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Hierarchical life-cycle design of reinforced concrete structures incorporating durability, economic efficiency and green objectives

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ABSTRACT

Current structural design methods mostly emphasize the short-term structural behavior while neglect the long-term performance, social effects and environmental impacts. To address these problems, the Life-Cycle Design (LCD) method considering environmental impacts and structural deterioration could be adopted within the design process to ensure that the structural performance satisfies various objectives. Due to the complexity and the long lifespan of engineering structures, as well as the lack of standardized design approach, studies and application of LCD that cover all the design objectives are limited. This paper proposes a hierarchical LCD method for concrete structures by combining traditional design with green design and other engineering aspects. The design process is divided into six levels that cover the aspects of structural safety and reliability, durability, economic efficiency, local environment, social impacts, and global environment. The proposed design method is then applied to a reinforced concrete highway bridge in marine environment for the purpose of illustration, and a comprehensive comparison between traditional design and the hierarchical LCD approach is made within six design levels. A brief discussion on the hierarchical LCD framework and the future works is presented before conclusions are made.

1. Introduction

From allowable stress design to limit state design, structural design concepts and methods have been developed and evolved for decades. However, current design methods still place major attention on the short-term structural performance, while neglect the long-term structural behavior and economic loss caused by structural deterioration, increasing live loads and environmental actions.

The environmental and ecological impacts of structural activities have become an increasingly significant issue in modern design concept, and environmentally conscious design, assessment and management methodology aiming to ensure structural performance in a life-cycle context is needed. Structures' green performance [1,2] is defined as the capability of efficient utilization of energy, water, and other resources; protecting occupants' health and improving productivity; and reducing waste, pollution and environmental degradation. The 2005 World Summit on Social Development suggested that the structural sustainability is supported by three pillars, i.e. the economy, society and environment [3,4]. The underlying concept of structural sustainability is that our engineering activities should find ways to meet current needs without destroying the opportunity for the development of future generations [18]. Significant achievements have been obtained in the establishment and application of structural green performance rating systems, such as LEED (Leadership in Energy and Environmental Design) [1] and BREEAM (Building Research Establishment Environmental Assessment Method) [5]. Sustainability and green performances of buildings and civil infrastructures have also been extensively reported in previous studies. Kibert [6] made a comprehensive discussion about green building design and sustainable construction from the backgrounds and foundations to green building assessment, design and implementation. Haapio and Viitaniemi [7] reviewed the environmental assessment tools of buildings considering the building types, users of tools, phases of lifecycle, databases and other aspects. The BEES (Building for Environmental and Economical Sustainability) software [8] is a freely available tool that assists the selection of building products with favorable performance in both environmental and economical aspects. Studies were also performed on the sustainable building materials, such as wood [9], new-type cement [10–12], unconventional insulation materials [13], and so on. For infrastructure, Mihyeon and Amekudz [14] reviewed sixteen sustainability initiatives for transportation systems and classified the indicators and metrics into five categories, namely economy, transportation, environment, safety and

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society. Sahely et al. [15] put forward a set of sustainability indicators for urban infrastructure systems by considering the interrelationships between infrastructure systems and surrounding environment, society and economy. Ugwu et al. [16] discussed the development of key performance indicators of infrastructure sustainability appraisal, and proposed an analytical decision model for sustainability evaluation. Shen et al. [17] developed the key assessment indicators for the sustainability evaluation of infrastructures by performing a questionnaire survey, and the sustainability indicators are produced by fuzzy set theory. Despite the abovementioned huge efforts and work, the quantification of sustainability characteristics and green performance is still needed [18]. More studies should be conducted to overcome the barriers [19,20] in the application of structural sustainability design.

Efforts were also paid to set up the inventory [21] of the life-cycle environmental impacts of engineering structures. Life-cycle assessment (LCA) [22, 23] method is a tool to evaluate the environmental impacts of products over their entire lifespans, i.e., “from cradle to grave”, focusing on the materials and energy input, as well as the emissions to air, water and land. Application of LCA [24–26] in civil engineering area has been broadly witnessed on residential and commercial buildings, new and in-use bridges, as well as communities and infrastructures. Limitations of LCA and other environmental evaluation methods should also be highlighted. The environmental evaluation process does not consider the structural requirements, and none of these methods combines traditional structural design with green design, which marginalizes structural engineers [19].

In order to maintain the long-term performance of structures, while simultaneously minimizing the total cost and environmental impacts, a Life-cycle Design (LCD) method considering multi-objectives is needed. LCD has been widely used in the industrial product design for environmental performance improvement and risk reduction [27,28]. In the design of engineering structures, an integrated LCD methodology was proposed by Sarja [29] to optimize human conditions, and minimize financial costs and environmental impacts. Bergmeister [30] applied LCD to the Brenner Base Tunnel project with an emphasis on the service life of the structure, without considering the environmental performance and sustainability. Due to the complexity [32] and the long lifespan of engineering structures, as well as the lack of standardized design approach, studies and application of structural LCD that consider all the design objectives are limited. Compared with traditional structural design method, LCD covers not only the initial stage (e.g., design and construction), but the entire lifespan of a structure, which places more importance to structural durability and life-cycle cost (LCC). Being an interdisciplinary design approach [25], the objective system of LCD is greatly extended. It contains the knowledge from not only traditional civil engineering, but also the aspects that were overlooked in the past, such as project management, environmental evaluation, and economics [31]. Efforts were made to integrate different professionals and disciplines involved in the LCD of structures through concurrent design [32]. Life-cycle management [33] and maintenance [34,35] of infrastructures have been studied and performed, but based on limited objectives such as reliability, costs, benefits, etc. Multi-objective optimization approach [36,37], whose effectiveness has been verified by extensive application, can help with engineering decision-making involving multiple design objectives. However, this approach is currently not able to cover all the design objectives in the life cycle of a structure, since the computational efficiency and accuracy can seriously decrease with increasing numbers of design variables. Thus, an innovative and practical LCD approach that combines the traditional structural design with green design objectives and other engineering aspects is urgently needed.

In light of the abovementioned research gaps, the authors proposed a hierarchical structural design methodology that systematically considers the multiple objectives associated with LCD. Section 2 gives a brief introduction of the LCD system. Section 3 presents the design process associated with six design levels considering different design objectives and indicators. The proposed approach is then applied to the design of a coastal reinforced concrete bridge in Section 4. Based on results of the case study, a comparison between the proposed hierarchical method and traditional design method is made in Section 5, and both the advantages and disadvantages are identified. Before the conclusions are drawn, a brief discussion on the hierarchical LCD framework and future works is made in Section 6.

2. Life-cycle design objective system

The objectives of LCD are divided into the following two parts [38]: traditional objective that considers structure performance, service life, as well as economic efficiency, and green objective that considers local environmental impacts, social impacts, and global environmental impacts. The detailed content of the traditional and green objectives is explained in the following sections.

2.1. Traditional objective

Traditional objective represents the most fundamental and common goals of structural design. It mainly consists of three correlated subobjectives, namely structural performance, service life and economic efficiency. The structural performance objective not only considers the structural behavior at project completion but also during the structural operation, maintenance and other future stages. Enhanced structural design usually can lead to a longer service life, but it also requires more monetary investment in the construction and maintenance activities. On the other hand, the life-cycle budget control should be carried out based on satisfying the precondition of the structural performance and service life requirements.

2.2. Green objective

The green objective aims at improving structural green performance. As defined previously, a green structure is supposed to minimize local and global environmental impacts, as well as the social impacts. Thus, the green objective is related with the local environmental, social, and global environmental objectives. The local environmental objective focuses on the short-term, small-scale environmental quality around a structure, and the global environmental objective emphasizes the long-term effects of structural activities in a global range. The objective of social impacts aims to improve the quality of living and working environment related to the structure. The scope and detailed indicators of green objective are discussed in the following sections.

3. Hierarchical life-cycle design method

The hierarchical relationships of LCD objectives are arranged by comprehensively considering the design concepts, the constraints in design codes and their relevancy degree to the structures. From the perspective of design concept, traditional design covers the fundamental purposes and primary drivers of a structural project, in which safety objective guarantees the functionality of structures, durability objective keeps the structural performance persistent enough to reach the designed service life, and the economic efficiency objective is in agreement with stakeholders’ primary demands of cutting down expenses. The green design is beyond the range of traditional structural design project [39,40] and aims to manage structures’ interrelationship with the environment and the human beings.

The hierarchy of design objectives is also associated with the constraints corresponding to the design codes. The terms and regulations for structural safety and reliability are strictly mandatory to ensure adequate strength, stiffness and stability, whilst the durability codes are half-mandatory and half-optional, including both detailed structural design requirements for specified environmental conditions (e.g., the thickness of concrete cover) and recommended durability improvement