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Materials and Design 26 (2005) 655–669

Materials & Design

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# Experimental and analytical study of flat-plate floor confinement

S.A. Ali Shah [a], Y. Ribakov [b,*]

[a] Institute for Structural Concrete and Building, Materials, University of Leipzig, Germany
[b] Department of Civil Engineering, Faculty of Engineering, College of Judea and Samaria, 44837 Ariel, Israel

Received 14 August 2003; accepted 13 August 2004

**Abstract**

Currently available analytical models were developed for homogeneous concrete and are therefore inapplicable to specimens cast with concretes of different strengths. The present study examines such composite structures, and more especially normal-strength floor concrete sandwiched between columns of high-strength concrete, as well as the aspect ratio (ratio of slab thickness to column dimension) and closely spaced slab reinforcement. The effect on column–slab joint strength of confinement by rectangular hoops and slab portions extending in all directions from the joint are investigated. Three series of experiments on column specimens were carried out and the experimental results compared with the analytical ones. The experimental results conform to the predictions made by the theoretical models. The same models were used to evaluate the effects on slab concrete behavior of confinement by lateral reinforcement and by a slab surrounding the column–slab joint. A surrounding-slab confinement factor was defined and developed for use in analysis. This study represents a first attempt to evaluate confinement effects in column–slab joints in the presence of surrounding slab. Application of the types of structure investigated here could yield improved strength and ductility, enabling smarter design.


*Keywords:* Analytical models; Concrete specimens; Normal-strength concrete; High-strength concrete; Aspect ratio; Joint strength; Surrounding slab; Rectangular hoops

## 1. Introduction

Reinforced concrete flat plates consisting of slabs (or slabs and beams) of normal-strength concrete (NSC) tied to columns of high-strength concrete (HSC) are a popular form of floor system for a wide range of buildings. The simple formwork of the system, its relatively simple reinforcement layout, and its flexibility in regard to laying of floor partitions make it cost effective. In the resulting structure, however, layers of floor concrete intersect the columns at each floor level. As these floor layers are usually made of lower strength concrete than the columns, under certain circumstances they may reduce the load-carrying capacity of the columns [1–5]. Moreover, a major problem associated with systems characterized by composite behavior in the joint region is that exact confinement analysis cannot be conducted by the methods ordinarily used for analysis of homogeneous concrete columns [12,14–16].

The problem of confinement and strength analysis has long preoccupied researchers in the field. Various analytical models have been developed for evaluating the effects of confinement on the strength and ductility of specimens cast with a single type of concrete [8,12,14]. However, these models cannot be used to predict confinement effects in structures made of two different types of concrete. Consequently, before practical application of such structures can become a reality, their behavior under confinement must be examined in detail.

* Corresponding author. Tel.: +972 3 9066 327; fax: +972 3 9066 351.
*E-mail address:* ribakov@yosh.ac.il (Y. Ribakov).

0261-3069/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.matdes.2004.08.017

Lateral confinement of concrete increases its load carrying capacity [10,13,16]. Confinement of a column concrete can be achieved by lateral as well as by longitudinal reinforcement. However, in flat-plate structures these two forms of reinforcement alone cannot be relied upon to improve the strength of the columns and of the joint concrete sandwiched between two columns. It seems that, by itself, confinement by a combination of longitudinal and rectangular lateral reinforcement does not afford a substantial increment in strength of the floor concrete [3,5]. However, there is definite evidence for an improvement in the strength and ductility of floor or joint concrete when confinement is applied by a slab extending outward in all directions from the column–slab joint [5].

The confined strengths of column and slab concretes may be ascertained using any of the known theoretical models, and the theoretical data can then be compared with experimental results to arrive at some preliminary deductions. The effects of confinement on different types of columns are examined in the study presented below.

## 2. Existing confinement models

HSC columns under monotonically increasing concentric compression show brittle behavior unless confined with transverse reinforcement. It follows that confinement exerts a significant influence on their strength and ductility [6]. However, the effects of confinement on HSC cannot be studied using models developed for NSC due to the differences in materials configuration [6]. The problem becomes even more acute when the aim is to evaluate the effects of confinement on column–slab joint structures made of concretes differing substantially in strength. Experimental data have now become available for HSC [7,8]. When used alongside the existing NSC database, these data have enabled researchers to propose unified models applicable to both NSC and HSC columns as well as to column–slab joints. Legeron and Paultre [7] have developed a simple and unified model for concrete columns confined by rectangular or square ties. It is based on the Cusson and Paultre model [8] for concentrically loaded HSC columns and is applicable for a wide range of concrete strengths (30–120 MPa).

### 2.1. Legeron and Paultre model

The Legeron and Paultre model consists of a parametric stress–strain curve (Fig. 1) and a procedure for determining the parameters defining the curve, namely the strain, $\varepsilon_{cc}$, at peak confined stress, $f_{cc}$, and the strain, $\varepsilon_{c50c}$, when the post-peak stress drops to 50% of peak capacity. The values of the parameters depend on the confinement stress. In the case of reinforced concrete columns, the confining stress is not constant as it depends on the stress in the confining steel, which in turn is related to the lateral expansion of the concrete under compression due to the Poisson effect.

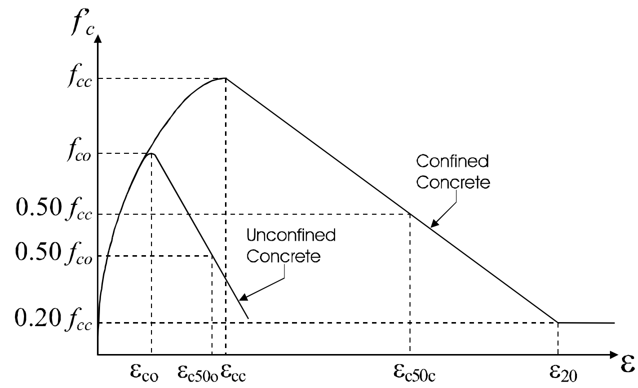

Fig. 1. Proposed stress–strain curve for confined concrete.

In the Cusson and Paultre model [8], two points ($\varepsilon_{cc}$, $f_{cc}$ and $\varepsilon_{c50c}$, $0.5f_{cc}$) are required to define the stress–strain curve. This earlier model was modified by Legeron and Paultre by assuming that the confining steel yields at the strain $\varepsilon_{c50c}$. Indeed, the Poisson coefficient of the concrete reaches 0.5 in the post-peak phase [8], inducing large strains in the confining steel and causing yielding even in very high yield strength steel (HYSS). These effects have been observed experimentally by Li et al. [10] and by Cusson and Paultre [11]. The confining stress at ($\varepsilon_{cc}$, $f_{cc}$) is the only unknown. For NSC and normal yield strength confining steel, the confining stress is taken to be the yield stress, as experimentally confirmed by Sheikh and Uzumeri [13]. It has been shown that such an assumption is not valid for high-strength materials [11]. Hence, it is necessary to determine the pressure due to confinement using the actual stress in the transverse steel at peak strength.

At peak stress, $f_{cc}$, the strain in the confining steel, $\varepsilon_{hcc}$, is given by [8]

$$\varepsilon_{hcc} = 0.5\varepsilon_{cc}\left(1 - \frac{f_{le}}{f_{cc}}\right), \qquad (1)$$

where the coefficient of lateral pressure is assumed to be equal to 0.5 and $f_{le}$ is the effective confined stress. Eq. (1) is implicit as $\varepsilon_{cc}$ and $f_{cc}$ depend on $f_{le}$, which is a function of $\varepsilon_{hcc}$.

The problem is solved using an iterative procedure, at each step of which the confining stress is determined according to the strain in the steel at the previous step. The stress and strain are computed using a relation that links confinement stress to enhanced strength and ductility of the confined concrete. Usually, this procedure converges rapidly. Cusson and Paultre's equations were modified in the Legeron and Paultre model. Some key parameters modified by Legeron and Paultre [7] are described below.