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ADVANCES IN STRUCTURAL OPTIMIZAITON OF TALL BUILDINGS IN HONG KONG

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Abstract

Transforming structural optimization theory into design practice of realistic civil engineering structures has always been regarded a difficult task. Under the research efforts conducted over the past few years at the Hong Kong University of Science and Technology (HKUST), a novel computer based optimization technique has been developed for the structural design of practical tall buildings subject to lateral stiffness and serviceability design performance constraints. The technique developed is applicable to a wide spectrum of types and forms of large-scale tall building structures in which steel, concrete, or a combination of mixed or composite steel and concrete may be considered as construction materials. While aiming towards the most economical element sizes of a tall building structure, the optimal design technique also ensures a minimum impact on the use of floor areas. The effectiveness and practicality of the optimization technique developed have been demonstrated through actual applications to the design of a number of tallest buildings in Hong Kong. This paper presents the recent advances and applications of the state-of-the-art optimization technique and points to on-going and future research developments.

Keywords: Tall Building Design, Optimality Criteria, Genetic Algorithms, Drift and Serviceability.

1. Introduction

Hong Kong is one of the world's most densely populated cites where tall buildings are a necessity. Nearly all of Hong Kong's more than seven million people live or work in high-rise buildings. Tall buildings have dominated the skyline of Hong Kong (Figures 1 and 2). Three of the world's first ten tallest office buildings and half of the world's 100 tallest residential buildings are located in Hong Kong. The continuing need for more commercial and residential space has resulted in high land costs and property prices. Structural engineers in Hong Kong have to face the challenge of not only designing safe and functional buildings in a relatively short time, but also ensuring that the design produced must be most economical.

Fig. 1 Hong Kong Skyline

Fig. 2 Typical Hong Kong Buildings

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Geographically, Hong Kong is situated in a typhoon-prone, but low seismic region. Wind loading is therefore the major factor governing the structural design of most buildings in Hong Kong. Previous studies [1,2] have indicated that wind loading in Hong Kong can get as high as twice those required in Chicago and four times the seismic force requirements used in Los Angeles. As modern buildings get taller and increasingly slender, the effects of wind-induced motions become more pronounced and the amount of structural materials required for lateral resistance and serviceability comfort increases drastically [3]. In fact, the design of tall buildings in windy climates is generally dominated by serviceability considerations in terms of wind-induced deflections and vibrations, rather than by member strength requirements.

Although it has long been realized that wind-induced dynamic serviceability and lateral stiffness are generally the major concerns in the design of tall buildings, research in structural design has not received as much attention as that for ultimate strength design of such structures. During the past several years much effort has been devoted at the Hong Kong University of Science and Technology in formulating an innovative effective optimization approach for tall building design. Such effort has resulted in a novel integrated computer system called OPTIMA, capable of working with existing structural engineering analysis software and producing optimal element sizes for tall buildings to satisfy all wind-induced serviceability design performance criteria in accordance with various building codes and practical constructability requirements. While aiming towards the most economical use of structural materials in tall buildings, OPTIMA also considers other cost factors associated with the impact to usable floor areas, architectural aesthetics, the quality of living space and comfort, and construction methods.

This paper presents the recent advances in structural optimization of tall buildings in Hong Kong. An overview of the optimal design problem formulation and optimization techniques developed for solution will be summarized with recent practical applications to a number of actual tallest building projects in Hong Kong. Recent research developments as well as outlook for future work in advancing design optimization for tall building design will also be discussed.

2. Tall Building Design Problem Formulation

Tall buildings are large-scale structures requiring enormous private and public investments. One major role of the structural engineer is to develop an efficient structural system that is safe for its intended life and serviceable for its intended function. Creation of the lateral stability system for a tall building is the first and most challenging task for a structural engineer. Typically several preliminary structural schemes for a building may be proposed at an early design phase and the final system is then decided after a careful evaluation on the cost efficiency of each scheme. Once the structural form of a building is established, the major effort is to size the structural members to satisfy all safety and wind-induced stability and serviceability design requirements. For a general tall building structure composed of $i_s = 1, 2, .., N_s$ skeletal steel, $i_c = 1, 2, .., N_c$ concrete frame elements and $i_t = 1, 2, .., N_t$ concrete shear wall panels, the optimal element sizing design can be formulated as follows.

$$\text{Minimize } \ \text{Cost}(A_{i_s}, B_{i_c}, D_{i_c}, t_{i_w}) = \sum_{i_s=1}^{N_s} w_{i_s} A_{i_s} + \sum_{i_c=1}^{N_c} w_{i_c} B_{i_c} D_{i_c} + \sum_{i_w=1}^{N_w} w_{i_w} t_{i_w}$$

Subject to:

$$\frac{\delta_l^{top}}{H} \le d_l^U \qquad (l = 1, 2, .., N_l) \qquad \text{- Top drift constraints}$$

$$d_j = \frac{(\delta_j - \delta_{j-1})}{h_j} \le d_j^U \qquad (j = 1, 2, .., N_j) \qquad \text{- Interstorey drift constraints}$$

$$\ddot{\delta}_l \le a_l^U \qquad (l = 1, 2, .., N_a) \qquad \text{- Wind induced acceleration constraints}$$

$$\sigma_p \le \sigma_p^U \qquad (p = 1, 2, .., N_p) \qquad \text{- Element strength constraints}$$

$$A_{i_s}^L \le A_{i_s} \le A_{i_s}^U \qquad (i_s = 1, 2, .., N_s) \qquad \text{- Steel element sizing constraints}$$

$$B_{i_c}^L \le B_{i_c} \le B_{i_c}^U \qquad (i_c = 1, 2, .., N_c) \qquad \text{- Concrete element width sizing constraints}$$

$$D_{i_c}^L \le D_{i_c} \le D_{i_c}^U \qquad (i_c = 1, 2, .., N_c) \qquad \text{- Concrete element depth sizing constraints}$$

$$t_{i_w}^L \le t_{i_w} \le t_{i_w}^U \qquad (i_w = 1, 2, .., N_w) \qquad \text{- Concrete wall thickness sizing constraints}$$

The design objective is to minimize the structure cost in which steel or concrete elements should have different values of unit cost coefficients that reflect the corresponding costs of materials. Horizontal beams and vertical columns having the same construction material may have different associated unit cost coefficients since they have different impact on the use of floor space. Since tall building design is generally controlled by serviceability stiffness requirements, member strength constraints can be considered as secondary constraints and need not be listed in the set of design constraints. In view of the fact that element strength constraints are local design requirements, they can be handled separately by a member-by-member design approach and the so-determined strength based element sizes can then be used as the lower limit of element sizes for the system level serviceability drift and acceleration design.

The primary design constraints to be considered in structural design of tall buildings involve the static wind drift and dynamic wind-induced accelerations. While the wind drift is related to the stability design consideration, the suppression of wind-induced accelerations is associated with motion perception serviceability design in tall buildings. To facilitate a numerical solution of the design optimization problem, it is necessary that the implicit drift and acceleration constraints be formulated explicitly in terms of design variables. Adopting regressional relationships for linking cross sectional properties as a function of cross section area A_{is} for steel sections [4, 5] and expressing concrete sectional properties in terms of a section's width B_{ic} and depth D_{ic}, and wall thickness t_{iw} [6] the drift constraints can then be formulated explicitly, using the principal of virtual work. Based on random vibration theory, the standard deviation of acceleration responses of a building can be obtained from the wind tunnel derived wind load spectra and expressed explicitly in terms of frequency via regression analysis. Once the explicit relationships between the wind induced acceleration and the natural frequencies of a building are established, the targeted minimum frequencies of the building can then be determined and written in a form of energy expressions in explicit terms of cross sectional design variables using the Rayleigh Quotient method [7, 8].

3. Optimization Methodology

In the context of tall buildings, one of the most challenging problems in structural optimization is to develop the capability to efficiently handle very large-scale structures with a large number of design variables and constraints. Moreover, it is also essential that the optimization algorithm must be generalized for various types of building structures. For practical applications to modern tall buildings, it is also important that the optimization technique be able to handle the use of different construction materials and to generate practical discrete member sizes.

The methodology for the solution of the explicit design problem of tall buildings is fundamentally based on the Optimality Criteria (OC) approach, which has gained much attention due to its high efficiency in solving large scale problems. In this approach, a set of necessary optimality conditions for the optimal design is first derived and a recursive algorithm is then applied to indirectly achieve the optimum by satisfying the optimality conditions. The OC approach is particularly suitable for large-scale tall building structures involving many design variables but yet relatively few active lateral stiffness design constraints. The efficiency of the OC optimization methodology is mainly influenced by the number of design constraints and is only weakly dependent on the number of design variables. Rapid and steady solution convergence is often found since the energy based formulation of the serviceability drift and acceleration design constraints has exploited to advantage the peculiar behavior of building structures, which globally behave as vertical cantilever framework such that the member force distributions for such structures are somewhat insensitive to moderate changes in member sizes. [5, 6, 8, 9].

While quick convergence can be normally achieved using the OC technique, it cannot always assure that the global optimum can be found. Advances in recent research have resulted in a hybrid methodology, namely the OC-GA method, which incorporates Genetic Algorithms (GAs) into the gradient based OC technique. The evolutionary GAs are in general more robust and present a better global behaviour than the OC. However, GAs alone may suffer from a slow rate of convergence towards the global optimum. In order to benefit from the advantages of both OC and GAs, a hybrid combination of both methodologies has been developed and thus the so-called OCGA method as an attempt to improve the robustness as well as the computational efficiency of the optimization procedure [10].

4. Optimization Software - OPTIMA

Under the recent research efforts conducted at HKUST, a novel computer system called OPTIMA has been developed for the optimal structural design of tall buildings. OPTIMA represents the first-of-its-kind computer system that is capable of working with most existing structural engineering analysis software and producing optimal element sizes for tall buildings to satisfy all design performance criteria in accordance with various building codes and practical constructability requirements.

The optimization methodology used in OPTIMA is based on a number of rigorously derived numerical algorithms such as Optimality Criteria Method, Genetic Algorithms, exhaustive searching, or their combinations. Depending on the specific behavior of a building structure, the most suitable numerical procedure will be automatically sought to achieve a smooth solution convergence. The design synthesis process involves recursive applications of structural analysis and design optimization processes. Both two and three dimensional symmetrical and torsionally asymmetrical building structures can be considered under multiple static and dynamics loading conditions. In addition, the optimisation technique is applicable to a wide spectrum of types and forms of large-scale tall building structures in which steel, concrete, or a combination of mixed or composite steel and concrete may be considered as construction materials.

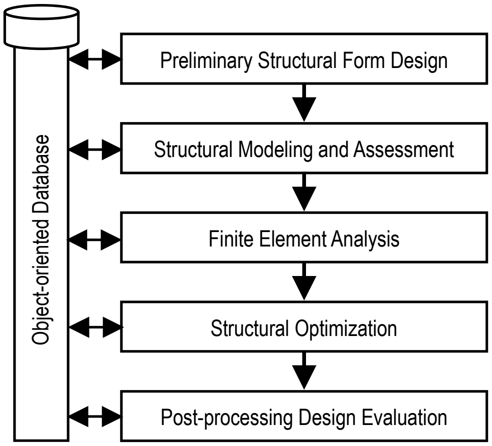

Fig. 3 Integrated Design Work Flow

OPTIMA has been based on an integrated system approach as outlined in Fig. 3 [11]. Major features of OPTIMA include: an object-oriented centralized database, advanced information gateway with existing finite element software, interactive graphical interfaces for high-level data management and modification, automated optimal design synthesis subject to static and dynamic wind-induced effects, intelligent post-processing design evaluation module for model checking and behavioral response visualizations of tall buildings.

5. Practical Tall Building Applications

The effectiveness of the computer aided structural optimization technology has been well proven through a number of landmark building projects in Hong Kong. Table 1 and Fig. 4 present a spectrum of selected buildings that have been optimized in the past few years using OPTIMA. Buildings optimized include: the 102-stoey Kowloon Mega Tower (the world's second tallest building being currently under construction), the 88-story Two International Finance Centre (currently the tallest building in Hong Kong) and the 75-story Sorrento Tower 1 (the tallest residential building in Hong Kong). Not only has the optimization technology demonstrated its effectiveness on supertall building structures, but also it has been shown to work well with typical medium-rise 41-story public housing blocks in Hong Kong. In general, savings of 10-30% in structural material cost and 1-5% increase in useable floor space have been achieved. More detailed results of some of the prominent building projects have been reported at a number of international and regional conferences [12, 13, 14].

Table 1 List of Building Projects Optimised by OPTIMA

Notable Projects	Building Height	Construction Material	Structural Form
Kowloon Mega Tower	474 m	Composite Steel and Concrete	Outrigger Braced System
Two International Finance Center	420 m	Composite Steel and Concrete	Outrigger Braced System
URA Project K11, Tsimshatsui	274 m	Composite Steel and Concrete	Outrigger Braced System
Sorrento Tower 1	255 m	Concrete	Coupled Shear Wall and Frame
The Harbourside Development (3 towers)	242 m	Concrete	Coupled Shear Wall and Frame
Victory Arch Development (2 towers)	230 m	Concrete	Coupled Shear Wall and Frame
Park Central Development (10 towers)	173 m	Concrete	Coupled Shear Wall and Frame
Cambridge House Development	161 m	Composite Steel and Concrete	Outrigger Braced System
Housing Authority Standard Housing Blocks (Harmony, Concord and New Cruciform Blocks)	125 m	Concrete	Coupled Shear Wall

Fig. 3 Selected Building Projects Optimized by OPTIMA

To demonstrate the effectiveness of the optimization technique developed, the results of three representative keynote building projects are briefly highlighted as follows.

Kowloon Mega Tower Tower

At a height of 474 m, the 102-story tower will be the world's second tallest building when complete by 2007. The tower comprises a reinforced concrete core with composite steel encased concrete mega-columns and steel outriggers at four different floor levels. The key challenges of this project were working with the lateral stiffness design of a complex outrigger braced structural systems and distributing the most cost effective material distribution of the structural system that uses a combination of structural steel, reinforced concrete and composite steel and concrete materials whilst taking due consideration of the impact to the usage of floor space. Not only did the optimization technique developed minimize the construction material cost, but it also maximized the value of floor space occupied by vertical walls and columns [13].

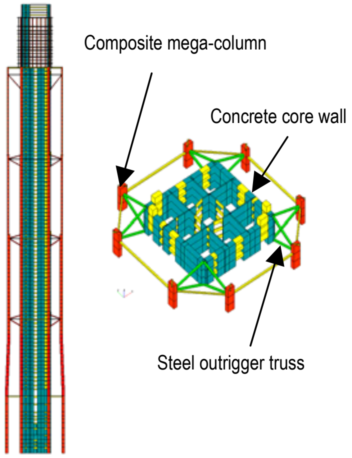

Fig. 4 Computer Model of Kowloon Mega Tower

The Harbourside Development

This project represents one of the largest single building structure in Hong Kong which is composed of three 69-storey towers monolithically linked together above a six-level podium. The building provides a total residential floor area of some 129,000 m^2 and is currently the second tallest residential building in Hong Kong. The lateral load resistance of the three towers is basically provided by a reinforced concrete coupled shear wall system supported on a podium framework. To maximize the frontal harbour view, the building was imposed to have a long dimension of 125m and an extremely narrow width of 25 m. Such a peculiar building shape imposes a greater challenge to the task of optimizing the structure with strongly coupled swaying and torsional effects. Compared to the initial design, the optimized final design resulted in significant savings in over 11% of the total material quantity and an average increase of 2.5 m2 usable floor area in each flat unit [15].

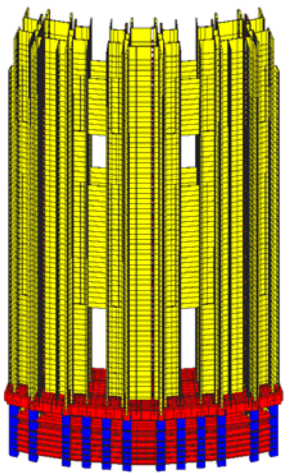

Fig. 5 Computer Model of Harbourside Development

Park Central Development

This development consists of a cluster of 10 building blocks ranging from 47 to 49 stories. Although these buildings are not very tall in height, they have resulted in remarkable optimization findings by allowing for structural layout changes using the novel hybrid OC-GA technique. Initially the building structure was developed based on a coupled shear wall system which forms a tic-tac-toe shape on plan. The hybrid OC-GA method recommends removing inefficient structural elements and creating new ones so as to result in the most optimal spider web form with minimized element sizes and maximized internal usable floor areas. It is evident that structural form optimization allows for more significant cost savings and more efficient use of floor space.

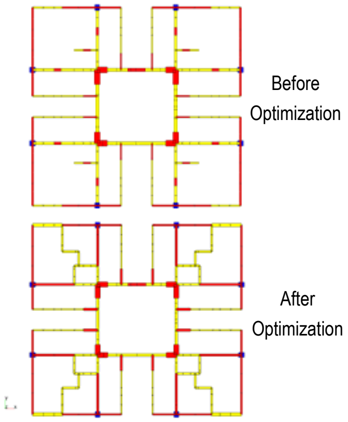

Fig. 6 Floor Plan of Park Central Development

6. Recent Advances and Future Outlook

Although remarkable progress has recently been made in element sizing optimization of tall buildings by which optimized large-scale structural designs can be achieved for a variety of loadings, material types and structural systems, further research efforts are still needed in the field of high performance computing and structural optimization of tall buildings. The following are only a few focused areas recently being researched by the author and his associates at HKUST.

Nonlinear Stiffness Optimization

Cracking is an inevitable phenomenon in reinforced concrete buildings due to the low tensile strength of concrete. The cracking of structural concrete generally leads to a reduction in the lateral stiffness of a tall building and thus to an increase in the lateral deflection of the building. Analysis and design of reinforced concrete structures are currently carried out on the basis of linear elastic theory by either neglecting the nonlinear effects of concrete cracking or considering these effects somewhat arbitrarily by reducing the flexural stiffness of cracked members. Although the use of nonlinear finite element analyses has allowed significant advancement in determining stiffness characteristics and calculating deflections of reinforced concrete structures, most of these nonlinear methods are computationally expensive and time consuming in the context of large-scale tall reinforced concrete buildings. Recently, Ning et al [16] presented a probability-based effective stiffness model to determine the relationship between flexural stiffness reductions and various bending moment profiles due to loading on the members. The most significant feature of the proposed effective stiffness model is its extensive applicability to members that are subjected to various types of loads. A practical cracking analysis procedure is established by integrating the proposed effective stiffness model and iterative algorithms with commercially available linear finite element analysis software, which can predict quantitatively the lateral deflection and nonlinear stiffness characteristics of reinforced concrete building structures under service loading conditions [17]. Very recently, Chan and Wang [18] have developed an effective numerical optimization approach for the stiffness-based optimum design of tall reinforced concrete buildings under service lateral loads, which takes into account the nonlinear stiffness characteristics after the cracking of concrete.

Performance Based Design Optimization

Performance-based design is a modern approach to seismic engineering, in which the design aim is to deliver a structure capable of meeting certain predictable performance objectives under different levels of earthquake motions, and the final design should be a good balance between the initial construction cost and the financial loss expectation occurred during the life time of the structure. According to the newly developed performance-based seismic design approach, an acceptability analysis needs to be conducted at various design load levels in order to ensure that the corresponding performance objectives are satisfactory. The acceptability checking procedures may employ various linear or nonlinear, static or dynamic analysis methods to assess the seismic responses of structures in relation to the acceptable design criteria. In the event of moderate and severe earthquake events, it has become important in identifying the patterns and levels of damage to assess a structure’s inelastic behavior and to understand the modes of failure using nonlinear analysis methods. Although there exist powerful finite element software for precise prediction of dynamic seismic responses of structures, structural optimization of large-scale building structures for various levels of elastic and inelastic seismic performance under multiple levels of earthquake events is generally a challenging and difficult task. Recent attempts have been made to develop an automatic optimal elastic and inelastic seismic drift design of concrete framework structures [19 - 21] and base-isolated building systems [22]. Research in the past normally expressed dynamic response performance constraints by calculating sensitivity derivatives of equations of motion with respect to design variables. Such a sensitivity formulation may be straightforward; but it requires enormous instantaneous sensitivity computations and may lead to divergent solution fluctuations. Our recent studies have shown that a more stable seismic drift responses modeled by various response spectrum, time history and pushover analysis methods can be formulated accurately by the Principle of Virtual Work [19-21].

Structural Form Optimization for Improving Economical and Environmental Sustainability

Sustainable green building design is now an emerging direction for the Hong Kong construction industry. Indeed sustainable development is on the global agenda, its basic idea being to balance the economical, environmental and social needs but not at the expense of future generations. Building construction, currently the major consumption of natural resources and energy has to fit in the context of sustainability. When designing a large-scale high-rise building, it is necessary to not only minimize construction cost, but also to ensure for most efficient energy use in its operation life. Natural ventilation and day-lighting are two important green features in establishing the structural form of residential buildings in the urban context of high-rise and high-density and, in Hong Kong, the humid environment. In this research endeavor, efficient energy considerations are incorporated in the design synthesis of the structural form of high-rise residential buildings. Structural form is the topological arrangement of structural elements like walls, columns and beams in a building. Its primary function is to provide strength, stability and resistance to withstand gravity loading and seismic and wind actions. It has long been recognized that a good structural form design can lead to more efficient design that could be impossible with traditional member sizing optimization. When conceptualizing the structural form within the general architectural layout of a building, it is important to realize that irremovable structural elements could significantly affect the functional use of floor areas and the indoor environment of the building. Although traditionally structural engineering and building services are two separate fields in the building industry, the integrated design optimization of the two has clear advantages in improving economical and environmental sustainability of large-scale high-rise buildings.

7. Conclusions

Structural optimization is an advanced computational technique, which replaces the traditional trial-and-error design procedure by a systematic goal-oriented design synthesis process. Remarkable progress has been made on developing an optimization procedure for element sizing optimization of practical tall buildings. The effectiveness of the state-of-the-art optimization software OPTIMA has been well attested through applications to the design of numerous tallest building projects in Hong Kong. While some initial successes in practical structural optimization have been demonstrated in the lateral stiffness and serviceability design of tall buildings, research is still needed to advance the field of structural optimization to further develop innovative techniques for a wider spectrum of design problems associated with practical engineering of buildings.

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