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Contribution of Reinforced Concrete Floor Slabs to Lateral Behavior of Tall Buildings

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Abstract This paper focuses on how the coupling of the columns and walls through the structural slab contributes to the overall stiffness and strength of lateral systems. The rationale and procedures behind the design approach, which may offer a shift from more conventional assumptions made regarding compatibility and connectivity of gravity and lateral structural systems, will be introduced. The impacts on serviceability and strength design will be discussed, and observations on key design and analysis approaches will be featured. Mass and stiffness assumptions will also be reviewed. A case study on the topic will be presented describing implementation of slab coupling into engineering of a building project.

Keywords Tall building behavior, reinforced concrete systems, lateral strength and serviceability, lateral compatibility, coupling

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1. Introduction

Advancements in instrumentation of tall buildings have highlighted that tall buildings, within the serviceability range of behavior, are typically more rigid after completion than estimated during the design process. This is in part because structural elements not considered by the designer to resist lateral load can, in fact, offer enough additional stiffness to make a difference in overall building dynamic response. For example, the added stiffness of concrete slab/column frames introduced through slab connections to an interior concrete core wall can have a significant impact on lateral stiffness and, therefore, the dynamic response of a tall building. Furthermore, strength demands for such connected slabs and columns and member detailing may be significantly affected. Thus, it is important that during design, structural engineers make realistic predictions that sufficiently bound the mass and stiffness of structural elements connected to the primary lateral load resisting system. They must fully explore these impacts on building motion and accelerations and properly capture the related strength demands. Following is a detailed discussion regarding structural layouts that are most prone to slab coupling, impact of slab coupling on serviceability and strength of tall buildings, and an in-depth case study of implementation of slab coupling and its impact using a tall building project.

2. Structural Layouts Prone to Slab Coupling

In essence, floor slab coupling in reinforced concrete buildings is moment frame behavior that is not specifically intended by the structural designer but occurs nonetheless due to the monolithic nature of these types of structures. Multiple factors, either individually or working in tandem, can influence the degree of slab coupling within a particular building. Like in a conventional frame, size, stiffness, and aspect ratios of slab/column/wall frames are all contributors. Thus, larger columns, oriented such that their strong axes are parallel to the laterally softer direction of the building will lead to more floor slab coupling. One example of such a scenario would be the usage of architecturally desirable blade columns in hospitality and residential occupancies in which aspect ratios are maximized such that the columns can be best integrated into the interior partitions. Moreover, slabs that are stiffer through either increased thickness or the addition of post-tensioning will also exhibit more coupling.

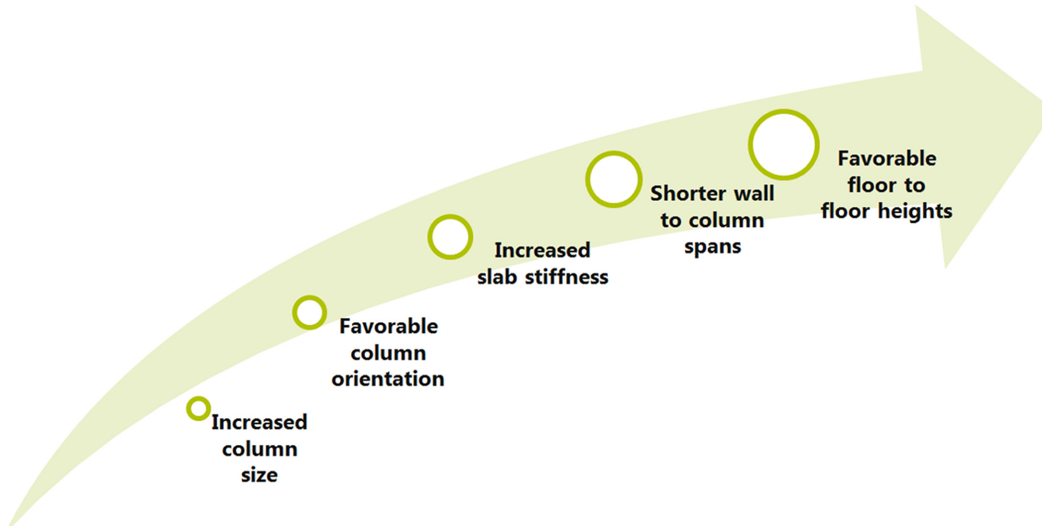

Figure 1. Factors Leading to More Pronounced Slab Coupling.

Dimensions of the frame are also important, Dimensions of the frame are also important: short floor slab spans between shear walls and columns as well as floor to floor heights that create favorable slab/column/wall frame aspect ratios can also magnify slab coupling. Lastly, buildings with large, centrally located elevator and stair core are likely to experience more slab coupling. Refer to Figure 1 for a summary of factors influencing slab coupling.

3. Impact of Slab Coupling on Serviceability Evaluations

Instrumentation of tall buildings in recent years has shown that structural models created using the finite element software generally underestimate the lateral stiffness of real buildings. This is likely caused by a combination of multiple factors such as omission of additional stiffness from non-structural partitions and finishes, overly conservative assumptions with respect to building mass and degree of damping, and the exclusion of additional stiffness from elements that are not specifically designated as part of the main lateral force resisting system. As will be shown in the subsequent case study, inclusion of slab coupling into the lateral analyses, provided the structural layout is favorable to this effect, can be beneficial in terms of building response under serviceability evaluations. Inclusion of frame action in conjunction with the primary lateral system results in increased lateral stiffness and reduced overall building deformations, lower inter-story drifts, and an improved acceleration response. From a behavioral and material economy standpoint, this can be especially advantageous when the driving factor for the lateral stiffness, as it often is in tall buildings, is satisfying the deflection and acceleration criteria.

4. Impact of Slab Coupling on Strength Design and Detailing

Explicit modeling of slab coupling in lateral analyses allows the structural designer to study the strength level demands resulting from this phenomenon. As the subsequent case study will show, depending on the susceptibility of the structure to slab coupling, lateral demands may exceed those resulting from gravity analyses and influence the design and detailing of structural elements. In the instances when lateral load combinations govern the design, increased flexural demands will occur in slabs near column and wall supports. Moreover, in the case of relatively short slab spans and low gravity loads, net positive bending moment near supports may occur. Careful attention needs to also be paid to the increased shear demands due to the brittle nature of this type of failure. Additional punching shear reinforcement may be required at columns where lateral load combinations govern the demands. Another area that warrants careful inspection is the slab to wall connection interface. This is especially prudent when the popular tall building construction “core first” methodology is used and a cold joint between slabs and walls is present. Lastly, the vertical structural elements in the primary lateral system are likely to experience reduced strength demands while demands in the “gravity” columns, on the opposite hand, may increase as they are now coupled to the walls via the slabs.

5. Practical Implementation - A Case Study

5.1. Description of basic building layout and systems

An in-depth exploration of impact of slab coupling was

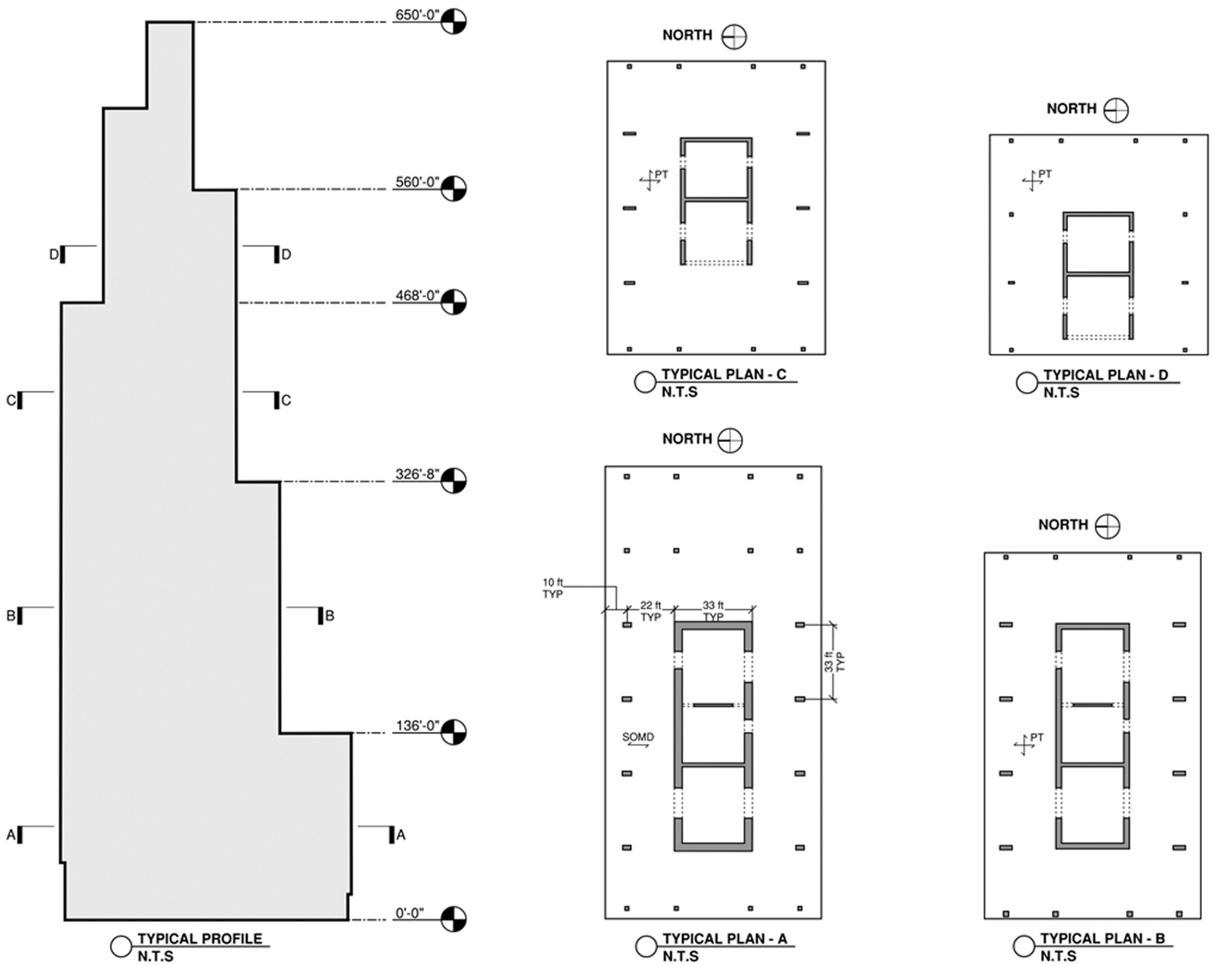

Figure 2. Typical Tower Profile and Plan Layout.

completed on a mixed-use, 49-story, 650-foot-tall tower project currently under construction. The tower has a slender profile, gradually tapering on two sides as the building rises in elevation. The lower portion of the tower framed in structural steel with composite deck, provides predominantly amenity and back of house space for the building, and has an average floor to floor height of 16’-0”. As the tower increases in height, the occupancy transitions to hotel spaces with a floor-to-floor height of 10’-8”. The tower then changes to residential occupancy with a floor-to-floor height of 11’-4”. Above the amenity spaces in the lower portion of the building, the floor system becomes 9” post-tensioned concrete slabs, with thickened slabs and beams at mechanical occupancies. The tower is in a low-seismic zone and the lateral design is driven by demands from wind loading. The tower structure primarily derives lateral strength and stiffness from a buttressed reinforced concrete central core, with walls varying in thickness from 42” at the base to 20” at the top, this is supplemented by moment frame action induced through post-tensioned slab coupling between the central core and blade-shaped columns with aspect ratios (long to short face of column) of approximately 2.5. The columns are oriented such that the strong axis is orthogonal to the laterally weak direction of the tower. Architectural planning calls for typical core to column spans of 22 feet in the north-south direction with 10-foot cantilevers while the spans in the east-west direction are typically 33 feet. All aforementioned elements also serve the double purpose of resisting gravity loads. The shape and orientation of the columns, the relatively short spans between the columns and core, and the stiff post-tensioned slabs all contribute to an increased effect of slab coupling, which is especially pronounced in the weak (north-south) direction of the building. A typical floor schematic and tower profile looking north is shown in Figure 2.

Since slab coupling was found to have a significant effect on the lateral behavior, the lateral force resisting system, for the purpose of deriving seismic loading, was classified based on the more stringent criteria as per requirements in the building code. This did not impact the design of the lateral system, however, as the tower is in a zone of low-seismicity and was still found to be

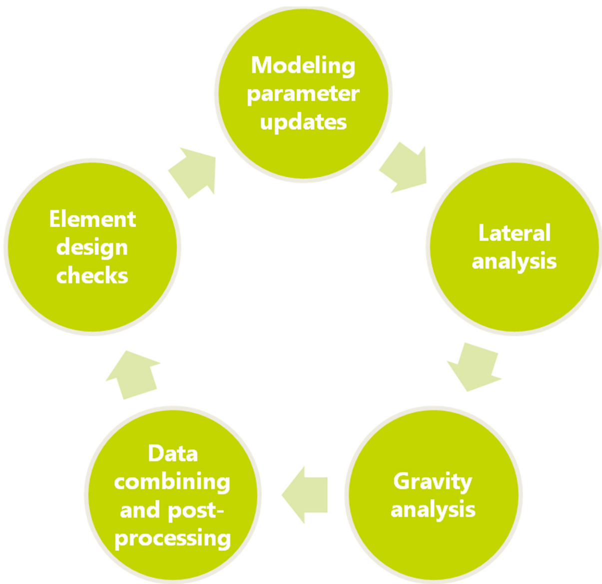

Figure 3. Process Diagram for Implementing Slab Coupling.

governed by wind loading.

6. General Analysis Procedure

As is common industry practice, various parts of lateral and gravity analyses were performed in separate software packages. To include the slab coupling into the design of the tower, the demands had to be mapped and combined using computational tools developed in-house. This was done using a process that involved careful management of large quantities of data using Microsoft Excel as well as data and graphic tools available within the Python programming language.

Additionally, proper execution of modeling was necessary. To capture slab behavior under lateral loads, slab elements within lateral analysis models had to be modeled including out-of-plane stiffness, which increased the number of elements and, consequently, model run times. Models had to be built with proper care to ensure suitable mesh size and arrangements that correctly

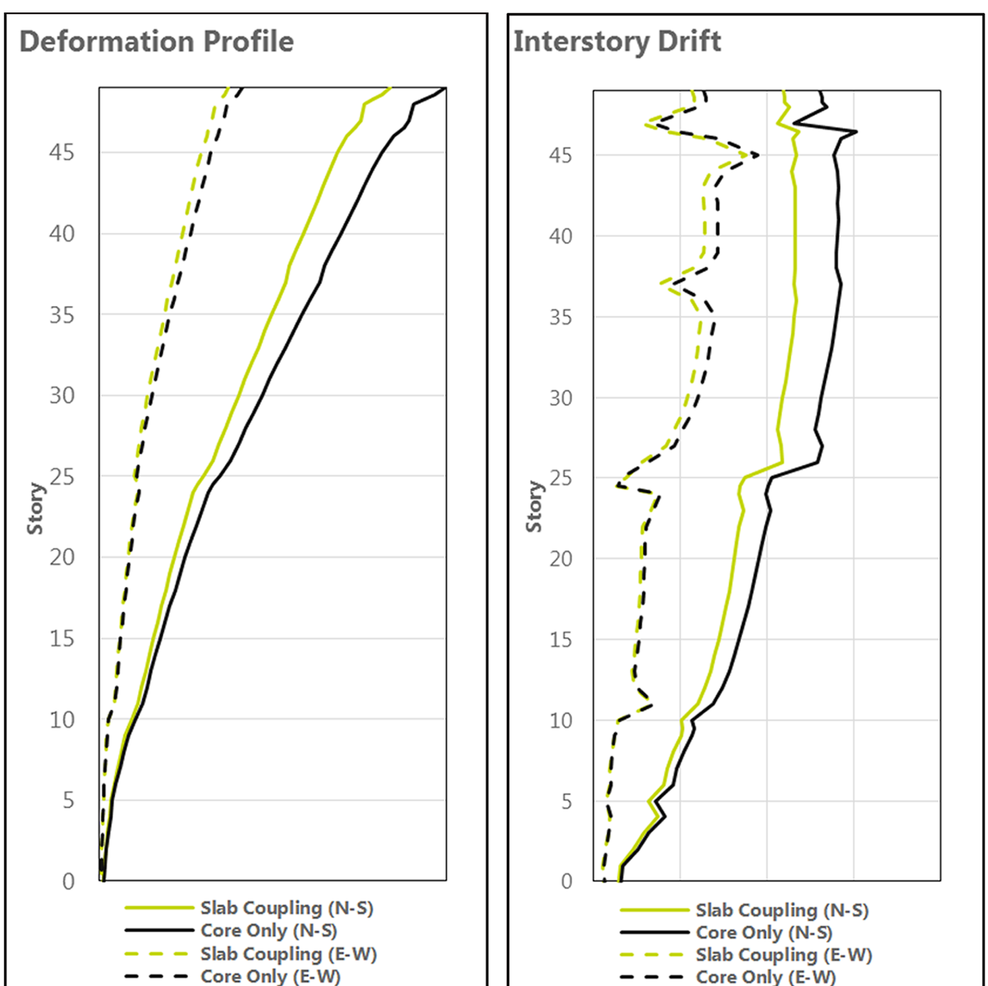

Figure 4. Deformation and Inter-Story Drift Profiles.

captured the lateral behavior of floor elements. Lastly, due to the inherent uncertainty associated with stiffness of post-tensioned slabs under various degree of loading, multiple bounding analyses had to be performed with slab stiffness varied, and system elements had to be rechecked to envelope the response.

The general description of the process for each analysis iteration is shown in Figure 3.

7. Impact of Slab Coupling on the Lateral Stiffness

An increase in lateral stiffness was observed when slab coupling was included in the models included in the models, which led to the possibility of thinner shear walls and the selection of a "core-only" system that did not require outriggers or belt walls for the project. The slab coupling resulted in a reduction in the building period of approximately 8% under strength and serviceability. This corresponded to a reduction of 10% in expected acceleration on the top-most occupied floor. The peak lateral deformations under service wind loads reduced by 12% and average inter-story drift was reduced by 15%. Furthermore, slab coupling helped mitigate the cracking stresses in the walls, leading to a stiffer lateral system. In the core only system, wall panels that were expected to experience cracking based on analysis with slab coupling showed vertical crack propagation in 6-8 additional stories. Refer to Figure 4 for comparison of deformation profiles with and without the inclusion of slab coupling.

8. Impact on Lateral System Demands and Slab Design

Slab coupling had a sizeable impact on strength demands of various elements forming the structural system. To envelope the expected strength-level slab stiffness range, lower and upper-bound analyses were used. Increased flexural demands were observed, which required adjustment to reinforcement quantities at slab/column joints. Furthermore, code combinations with lower-bound assumptions on dead and live loads resulted in net positive bending in some of the beam-column joints, in turn leading to bottom mild reinforcement being required-an uncommon reinforcement pattern for post-tensioned flat plates with limited mild steel. Generally, increased moments in the range of 15% to 30% were observed at beam column joints in the north-south direction; effects were less pronounced in the east west-direction with longer spans and more flexible column orientations. Lateral combinations were also found to govern one-way and punching shear demands in the slab. Largely, it was found that the slab thickness was satisfactory to carry the increased one-way shear demand through concrete alone. However, approximately 20% extra beam-column joints were observed to require punching shear reinforcement due to additional impact of lateral demands. Similar increases were observed at slab to wall connection interfaces where dowel quantities had to be adjusted to account for increased one-way shear and flexural demands. As expected, slab design was governed by upper-bound slab stiffness assumptions as more load was attracted into core/column and slab moment frames.

Secondary lateral stiffness from slab coupling also resulted in reduced demands on shear walls as well as a reduction in quantity of wall panels experiencing net tension. Under the ultimate strength limit state, 11% fewer walls were found to experience net tension with slab coupling effects included. Additionally, inclusion of slab coupling reduced the portion of overall overturning moment resisted by the core by approximately 8%. Column demands, on the other hand, increased as these began to participate in the lateral system. However, no meaningful revisions were required to the design of column elements as detailing for gravity was generally able to accommodate the additional lateral demands. As expected, lower-bound slab stiffness assumptions governed the design of shear walls, as more load was attracted into the core while the moment frame action via slabs reduced.

9. Conclusion

The extent of slab coupling effects on strength and serviceability performance of tall buildings can vary based on several factors such as span length, floor to floor height, primary lateral system layout, slab stiffness, as well as column shaping and orientation. In most scenarios, addition of slab coupling effects into lateral analyses will lead to an increase in overall lateral stiffness resulting in improved lateral performance. The increase in contribution to lateral behavior, however, will consequently result in an increase in flexural and, more importantly, shear (brittle failure mode) demand on slabs. In cases where layouts are favorable to increased effects of slab coupling, increased reinforcement demands in the slabs are likely to result. Provided slab coupling is inherent, stemming from the monolithic nature of reinforced concrete structures and associated compatibility demands, slab coupling should be studied by the structural designer, especially on projects susceptible to the pronounced effects resulting from this phenomenon. The current state of analysis software and increased availability of computational tools at disposal of structural engineers should allow for the implementation of this type of rigorous analysis on projects.