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Decision Framework for the Optimal Installation of Outriggers of Super-Tall Buildings

Zhou Kang[1], Li Qiusheng[1]
[1]Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong

Abstract：As the most important structural component of super-tall buildings, the installation sequence of outrigger system is often determined simply based on the experience of engineers, which may pose a threat to the structural safety and stability. This study proposes a complete decision framework to obtain the optimal installation plan for outrigger system, in which the construction simulation and safety analysis of the structural systems are well integrated. The proposed framework was applied to the second tallest building in China with total height of 600m. Firstly, the finite element method (FEM) model used for the construction simulation was validated by field measurements during typhoon 'Nida'. Subsequently, on the basis of the validated FEM model, the lower limits (earliest) for installing outriggers were obtained through the safety analysis of outrigger trusses during service stage, while the analysis of structural stiffness and global stability at the construction stage was performed for the determination of the upper limits (latest). Thereupon, the rational plan for installing outrigger system was established. The outcomes of this study are of great interest for structural engineers and researchers involved in the construction management of installing outriggers, and could provide valuable implication for other similar projects.

Keywords: Super-tall building; Decision framework; Optimized installation sequence of outrigger; Construction simulation; Structural safety and stability; Additional stress

1. Introduction

The rapid developments of materials, construction technologies and structural systems have given rise to significant increase of skyscrapers over the past decades. In general, there are two major issues dominating the structural design of skyscrapers, namely the top drifts and base moments of core-tubes under lateral loads, such as earthquake or wind loads [1]. It is noted that the outrigger system is considered one of the most effective structural systems to improve the overall structural lateral stiffness, which has been widely used in high-rise buildings [2]. Given the importance of outrigger systems in tall buildings, the installation sequence of the outrigger system is of great concern in the construction of tall buildings [3]. In practices, the installation of outrigger systems can be classified into three types, which are introduced briefly as follow:

(1) Installation of outriggers at the early construction stage

Installing an outrigger system at the early construction stage of a tall building can efficiently enhance the structural performance since the installed outrigger system could improve the structural stiffness and stability from the beginning of the construction. However, the accumulative differential deformation between external columns and core-tubes due to creep and shrinkage of concrete during the construction could result in increasing additional stresses in the outriggers, and thereby deteriorating the safety margin of outriggers during the long-term service stage [4].

(2) Installation of outriggers at the late construction stage

For this type of installation strategy, the installation of outrigger systems commences upon the completion of the core-tube and exterior-frame [5]. In this case, the additional stresses in the outriggers, induced by the differential deformations between the external columns and core-walls, can be eliminated considerably. Nevertheless, the absence of the outrigger systems during the construction stage may lead to the lack of the load-resisting system, which can therefore lead to the reduction of structural stiffness or structural stability, particularly for super-tall buildings [3].

(3) Experiential installation of outriggers during construction

To take into account of both the advantages and disadvantages arisen in the aforementioned two types of installation strategies, it is of great concern to come up with a compromise option. However, as no suitable guideline is readily available for the installation sequence of outriggers in practice, the procedure of installing outriggers is often determined simply based on the experiences of structural engineers or project managers [3]. It is worth noting that inappropriate installation plan of outriggers may cause safety risks during both construction and service stages, and it is therefore imperative to establish an effective procedure to determine the optimal installation plans of outriggers for high-rise buildings.

The objective of this study is to present a decision framework that combines the analysis of structural safety and stability during construction stage with the safety analysis of outriggers during service stage, which aims to identify the optimal installation plan for construction of outrigger systems in tall buildings. To the best knowledge of the authors, such a framework has not been proposed in the accessible documents. The remaining contents in this paper are structured as follows: Section 2 introduces the decision framework for determining the optimal installation plan of outrigger systems. Section 3 presents the application of the proposed method to the installation of outriggers into 600m-high Ping-An Financial Center (PAFC), and Section 4 summarizes the main findings of this study.

2. Methodology

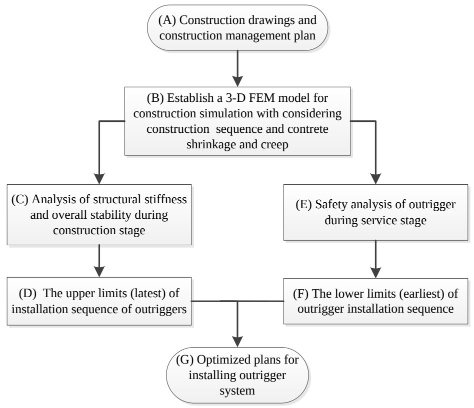


Fig. 1. Flowchart illustrating the methodology for optimized installation of an outrigger system.

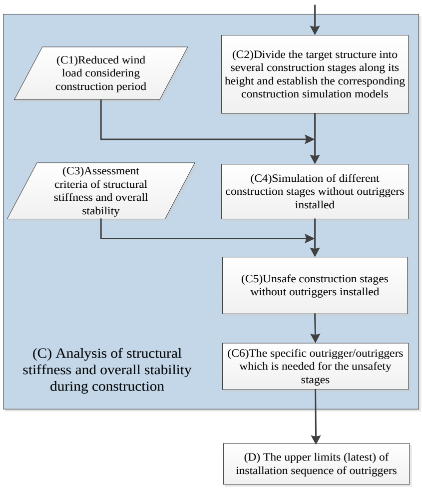


Fig. 2. Sub-Flowchart ‘C’ in Fig. 1.

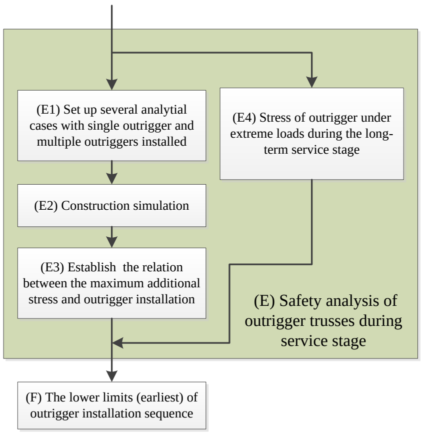


Fig. 3. Sub-flowchart ‘E’ in Fig. 1.

The decision framework presented in this section aims to provide an efficient and optimized design procedure of determining reasonable installation plan for the outrigger system, in which the construction simulation is embedded into the analysis of structural safety and stability. Fig.1 illustrates the flowchart for the methodology of this framework and the sub-charts in Fig.2 and 3 present the details involved.

The proposed framework is divided into three parts. In the first part, i.e., Sections ‘A’ and ‘B’ in Fig. 1, a three-dimensional (3-D) FEM model of the target building will be established according to the design and construction drawings. Meanwhile, the construction sequence, as well as the shrinkage and creep of concrete are also taken into account in the FEM model for construction simulations.

Next, in the Section ‘C’ of the framework, the structural safety and stability during construction stage will be examined, which attempts to facilitate the determination of the installation sequence of outriggers. As mentioned hereinbefore, the outrigger system is supposed to be installed as early as possible to ensure the structural stiffness and stability. Thus, the upper limits (latest) of installation sequence of outriggers can be obtained through the analysis of structural safety and stability during the construction stage as illustrated in Sections ‘C’ and ‘D’.

The third part of the proposed framework, including Sections ‘E’ and ‘F’ in Fig. 1, aims to guarantee the safety of the outrigger system at service stage given the fact that the stress state of outriggers continues to vary at the service stage, while those of core tube and external columns remain stable. The primary safety concern for the installation of outriggers is the additional stresses of outriggers caused by the differential deformations between external columns and core-walls. If outriggers are installed earlier, the additional stresses existed in outriggers would increase, which consequently leads to the deterioration of the safety of the outriggers during service stage. Hence, the lower limits (earliest) of installation sequence of outriggers can be determined through the analysis of the safety of the outriggers during service stage.

Accordingly, the optimized installation plan for an outrigger system can be obtained by integrating the lower and upper bounds of installation sequence of outriggers in terms of structural safety and stability at both construction and service stages.

3. Analysis of the outrigger installation sequence for PAFC

In this section, the proposed framework is applied to determine the optimized installation sequence of outrigger at PAFC. PAFC is a 118-story building with a total structural height of 600m, which has a mega-frame core tube structure. The core-tube and the mega columns are connected by the four outrigger trusses at different levels (Fig.4) to improve the lateral stiffness and the overall integrity of the super-tall building.

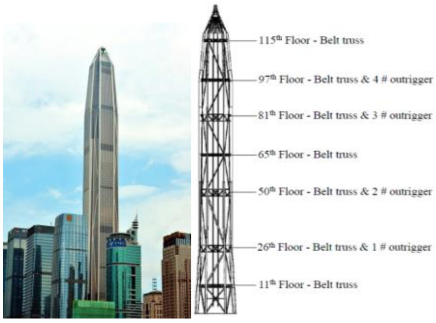


Fig. 4. Overall view and layout plan of outriggers of PAFC

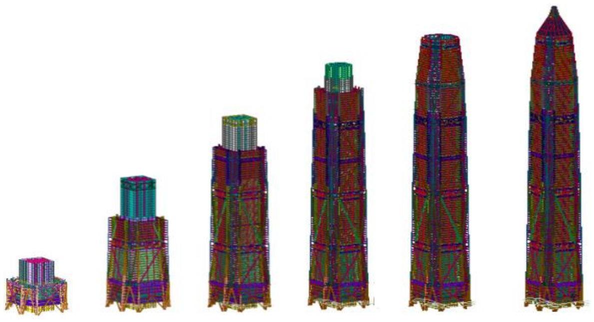
3.1 FEM model of PAFC and its validation

A finite element method model of PAFC, as shown in Fig. 5, was established in this study. To account for the effects of concrete creep and shrinkage, CEP-FIB Model Code (1990) [6] was adopted according to the suggestion of Chen [7].

Table 1. Measured and calculated natural frequencies of PAFC

Modes (Hz)	Sway modes				Rotational modes	
	Direction X		Direction Y			
	Mode 1	Mode 2	Mode 1	Mode 2	Mode 1	Mode 2
Measured	0.120	0.403	0.122	0.417	0.283	0.708
Calculated	0.138	0.442	0.142	0.450	0.325	0.767
Difference	13.0%	8.8%	14.1%	7.3%	12.9%	7.7%

To validate the FEM model, field measurement study of the wind-induced vibrations of PAFC during super typhoon 'Nida' (No. 201604) were implemented and the data were analyzed to determine the dynamic properties of PAFC. The natural frequencies determined from field measurement study and numerical simulation are compared in Table 1, in which the discrepancies were about 7% to 14%. It can therefore be reasonably assumed that the FEM model is valid. Additionally, to describe the actual construction sequence of PAFC, a total of 28 consecutive construction stages, were modelled step by step, and among which seven models at service stage of 1-, 2-, 5-, 10-, 20-, 50- and 100-service year were constructed to investigate the long-term effects of concrete shrinkage and creep.



CS-5 CS-10 CS-15 CS-20 CS-26 CS-28

Fig. 5. Construction sequence models at different stages

3.2 Analysis of structural stiffness and overall stability during construction stage

The structural performance of each construction stage without outriggers installed is assessed and the structural stability and stiffness results are given in Table 2 and Fig. 6. It can be seen from Fig. 6 that the structural stiffness can well satisfy the requirements specified in Chinese code during the whole construction without outriggers installed. However, stages 23 and 28 were identified as the unsafe construction stages without outriggers installed. To further examine the structural instability at stages 23 and 28, the installations of the 1#, 2#, 3# and 4# outrigger at stages 23 and 28 were analyzed in detail, and the results are given in Table.2. It shows that, 1# or 2# outrigger should be installed at the beginning of stage 23 to ensure the structural safety during the whole construction stage. Therefore, the upper bounds (latest) for installing outrigger of PAFC are determined on basis of the analysis of structural stiffness and overall stability during construction stage.

Table 2. Structural stability assessment of different construction stages

Construction stage	Outrigger	Stiffness to gravity ratio		Structural stability
		X-dir.	Y-dir.	
CS-23	none	1.37	1.36	Unstable
CS-28	none	1.35	1.34	Unstable
CS-23	1#	1.43	1.41	Stable
	2#	1.46	1.45	Stable
	3#	1.41	1.39	Unstable
	4#	1.39	1.38	Unstable
CS-28	1#	1.42	1.40	Stable
	2#	1.45	1.44	Stable
	3#	1.40	1.38	Unstable
	4#	1.38	1.37	Unstable

*According to Chinese design code, ratio of rigidity-to-gravity shall be larger than 1.40 to guarantee structural stability.

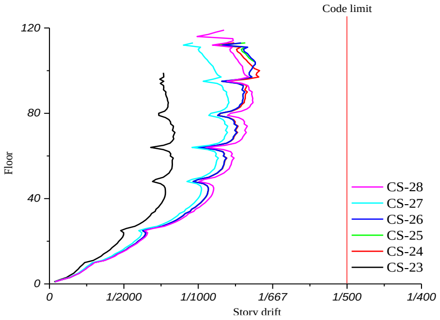


Fig. 6. Structural stiffness examination for wind load of different construction stages without outriggers

3.3 Safety analysis of outrigger during service stage

In order to ensure the safety of outrigger trusses during service stage, the specification of the additional stress in outriggers is given as follows.

$$S + S_{add} \le R \tag{1}$$

where S is stress of outriggers under extreme loads during service stage; S_{add} is the additional stress of outriggers caused by differential vertical deformations between the exterior columns and the core tube, and R is the strength of material.

The relations between the maximum additional stresses and installation sequences of outriggers are illustrated in Fig. 7. And the stress in outriggers subjected to extreme loads during the service stage is presented in Table 3, together with the strength of material. Thus, in order to prevent the occurrence of overstresses in outriggers, 1# and 2# outriggers should not be installed earlier than the construction stages of the 76th and 84th floor, respectively; while 3# and 4# outriggers can be installed at their earliest stage, namely at the construction stages of 100th and 107th floor, respectively.

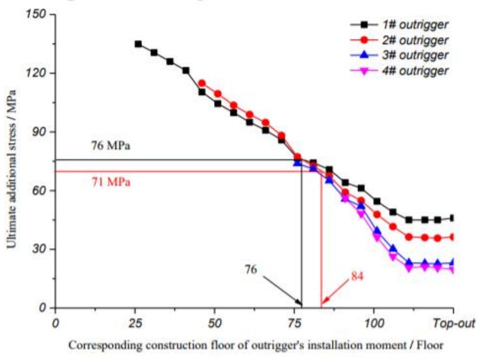


Fig. 7. Relations between the maximum additional stresses and installation sequence

Table 3. Stresses and strength of material of outriggers (MPa)

	Steel specification	R	S	R-S
1# outrigger	Q460GJ	340	264	76
2# outrigger	Q460GJ	340	269	71
3# outrigger	Q420GJ	305	193	112
4# outrigger	Q420GJ	305	117	188

3.4 Rational installation schedule for outrigger and its verification

Based on the above analysis, the lower (earliest) installation limits of outriggers can be obtained from the analysis of the safety of outrigger trusses at the service stage, while the upper limits are determined from the analysis of structural stiffness and overall stability during the construction stage. Consequently, the optimized installation plan for outrigger system are listed in Table 4, which are expected to be capable to commendably guarantee structural safety and stability in both construction and service stages.

Table 4. The optimized installation plan for outriggers

1# outrigger	[76th floor a, 115th floor]
2# outrigger	[84th floor, 115th floor]
3# outrigger	[81th floor, 118th floor]
4# outrigger	[97th floor, 118th floor]

4. Concluding remarks

This paper presents the establishment of a complete decision framework that combines the structural safety and stability analysis during the construction stage with the safety analysis of outriggers during the service stage, which aims to obtain the optimized installation sequence for outrigger system. The proposed framework was adopted for the determination of optimized installation sequence of outrigger system for PAFC. An elaborate 3D FEM model of PAFC was constructed and its accuracy was validated by field measurement data obtained during typhoon ‘Nida’. Subsequently, on the basis of the validated FEM model, the lower limits (earliest) for installing outriggers were obtained through the safety analysis of outrigger trusses during service stage, while the analysis of structural stiffness and global stability at the construction stage was performed for the determination of the upper limits (latest). The outcomes of this study are of great use for structural engineers and researchers involved in the construction management of outrigger installation, and provide valuable implications for many other similar super-tall buildings.

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