Chapter 1

Introduction

Concrete is the most prevalent construction material in the world (Craig et al., 1996). It has been used in widely varying structural applications from the dome of the Pantheon to Hoover Dam to the Guggenheim Museum. Much has been learned about concrete behavior through its varied and historical use. One of the most recent lessons came from the February 9, 1971 magnitude 6.6 San Fernando earthquake. Damage to reinforced concrete structures, even some recently built to the latest building code, was extensive. Engineers discovered that the buildings of the time were non-ductile and that the design of future concrete structures would require more ductility to withstand seismic loading. While the idea of confinement was not a new one, the level of confinement demanded in seismic zones, and the details of its implementation, required new understanding. Special details for ductile response were implemented into the building code as a result of the lessons learned in the San Fernando earthquake. The January 17, 1994 magnitude 6.7 Northridge earthquake provided a reminder of the danger presented by the existing non-ductile reinforced concrete structures, built before the change in the building code. Today, the design of new reinforced concrete structures in active seismic zones and the problem of existing non-ductile reinforced concrete structures are both important challenges. This thesis seeks to aid engineers by providing a design tool to evaluate the ductility and strength of confined reinforced concrete members.

Concrete shows a significant change in strength and ductility due to confinement. Confinement can come in many forms. The traditional method is to wrap the concrete member with hoops or spirals of steel rebar. Many new forms of confinement have arisen to be used in the retrofit of existing non-ductile concrete structures. Steel jackets, welded wire fabric, and fiber reinforced polymer (FRP) composites are some of the many confinement strategies employed in retrofits. Methods to evaluate the performance of concrete members under different forms of confinement are required to evaluate and compare different retrofit strategies. Of importance to designers is the increase in the peak stress, the strain at peak stress, and the post-peak behavior of the concrete. This thesis provides a tool to predict these important quantities.

Due to the extensive use of concrete, experimental test data for concrete is abundant. However, reviews of test data in this thesis show that concrete behavior can be inconsistent. The inconsistencies are likely due to the fact that concrete is an amalgamation of various different materials. Something as fundamental as the concrete compressive strength, f'_c, will be quite different among specimens from the same mixture of concrete. Further, the behavior of concrete can be rather complex, changing drastically with different load configurations and histories. The combination of the inconsistency and complexity make it extremely difficult to accurately model. However, since the use of concrete is widespread and extensive, attempts to model this material are necessary. The inconsistency and complexity of the material must be kept in mind when defining any concrete model. The goal of the model is to capture the overall trends seen in the behavior, not specific details observed in a particular test.

Many models currently exist for reinforced concrete. Several different approaches have been considered. Some models perform simple curve fits to confined tests and use these fits to predict the behavior of a similarly confined section. Others use nonlinear elasticity or plasticity models to capture the more complicated effects and predict the behavior of concrete in a general sense. Somewhat more recently, attempts have been made to create endochronic models for concrete. Each approach has its strengths, complexity level, and complications. The intended use of any particular concrete model may dictate which approach is best suited. For a more in-depth discussion of the different types of concrete models, see Chen (1982).

This thesis presents a new model to represent the confined behavior of concrete. It predicts the change in the behavior of concrete when confined. The model utilizes plasticity theory to represent the behavior of concrete under multiaxial loading. Relevant plasticity theory is reviewed in Chapter 2. The changes in the stress and strain behavior of confined concrete due to the current three-dimensional load state are implicitly taken into account. The concrete model is defined and discussed in Chapter 3.

In Chapter 4, a large set of experimental data is compiled consisting of tests on a variety of concretes which have a wide range of different properties. Test data from concrete with different compressive strengths, aggregate sizes and properties, water-cement ratios, saturation values, ages, additives, and many other variables are utilized to estimate the model parameters. Including a large variety of concrete variables allows the model to represent a more generalized behavior of concrete.

The new material model for concrete is implemented into a finite element (FE) program, described in Chapter 5, for use in representing reinforced concrete structural members. By implicitly including the multiaxial behavior in the concrete model, the confining material can be explicitly included in the FE model. This allows for any type of confinement to be considered. As new retrofit strategies are considered and new confining materials are created, the FE model can be used to predict and evaluate the behavior of the concrete due to the retrofit.

The FE model is utilized to predict the behavior of confined reinforced concrete member laboratory tests in Chapter 6. Different load types and confinement configurations are considered. The predictions of the FE model are then compared to the experimental data to evaluate the performance of the FE model. In Chapter 7, the FE model is used to perform a comparison of the behavior of circular versus square cross sections, as well as a comparison of the performance of members with steel rebar confinement versus FRP confinement. The confined concrete members are compared under both axial load and moment. The performance results of the different members are discussed.

Chapter 8 discusses the conclusions drawn from this thesis. While discrepancies in the experimental data led to some differences between test results and FE model predictions, the FE model did not exhibit any obvious or clear errors. The model was able to capture the general behavior of concrete under confinement. Use of the FE model to compare square to circular cross sections, and steel hoop to FRP confinement, emphasized the effects of cross sectional shape and confinement material on concrete behavior. Significantly different behaviors were exhibited by sections confined by FRP versus steel hoops. While both sections withstand large strains, the FRP confined sections fail at their peak stress while the steel confined sections exhibit strain softening post-peak. This raises the question of how to define ductility for this type of section. Thus, designers must determine exactly what type of performance they want out of the member. With that behavior in mind, the model defined in this thesis serves as an excellent tool to predict concrete behavior for the different configurations being considered.