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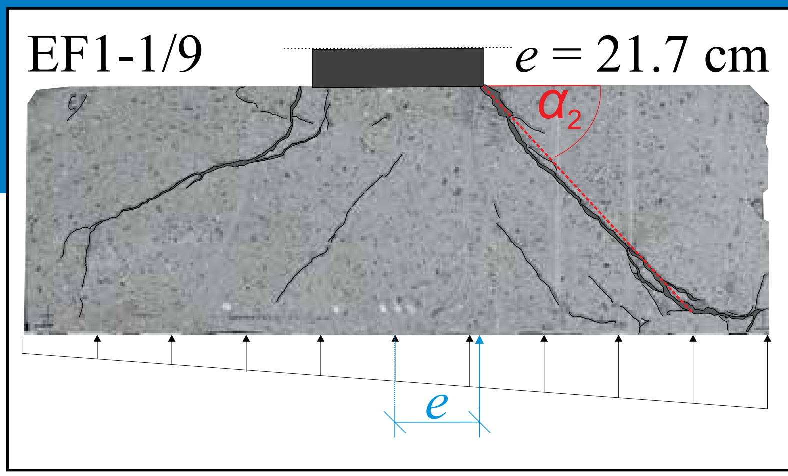

Punching Shear of Concrete Slabs: Insights from New Materials, Tests, and Analysis Methods

SP-357

Editors:
Aikaterini Genikomsou, Trevor Hrynyk, and Eva Lantsoght

American Concrete Institute
Always advancing

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Punching Shear of Concrete Slabs: Insights from New Materials, Tests, and Analysis Methods

The design, analysis, and performance of structural concrete slabs under punching shear loading conditions are topics that have been studied extensively over many decades and are well documented in the literature. However, the majority of the work reported in these areas is generally related to conventional concrete slabs subjected to highly idealized loading conditions.

Structural engineers need to find new, innovative ways and methods to design new structures but also to strengthen existing infrastructure to ensure safety, resilience, and sustainability. These challenges can be addressed through the use of integrated systems and high-performance technologically advanced materials. We live in a new era of improved computational capabilities, advances in high-performance computing, numerical and experimental methods, and data-driven techniques, which give us broader access to larger and better data sets and analysis tools. These new advancements are essential to develop deeper insights into the structural behavior of concrete slabs under punching shear and to implement and analyze new materials and loading conditions.

This Special Publication presents recent punching shear research and insights relating to topics that have historically received less attention in the literature and/or are absent from existing codified design procedures. Topics addressed include: the usage and impacts of alternative/modern construction materials (new concrete and concrete-like materials, nonmetallic reinforcement systems, and combinations thereof) on slab punching shear resistance, novel shear reinforcement or strengthening systems, the influence of highly irregular/nonuniform loading and support conditions on slab punching shear, impact loading, new design and analysis techniques, and the study of the punching shear behavior of footings.

This Special Publication will be of interest to designers who are often faced with punching-related design requirements that fall outside of traditional research areas and existing code provisions, as well as for researchers who are performing research in related areas.

Perspectives from a broad and international group of authors are included in this Special Publication, relating to a variety of punching-related problems that occur in research and practice. In particular, researchers from the United States, Canada, Ecuador, the Netherlands, Italy, Brazil, Israel, Portugal, Spain, the United Arab Emirates, and Germany contributed to the articles in this Special Publications.

To exchange views on the new materials, tests, and analysis methods related to punching, Joint ASCE-ACI Committee 421, “Design of Reinforced Concrete Slabs;” Joint ASCE-ACI Committee 445, “Shear and Torsion;” and subcommittee ACI 445-C, “Punching Shear,” organized two sessions titled “Punching shear of concrete slabs: insights from new materials, tests, and analysis methods” at the ACI Spring Convention 2023 in San Francisco, CA. This Special Publication contains several technical papers from experts who presented their work at these sessions, in addition to papers submitted for publication only.

Co-editors Dr. Katerina Genikomsou, Dr. Trevor Hrynyk, and Dr. Eva Lantsoght are grateful for the contributions of the authors and sincerely value the time and effort of the authors in preparing the papers in this volume, as well as of the reviewers of the manuscripts.

Aikaterini Genikomsou, Trevor Hrynyk, and Eva Lantsoght
Co-editors

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EFFECT OF THE SHEAR REINFORCEMENT ANCHORAGE AND DETAILING ON THE PUNCHING RESISTANCE OF FLAT SLABS

Guilherme S. Melo, Maurício P. Ferreira, Marcos H. Oliveira, Henrique J. Lima,
Manoel M. Pereira-Filho, Victor H. Oliveira, João P. Siqueira and Rodolfo Palhares

Synopsis: Flat slabs with shear reinforcement not properly detailed and anchored as stated by ACI have been used in practice due to simplicity and the gained construction speed. This paper presents the results of 12 tests on slab-column connections with closed stirrups with anchorage variation and prefabricated truss bars as punching shear reinforcement. The behavior of the slabs, in terms of cracking pattern, displacements, and shear reinforcement strains, were analyzed, and ultimate loads were compared with estimations by ACI 318-19. Comparisons with the reference slabs without shear reinforcement showed that these two types of shear reinforcement effectively increased the load-carrying capacity of the tested slabs. For tests on slabs with closed stirrups, it was observed that if ACI detailing rules are followed, improvements in response and ductility of the slab-column connections should be expected. In the case of the slabs with prefabricated truss bars, it was observed that they were able to reach levels of punching shear resistance close to those of a reference slab with well-anchored stud rails. In both cases, further experimental research is needed. ACI 318-19 presented safe strength predictions for the different types of shear reinforcement tested, and in the case of the prefabricated truss bars, this was due to the conservative limitations imposed for calculating the crushing strength of the concrete strut close to the column.

Keywords: Closed stirrups, Experimental analysis, Flat slabs, Punching shear results, Prefabricated truss bars, Shear reinforcement, Shear reinforcement anchorage, Stud rail.

INTRODUCTION

Using shear reinforcement in slab-column connections is generally associated with improvements in deformation capacity and punching shear strength. However, designers and constructors must pay special attention to the shear reinforcement detailing and assembling to achieve these goals in practice because their structural performance is highly dependent on their anchorage capacity[1,2]. ACI 318-19[3] states that the shear reinforcement shall enclose the longitudinal bars or be anchored at the level of the flexural rebars to guarantee its effectiveness, resulting in higher labor costs and increasing the probability of inconsistencies between design and construction, due to on-site adjustments and improvisation.

Caldentey et al.[4] and Costa[5] investigated the response and resistance of slab-column connections with closed stirrups detailed as used in practice in Spain and Brazil. The fundamental idea is that stirrups should not embrace tensile, compression, or both flexural rebars to simplify the construction process. The experimental results presented by Caldentey et al.[4] show no significant changes in the load-carrying capacity of the slabs in which closed stirrups enclosed only the compression flexural rebars. However, the scientific literature does not present experimental results that support the use of closed stirrups anchored only in the tensile flexural bars or without anchoring in any flexural reinforcement layer.

The development of punching shear reinforcement that does not require involvement or anchorage at the height of the flexural bars attracted scientific efforts, highlighting the tests carried out by Yamada et al.[6], Regan and Samadian[7], Park et al.[8], Trautwein et al.[9], and Furche et al.[10]. However, in Furche et al.[10], the shear reinforcement fully projects through the level of the upper and lower flexural rebars. In this context, Ferreira et al.[11] tested continuous stirrups in the shape of truss bars under one-way shear on reinforced concrete wide beams, which had their desirable structural performance was later confirmed by further tests carried out by Tapajós[12] and Pinto[13].

This paper summarizes the results of tests on slab-column connections carried out at the University of Brasilia and Federal University of Pará, Brazil, focused on the correlations between the punching shear resistance and the shear reinforcement anchorage. Tests at the University of Brasilia investigated cases of slabs with closed stirrups distributed on cruciform arrangements with different anchoring possibilities regarding the compression and tension layers of flexural reinforcement, shown in Lima et al.[14]. These tests were divided into two series. One slab without stirrups (slab RS) was tested as a reference in the first four tests. The other three slabs had a shear reinforcement ratio of 0.30%, and the main variable was the stirrups anchorage. In Slab FA-01, stirrups were fully anchored within the tension and compression flexural bars. In Slab CA-01, the stirrups enclosed only the compression flexural bars. Finally, in slab NA-01, the stirrups did not enclose the top and bottom flexural bars. The shear reinforcement ratio was reduced to 0.13% in the second series of tests, which had four slabs with shear reinforcement. The anchorage conditions followed the concepts of the first three tests slabs with stirrups. The fourth test was slab TA-03, in which the stirrups enclosed only the tension flexural bars.

The experimental program developed at the Federal University of Pará comprised four tests focused on investigating the upper strength limits of slabs with prefabricated truss bars as punching shear reinforcement, presented in Ferreira et al.[15]. One reference slab without shear reinforcement was tested, and the others had large amounts of shear reinforcement. One slab with radially arranged stud rails and 1.15% shear reinforcement ratio served as a reference for two slabs with the prefabricated truss bars as punching shear reinforcement. One had vertical ($\alpha = 90°$) truss bars and the other had inclined ($\alpha = 60°$) truss bars with 1.14% and 1.18% shear reinforcement ratio, respectively. Results are discussed in terms of response and resistance. Experimental strengths are also used for comparisons with theoretical strengths estimated following the equations from ACI 318-19.

DESIGN RULES FROM ACI 318-19

Detailing Rules

ACI 318-19 presents detailing rules and spacing limits to guarantee adequate structural performance for different kinds of stirrups and headed studs. According to ACI 421.1R-16, shear reinforcement consisting of vertical bars mechanically anchored at each end by a plate or head can develop the yield strength of the bars and have been used successfully as punching shear reinforcement. Furthermore, ACI 318-19 and ACI 421.1R-08 specify that the shear reinforcement shall be symmetrically distributed about the center of the critical section of a slab-column connection, respecting the spacing limits (s_0 and s_r), as illustrated in Figure 1. This recommendation aims to guarantee that the