Chapter 1
Introduction

High strength concrete (HSC) is frequently used in building columns. Many studies have demonstrated the economy of using HSC columns in high rise buildings. HSC structural columns are particularly prominent for the possibilities of increased load-carrying capacities and stiffness. Such capacity or stiffness enhancement may result in reduced column size and increased floor space compared with NSC structures. The presumed vulnerability of columns made of HSC in seismic regions has been overturned in the light of recent research results published in literature. Seismic design of reinforced ductile frame building according to CSA A23.3 (2004) and ACI 318 (2008), provides a relative condition of a strong column and weak beam at the beam-column connection. The intent is to encourage hinging in the beams rather than in the columns. However, building performance during major earthquakes [Akira and Hirose (1989)] indicates that hinging may form in columns. Therefore, the possibility of plastic hinge formation at column ends demands that building columns in seismic areas have sufficient ductility.

Sheikh and Khoury (1991) and Sheikh *et al*. (1994) observed lower ductility in HSC columns as compared to NSC columns concluding that the amount of transverse reinforcement required for a given performance of a column under a certain axial load level is proportional to the concrete strength. Bayrak and Sheikh (1998) reported that an increase in the axial load reduces the column deformability and ductility, and accelerates strength and stiffness degradation, and suggested incorporation of the axial load level as a design parameter in the design of the confinement reinforcement. ACI-ASCE Committee 441 has not yet reached a consensus on required confinement reinforcement for ductile HSC columns since limited tests on columns under cyclic flexure and significant axial compression, specifically with axial-load in the range of 20% to 40% have been concluded. Saatcioglu and Biango (1999) suggested the ratio $\rho_s f_{yh}/f'_c$ to be used as a design parameter for the confinement of HSC columns.

Fibers reinforced concrete; FRC is a construction material utilized widely for nonstructural members and only recently for structural applications. According to Kimura *et al*. (2007), the maximum flexural strength of HSC provided with steel fibers increases the fibers prevent the separation between the concrete core and cover. The steel fibers may play the same role of transverse reinforcement and can be considered as a confinement factor in the ductility assessment of HSC columns. However, information on the ductility of HSC and FRHSC columns has been limited, with most of the available information is based on experimental testing of small scale columns under concentric axial load only. Lee, H. (2007) indicated that the steel fibers are more effective in improving the strength and ductility capacity than the stiffness and energy capacity of the column. Sharma *et al*. (2007) pointed out that the enhancement in column response is lower in columns containing larger amounts of transverse reinforcement. In other words, the fibers can be more effectively utilized to enhance the performance of HSC columns if the lateral steel content is relatively low.

This research work is aimed to study experimentally the behavior of HSC columns with and without steel fibers under simulated earthquake loading. Fourteen HSC column specimens were subjected to combined axial load and reversed cyclic flexure. The primary objective of the study was to investigate the suitability of using HSC and FRHSC columns in regions of moderate to high seismic risk. Variables covered in this investigation were the steel fibers content, transverse reinforcement ratio, yield strength of transverse reinforcement, axial load level, concrete compressive strength and confinement index. Besides, the study addressed the adequacy of present code requirements for seismic design of HSC columns.

A simple equation was proposed to predict the compressive strength of fibers concrete. A mathematical model was developed to express the stress-strain relationship for concrete under compression based on Razvi and Saatcioglu (1999). A non-linear finite elements analysis was carried out using a computer package "ANSYS 10.0". A correlative study, based on the envelope of lateral load deflection hysteresis, was conducted to verify the analytical model with the experimental results. The envelope of lateral load deflection curve is considered the key aspect in studying the columns behavior as it involves many response parameters including column ultimate strength, maximum deformation, and ductility performance. A parametric study was conducted using NLFEA to investigate the performance of FRHSC columns in seismic zones. The parameters considered were the amount of steel fibers, concrete compressive strength, axial load level, confinement index, yield strength of transverse reinforcement, amount of longitudinal steel and slenderness ratio of the column. In addition, a design equation that relates the required amount of lateral steel in HSC columns to the axial load level and steel fibers content to column performance was developed. The equation was calibrated against a sufficient experimental results published in literature. The overall aim of this study is to develop a rational procedure for the design of confinement reinforcement to achieve an acceptable ductility.

Chapter 2 presents an introduction to high strength concrete, fibers reinforced concrete, fibers types and mechanical properties of FRHSC. A review on the available research studies on HSC columns under cyclic loads is introduced. Available confinement models of HSC columns are also included.

The experimental program including test columns details, materials used, instrumentation and testing procedures is given in Chapter 3.

Chapter 4 presents analyses of the experimental results and observations.

Detailed discussions on the experimental results and findings are introduced in Chapter 5.

Chapter 6 presents a simple modified confinement model for FRHSC columns. The model was incorporated in non-linear finite element analyses of test specimens.

Chapter 7 includes a wide range of NLFE analyses to study the performance of HSC and FRHSC columns under seismic load. In addition, an empirical modification is presented for the confinement reinforcement required by the current ACI Code.

Conclusions and recommendations for further research work are drawn in Chapter 8.