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Prediction of Punching Shear Strength of HSC Interior Slab-Column Connections

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Abstract

Flat plate systems are widely used in reinforced concrete structures. Using of high-strength concrete has been common recently. In the current international codes of practice for concrete structures, the design methods for assessment of punching shear capacity are based on experimental data of flat plates with Normal-Strength Concrete (NSC). The aim of this research is to come up with new formula for punching shear resistance, consistent with data of flat plates made from High-Strength Concrete (HSC). Test results of 61 HSC interior slab-column connection specimens were collected from the literature. The available test results were not only compared with current code provisions but with equations proposed by other researchers as well. A new formula for predicting punching shear strength of HSC interior slab-column connections is proposed. An innovative design equation is also suggested.

Keywords: *punching shear strength, interior column connections, flat plates, high strength concrete*

1. Introduction

The use of high-strength concrete (HSC) for structural components, is becoming exceedingly common in the Kingdom of Saudi Arabia as well as the rest of the world. A number of structures including bridges are being built with High-Strength Concrete (HSC)/High Performance Concretes (HPC) with strengths exceeding 60 MPa, due to the number of advantages offered by such concretes (Subramanian, 2005).

Flat plate slab system does not have beams, column capitals, or drop panels, which make them both attractive and cost-effective at the same time. Moreover, the elimination of beams reduces the overall height of the floor in a multi-storey building thereby creating additional floor space. Another advantage of a flat plate slab system is the flexibility in partition location. As a result of these desirable features, the use of this slab system has become common in structures like multi-storey buildings, car parks, etc.

Flat plate slabs exhibit higher stress at the column connection and are most likely to fail due to a sudden and brittle punching shear rather than flexural failure, especially when a high reinforcement ratio is used. Such a failure generally occurs due to transfer of vertical shearing force and bending moment between the slab and the column. The vertical shearing force is mainly caused as a result of gravity loads, while the unbalanced bending moment is a result of non-uniform gravity loads or any lateral loads due to wind or earthquake forces. As a result of this load concentration and the unbalanced moments, the punching shear failure of the slab occurs at a load well below the flexural capacity of the slab thereby resulting in concrete crushing along the periphery of the columns, before the steel reinforcement reaches the yield strain. Fig. 1 shows the typical punching failure of a slab near the vicinity of a column. The observed angle of failure surface was found to vary between 26º and 36º for normal strength concrete and 32º and 38º for HSC (Marzouk and Hussein, 1992).

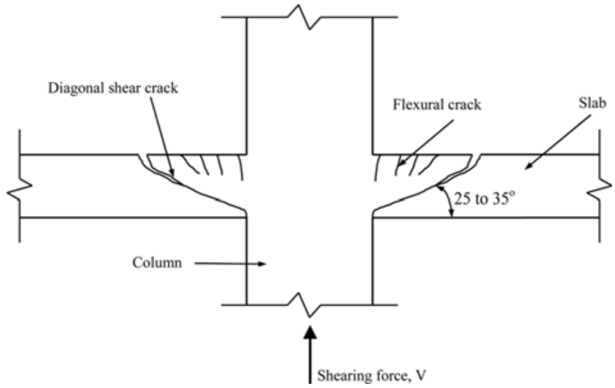

Fig. 1. Flexural and Shear Cracks in the Flat Slab Near the Vicinity of Column

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Fig. 2. Punching Shear Failure at Interior Slab-Column Connections - Piper's Row Car Park, Wolverhampton, UK, 1997 (Wood, 2003a, 2003b)

Errors in predicting the punching shear capacity have been known to cause catastrophic failures resulting in huge loss of life and property. One such failure is the collapse of the six-year old, five-storey Sampoong Department store (originally designed as an office block and later converted to department store with reckless structural modifications) in Seoul, Korea in 1995. This collapse under service conditions killed 498 people (Gardner *et al.*, 2002). Another example is the partial collapse of the Pipers Row Car Park, Wolverhampton, West Midlands, UK, on 20th March 1997. The collapse of the deteriorating, 120tonne section of the top floor slab, measuring 15×15 m, occurred at night under dead load only. Fortunately, the car park was empty, so there were no injuries, but the closure and subsequent demolition of the whole 400-space car park caused substantial disruption. As seen in Fig. 2, punching shear failure at one column led to a progressive collapse as similar failures followed at seven adjacent columns (Wood, 2003a, 2003b).

In the case of slab-column connection, the use of HSC improves the punching shear resistance allowing higher forces to be transferred through the slab-column connection. However, this increase in the shear resistance is offset by the increased brittleness of the system. In fact, HSC members exhibit in some instances different failure mechanisms, compared with the normal-strength concrete members, and simple extrapolation of models and equations meant for normal strength to HSC may lead to unsafe designs (Subramanian, 2003).

The behavior of normal-strength concrete slab-column connection for flat plates has been sufficiently investigated under gravity loading as well as lateral loading. However, only a few studies have been carried out on the behavior of HSC slab-column connection under gravity loading.

Smadi and Yasin (2008) studied the behavior of high strength fibrous concrete slab-column connections under gravity and lateral loads. For the study, ten slab-column connections were tested under combinations of gravity and lateral loads and the variables selected were, strength of concrete, volumetric ratio of steel fibers, type of steel fibers, and moment to shear ratio. Both Normal-Strength Concrete (NSC) and High-Strength Concrete (HSC) slabs were tested as per the testing regimen. Based on the results of the experimental study, it was found that, the addition of steel fibers does significantly enhance the performance of the tested slab. It improved the shear strength, increased the ductility due to deflection and rotation, yielded greater stiffness and smaller cracks widths. Further improvement was also obtained when larger aspect ratio of steel fibers was used. For specimens constructed with HSC, the ultimate shear strength increased by 7-21%, compared with specimens constructed with NSC. The displacement and rotation ductility ratios for HSC specimens were larger than those for NSC by 11-64% for displacement ductility and 106-123% for rotation ductility. Their corresponding energy absorptions due to deflection and rotation were also larger by 48-150% and 93-246%, respectively. Incorporating steel fibers with high-strength concrete improved the overall deformation characteristics of the tested specimens and resulted in less sudden and more gradual failure mode.

In another study, Ngo (2001) compiled the experimental results from 4 research studies on high-strength concrete flat slabs, which were used to review the existing recommendations in design codes for punching shear failure of normal strength slabs. Design codes referred in this study are AS3600 (1994) and CEB-FIP MC 90 (1993). Comparison of test results with code predictions revealed that the CEB-FIP formula is un-conservative for HSC flat slabs as it overestimated the punching shear strength for 34.5% of the data points. However, the AS3600 formula was un-conservative for only 10.3% of the data points.

In a study, Hallgren and Kinnunen (1996) tested 10 circular HSC slabs, with and without shear reinforcement, supported on concrete column stubs. The parameters studied involved varying concrete strengths from 85 to 108 MPa and varying the two way main flexural slab reinforcement ratios from 0.003 to 0.012. The slabs were identical in shape and size with Normal-Strength Concrete (NSC) slabs tested previously. The tests showed that a significant increase of the punching shear strength can be gained by using HSC. The tests also indicated a more efficient use of the flexural reinforcement in HSC slabs than in NSC slabs. Comparisons between ultimate loads observed in the tests and corresponding punching loads calculated according to different current design methods showed that modifications of most of the design methods are required in order to be equally valid for HSC slabs and for NSC slabs. Some of the slab tests were simulated numerically by using the non-linear finite element method. The concrete behavior was modeled with a smeared crack approach