Evaluation of the Effects of Service Core Reduction on Tall Building Structures

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Abstract. One of the primary goals in tall building design is the optimum design of service core where the vertical transportation, building services, HVAC elements etc. are situated. Particularly for supertall (+300) office buildings, a significant portion of the core space is occupied by elevators when compared to the rest of the service core elements. Actually, with the utilization of recently developed elevator technologies, it is possible to decrease the elevator footprint area and thereby to decrease the service core area. Nevertheless, the core of a tall building usually is also a part of the lateral load resisting system, namely as a structural core. This study aims to investigate the effects of service core reduction which is a consequence of the elevator footprint decrease on interior and exterior tall building structures. Generic computer models of outriggered frame and framed-tube buildings with 300m height (75 story) are produced. Then, the service core area of both buildings is decreased considering the effects of recent advances in elevator technology. First, the strength and the stiffness constraints as well as serviceability of primary and reduced core buildings are evaluated in terms of code-based design loads for each outriggered frame and framed-tube structural systems. Then, primary and reduced core buildings of outriggered frame and framed-tube structural systems are compared in terms of the change in top drift to building height ratio, the increase in leasable area and to access to natural light.

1. Introduction
Tall buildings have less economic efficiency per square meter because less usable space is obtained in contrast to higher construction expenses [1]. Thus, optimum design of service core is critical in tall building design in order to increase floor area efficiency.

With the recent developments in elevator technologies, elevator footprint area can be significantly decreased which is an important part of the service core. The service core is generally the structural core of a tall building. Therefore, if the service core is reduced due to the decrease in the elevator footprint area, the structural system of a tall building will be affected by this change.

In this study, the effects of the service core reduction which is the result of the decrease in elevator footprint on tall buildings with outriggered frame and framed-tube systems are investigated by generating various computer models.
2. Service Core in Tall Building Design

Service core design is a fundamental element in tall building design. It is defined as “An element that gathers the space necessary to provide visual, physical and functional vertical connections that work effectively to distribute services through the building” by Trabucco [2]. Because of its importance, planning of the service core starts at early stages of the design process.

2.1. Types and configurations of service core

There are many proposals for the classification of service core configurations in the literature. For example, Grondzik, Kwok, Stein and Reynolds [3] defined six alternatives for service core configurations as; edge core, detached core, central core, two cores, corner cores and random cores.

Selection of the suitable service core configuration depends on many factors such as, function of the building, building users and building codes and legislations [4]. The detailed comparison of these six alternatives are indicated in figure 1.

![Figure 1. Service core configurations and their comparison [3]](image)

2.2. Functional elements of service core

Functions of the service core is classified by Trabucco [2] in three groups:

1. Services: the main servant facilities of the building necessary to its existence and operation, such as elevators, their shafts and corridors, egress stairs and secure spaces, machine and electrical/ communication rooms, toilets and storage rooms.

2. Subservices: vertical risers, ducts, pipes and chutes, whose sub servant role derives from being necessary to the operation of the main services. They are generally placed in the residual areas left free by the design of the main utilities.

3. Core: the structural shell that often encircles the services. The core exists when the structural scheme of the building requires shear walls/trusses or moment-resisting frames to withstand the horizontal forces; otherwise, it is omitted.
2.3. Vertical communication systems
As the building height increases, more elevators are required which results in the decrease of floor area efficiency [2]. Therefore, optimization of vertical communication systems is one of the main goals in tall building design. There are some specific strategies for the efficient operation of conventional elevators. But, the primary focus of recent developments in the elevator industry is the minimizing the footprint area of elevator shafts by making use of new technologies.

2.3.1. Elevator operation strategies. Parker and Wood defines the goals of vertical traffic design as; effective circulation, minimum cost, life safety, security and energy efficiency [5]. In order to achieve these objectives, the number, speed and capacity of the lifts required should be carefully selected. In addition, the most suitable arrangement in terms of zoning, group control algorithm and the use of special elevator technologies should be identified [6].

The terms of zone, stack and transfer floors in elevator arrangement strategies are defined by Al-Sharif [7] as indicated below.

- **Zone** is a group of contiguous floors which are served specially by a number of elevators.
- **Stack** is a contiguous group of floors but served by a sky lobby and away from the main lobby of the building. A stack can include multiple zones.
- **Transfer floors** allow passengers to move between different zones without the need to travel to the main lobby. Transfer floors are shared by both users of two adjacent floors.

The most important thing in the determination of elevator arrangement strategies is the functional use of the tall building. The amount of population, traffic conditions in terms of rush hours and the need for quality and quantity of services changes according to functional use of buildings. For instance, in office buildings, there are two main daily users as employees and visitors. Since the working hours is generally fixed, these rush hours lead to an enormous elevator traffic need according to Loon [8].

2.3.2. Developments in elevator technologies. Gerstenmeyer and Jetter [9] identified the elevator systems mainly based on the number of elevator cars as single car elevators, paternosters, double-deck elevators and multi-car elevators.

The multi car elevator concept is the most recent elevator technology in which multiple cabins run in the same shaft [9]. With the application of one of the recent multi car elevator systems, elevator footprint can be reduced up to 50 percent [10].

For the tremendous increase in elevator shafts especially for super tall buildings (+300) with mostly unused and inefficient space. Multi car elevators can enable great efficiency for buildings. According to Mueller and Schoellkopf [10], multi car elevators are ideal in one loop for 600 meters driveway, namely 300 meters height, yet without a height limitation.

In office buildings, elevator capacity varies during the day since people arrive to the building about at the same time. Thus, multi car elevators can be an ideal option for tall office buildings. Many multi-car elevator concepts are adaptable to the necessities of rush-hour transportation flow as it is indicated previously [8]. For instance, with the application of recent elevator systems, the service core area can be dramatically reduced as indicated in figure 2.
Figure 2. The reduction of the service core with the application of new elevator systems

Actually, service core is not only composed of the elements of building services elements but it is also the backbone of a building for structural strength. If the service area is reduced due to the application of recently developed elevator technologies, the whole structural system and thus the building performance will be affected by this change.

3. Effects of Recent Elevator Technologies on Structural System Performance

The effects of the service core reduction on tall buildings depend on the type of the structural system because the contribution of the service core to resist lateral loads changes according to the structural system type of a tall building. If majority of the structural elements take place within the interior of the building, the system is categorized as interior structure. On the other hand, if major part of the structural elements is located at the perimeter of the building, the system is defined as exterior structure. For this study, generic building models with outriggered frame system representing interior structures and buildings with framed-tube system as exterior structures are generated according to the classification of tall building structural systems by Ali and Moon [11].

3.1. Parameters of generic tall buildings

All generic building models are considered as 300m office buildings since multi car elevators are ideal for office buildings due to rush traffic hours and ideal but not limited [10] for buildings with 300m height. For tall office buildings, column-free space is preferred between the exterior façade and the building core so no columns are used in lease span area of generic computer models are modelled without interior columns. Besides, the floor plans of generic building models are symmetric along x and y direction with a square plan. The general parameters of generic models are indicated in table 1.

Table 1. Parameters of generic building models

| Building Parameters         |                  |
|-----------------------------|------------------|
| Building Height:            | 300 meters       |
| Number of Floors:           | 75               |
| Function:                   | Office           |
| Structural System:          | Outriggered frame or Framed-tube |
| Structural Material:        | Concrete (C90/105) |
| Aspect Ratio:               | 8                |
| Typical Floor Area:         | 1406.25 m²       |

3.2. Sample buildings

The service core area (C), total column area per floor (TC), elevator footprint area (E) and the shear wall thickness (SW) of generic building models are determined according to the features of sample
office buildings around 300m height with outriggered frame and framed-tube system. Average values of building parameters of sample office buildings for each case are calculated to establish a framework for generic computer building models. The formulations of these parameters are:
- C/T: the ratio of the service core area to the typical floor area,
- TC/T: the ratio of total column area to typical floor area,
- E/(T-C): the ratio of elevator footprint area to net floor area,
- SW: thickness of the service core wall.

![Diagram of C, T, and E](image)

Figure 3. Demonstration of “T, C and E” on typical floor plan of One Liberty Place

Sample buildings around 300m height with concrete or composite structural system and columns are selected for calculating the average values of building parameters for generic buildings which is mentioned above.

3.3. Characteristics of generic tall buildings
The average values of existing building cases are used as a guideline in the preliminary dimensioning process of generic computer models. The average value of sample buildings and the values that are used in the design of generic buildings with outriggered frame and framed-tube systems are shown comparatively in tables 2 and 3.

| Table 2. Average value of sample and generic building models with outriggered frame system |
|-----------------------------------------------|
| SW (cm) C/T E/(T-C) TC/T |
| Average Value of Sample Buildings 94 0.23 0.14 0.02 |
| Values of Generic Building Models 100 0.23 0.14 0.02 |

| Table 3. Average value of sample and generic building models with framed-tube system |
|-----------------------------------------------|
| SW (cm) C/T E/(T-C) TC/T |
| Average Value of Sample Buildings 65 0.21 0.12 0.03 |
| Values of Generic Building Models 65 0.22 0.14 0.03 |

3.3.1. Outriggered frame building with primary core. Two level of outriggers with 2 story height is placed at 1/3 and 2/3 of the building. In that way, the maximum story displacement to building height ratio, which should be around 1/500 [12] is satisfied when the building is subjected to the design wind loads. The floor plan with the indication of outriggers (red lines) of primary core version of the outriggered frame buildings is indicated in figure 4.
3.3.2. Outriggered frame building with reduced core. If the outriggered frame building in figure 4 utilizes recently developed elevator technology, the elevator footprint area within structural core decreases. This version is named as reduced core building as demonstrated in figure 5. In this case, two parameters of primary core building with outriggered frame system change while the other two remains the same (SW and TC/T):

- \( \frac{E}{T-C} \): 0.07
- \( \frac{C}{T} \): 0.177

3.3.3. Framed-tube building with primary core. 36 columns are placed in a typical floor plan with equal spacing since the spacing between column axes of framed-tube building should be between 1.5
meter to 4.5 meter [12]. In framed-tube buildings, the columns are used with deep spandrel beams. The beam dimensions are identified with the same dimensions of columns as in the case of several real buildings. The floor plan of the generic building with primary core is demonstrated in figure 6.

Figure 6. Floor plan (left) and elevation (right) of framed-tube building with primary core

3.3.4. Framed-tube building with reduced core. If the framed-tube building in figure 6 utilizes the recently developed elevator technology, the service core area decreases due to 50 percent decrease in total elevator footprint area (figure 7). In this case, two parameters of the building with primary core change as:
• E/(T-C): 0.07
• C/T: 0.171

Figure 7. Floor plan (left) and elevation (right) of framed-tube building with reduced core
4. Analysis and discussions
All the structural analyses under different load types and corresponding combinations as well as some basic capacity and design checks based on built-in specifications (i.e. ACI 318-14 and ASCE 7-10) have been made by ETABS program. Wind and earthquake loads are applied to generic models and all structural members of each generic model are controlled with stress-based design check. Since wind and earthquake loads depend on site conditions, the scenario location is examined for structural analysis of generic models. For primary and reduced core building model cases, the building site is determined as Central Park region in New York, USA.

The wind governs the design on the structural systems since the buildings in this study are 300 meters in height which is categorized as supertall buildings by Council of Tall Buildings and Urban Habitat (CTBUH). Such a generalization is limited with the seismicity of the region. Since the generic buildings are assumed to locate in Central Park Region in New York, design wind loads create larger demands on building models than earthquake loads do. Thus, the structural systems of tall buildings are compared according to the top drift to building height ratio under design wind loads.

4.1. Comparison between outriggered frame buildings with primary and reduced core
The results summarized in table 4 verify that, as the service core is reduced, the maximum top displacement increases inevitably. Moreover, the ratio of moment-share between the structural components of the service core and the perimeter columns changes. When the core area is reduced, the lateral loads and accordingly the moments over the perimeter columns increases. Consequently, the structural system performance significantly reduces in terms of both stiffness and strength by the service core decrease.

| Load Combination for Wind | Outriggered Frame Primary | Outriggered Frame Reduced |
|---------------------------|---------------------------|--------------------------|
| Top Drift:                | 642.927 mm                | 787.406 mm               |
| Top Drift to Height Ratio:| 0.0021 (1/476)            | 0.0026 (1/385)           |

4.2. Comparison between framed-tube buildings with primary and reduced core
All the structural members of the framed-tube building with primary core satisfy the strength limit state under the wind and the seismic load combinations. However, 52 columns of the reduced core framed-tube building fail in satisfying maximum allowed steel percentage. The structural analysis results of the framed-tube buildings under the wind load combination is presented in table 5.

| Load Combination for Wind | Framed Tube Primary | Framed Tube Reduced |
|---------------------------|---------------------|---------------------|
| Top Drift:                | 630.325 mm          | 711.429 mm          |
| Top Drift to Height Ratio:| 0.0021 (1/476)      | 0.0024 (1/417)      |

5. Conclusions
The structural analysis results of outriggered frame and framed-tube buildings showed that, if the area of service core gets smaller due to the reduction in necessary elevator footprint area, the structure of tall buildings become more sensitive to wind and seismic induced loads. Thus, although more leasable area can be gained by the reduction of the core, it is necessary to strengthen the structural system of reduced core in order to resist wind and earthquake loads for a given level of safety equivalent to the primary core system in terms of top drift, which unavoidably reduced the additional leasable area for some extend. There are other trade-offs like the access to natural light for the area close to the reduced core because of the increase in lease span as well as perimeter columns with larger cross-sections. The comparisons among alternative structural systems, namely outriggered frame and framed-tube...
systems, revealed that the latter performs better than the former since the structural contribution of service core is inherently secondary in framed-tube buildings.

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