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FIRE RESISTANCE OF REINFORCED CONCRETE COLUMNS: A PARAMETRIC STUDY

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SUMMARY

Experimental and theoretical studies were carried out to develop general methods for the prediction of the fire resistance of reinforced concrete columns. In these studies, which were carried out jointly between the National Research Council of Canada and the Portland Cement Association, 41 columns were tested. The parameters studied included load level, amount of steel reinforcement, effective length of column, concrete strength, moisture content, area and shape of cross section, aggregate type, axial restraint of thermal expansion and load eccentricity. The experimentally discovered effects of these parameters are discussed.

INTRODUCTION

Research on reinforced concrete columns[1, 2] was started in Canada in the early 1970's for the purpose of updating the fire resistance ratings in the National Building Code of Canada (NBCC)[3]. This research consisted of theoretical studies, the results of which were compared with those of a limited number of tests carried out in Germany. The studies were initiated in recognition of the fact that the ratings given in the Code for reinforced concrete columns were based on test results obtained in about 1920, and that, since that time, design procedures had changed and safety factors had decreased. The results of this research were incorporated in the NBCC in 1975.

In the late 1970's, a full-scale column fire test facility[4] was constructed at the National Research Council of Canada (NRCC). At that time an extensive program of joint research was established between NRCC and the Portland Cement Association (PCA). The purpose of this research was to re-examine the NBCC ratings, to validate mathematical models that existed or had to be developed at that time, and to study the effect of all important variables that affect the fire resistance of reinforced concrete columns.

Testing of columns started in 1979. In total, 41 full-scale reinforced concrete columns were tested in the program. The columns were manufactured by PCA in Skokie, IL, and tested at the Fire Research Section of NRCC. The results of the tests, which have been documented[5], will be discussed in this paper.

STUDY VARIABLES

In this study, the effect of the following variables on the fire resistance of reinforced concrete columns was investigated:

1. load level,
2. percentage of longitudinal reinforcing steel,
3. effective length,
4. concrete strength,
5. relative humidity in concrete,
6. column cross sectional area,
7. column shape (square, circular, or rectangular),
8. concrete aggregate type,
9. axial restraint of thermal expansion, and
10. load eccentricity

TEST SPECIMENS

The column test specimens were manufactured in three series comprising 12 columns in Series I, 12 columns in Series II and 17 columns, including the T-series, in Series III (Table 1). The various series of columns were constructed in consecutive phases, making use of experience obtained in prior phases. A detailed description of the columns and the materials of which they were composed is given in Reference 5. The basic properties of the column specimens are listed in Table 1.

Ten of the specimens, which were tested under different loads, were nearly identical and used as reference specimens. These specimens (which are marked with an asterisk in Table 1) were different only in measured concrete strength and relative humidity.

Dimensions

All columns were 3810 mm (12 ft 6 in.) long from endplate to endplate (Figure 1).

The reference cross-section, which is shown in Figure 1, was 305 x 305 mm (12 x 12 in.). Square sections of 203 mm (8 in.) and 406 mm (16 in.), rectangular sections of 305 x 457 mm (12 x 18 in.) and 203 x 915 mm (8 x 36 in.), and circular sections of 355 mm (14 in.) diameter were also used to investigate the effect of size and shape on fire resistance. All but one column had 38 mm (1.5 in.) cover to the tie bars, and 48 mm (1.875 in.) cover to the vertical steel. Column II-12 had 64 mm (2.5 in.) cover to the vertical steel. Several 305 x 305 mm (12 x 12 in.) columns were built with brackets for eccentric loading (Figure 2).

Concrete Types

Three types of concretes were investigated, i.e., normal weight concretes made with siliceous and carbonate aggregates and a lightweight concrete made with expanded shale aggregate. The concrete of the reference columns was made with siliceous aggregate. The mix of this concrete was designed to produce a concrete strength of 34.5 MPa (5000 psi) at 28 days after the pouring.

TEST APPARATUS AND PROCEDURE

Furnace

The tests were carried out by exposing the columns to heat in a furnace especially built for testing loaded columns and walls. The test furnace, which uses propane as fuel, was designed to produce the conditions to which a member might be exposed during a fire, i.e. temperatures, structural loads, and heat transfer. It consists of a steel framework supported by four steel columns, with the furnace chamber inside the framework (Figure 3). The characteristics and instrumentation of the furnace are described in detail in Reference 4.

Loading

The loads were applied by hydraulic jacks. The main load was provided by a jack acting along the axis of the test column. This jack, which is located at the bottom of the column, has a capacity of 1000 t.

Most tests were carried out with the ends of the

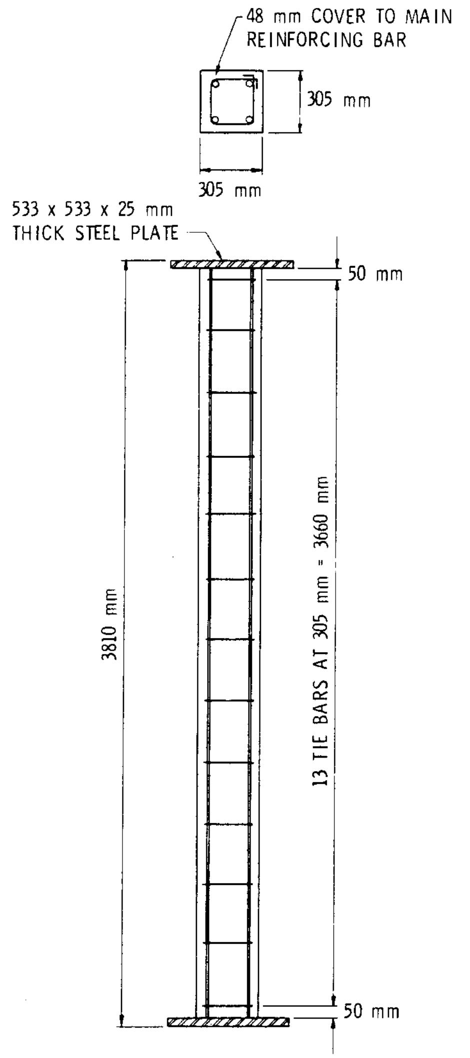

Figure 1. Reference test column and location of reinforcing bars

Table 1. Summary of Test Parameters and Results

Col. No.	Test Purpose	Cross Section mm	Steel %	Aggre-gate	Conc. R.H. %	Conc. Strength MPa	Test Load kN	Max. Allow. Load kN	Test/ Max. Load	Failure Time hr
I-1	Standard, dry	305x305	2.19	Sil	5		0			>4:00
I-2*	Load, dry	305x305	2.19	Sil.	15	36.9	1333	1271	1.05	2:50
I-3*	Load	305x305	2.19	Sil.	70	34.2	800	1222	0.65	3:38
I-4*	Load	305x305	2.19	Sil.	63	35.1	711	1231	0.58	3:40
I-5	Size, dry	406x406	2.47	Sil.	9	40.7	0			>5:00
I-6	Size, dry	203x203	2.75	Sil.	29	42.3	169	355	0.48	3:00
I-7*	Load	305x305	2.19	Sil.	74	36.1	1067	1244	0.86	3:28
I-8*	Load	305x305	2.19	Sil.	74	34.8	1778	1222	1.46	2:26
I-9*	Load	305x305	2.19	Sil.	75	38.3	1333	1298	1.03	3:07
I-10	Aggregate	305x305	2.19	Carb.	75	40.9	800	1373	0.58	8:30
I-11	Aggregate	305x305	2.19	Carb.	75	36.9	1067	1271	0.84	6:06
I-12	Aggregate	305x305	2.19	Carb.	76	39.9	1778	1346	1.32	3:36
II-1	Free translation, fixed-hinged	305x305	2.19	Sil.	65	41.6	342	342	1.0	5:40
II-2*	Full axial restraint	305x305	2.19	Sil.	75	43.6	(1044/2049)[2]	1436	0.73	3:21
II-3*	Full axial restraint	305x305	2.19	Sil.	75	35.4	(916/1914)[2]	1244	0.74	3:30
II-4*	High-strength concrete	305x305	2.19	Sil.	75	52.9	1178	1644	0.72	3:47
II-5*	High-strength concrete	305x305	2.19	Sil.	75	49.5	1067	1573	0.68	3:54
II-6	Aggregate	305x305	2.19	Shale	79	46.6	1076	1507	0.71	3:08
II-7	Aggregate	305x305	2.19	Shale	80	42.5	947	1404	0.67	4:19
II-8	% Steel	305x305	4.38	Sil.	61	42.6	978	1618	0.60	4:12
II-9	% Steel	305x305	4.38	Sil.	75	37.1	1333	1489	0.90	3:45
II-10	Load	406x406	2.47	Sil.	80	38.8	2418	2782	0.87	4:22
II-11	% Steel	406x406	3.97	Sil.	75	38.4	2795	2795	1.0	4:45
II-12	% Steel/Load, thick cover	406x406	3.97	Sil.	68	46.2	2978	3516	0.85	3:33†
III-1	Fixed-hinged	305x305	2.19	Sil.	60	39.6	800	1227	0.65	4:02
III-2	Fixed-hinged	305x305	2.19	Sil.	64	39.3	1000	1218	0.82	3:40
III-3	Ecc. load (24mm), hinged-hinged	305x305	2.19	Carb.	56	39.9	1000	1000	1.0	3:01
III-4	Fire intensity	305x305	2.19	Carb.	45	37.6	1067	1284	0.83	5:28
III-5	Shape-rectangular	305x457	2.22	Sil.	65	42.5	1413	2102	0.67	5:56
III-6	Shape-mini-wall	203x915	1.22	Sil.	58	42.1	756	1360	0.56	5:35
III-7	Ecc.load, partial rotation	(305x305)[1]	2.19	Sil.	44	42.1	973, (49/32)[3]	1022	1.0	2:50
III-8	Ecc.load, rotation const.	(305x305)[1]	2.19	Sil.	32	42.8	987, (49/9)[3]	1435	0.72	3:45
III-9	Ecc.load, rotation const.	(305x305)[1]	2.19	Sil.	41	44.5	889, (49/12)[3]	1440	0.65	3:30
III-10	Ecc.load, load const.	(305x305)[1]	2.19	Sil.	64	38.8	933, (44/44)[3]	977	1.0	2:47
III-11	Shape-circular	355 diam.	2.34	Sil.	78	41.6	1431	1778	0.80	4:05
III-12	Shape-circular	355 diam.	2.34	Sil.	76	42.4	1431	1778	0.80	3:40
III-13	Room-temp. crush	305x305	2.19	Sil.	60	40.7	3833	1370	2.80	---
III-14	Ecc.load (24 mm) fixed-hinged	305x305	2.19	Sil.	25	37.9	1178	1178	1.0	3:03
T-1	Residual strength 1 hr fire	305x305	2.19	Sil.	87	38.9	993	(2671)[4]		---
T-2	Residual strength 2 hr fire	305x305	2.19	Sil.	82	41.8	1022	(1987)[4]		---
T-3	Hinged-hinged	305x305	2.19	Sil.	57	41.6	1022	1044	1.04	3:41

* Reference columns
† Test was stopped due to air fan burnout
()[1] Column with brackets
()[2] Initial load/maximum load
()[3] Initial eccentric load/eccentric load at end of test
()[4] Residual strength (kN)

columns fixed, but different effective lengths were obtained in some tests by pinning the top end (III-1, III-2) or both ends (T-3), or by pinning the top end and allowing it to move horizontally (II-1).

Six columns were tested under an eccentric load. In two tests the eccentric load was applied by offsetting the column by 24 mm (III-3, III-14). Four tests were carried out on columns with brackets (III-7 to III-10). In these tests the eccentric loads were applied by two additional jacks located at 508 mm from the centre of the column (Figure 2). In two of these tests the initial rotation of the brackets (after loading) was kept constant to simulate full restraint against rotation of the ends (III-8, III-9); in one test the eccentric loads were kept constant to simulate no restraint against rotation (III-10); in one test the eccentric loads were gradually reduced, from 49 to 32 kN at a rate of 1 kN per 10 minutes, to simulate partial restraint against rotation (III-7).

The load level in the various tests varied from zero to higher than the maximum allowable load calculated according to acceptable design standards, i.e., the Canadian National Standard "Design of Concrete Structures for Buildings" (CAN3-A23-M84)[6] or the "Building Code Requirements for Reinforced Concrete" (ACI 318-83), adopted as a standard by the American Concrete Institute[7].

Fire Exposure

Most columns were exposed to the ULC-S101 (ASTM-E119)[8, 9] standard fire. Two columns (T-1, T-2) were exposed to a standard fire[6, 7] for limited periods after which the columns were cooled down and crushed for the purpose of determining the residual strengths of the columns. One column (III-13) was crushed at room temperature for the purpose of verifying the accuracy of the calculated initial strength of the column. Another column (III-4) was subjected to a high-intensity fire, which simulated a hydrocarbon oil pool fire[5].

Failure Criterion

In all tests the columns were considered to have

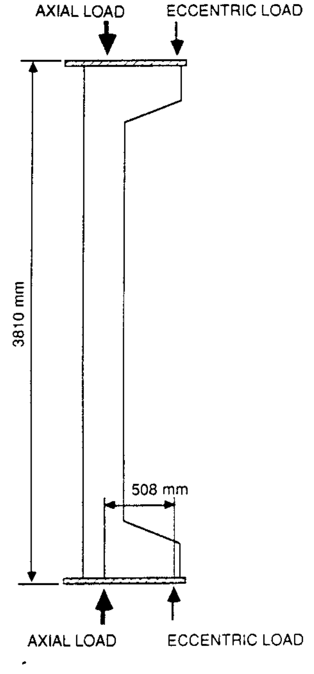

Figure 2. Columns with brackets for eccentric loading

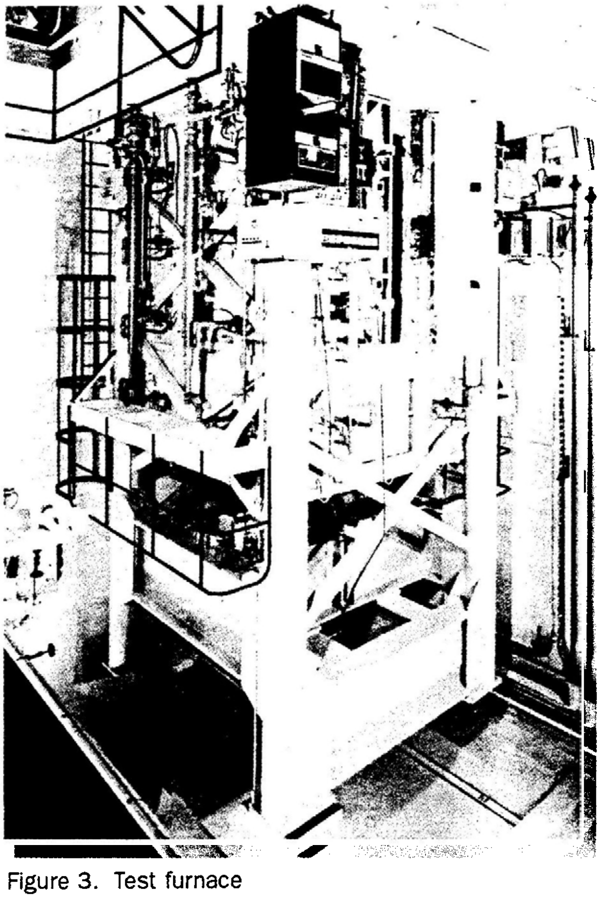

Figure 3. Test furnace

failed, and the tests were terminated, when the main hydraulic jack, which has a maximum speed of 76 mm/min, could no longer maintain the load.

INFLUENCE OF STUDY VARIABLES

The influence of the various study variables on the fire resistance of the columns is shown in Figures 4-13 and summarized in Table 1.

In Figure 4 the fire resistances of the ten reference columns, tested under various loads, and a reference curve reflecting the fire resistance of these columns as a function of the load, are shown. As expected, the fire resistance increases with reduction of the load. In the range of loads investigated, i.e. from about 100 to 50 percent of the maximum allowable load, the increase in fire resistance is about 25 percent. Also in Figure 4, the current fire resistance ratings permitted in the NBCC and the proposed ratings for the next NBCC, which are substantially less conservative, are shown.

The influence of the various study variables can be assessed by comparing the fire resistances, measured under the various conditions studied, with the reference fire resistances. These comparisons are made in Figures 5-13 for the following variables:

1. Percentage of Reinforcement

The results (Figure 5) indicate that increasing the reinforcement will increase the fire resistance. The effect of doubling the reinforcement from 2.19% in the reference columns to 4.38% (II-8 and II-9) is about 10%.

2. Effective Length

The effect of column effective length is shown in Figure 6. Theoretically, it is expected that for the same load and column section the fire resistance will decrease with increase of effective length. The maximum allowable load, however, also decreases with increase of effective length. The results indicate that the effect of decrease in load more than compensates for the effect of increase of effective length, resulting in an increase of fire resistance. Especially for longer columns, the increase is substantial (II-1). For this column, for example, the maximum allowable load reduces to 342 kN from about 1350 kN, when the column effective length is increased from 2.55 to 7.62 m. This large reduction in load apparently more than compensated for the unfavorable effect of increase of column length, resulting in an increase of fire resistance from about 3.5 hr to almost 5 hr.

3. Concrete Strength

The influence of concrete strength is shown in Figure 7, where the fire resistance of the two columns made with a high strength siliceous aggregate concrete (50 MPa) are compared with the reference fire resistances. Because the load on these columns (II-4, II-5) was increased in accordance with the higher strength of the

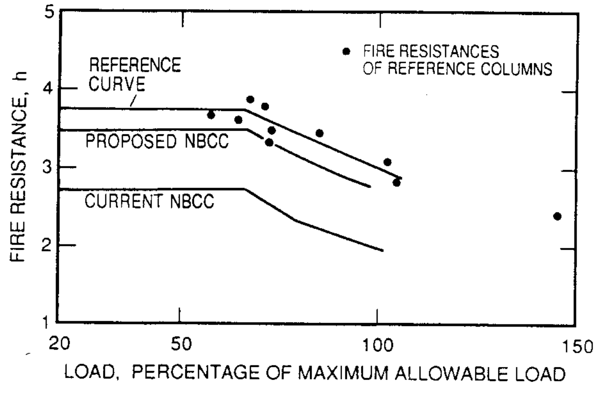

Figure 4. Fire resistances of reference columns and current and proposed NBCC ratings

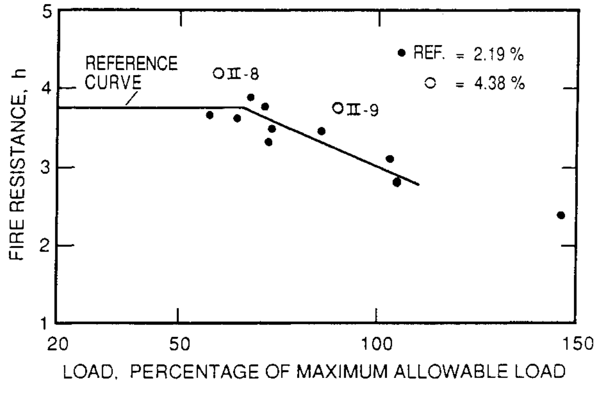

Figure 5. Influence of reinforcement

columns, there was no significant increase in the fire resistance of the columns.

4. Relative Humidity

In Figure 8, the fire resistance of a nearly dry column (I-2) is compared with that of a similar column (I-9) with a normal concrete moisture condition (75% R.H.). The test results as well as results of theoretical studies carried out earlier[10] showed that the influence of the moisture content of the concrete on the fire resistance of the column is small. Variations of fire resistance, due to variations of moisture content, may in the practical region, i.e., a moisture condition at equilibrium in air of 50 to 75% R.H. at about 20°C, be neglected.

5. Column Cross Sectional Area

Figure 9 illustrates the influence of the cross sectional area of the column on its fire resistance. The test results indicate that column cross section has a large influence on the fire resistance of the column. Under commensurate loading, the fire resistance increased by about 30% by doubling the area. For one column (II-11) the increase was over 40%, but in this case, part of the increase was probably caused by the significantly higher percentage of steel reinforcement in this column.

6. Column Shape

The influence of column shape, i.e. square, circular or rectangular, on the fire resistance of the column is illustrated in Figure 10. The columns with rectangular cross section (III-5, III-6) have under commensurate loading substantially higher fire resistance than those with square cross section with the same thickness. The fire resistances of the columns with rectangular cross section are about 50% higher than those of the columns with square cross section with equal thickness. The reason for the substantial difference in fire resistance is probably that the heating of the core of columns with rectangular cross section approaches that of a wall, which is heated on two sides, whereas the columns with

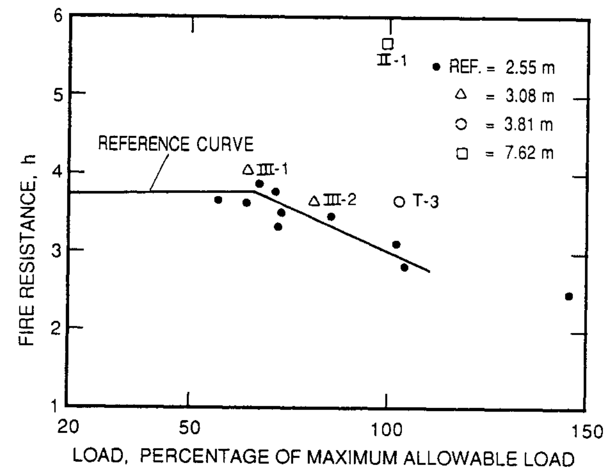

Figure 6. Influence of effective length

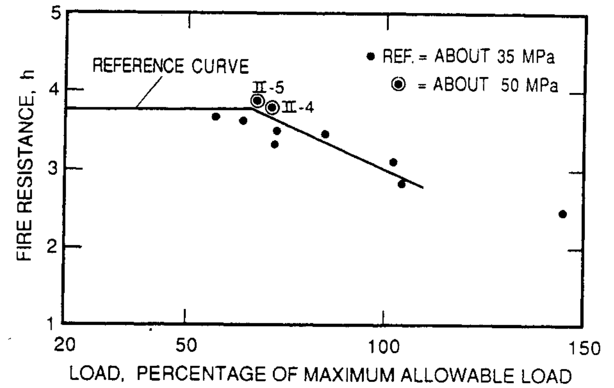

Figure 7. Influence of concrete strength

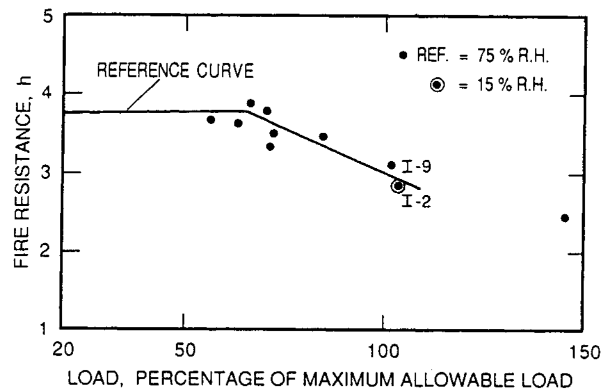

Figure 8. Influence of relative humidity in concrete

square cross section are heated on four sides.

The fire resistances of columns with circular cross section (III-11, III-12) were 5-10% higher than those of columns with square cross section with approximately the same area. Because in fact the cross sectional area of the columns with circular cross section was about 7% greater than that of the columns with square section, the difference in fire resistance of 5-10% can be regarded as insignificant.

7. Aggregate Type

The results of tests on columns made with carbonate aggregate concrete (I-10, I-11, I-12) and on columns made with expanded shale aggregate concrete (II-6, II-7) are shown in Figure 11. It can be seen that the carbonate aggregate concrete columns have extremely high fire resistances as compared to the reference columns which were made with siliceous aggregate. For example, the carbonate aggregate column (I-11) had a fire resistance of more than 6 hr, whereas the fire resistance of the comparable siliceous aggregate concrete column was about 3.5 hr.

The fire resistances of the columns made with expanded shale aggregate are about the same as those of the reference columns.

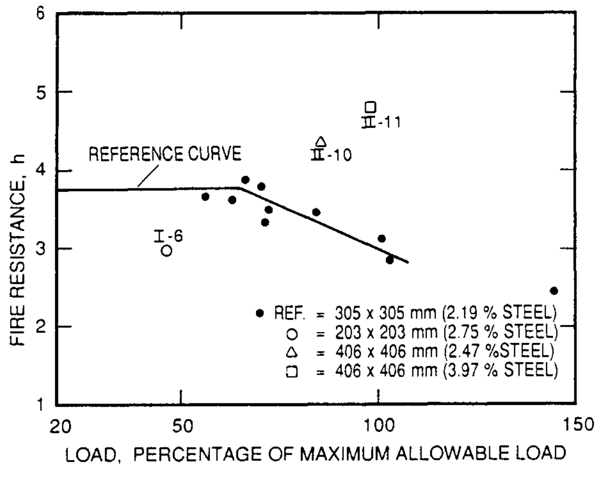

Figure 9. Influence of cross sectional area

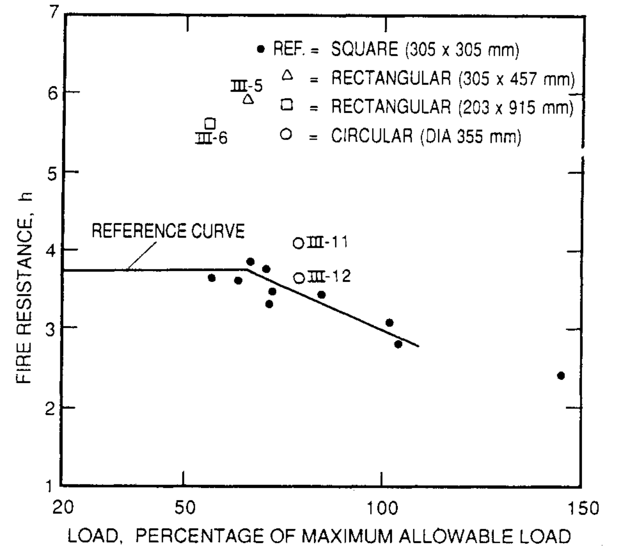

Figure 10. Influence of column shape

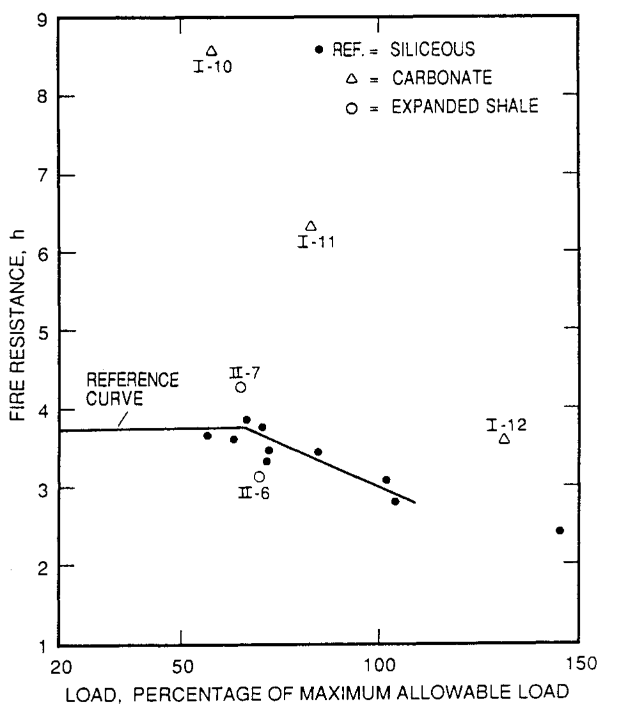

Figure 11. Influence of aggregate type

8. Restraint of Axial Thermal Expansion

To investigate the possible detrimental effect of restraint of thermal expansion, two columns (II-2, II-3) were tested under full restraint, i.e., expansion of the column was prevented during the tests by application of additional load that kept the length of the column constant with a precision of ±0.002 mm. The results, which are shown in Figure 12, indicate that restraint of axial thermal expansion does not reduce the fire resistance of the column although the load temporarily increased to more than twice the initial load during the test[5].

9. Load Eccentricity

The results of tests on six eccentrically loaded columns are shown in Figure 13. The eccentricity of the load was that required by the ACI 318 Code[6] and the CSA A23.3 Standard[7] for concentrically loaded columns. In the case of the columns studied, the eccentricity equates to 24 mm. This was obtained by offsetting the load 24 mm from the centre of the column section (III-3, III-14), or by applying the appropriate eccentric load on the columns with bracket at a distance of 508 mm from the centre of the column section (III-7 to III-10). One of the columns was made with carbonate aggregate concrete (III-3). The others were made with siliceous aggregate concrete.

The reduction in fire resistance due to eccentric loads was the highest for the carbonate aggregate column (III-3). The reduction in fire resistance for this column was approximately 40% when compared with the fire resistance of concentrically loaded carbonate aggregate concrete columns (see Figure 11). For the siliceous aggregate concrete columns, the highest reduction in fire resistance due to eccentric load was approximately 10% (III-10). This reduction was found in the test, in which the eccentric load was kept constant, simulating the worst case that the surrounding structure provides no restraint against rotation of the ends of the column. In all other cases there was no pronounced effect of load eccentricity.

Conclusions

Of the variables studied in the NRCC/PCA study program, load, cross sectional area for similar shapes, and type of aggregate have the largest influence on the fire resistance of reinforced concrete columns. Particularly the use of carbonate aggregate, instead of siliceous aggregate, will substantially increase the fire resistance of the column. Rectangular columns also produced fire resistances that are substantially higher than those of square columns of same thickness.

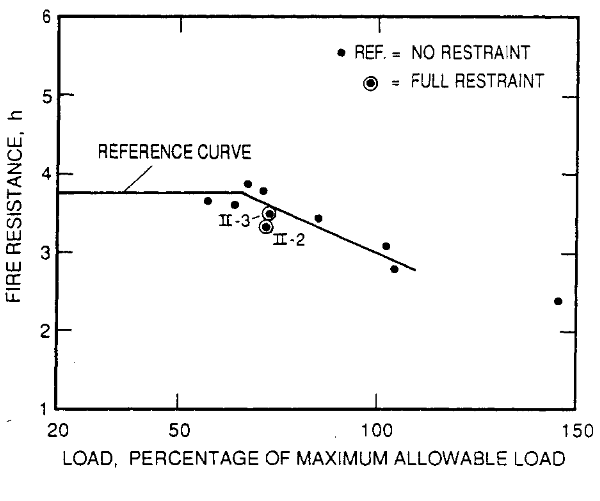

Figure 12. Influence of restraint of axial expansion

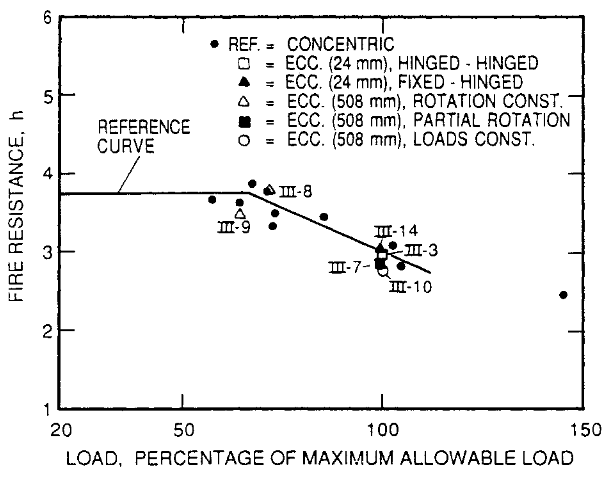

Figure 13. Influence of load eccentricity

Increase of the amount of reinforcing steel and effective length of the columns produce relatively small increases in fire resistance, if a load is applied that is commensurate with the increase of amount of steel and column length. Application of small eccentric loads causes a small reduction in fire resistance.

The influence of concrete strength, concrete moisture content and restraint of axial column expansion is insignificant.

The fire resistances of the columns studied are considerably higher than those assigned to them in the National Building Code of Canada[3] and in the American Concrete Institute Guide 216[11]. The difference is mainly caused by the substantial increase in experimental and theoretical data, which enables a less conservative approach in establishing fire resistance ratings. New ratings, based on the results of this study, will be incorporated in these documents.

Although a large number of tests were carried out, they do not provide sufficient information on fire resistance for many values of the variables beyond the values studied in the tests. They provide basic data, however, that enable the development and validation of mathematical models capable of calculating fire resistances for any value of the variables in the practical range. The development of such models is now in an advanced stage[10].

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