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Performance Based Optimal Design for Supertall Building Structures – A Life Cycle Methodology

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Abstract

The traditional design method for super tall building structures simply omits the different structural states during the construction stage, and assumes that after the construction stage, there is only one structural state across the whole service life. Additionally, a super tall building structure has high impacts on the environment due to its huge material consumption. The high environmental impacts are also not covered in current design practices since only economic costs are considered by the traditional design method. Thus a super tall building structure can hardly reach its optimal performances across the whole life cycle by using the traditional design method. A life cycle methodology (PBOD-LCM) is proposed in this paper for the performance based optimal design of super tall building structures, aiming to minimize the economic and environmental costs with optimal structural performances across the whole life cycle. The concepts, frame and critical aspects of PBOD-LCM are thoroughly addressed in this paper, and should be considered for future projects.

Keywords: Embodied carbon objective, life cycle methodology, performance based optimal design, super tall building structures, time slice approach, time-dependent analysis

Introduction

Structural design can be divided into feasible design and optimal design. The feasible design doesn't consider the structural costs. It only meets some certain performance goals. Therefore, feasible design often has great redundancy and leads to the waste of building materials, manpower resources, etc. The process of simple optimization to an existing feasible design with great redundancy is called design optimization. However, the concept of optimal design is not equivalent to design optimization. Design optimization is a process to optimize an existing feasible design, while optimal design aims to find a structural solution to meet performance goals with minimal costs.

Compared with feasible design, the optimal design can reach the best structural scheme. Optimal design can quantify design efficiency through specific indicators, such as minimum structural volume, lightest structural weight, and minimum structural cost. Then the optimal design is closely linked to the building design and is checked by mathematical models. This converts the design problem into a strict optimization problem. With the aid of advanced computation analysis tools, the best structural scheme can be achieved.

The structural optimal design is part of the research of structural design methods, which can systematically improve design efficiency. The aim of structural optimal design is to help civil engineers design more efficient structures under the premise of meeting safety goals. The progressiveness of optimal design is not driven by the use of an optimization algorithm, sensitivity analysis or other optimization technical means, but by the changes of design ideals. Feasible design only emphasizes the feasibility of design results, but the optimal design focuses on the optimization of design results. That is to say, the progressiveness of design ideas determine the progressiveness of optimal design methods (Dong, 2015).

Traditional design is a feasible design meeting the requirements of design codes. It doesn't consider the time-dependent performances of structures and structural costs across the whole life cycle. Therefore, based on the traditional single-dimensional structural performance, this paper adds the dimensions of time and structural cost (see Figure 1). A new design approach, called "PBOD-LCM, integrating the Performance Based Optimal Design and Life Cycle Method", is introduced in this paper for the performance based optimal design of super tall building structures, aiming to minimize the economic and environmental costs with optimal structural performances across the whole life cycle. In other words, PBOD-LCM is an optimal design meeting the requirements of time-dependent performances and with minimum structural costs across the whole life cycle.

PBOD-LCM relates to three dimensions, namely, time, structural performance and structural cost. The time dimension includes time-dependent features of super tall buildings (time-dependent materials, time-dependent structures and time-dependent loads), time-dependent effects analysis methods, time-dependent effects construction control, time-dependent effects monitoring and structure remaining service life. The structural performance dimension includes seismic performances and wind performances (strength, stiffness and building comfort). The structural cost dimension includes economic costs and environmental costs. In fact, these three dimensions are not completely independent, but are interrelated. For example, the structural performance of PBOD-LCM considers time and structural cost, namely, it is time-dependent performance. The structural cost of PBOD-LCM also considers time, namely, its structural cost across the whole life cycle. The three dimensions constitute the frame of PBOD-LCM (see Figure 1).

PBOD-LCM is a new design idea and method, it includes life cycle design, and performance based design and optimal design. Based on this concept, framework and its critical aspects, this paper clarifies the specific meaning and significance of PBOD-LCM in detail in engineering design practices.

Basic Concepts

Life Cycle Design

The time-dependent features of super tall buildings consist of the time-dependent features of settlement and the time-dependent features of superstructure, which both are related to three factors, namely, time-dependent materials, time-dependent structures and time-dependent loads (Zhang, 2011).

The time-dependent effects analysis methods include elastic time-dependent effects analysis and inelastic time-dependent effects analysis. The traditional inelastic time-dependent effects analysis only uniaxially considers the impact of time-dependent deformation for time-dependent internal structural forces. In fact, the inelastic deformation between different members will affect the internal forces distribution. Meanwhile, the redistribution of internal forces will again affect the inelastic deformation. The circulation between time-dependent deformation and time-dependent internal structural forces can be called coupling effects (Yu, 2013). The impacts of these coupling effects on internal structural forces and deformation cannot be ignored.

The time-dependent construction control effects of super tall buildings mainly includes three parts; elevation control, preceding construction of central service core, and lock-in scheme of outrigger system (Liu, 2011). Firstly, elevation control means the structural vertical deformation pre-compensation, aiming to meet elevation accuracy of buildings. Secondly, the construction of the central service core means the core is ahead of the outer frame to ensure structural safety and stability. Thirdly, the lock-in scheme of the outrigger system means controlling the lock-in order of outrigger trusses, aiming to release the secondary internal forces of horizontal members to maintain structural safety.

Based on the complexity of the time-dependent effects, the time-dependent health monitoring has become one of the indispensable analyses and design methods for super tall buildings (Yan, 2015). The health monitoring contents of super tall buildings include climate and environment monitoring, structural load monitoring and structural response monitoring.

The structural design service life refers to the predetermined service years of structures. In order to achieve the life cycle performance based design, the load response, structural resistance and reliability over different times need to be calculated and checked. In PBOD-LCM, the concept of structural service life is proposed. The structural service life refers to the differences between structural design service life and structural past service life (Jiang, 2014). The equation is as follows:

$$T_S = T_L - T_i \quad (1)$$

In Equation 1, T_S is the structural service life, T_L is the structural design service life and T_i is the structural past service life.

In addition, the life cycle design includes economic costs and environmental costs across the whole life cycle. The economic costs across the whole life cycle are mainly composed of the construction, maintenance and property lost due to structural failure in case of a disaster (Jiang, 2014). The previous study has already put forward that the optimization objective is to minimize the life cycle cost (Frangopol & Liu, 2007). Experts in China and other countries conducted a thorough study on the theoretical and analytical models (Wen & Kang, 2001). The analytical model equation is given by:

$$C_{tot} = C_b + C_m + C_f \quad (2)$$

In Equation 2, C_b represents construction cost, C_m is maintenance cost, and C_f is the loss cost. Life cycle carbon emissions include embodied carbon, operation carbon and end-of-life carbon, in which the end-of-life carbon includes the demolition carbon emissions and recycling carbon emissions. Embodied carbon of structural systems contributes to the most carbon emissions during the

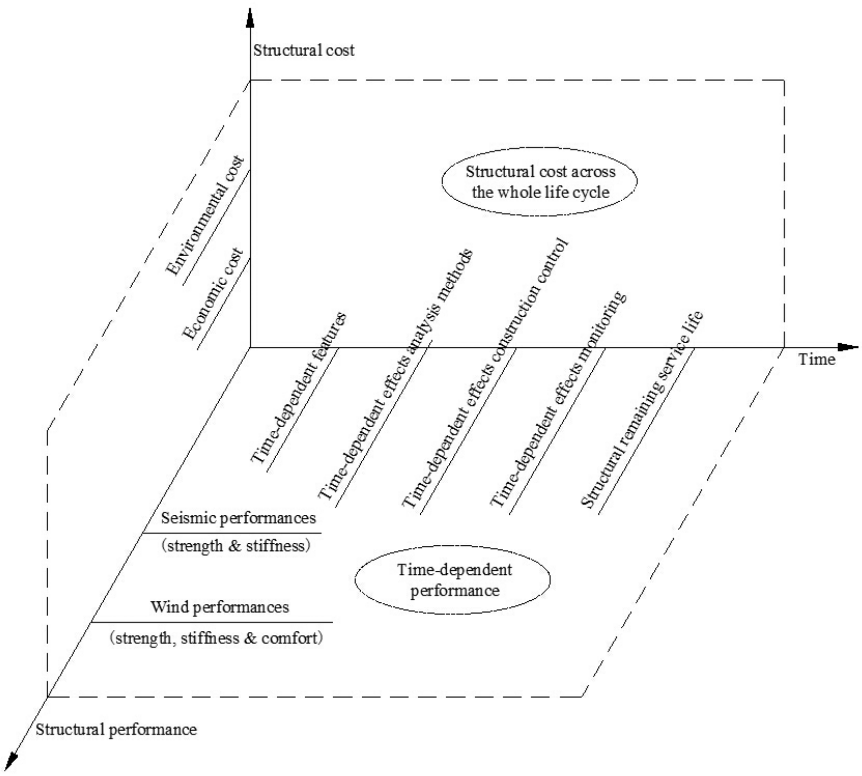

Figure 1. PBOD-LCM relates to three dimensions, namely, time, structural performance and structural cost. This is the relationship diagram of three dimensions in PBOD-LCM (Source: Shehong Liu)

Return Period of Earthquake / Year	Construction Stage			Service Stage		
	Deformation	Strength	Stability	Deformation	Strength	Stability
5	√					
10		√	√			
50				√	√	√
475				√	√	√
2000				√	√	

Table 1. The performance based design includes seismic performance based design and wind performance based design. Performance requirements under seismic actions and wind loads should be considered for super tall buildings. This is the structural performance under seismic actions. (Source: Yaoming Dong)

Recurrence Interval / Year	Construction Stage			Service Stage			
	Deformation	Strength	Stability	Human Comfort Performance	Deformation	Strength	Stability
5	√						
10		√	√	√			
50					√		
100						√	√
1700							√

Table 2. The performance based design includes seismic performance based design and wind performance based design. Performance requirements under seismic actions and wind loads should be considered for super tall buildings. This is the structural performance under wind loads. (Source: Yaoming Dong)

construction stage of super tall buildings and thus is an important index to measure the environmental impacts of super tall buildings (Fang, 2014).

The relationship between economic and environmental costs can be reflected through the concept of the emission reduction cost. Emission reduction cost is an extra cost in order to reduce the unit emission, which is a key factor affecting greenhouse gas emission reductions. The total cost TC in a building structure life cycle is given by:

$$TC = AC + u_c * C_f * ß \quad (3)$$

where u_c is the emission reduction cost of the structure life cycle (USD/t CO_2), C_f is the total carbon emissions over the structural life cycle, *ß* is the conversion factor of carbon and carbon dioxide, *AC* is the cost of the entirety of the building structure, $u_c * C_f * ß$ is carbon emission cost over the structural life cycle.

Performance Based Design

The performance based design includes seismic performance based design and wind performance based design. Performance requirements under seismic actions and wind loads should be considered for super tall buildings. Structural performance under seismic actions and wind loads are listed in Table 1 and Table 2 (Dong, 2015).

The performance-based design of structure, structural components, structural members, equipments and pipe lines should be taken into account. To ensure safety in the construction and service stage, structural strength, stiffness, stability and ductility under different actions should meet the design constraints required by Chinese codes.

A series of global constraints, assembly constraints, and component constraints for performance-based seismic design are stipulated by Chinese codes. Load combinations, importance factors, seismic adjustment coefficients and allowable constraints related to design constraints change based on seismic regions, along with the seismic performance objectives of structure and members, and the seismic grade of members. The process of determining seismic design constraints for performance-based seismic design is shown in Figure 2.

The wind-induced vibrations of super tall buildings become significantly excessive due to strong wind loads, super tall building height and high flexibility (see Figure 3) (Yu, 2014). Therefore, proper wind-resistant based design is of great importance for wind-sensitive buildings.

Wind loads on high-rise buildings consist of components of three directions, along-

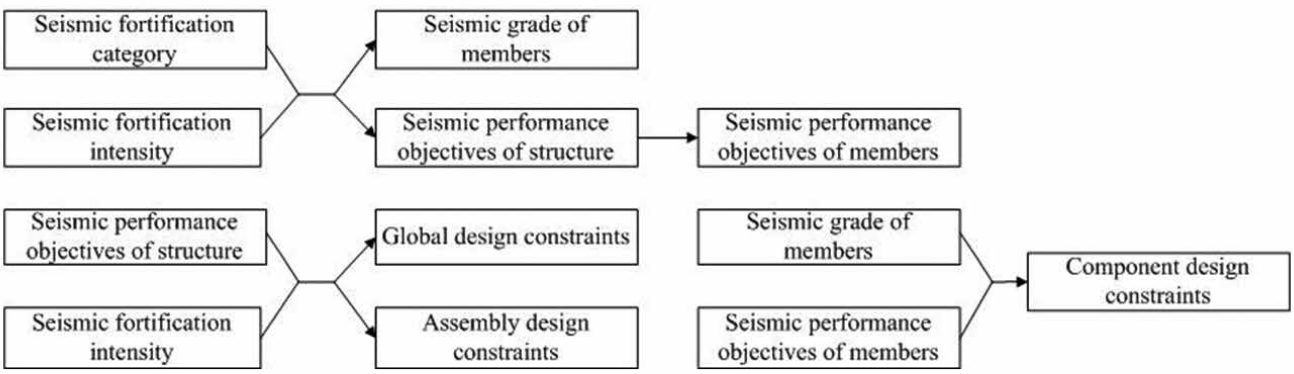

Figure 2. A series of global constraints, assembly constraints, component constraints for performance-based seismic design are stipulated in Chinese codes. Load combination, importance factor, seismic adjustment coefficient and allowable constraints related to design constraints change with seismic fortification category, seismic performance objectives of structure and members, and seismic grade of members. This is the process of determining seismic design constraints (Source: Yaoming Dong)

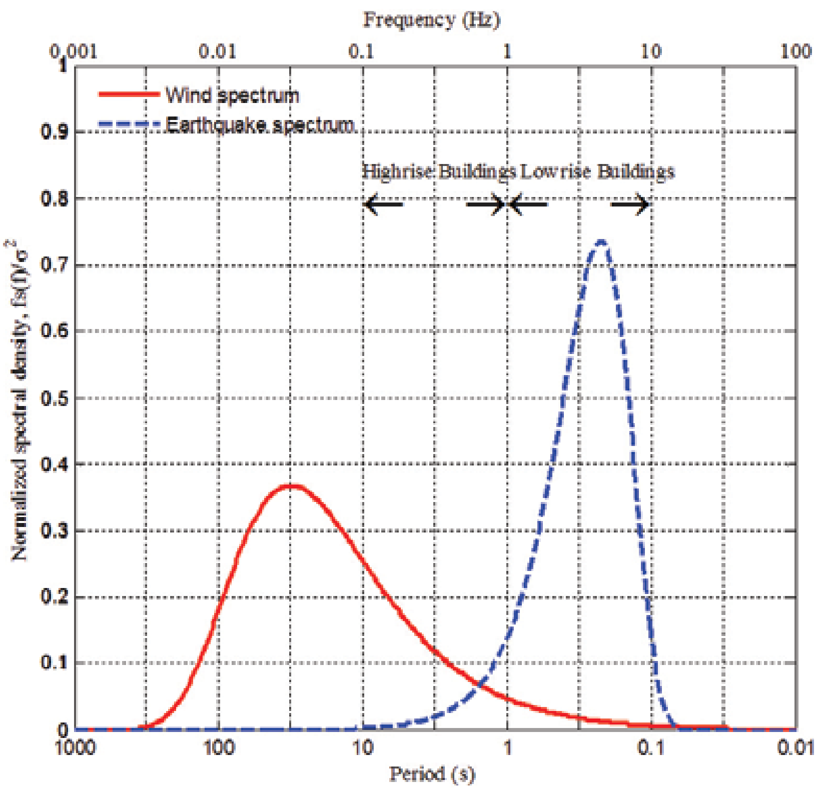

Figure 3. The wind-induced vibrations of super tall buildings become significantly excessive due to strong wind loads, super building height and high flexibility. This is the comparison of wind power spectrum and earthquake power spectrum (Yu, 2014). (Source: Tianyi Yu)

wind, cross-wind and torsional-wind loads. Along-wind loads are mainly influenced by the turbulence of the flow. Cross-wind loads are caused by flow separation and vortex shedding. The asymmetrical distribution of wind pressures on faces of the buildings results in the torsional-wind loads.

Both traditional wind tunnel tests and computational fluid dynamics (CFD) were conducted to study the mechanism of wind loads on buildings. The characteristics of wind loads both in time domain and frequency domain were analyzed, including the power spectrum densities, correlation coefficients, coherence functions and non-Gaussian features.

The structural vibration control technique, which was firstly proposed in the civil engineering field by Yao back in 1972, are used to control or suppress structural vibration caused by dynamic loads. This technique developed fast and caught much attention of engineers (Lin, 2013).

Tuned Mass Dampers (TMD) and Tuned Liquid Column Dampers (TLCD) have been widely used to control the vibration for super tall buildings for decades. As an economical vibration control option, the fire protection water tanks installed in super tall buildings are commonly utilized as TLCD to control the structural vibrations. The author has proposed a new type of vibration control device based on TLCD called Vertical Distributed Multiple Tuned Liquid Column Dampers (VD-MTLCD) to fully utilize the fire protection water tanks (Lin, 2013). However, there are many cases that buildings with the TLCD system alone can hardly meet the human comfort criteria due to the storage limit of water tank, and additional TMD system can be installed to further reduce the structural vibration.

Two measures are commonly taken to reduce the excessive wind-induced acceleration responses. One is to install supplementary damping systems to absorb dynamic energy, and the other is to fine-tune design variables of structural members according to computational optimization principles. Comparing with supplementary damping systems, the computational optimization method is more cost effective for slightly excessive wind-induced acceleration response scenarios. A computational optimization method based on sequential quadratic programming algorithms to reduce slightly excessive wind-induced acceleration responses by a comprehensive analysis of the relationship between across wind acceleration responses and member sizes is needed in the engineering practice.

Optimal Design

On the basis of the initial design, the optimal design team uses experience based structural optimization, artificial structural optimization, numerical structural optimization and integrated optimization methods to get a more optimized design. The whole process can be named as optimal design. The main difference between traditional design and optimal design is that the former mainly focuses on the feasibility of the design, while the latter mainly focuses on the optimization of the design under the premise of design feasibility.

The mathematical model of optimization problems has three key elements: optimization variables, design constraints and optimization objectives. Optimization variables are the design parameters of a structure, such as member size, section shape and structural geometry. Design constraints are the constraints which optimization variables must satisfy, such as strength, stiffness and stability constraints, and so on. Optimization objective is the assessment standard of a design. In the field of structural optimization, structural cost is the main optimization objective.

According to the design constraints and engineering experiences, the designer firstly proposes a design scheme with reference to similar engineering designs. Then the designer modifies the design scheme and checks strength, stiffness and stability constraints repeatedly to get a more optimized design. The optimization results and efficiency are mainly up to the designer's experiences and understanding of the structure.

Sensitivity index is taken as a reference index for structural member optimization in the artificial structural optimization method. According to the sensitivity index of members, the designer can adjust the material distribution directly to reduce the structural economic costs on the premise of meeting all the design constraints. Compared with the experience based structural optimization method, the artificial structural optimization method is easy to be mastered by engineers and more efficient, providing a clearer optimization direction.

The core of the numerical structural optimization method is establishing the mathematical relationships between optimization variables and design constraints and optimization objectives.

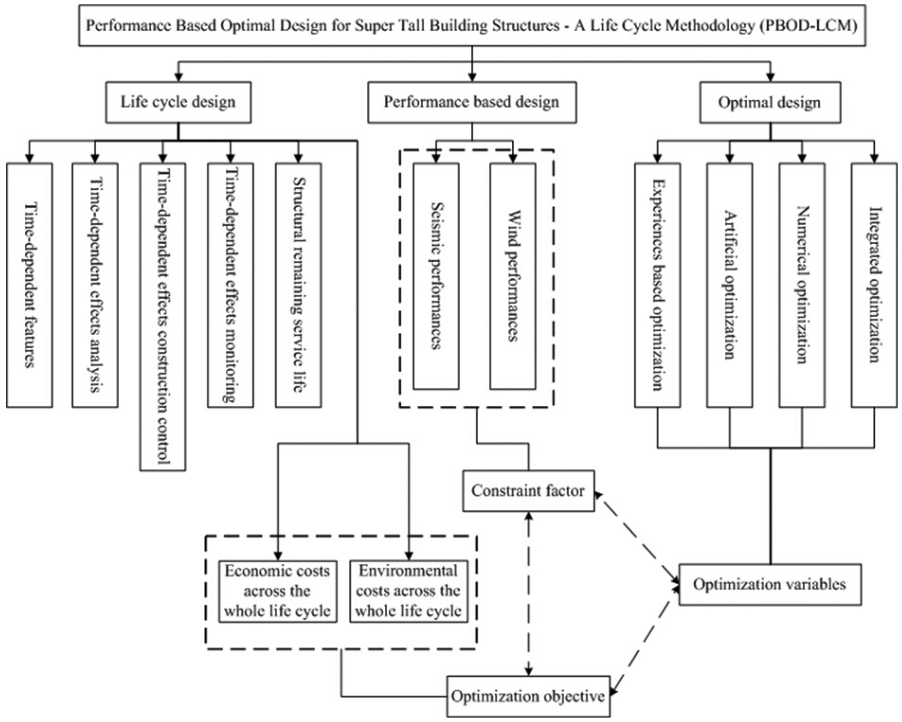

Figure 4. PBOD-LCM relates to life cycle design, performance based design and optimal design. This is the basic frame of PBOD-LCM (Source: Shehong Liu)

Once the mathematical relationships have been established, numerical optimization algorithms such as the optimality criteria method and sequential quadratic programming method can be used to optimize the structural member size. Based on rigorous mathematical and mechanical theory, the numerical structural optimization method is more efficient and easier to get an optimal solution than the first two optimization methods.

Compared to a primitive design, designing with technology of passive energy dissipation systems is called performance improvement design in this paper. The ability of the performance improvement design to resist earthquake and wind or other natural disasters has been promoted, and the loss cost is smaller than the primitive design. Nevertheless, the existing technology of passive energy dissipation systems is expensive and will bring up the construction cost of the whole structure. Thus, for the entire lifecycle of the structure, performance improved design may increase the total cost and the improvement of performance may also be superfluous to the demand of the stiffness and strength to resist natural disasters, therefore performance improved design does not have many economic advantages.

The internal forces of structural members can be reduced due to additional damping generated by the installation of passive energy dissipation system. The additional damping also enables further optimization for the structural components. This paper aims to optimize the main structure based on the performance improved design, namely integrated optimal design. The integrated optimal design enhances structural performance and reduces the lost cost caused by the disaster, it can save overall structural cost after the main structural optimal design. For the whole life cycle, integrated optimal design can realize the full potential of the technology of passive energy dissipation systems (Zhang, 2015).

Basic Frame

PBOD-LCM relates to life cycle design, performance based design and optimal design. The basic frame of PBOD-LCM is shown in Figure 4. The performance based design includes seismic performance based design and wind performance based design. Specifically, the performances include strength, stiffness, building comfort and so on. They are often treated as constraint factors of structural optimal design. The structural costs include economic costs and environmental costs across the whole life cycle, and they are often treated as optimization objectives of the structural optimal design. The constraint factor, optimization objective and optimization variables constitute the three

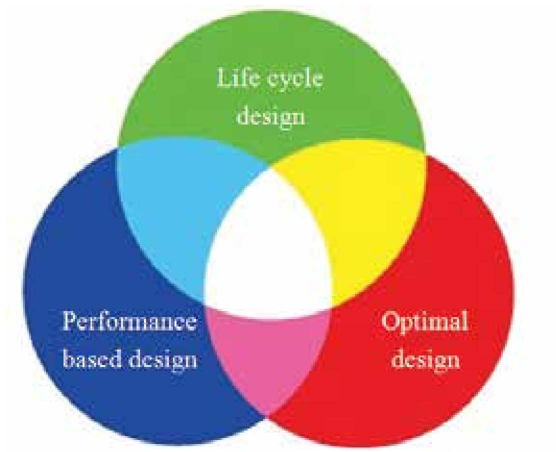

Figure 5. The life cycle design, performance based design and optimal design are not completely independent, and they are correlated to each other (Source: Shehong Liu)

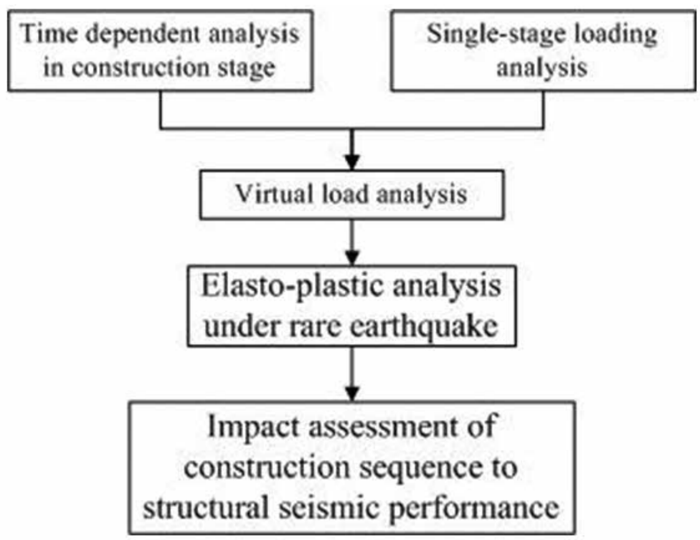

Figure 6. According to superposition principle of the elastic system, a set of virtual load vectors are obtained and applied at the same time with gravity load to obtain the internal forces of critical structural members, and then elasto-plastic analysis under rare earthquake is conducted. Thus construction stage is taken into consideration in performance-based seismic design. This is the process of studying the influence of construction sequence (Source: Peiwei Dong)

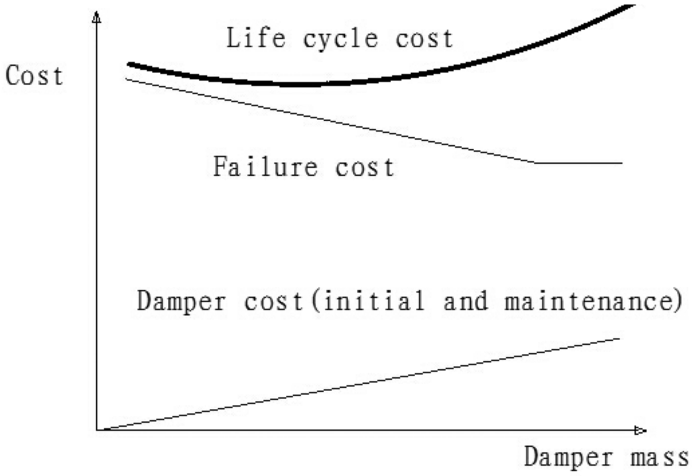

Figure 7. Life cycle performance based optimal design is an optimal design method with the minimum life cycle cost, which meets time-dependent performance requirements in a whole structural life cycle. This is the life cycle cost based optimal design theory. It is an example of the life cycle cost based human comfort performance design for super tall buildings with dampers like TLCD, CTD or TMD. (Source: Lilin Wang)

elements of structural optimal design.
In fact, the life cycle design, performance based design and optimal design are not completely independent, and they are correlated to each other (see Figure 5).

Critical Aspects

Time Slice Approach

A time slice approach is utilized by PBOD-LCM to conduct optimal design for various structural performances of super tall buildings upon typical time slices during the life cycle. The application of a time slice approach can realize optimal structural performances of super tall buildings across the whole life cycle. For example, the structural design service life of one building is 50 years, and four typical time slices can be selected. First is the initial moment (where remaining structural service life is 50 years), the second one is when the structural service life is past 20 years (where remaining structural service life is 30 years), the third one is when the structural service life is past 40 years (where remaining structural service life is 10 years), and fourth is when the structural service life is past 50 years (where remaining structural service life is past 0 years). If the structural performances in the above four typical time slices meet the performance goals, it can be considered that the building meets the life cycle performance design requirements.

Life Cycle Seismic-Resistant Performance Based Design

The virtual load method is to simulate the construction sequence based internal forces of critical structural members using traditional gravity analysis, introducing the virtual load vectors (Dong, 2014). The building structures can be generally considered elastic under gravity loads. According to superposition principle of the elastic system, a set of virtual load vectors are obtained and applied at the same time with gravity loads to obtain the internal forces of critical structural members, and then elasto-plastic analysis under rare earthquake loads is conducted. Thus the construction stage is taken into consideration in performance-based seismic design. The process flow chart of studying the influence of construction sequences to structural elasto-plastic behavior using the virtual load method is shown in Figure 6.

Life Cycle Wind-Resistant Performance Based Design

It is significantly important to choose a proper human comfort performance design criterion because there are noticeable differences in design loads for different criteria. Multi-level performance goals are adopted by Japanese guidelines for evaluation of habitability to building vibration (AIJES-V001-2004) and most importantly, each-level acceleration limitation is relevant to the structural frequency. Therefore, Japanese guidelines are taken as a criterion for human comfort performance design in this study.

Life cycle performance based optimal design is a preferred method with the minimum life cycle cost, which meets time-dependent performance requirements in a whole structural life cycle. Its basic theory is shown in Figure 7 with an example of the life cycle cost based human comfort performance design for super tall buildings with dampers like TLCD, CTD or TMD.

Numerical Structural Optimization

Too many optimization variables will reduce optimization efficiency, so it is necessary to select optimization variables reasonably. There are several measures that can be adopted to reduce the number of optimization variables, such as using the geometric relationships between variables, assigning similar structural members to a group, using a fractional structural optimization method, and so on.
The optimal design of super tall building structures has to satisfy many design constraints. Here are some tips for the selection and processing of design constraints: one is reducing the unnecessary design constraints, the other is that the function expression of design constraints should be only related with optimization variables, other parameters can be taken as constants in the same iteration.

Integrated Optimization

For the optimal placement of energy dissipation equipment, Zhang proposed to use grid shear deformation (GSD) of each floor as the index for the optimal placement of energy dissipation equipment (Zhang, 2015). The GSD indices of different grids will reflect the internal forces of energy dissipation equipment installed in the grids, which are closely related to the energy dissipated by energy dissipation equipment during the earthquake.

This paper aims to develop an optimal number design method considering economic, environmental and life cycle factors. The economic index considers both the energy dissipation equipment costs and the cost savings of main structure for the installation of different numbers of energy dissipation equipment. The environmental index will introduce the embodied carbon and emission reduction cost to compare different schemes in environmental aspects (Zhang, 2015). For the life cycle cost analysis, a seismic lost cost analysis method based on probability is proposed in this study. The life cycle cost method can help engineers to conveniently obtain the seismic loss costs of the main structure and repairing costs of energy dissipation equipment after the earthquake.

Conclusions

The main conclusions are as follows:

- The traditional design is a feasible design meeting the requirements of design codes and it doesn't consider the time-dependent performances of structures and structural costs across the whole life cycle. However, PBOD-LCM is an optimal design meeting the requirements of time-dependent performances and with minimum structural costs across the whole life cycle. It not only considers the time-dependent features of super tall buildings, but also treats structural economic and environmental costs across the whole life cycle as an optimization objective. The PBOD-LCM addressed in this paper is suitable for the design of super high-rise building structures and can improve the economy and environment of structures.
- The life cycle design includes time-dependent features of super tall buildings (time-dependent materials, time-dependent structures and time-dependent loads), time-dependent effects analysis methods, time-dependent effects construction control, time-dependent effects monitoring, remaining structural service life and structural costs across the whole life cycle. The structural costs include economic costs and environmental costs, and they are often treated as an optimization objective of optimal structural design.
- The performance based design includes seismic performance based design and wind performance based design. Specifically, the performances include strength, stiffness, building comfort and so on. They are often treated as constraint factors of structural optimal design.
- The optimal design is a design approach where the optimal design team uses experience based structural optimization, artificial structural optimization, numerical structural optimization and integrated optimization methods to get a more optimized design after the initial design. The whole process can be named as optimal design. The main difference between traditional design and optimal design is that the former mainly focuses on the feasibility of the design, while the latter mainly focuses on the optimization of the design on the premise of the feasibility of the design.
- The life cycle design, performance based design and optimal design are not completely independent, and they are correlated to each other.

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