Size Effect on Fire Resistance of Reinforced Concrete Columns and Beams

Liu Lixian[1], Reddy D.V.[2], Sobhan K.[2]

(1:Yunnan University, Kunming, China, 2: Florida Atlantic University, Boca Raton, Florida, U.S.A.)

ABSTRACT

It is important to consider the effect of cross-section size and concrete cover thickness on fire resistance on concrete columns and beams, because at same load level, the fire endurance generally increases with an increase of member cross-section size and concrete cover thickness. A lot of research has been conducted in size effect on concrete members at room temperature. However, the study of size effect on fire resistance of RC is rare. A new concept, namely, equivalent fire duration was developed in this paper. Based on numerical analysis and test data available in the literature, this paper presents the effects of (1) the cross-section size on fire resistance on RC columns and beams, and (2) the thickness of concrete cover on fire endurance of RC beams

Keywords: Size effect; Fire resistance; Reinforced concrete;Column; Beam.

1. INTRODUCTION

It is a well known fact that size has an effect on nominal strength of specimens made with quasibrittle materials such as concrete, rock, ice, ceramic, and composite materials (Bazant 1984, 1993, 1999; Bazant et al 1991; Bazant & Xi 1991, Bazant & Xiang, 1994, 1997, Kim, 1990, 1999, 2000, 2001). In compressive and flexural failures of quasibrittle materials, the size effect is quite apparent. Recently, investigations of the size effect on nominal strength have become a focus of interest to many researchers (Cotterell 1972; Bazant & Xiang 1994, 1997; Kim, 1999, 2000, 2001). Gonnerman (1925) experimentally showed that the compressive strength decreases as the specimen size increases. This phenomenon of reduction in strength, dependent on specimen size, is called the "reduction phenomenon", due to the statistical effect of an inherent larger of "flaws" in the larger sample. However, careful literature study shows that rare attention has be paid to the size effect on mechanical properties of RC members in fire condition. Yong (2006), Reddy et al. (2006) indicate reduction in fire resistance rating in the reduced cross-section, i.e., ¼ exposure time of that for the full-scale specimens, based on small scale specimen fire exposure testing in a furnace. The Heisler/Gröber charts were used for the heat transfer analysis, but these are approximate in view of their applicability only to steady state conditions, and constant thermal properties.

Fire testing, especially full scale, is expensive and time consuming, for large scale, complicated structures, and the value from small scale laboratory tests differ from that of real large structures due to the scale effect. The primary objective of this paper was to study the size effect on fire performance of axially loaded square RC columns and simply supported beams using the numerical modeling developed by Liu (2009).

This problem has been studied on three aspects: (i) Development the fire endurance of the reference column as a function of the load level, as shown in Fig. 1, based on fire test data or validated numerical modeling; (ii) Development of the relationship between the load capacity of RC columns/beams in fire condition and the cross-section size; and (iii) Determination of the relationship between the fire endurance of RC columns/beam and the cross-sectional size; (iv) Determination of the relationship between the fire endurance of RC beams and the concrete cover thickness.

2. Size Effect on Fire Resistance of Axially Loaded RC Column

2.1 Theoretical Investigation of the Size Effect

In solid mechanics, the size effect is understood as the effect of the characteristic structure size on the nominal strength of structure, with geometrical similarity. Bazant (1984) derived the size effect law (SEL) from dimensional analysis and similitude arguments for geometrically similar structures of different sizes, with initial cracking considering the energy balance at crack propagation in concrete as follows:

$$\sigma_N = \frac{P_u}{bd} = \frac{Bf_t^{'}}{[1+(d/\lambda_0 d_a)]^{0.5}} \tag{1}$$

where σ_N is nominal strength, P_u is maximum load, b is thickness of specimen, d is characteristic dimension, $f_t^{'}$ is the direct tensile strength of concrete cylinder, d_a is maximum aggregate size, and B and λ_0 are empirical constants. σ_N is not a real stress but a load parameter having the dimension of stress. The definition of d can be arbitrary (e.g. the column depth or half-depth, the column effective length, etc.), because it does not effect geometrically similar structures.

Loading by high compressive stress without adequate lateral confining stresses results in damage in the form of axial splitting microcracks due to pores, inclusions or inclined slip planes. This damage restricts into a band that propagates either axially or laterally. For axial propagation, the energy release from the band drives the formation of the axial splitting fracture, and since this energy release is proportional to the length of the band, there is no size effect. For lateral propagation, the stress in the zones on the sides of the damage band gets reduced, which causes an energy release that grows in proportion to d2, while the energy consumed and dissipated in the band grows in proportion to d. The mismatch of energy release rates inevitably results in a deterministic size effect of the quasibrittle type. This effect can be approximately described by the equivalent linear elastic fracture mechanics. The resulting size effect on the nominal strength of large structures failing in compression was derived by Bazant (1997) and has the form:

$$\sigma_n = C_1 d^{-2/5} + C_0 \tag{2}$$

where C_1, C_0 are constants.

2.2 Reference Column

Table 1 Summary of the Details of Studied Columns

Cross sectionSize d(mm)	Concrete strength MPa	Longitudinal reinforcement				Load capacity of column at room temperature		
		diameter mm	No.	Steel ratio(%)	Strength MPa	Pc* kN	Ps** kN	P*** kN
300	35	18	4	1.13	420	3150	427	3577
350		22	4	1.24		4287	640	4927
400		25	6	1.23		5600	828	6428
450		20	8	1.24		7087	1063	8150
500		22	8	1.22		8750	1289	10039
550		20	12	1.25		10587	1601	12189
600		22	12	1.27		12600	1942	14542

* Pc= the contribution of concrete to total strength at room temperature
** Ps= the contribution of longitudinal reinforcement to total strength at room temperature
*** P= the total strength of the column at room temperature

Consider a column which is 305mm long with square cross section of 305mm, as the reference column. Four longitudinal reinforcing bars with a diameter 18mm are used ($\rho = 1.13\%$). The bars are tied with 8mm ties. The main reinforcing bars have specified yield strength of 420 MPa. The compressive strength of the concrete is 35 MPa, and the concrete cover thickness is 30mm. The studied columns with different cross-section sizes, shown in the Table 1, have the identical load ratio, slenderness ratio, and approximately the same reinforcement ratio. The fire duration (tr) and load capacity (Pr) of the reference column in fire condition are taken as the reference values.

The parametric studies conducted by Liu (2009) indicate that concrete strength ($f_c^{'} = 30 - 50MPa$), steel reinforcement ratio ($\rho = 1\% - 4.5\%$), and moisture content (0~3% by weight) do not have a significant effect on the fire resistance of axially loaded RC columns. These values represent the characteristic values in practical RC columns. So, any column, with similar details as mentioned above can be taken as the reference column, since the slenderness ratio is same, that is, there is no characteristic length (Bazant, 1997). The reference column given above represents most practical cases.

The nominal load capacity (normalized to design load capacity) of the reference column in the fire condition is shown in Fig. 1, together with the fire test results of Lie ,1988. It can be seen there is a good agreement between the tested and the calculated values, using the numerical modeling developed by Liu (2009). For the reference column, its fire endurance at a given load level or the load capacity at a given fire duration can be directly obtained from Fig. 1.

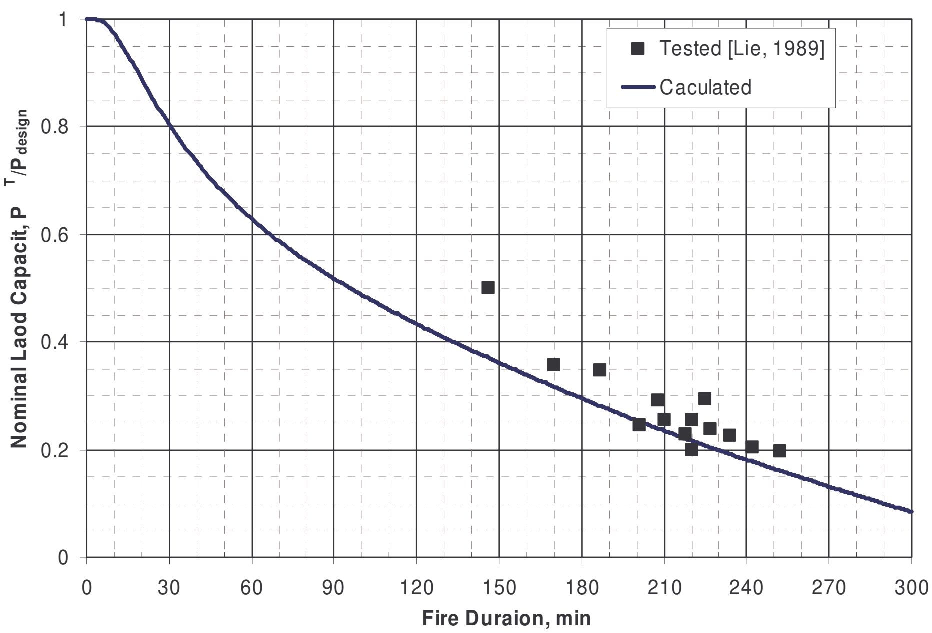


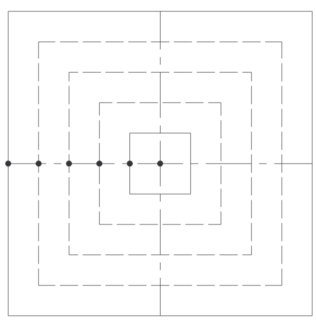
Fig. 1 Nominal load capacity of the reference column during fire

2.3 EQUIVALENT FIRE DURATION

To study the size effect on the fire performance of RC columns, the first step is to develop the relationship between "equivalent fire duration" and cross-section size. For geometrically similar concrete columns with similar details, if the temperature distributions are similar, the nominal strengths of these columns should be similar, or a function of cross-section size. Taking one column as the reference column, the fire durations of other columns required to reach the same temperature distribution, as in the reference column, are called " equivalent fire durations"

Take the fire durations of the reference column, such as 30min, 45min, 60min, or 120min, as the reference fire durations. The temperature distributions at these times in the cross-section of the reference column are taken as the reference temperature distributions. Actually, any fire duration of the reference column can be taken as the reference fire duration.

For convenience, in this study, the temperature distribution in the cross-section of the reference column exposed to standard fire for two hours is taken as the reference temperature distribution. It is assumed that all the columns are exposed to the ASTM E119 fire on all sides. This temperature-time curve course is described by Eq. (2). The column cross section is divided into 10 or more layers with equivalent depth, shown in Fig. 2. The criterion of similar temperature distribution can be defined as that of the temperatures at every geometrically equivalent layer (Fig2), being the same or as close as possible, and the average temperatures in the cross-sections with different dimensions being the same. The temperatures of each layer at given fire exposure time for d=300 and 400mm,respectively, are shown in Table 2 and Fig. 3 for equivalent fire durations.



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ERROR: rangecheck
OFFENDING COMMAND: .buildcmap

STACK:

-dictionary-
/WinCharSetFFFF-V2TT9BF4ACCAt
/CMap
-dictionary-
/WinCharSetFFFF-V2TT9BF4ACCAt
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