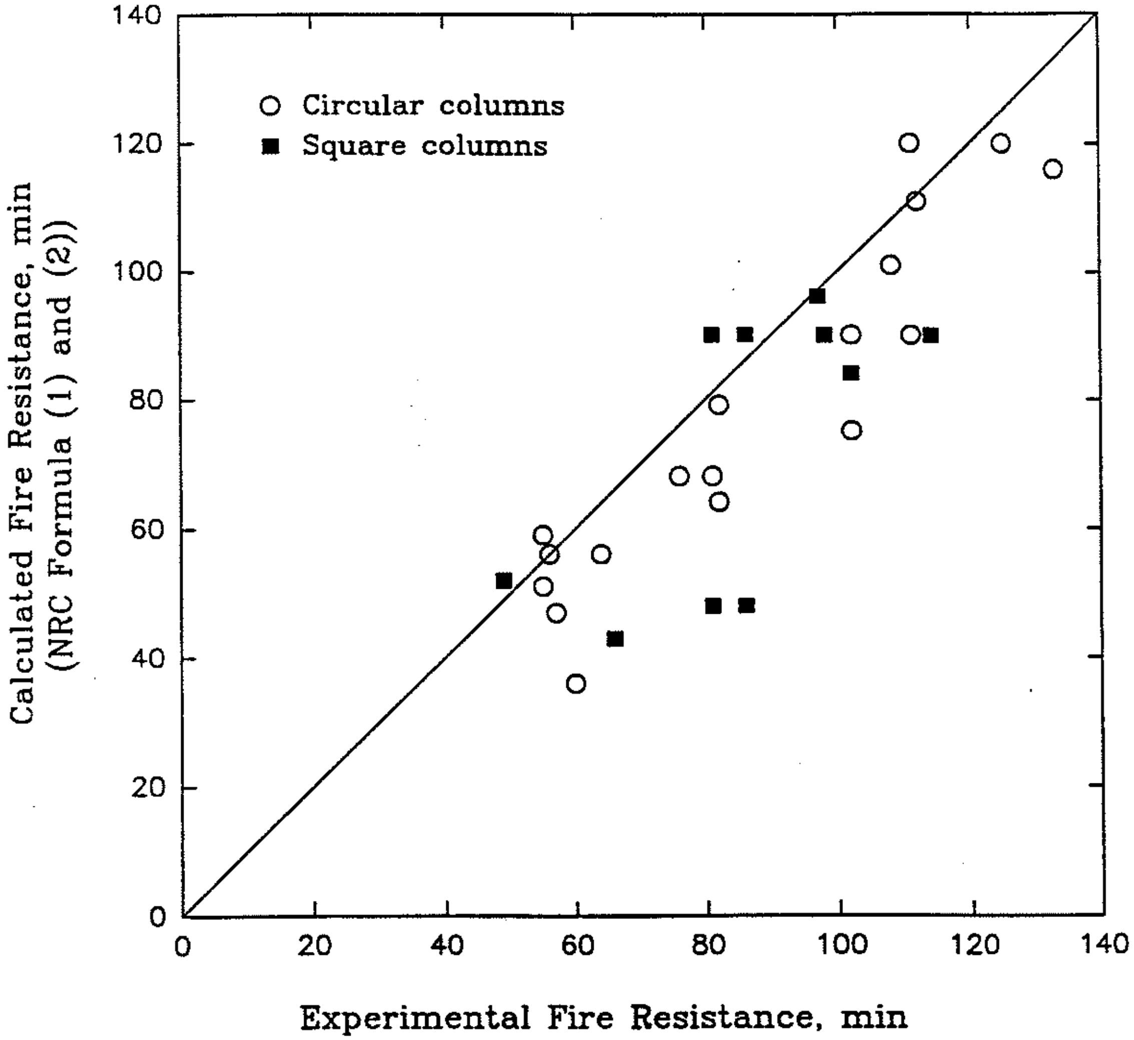

Figure 6. Comparison between the Fire Resistances Calculated with the NRC Formula (1) and (2) and Experimental Fire Resistances for Square and Circular Columns filled with Plain Concrete