Title of the Thesis: **LOAD DISTRIBUTION ANALYSIS BETWEEN INTERCONNECTED SLABS-FORMWORK SYSTEMS DURING THE CONSTRUCTION OF HIGH-RISE REINFORCED CONCRETE BUILDINGS**

ABSTRACT

This research deals with the construction and preconstruction phases of high-rise cast-in-place reinforced concrete (RC) buildings while using the shoring and reshoring systems. Shoring and reshoring as temporary structures support several consecutive immature slabs to distribute and balance the load between the interconnected system. In the preconstruction phase, the loads to be borne by shores/reshores and slabs are predicted at each construction step. In the construction phase, real-time monitoring regarding the response of the slabs and shores/reshores is conducted. To evaluate structural safety during construction, it is essential to ascertain the load distribution between interconnected slabs-shores/reshores systems (ISSRS) resulting from casting new slabs and performing reshoring activities. However, improper load distribution between the slabs and shores can lead to catastrophic failures. This issue has prompted the development of methods to analyze and accurately predict the load distribution during construction steps. According to the literature review, three methods for analyzing the load distribution between ISSRS are well-known. These methods are the simplified method (SM) of Grundy and Kabaila (1963), the improved simplified method (ISM) of Duan and Chen (1995), and the three-dimensional refined method (3D RM) of Liu et al. (1985). The first two methods are manual calculation procedures, and the third is a finite element-based (FE-based) method in which each construction step needs to be modeled separately.

In the first objective, this study presents the shore load method (SLM), a manual computational process. It investigates how various shores and reshores distribution schemes on

both spans of two-way slabs affect the time-dependent stiffness of concrete slabs, which was often overlooked in other simplified methods. The findings from the various examples analyzed using the SLM were compared with those of the SM and ISM, where the results from 3D RM were selected as benchmarks. In different construction steps, the results showed that the previously proposed simplified methods underestimated the load on the younger slabs by different percentages than the 3D RM. In contrast, the results from the SLM showed a more robust correlation with the findings derived from the 3D RM that requires standard structural analysis software. Still, the close correlation of the SLM to the 3D RM does not present the necessary accuracy, and the reason is that the previously proposed FE-based methods have their limitations regarding load distribution analysis. Therefore, the SLM was recommended as a base for further investigations to develop a more advanced manual calculation method.

A significant gap in the literature is the lack of continuous real-time monitoring systems for slabs and shores/reshores systems, leading to serious safety hazards and structural failures. According to the literature, most structural monitoring technologies have focused on permanent structures rather than temporary ones. No study proposes a developed way for real-time assessment of the ISSRS during construction. In response, the second objective of this study is to introduce a cost-effective and reliable smart sensing network system (SSNS) that integrates sensors of various types, auxiliary intermediate modules, and microcontroller platforms, enabling real-time assessment of slabs and shores/reshores. The SSNS was implemented while constructing a three-storey RC flat plate slab model. The results showed that the findings from the SSNS had over 97% correlation with the analytical formulas while measuring the strain. The load on shores increased when the ambient temperature decreased, consistent with prior studies. The data from SSNS aligned 91% with the finite element analysis (FEA) results for assessing the deflection. The SSNS showed an accuracy of 95% regarding measuring the load magnitude on the individual shore elements supporting the fresh concrete slab. In addition, it was able to represent the immediate load redistribution on the shores while removing the formwork system. While adding a new load, the SSNS represented close values to the FEA results with 99% accuracy regarding the magnitude of the shared load on lower slabs and shores/reshores supporting each of those slabs. Overall, the SSNS is a practical and cost-effective solution for enhancing structural safety and assessing the performance of slabs and shores/reshores during construction.

The analyzed results from the previously proposed methods show two layers of inconsistencies regarding the load distribution between slabs and shores/reshores. The first layer highlights an inconsistency between the methods regarding the load distribution on slabs and shores/reshores. The second layer highlights a significant difference between the results from the methods and experimental measurements. The third objective of this study is to minimize these discrepancies by introducing an idealized contact stiffness between slabs and shores/reshores, a critical factor not considered in previous studies. Experimental results from the second objective at various construction steps were compared with outputs from the prepared finite element model (FEM) and other methods in two scenarios: one without contact stiffness and one with it incorporated into the analysis. In the first scenario, where the contact stiffness was neglected, the prepared FEM and other methods overestimated the load on lower levels of reshores than experimental measurements. Maximum discrepancies were up to 1267%, 957.8%, 767.4%, and 617.4% for the SM, ISM, 3D RM, and prepared FEM, respectively. In the second scenario, the modified FEM and the other modified methods had much better consistency with the experimental data. The mentioned maximum discrepancies were reduced to 88.4%, 13.3%, and -12.7% for the modified ISM, modified 3D RM, and modified FEM, respectively, where the SM could not handle the contact stiffness. Similarly, the maximum underestimations of the incremented load on each slab, initially -88.1%, -71.2%, and -62.5%, were reduced to -18.1%, -2.4%, and 0% for the three modified methods, respectively. These findings highlight that contact stiffness is the key factor influencing load distribution between slabs and shores/reshores. Addressing it in analysis minimizes discrepancies and significantly improves the accuracy of load distribution predictions. Compared to all, the modified FEM represented the best results regarding the load prediction between ISSRS in all construction steps. However, using FEMs is challenging; evaluating the load distribution among various combinations of levels of shoring and reshoring using the FE software is complex. As in each combination, individual simulation for every construction step is required, which will be time-consuming and perhaps costly.

In the fourth objective, this study introduces the contact stiffness method (CSM), integrating the SLM and the principles of contact mechanics. Measurements recorded while constructing the experimental model were compared with results from the CSM and three other methods. The minimum differences in overestimating the load on shores/reshores from the individual of these three methods were 194%, 115%, and 70%, respectively. In the same construction step, the CSM showed an 8% difference. The maximum differences in overestimating the load on shores/reshores from each of these three methods were 1267%, 417%, and 269%, respectively. Whereas in the same step, this value for the CSM was 3%. The findings evidenced that CSM is a more precise and practical instrument for analyzing load distribution and improving high-rise building projects' safety and efficiency.

Finally, this study emphasizes the vulnerability of high-rise RC flat plate slabs to punching shear failure during construction when supported by shoring/reshoring systems. Despite their widespread use, limited research examined the punching shear behavior of these slabs without shear reinforcement at early concrete ages, and existing building codes provide inconsistent results. This inconsistency and a lack of framework for predicting safety during construction using shoring/reshoring increase the risk of failure since applied loads typically exceed designed ones, and young concrete may not ultimately sustain them. This study proposes a

factor of safety (FoS) that accounts for punching shear capacity and fluctuating load distribution between slabs and shores/reshores during construction. Six interior slab-column elements without shear reinforcement were tested at various concrete ages. Unlike many building codes, flexural reinforcing increased punching shear capacity but less at lower concrete ages, highlighting the necessity for precise safety predictions during construction. Also, an empirical formula was proposed to predict the punching shear capacity of RC flat plate slabs without shear reinforcement. Based on a vast set of experimental data from previous studies, the formula presented superior accuracy compared to building codes, with a mean load capacity ratio (μ) of 1.04, a coefficient of variation (CoV) of 14.2%, and a coefficient of determination (R^2) of 0.93. Finally, the CSM was used to analyze slab-shore/reshore load distribution to evaluate FoS for two identical examples having different shoring levels. The risk of structural failure was predicted for one of the examples in some construction steps. Then, for such unsafe predicted construction and risk of structural failure, the requirement for increasing any of the cycle time, number of shoring levels, grade of concrete, or reinforcement percentage was emphasized.

The research concludes by recommending a comprehensive approach for enhancing the structural safety of high-rise RC buildings during construction, incorporating real-time monitoring, refined load distribution models, and updated safety standards. These measures aim to reduce risks of structural failure and optimize construction procedures, ultimately improving building integrity and reducing failures during critical construction phases.

Keywords: Formwork; Shoring and reshoring; High-rise RC buildings; Safety evaluation; Smart sensor network system; Shore load method; Finite element model; Contact stiffness method; Flat plate slab.