High-Strength Concrete Columns: State of the Art

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This report reviews the state of the knowledge of the behavior of high-strength concrete (HSC) columns. High-strength concrete, as used in this report, is defined as concrete with compressive strength exceeding 70 MPa (10,000 psi). The report provides highlights of research available on the performance of HSC columns under monotonically increasing concentric or eccentric compression, and with incrementally increasing lateral deformation reversals and constant axial compression.

Research results are used to discuss the effect of cover concrete and parameters related to transverse reinforcement on strength and ductility of HSC columns subjected to concentric load.

The behavior of HSC columns subjected to combined axial load and bending moment is discussed in terms of variables related to concrete and transverse reinforcement. In addition to discussion on flexural and axial capacity, this report also focuses on seismic performance of HSC columns.

Keywords : axial load; bending moment; columns; cover concrete; ductility; flexural strength; high-strength concrete; longitudinal reinforcement; seismic design; transverse reinforcement.

CONTENTS

CHAPTER 1—INTRODUCTION

One application of high-strength concrete (HSC) has been in the columns of buildings. In 1968 the lower columns of the Lake Point Tower building in Chicago, Illinois, were con-

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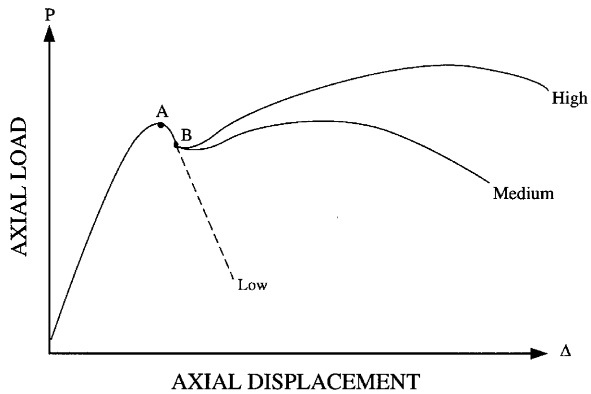

Fig. 1—Schematic behavior of HSC columns subjected to concentric axial loads, incorporating low, medium, and high amounts of transverse reinforcement

structed using 52 MPa concrete.[1] More recently, several high rise buildings[1-4] have utilized concrete with compressive strengths in excess of 100 MPa in construction of columns.

Many studies[4-9] have demonstrated the economy of using HSC in columns of high-rise buildings, as well as low to mid-rise buildings.[10] In addition to reducing column sizes and producing a more durable material, the use of HSC has been shown to be advantageous with regard to lateral stiffness and axial shortening.[11] Another advantage cited in the use of HSC columns is reduction in cost of forms. This is achieved by using HSC in the lower story columns and reducing concrete strength over the height of the building while keeping the same column size over the entire height.

The increasing use of HSC caused concern over the applicability of current building code requirements for design and detailing of HSC columns. As a result, a number of research studies have been conducted in several countries during the last few years. The purpose of this paper is to summarize major aspects of some of the reported data.

The major objectives of reported studies have been to investigate the validity of applying the current building code requirements to the case of HSC, to evaluate similarities or differences between HSC and normal-strength concrete (NSC) columns, and to identify important parameters affecting performance of HSC columns designed for seismic as well as non-seismic areas. These concerns arise from the fact that requirements for design and detailing of reinforced concrete columns in different model codes are primarily empirical and are developed based on experimental data obtained from testing column specimens having compressive strengths below 40 MPa.

The reported information can be divided into two general categories: performance of HSC columns under concentric axial load; and performance of HSC columns under combined axial load and bending moment. This report gives the highlights of the reported data in each of these categories. In this report, HSC is defined as concrete with compressive strength greater than 70 MPa.

CHAPTER 2—PERFORMANCE OF HSC COLUMNS UNDER CONCENTRIC LOADS

The majority of reported studies[12-27] in the field of HSC columns concern the behavior of columns subjected to concentric loads. Understanding the behavior of columns under concentric loads assists in quantifying the parameters affecting column performance. However, conclusions from this type of loading should not necessarily be extended to the case of combined loading, a situation most frequently encountered in columns used in buildings.

Reported data indicate that stress-strain characteristics of high-strength concrete, cover concrete, and parameters related to confining steel have the most influence on response of HSC columns subjected to concentric loads. The effect of the first parameter is discussed in Sec. 3.1. The remaining two parameters are discussed in the following sections.

2.1—Effect of cover concrete

Figure 1 shows a schematic load-axial deformation response under concentric loads of HSC columns with transverse reinforcement. As concrete strength increases, the ascending portion of the curve approaches a straight line. In general, spalling of the cover concrete is reported[12-27] to occur prior to achieving the axial load capacity of HSC columns, as calculated by the following equation:

$$P_o = 0.85 f'_c (A_g - A_{st}) + A_{st} f_y \qquad (1)$$

where:

- P_o = Pure axial load capacity of columns calculated according to the nominal strength equations of ACI 318-89
- f'_c = Concrete compressive strength
- A_g = Gross cross-sectional area of column
- A_{st} = Area of longitudinal steel
- f_y = Yield strength of longitudinal steel

The 1994 edition of the Canadian Code for Design of Concrete Structures also uses this equation for computing P_o, except that the factor 0.85 is replaced by

$$\alpha_1 = (0.85 - 0.0015 f'_c) \geq 0.67$$

in which f'_c is in MPa. Hence, P_o calculated by the Canadian code will be somewhat less than that calculated by ACI 318-89.

Point A in Fig. 1 indicates the loading stage at which cover concrete spalls off. The behavior of HSC columns beyond this point depends on the relative areas of the column and the core and on the amount of transverse reinforcement provided. Following spalling of the cover concrete, the load-carrying capacity of columns generally drops to point B in Fig. 1. Beyond this point, Bjerkeli et al.,[19] Cusson et al.,[25] and Nishiyama et al.[28] report that it is possible to increase the maximum axial strength of columns up to 150 percent of that calculated by the ACI 318-89 provisions and obtain a ductile behavior by providing sufficient transverse reinforcement. The effect of the amount of transverse reinforcement is

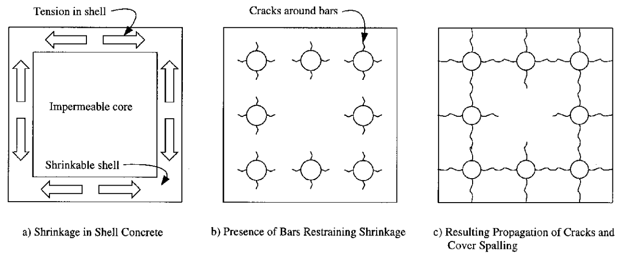

Fig. 2—Factors promoting cover spalling in high-strength concrete columns (adapted from Ref. 29)

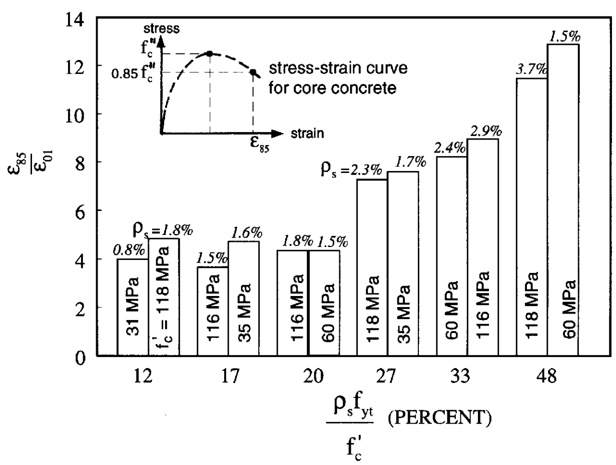

Fig. 3—Columns with different concrete strengths showing similar axial ductility ratios (f'_c = concrete compressive strength based on standard cylinder test) (adapted from Ref. 30)

shown schematically in Fig. 1 and will be discussed further in later sections.

The loss of cover concrete in HSC columns before reaching the axial capacity calculated by ACI 318-89 is contrary to the observed behavior of concrete columns made of NSC. Collins et al.[29] provide the following explanation for the factors resulting in early spalling of cover concrete in HSC columns. According to those authors, the low permeability of HSC leads to drying shrinkage strain in cover concrete, while the core remains relatively moist. As a result, tensile stresses are developed in the cover concrete as shown in Fig. 2a. Moreover, longitudinal steel, as depicted in Fig. 2b, promotes additional cracking. The combination of these two mechanisms (see Fig. 2c) then results in the formation of a cracking pattern that, according to those authors, is responsible for early loss of cover concrete, thereby preventing HSC columns from reaching their axial load capacity predicted by Eq. (1) prior to spalling of cover concrete.

Early spalling of concrete cover may also be initiated by the presence of a closely spaced reinforcement cage that separates core and cover concrete. Cusson et al.[25] attributed the spalling of the cover to planes of weakness created by the dense steel cages. They state that spalling becomes more prevalent as the concrete strength increases.

Saatcioglu and Razvi[27,30] also observed early spalling of cover concrete in their tests. Those researchers indicated that the presence of closely spaced reinforcement cage between

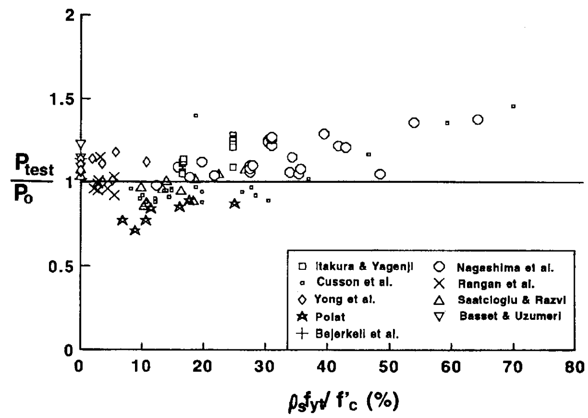

Fig. 4—Comparison of experimental and calculated concentric strengths of columns (adapted from Ref. 30)

the core and the cover concrete provided a natural plane of separation, which resulted in an instability failure of the cover concrete under high compressive stresses. The spalling in their tests occurred at a stress level below that corresponding to the crushing of plain concrete.

2.2—Effect of volumetric ratio of transverse reinforcement

In the case of NSC, an increase in the amount of transverse reinforcement has been shown to increase strength and ductility.[31] The same observation has been reported[19,25,27] for the case of HSC, though to a lesser degree. Some researchers have attributed this phenomenon to the relatively smaller increase in volume during microcracking of HSC, resulting in less lateral expansion of the core. The lower lateral expansion of core concrete delays the utilization of transverse reinforcement.

Reported data[12-27,30] indicate that in the case of HSC, little improvement in strength and ductility is obtained when the volumetric ratio of transverse reinforcement is small. For instance, Bjerkeli et al.[19] report that a volumetric ratio of 1.1 percent was not sufficient to generate any improvement in column behavior, while the use of 3.1 percent resulted in columns performing in a ductile manner.

Sugano et al.,[32] Hatanaka et al.,[23] and Saatcioglu et al.[27,30] report a correlation between the non-dimensional parameter, $\rho_s f_{yt}/f'_c$, and axial ductility of HSC columns subjected to concentric loads. Figure 3 shows the relationship between this parameter and axial ductility of columns with different compressive strengths. In this figure, the axial ductility of columns is represented by the ratio $\varepsilon_{85}/\varepsilon_{01}$, where ε_{85} is the axial strain in core concrete when column load on the descending branch is reduced to 85 percent of the peak value and ε_{01} is the axial strain corresponding to peak stress of plain concrete. For each pair of columns compared, similar reinforcement arrangements and tie spacings were maintained. As indicated in this figure, columns of different compressive strength having the same $\rho_s f_{yt}/f'_c$ value result in almost the same axial ductility, provided that certain minimum limitations are met for the volumetric ratio and spacing of transverse reinforcement.[30]