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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 and neglect the long-term performance, social effects and environmental impacts. Therefore, 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. Nowadays, LCD is still more of a concept to civil engineers, rather than a practical approach. Therefore, application of LCD in structural design is needed. This paper proposes a hierarchical LCD method for concrete structures by combining traditional design and green design. The design process is divided into six levels and covers the aspects of structural safety and reliability, durability, economic efficiency, environmental, users' and social impacts, and sustainability. This approach is applied to a reinforced concrete coastal highway bridge. A comprehensive comparison between traditional design and the Hierarchical LCD approach is made within six design levels. Additionally, a relevant sensitivity analysis is conducted to determine the effects of weight factors on the green design process.

Keywords: Life-cycle design; durability; life-cycle cost; sustainability; green design; CO_2 emissions; reinforced concrete structures.

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1. INTRODUCTION

From Allowable Stress Design to Limit State Design, structural design concepts and methods have been developed and evolved for decades. However, most of the design methods still place attention only on the short-term structural performance, neglecting the long-term structural behavior and economic loss caused by structural deterioration, increasing live loads and environmental actions.

On the other hand, environmental and ecological impacts of structural activities have become a significant issue in modern design philosophy. Thus, 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 environment degradation. The establishment of structural green performance rating system, aiming to assess structural environmental impacts, started early in the United States (e.g., LEED [1]) and Europe (e.g., BREEAM[3]), and have been used worldwide. Additionally, efforts were also paid to set up the inventory[4]of the life-cycle environmental impacts of structures. Green design [5]and evaluation[6][7] of residential and commercial buildings, new and in-use bridges, communities and infrastructures were also studied. However, none of these studies combine traditional structural design with green design. Green design is still reckoned as a secondary objective, and the green indices are mostly qualitative and hard to implement. Given this, the authors aim to fill in the research gaps and establish a comprehensive design methodology considering both traditional and green design objectives.

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 is an extension to the traditional design method. Compared with traditional design method, LCD covers not only the initial stage (e.g., design and construction), but the entire lifespan of a structure. Also, the objectives of LCD are greatly extended by combining both construction and non-construction industries, especially green design objectives. Furthermore, LCD considers structural deterioration induced by environmental actions. With respect to the economic aspect, life-cycle cost (LCC) is used as one of the representative indicators to evaluate the costs that could occur during the whole lifespan of a structure.

During the past few years, there have been various studies associated with life-cycle analysis, such as life-cycle assessment[8], management[9][10][11][12], and optimization [13]. However, studies about LCD are really limited. Nowadays, LCD is still more of a concept to most structural designers, rather than a practical method. Only few studies focus on the overall framework and practical application of LCD in structural design process. Bergmeister[14] mentioned that application of LCD approach on important structures is still quite limited, so he applied LCD to the Brenner Base Tunnel project. Being an interdisciplinary design system, LCD contains the knowledge from not only traditional civil engineering, but also the aspects that were overlooked in the past, such as system management, environmental evaluation, and economics, making the traditional approach unable to fulfill all requirements[15]. Thus, an innovative and practical LCD approach that combines the traditional structural design systematically with green design objectives and other engineering aspects is urgently needed.

Overall, this paper aims to propose a design approach considering 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.

Subsequently, in section 4, the proposed approach is applied to the design of a coastal reinforced concrete bridge. In section 5, based on results of the case study, a comparison between the proposed hierarchical method and traditional design method is made, and both the advantages and disadvantages are identified. Finally, sensitivity analysis is performed to discuss the effects of different parameters (e.g., weight factors) on structural design outcomes.

2. Life-cycle Design Objective System

The objectives of LCD are divided into the following two parts[16]: traditional objective, considering structure performance, service life, as well as economic efficiency; and green objective, considering environmental impacts, users' and social satisfaction, and sustainability. The detailed information about the traditional and green objectives is explained in the following sections.

2.1 Traditional Objective

Generally, the traditional objective represents the most fundamental and common goals of structural design. It mainly consists of three correlated sub-objectives, namely structural performance, service life and economic efficiency. The performance objective not only focuses on the structural performance at the end of construction phase, but also on the performance during structural operation and maintenance phase. Enhanced structural design usually can lead to a longer service life, while also requires more monetary investment in the construction and maintenance of the structure. On the other hand, the optimization of LCC should be obtained by considering both the structural performance and service life requirements.

2.2 Green Objective

The green objective aims at building green structures and improving structural green performance. As defined previously, a green structure is supposed to minimize environmental impacts, satisfy users' and social need and reduce resource consumption. Thus, the green objective is related with the environmental, users' and social, and sustainable objectives.

The structural sustainability is supported by three pillars, i.e. the economy, society and environment [17][18]. This paper presents a novel green objective system, in which the environmental objective focuses on the short-term environmental quality around a structure; the sustainability objective intends to evaluate the long-term effects of structural activities on the global atmosphere environment and ecosystem; the objective of users' and social satisfaction aims to improve the quality of living and working environment related to the structure. Detailed indicators of green objective are discussed in the following sections.

3 Hierarchical LCD Method

From the perspective of design philosophy, traditional design aims to achieve the fundamental purposes of a structural project, including safety, durability and economy. The green objective is derived from a more rational and philosophical point of view[19][20]. Its purpose is to manage the interrelationship between engineering structures and their surrounding environment, human beings, and ecological systems. In this paper, both traditional and green design objectives are considered and combined in the structural design process within a life-cycle context.

Meanwhile, the hierarchical relationships of LCD objectives can also be arranged considering the constraints in corresponding design codes. For example, the terms and regulations for structural safety and reliability design are strictly mandatory to ensure adequate strength, stiffness and stability. For durability design, the 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 and anti-corrosion techniques (e.g., coatings). When it comes to economic constraints, the selection of the solution is mainly determined by investors and stakeholders. With respect to the green design, most indicators are qualitative. Manuals and guides (e.g., LEED) provide some compulsory indicators (e.g., toxic emissions), while the others are used for comprehensive marking (e.g., ecological exploitation and restoration).

Based on the design philosophy and the constraint conditions mentioned above, the fundamental objectives with stricter restrictions are placed on the basic levels (e.g., safety and reliability), and the relatively abstract objectives with less restrictions are arranged on the upper level (e.g., sustainability). The hierarchical flowchart of the LCD objectives is illustrated by the pyramid in Figure 1. Since the objectives are arranged based on their necessity and significance, the LCD can be achieved using six steps: Level 1-safety and reliability design, Level 2- durability design, Level 3- economic evaluation, Level 4- environmental evaluation, Level 5- users' and social evaluation, and Level 6- sustainability evaluation. Detailed information of these six levels is introduced in the following sections.

3.1 Traditional Design Objectives

3.1.1 Safety and Reliability Design- Level 1

The Load and Resistance Factor Design (LRFD)[21][22] method is widely adopted in current design codes, using partial coefficients on resistance and load effect to provide the structural components and/or system with adequate load-bearing capacity and reliability level. The safety requirement in LRFD is

$$\phi R_n \geq \sum_i \gamma_i Q_i \tag{1}$$

where R_n is resistance; Q_i is the ith load effect; γ_i is the load factor for the ith load effect; and ϕ is the resistance factor.

Geometric dimensions and material properties are among the essential parameters in Level 1. Different combinations can lead to solutions with different durability, LCC and green performance. In the following design process, additional constraints will be applied to the initial design solutions considering different objectives and requirements.

3.1.2 Durability Design- Level 2

To keep structures functional during their entire lifespan, initial durability design and future durability maintenance are both necessary. Usually, there are three steps in the durability design process.

3.1.2.1 Step One: structural requirements

For structures in aggressive environments, the Code for Durability Design of Concrete Structures[23] provides detailed structural requirements considering the type and intensity of environmental actions on structures. When the location of a structure is specified, the environmental actions can be determined, and the durability structural requirements mentioned above can be used to eliminate the solutions that do not satisfy the durability goal.

3.1.2.2 Step Two: durable service life prediction

Another major issue associated with durability design is to predict the durable service life of a structure. For reinforced concrete structures located in marine environment, steel corrosion induced by chloride penetration is one of the dominant durability problems. The chloride-induced deterioration of reinforced concrete structures can be divided into 4 stages, namely the initiation, propagation, cracking and degradation stage[24][25], as shown in Figure 2. Once surface cracks occur, structural mechanical performance and resistance to harmful ions will begin to drop dramatically. Herein, the Durable Service Life T_D of reinforced concrete structures is defined as the time period before cracks appear,

$$T_D = T_0 + T_{cr} \tag{2}$$

where T_0 is corrosion initiation time; and T_{cr} is the time interval between corrosion initiation and crack initiation.

When the chloride concentration around the reinforcements exceeds a critical level, the corrosion will start. Usually, Fick's Second Law is used to predict the depassivation of reinforcements, which is computed as[26][27].

$$T_0 = \frac{x^2}{4D_f}\left[erf^{-1}\left(\frac{C_S - C_{Cr}}{C_S}\right)\right]^{-2} \quad (3)$$

where $erf^{-1}(x)$ is the inverse function of error function $erf(x)$; C_s is the chloride concentration on concrete surface; C_{cr} is the critical chloride concentration; x is the thickness of concrete cover; and D_f is the chloride diffusion coefficient. D_f depends on many factors, such as concrete quality (e.g., water cement ratio, porosity, etc.) [28] [29], dosage of admixtures [30], temperature and moisture[31][32], etc.

Different models can be used to compute the crack initiation time. Bazant[33] stated that the corrosion products can cause tensile stress to the concrete around the steel bar. Liu and Weyers[34] mentioned that part of the corrosion products can fill in the gaps and pores around the reinforcements before any pressure occurs. Generally, T_{cr} relies on multiple factors, such as the reinforcement corrosion rate, volume of corrosion products, quality of concrete, thickness of concrete cover, etc. [35] [36] [37]. Equation (4) [38] is used herein to predict T_{cr}.

$$T_{cr} = 234762(d + kx) \times \frac{\left\{(0.3 + \frac{0.6x}{E_{cef}})\frac{f_{tk}}{E_{cef}}\left[\frac{(r_0 + x)^2 + r_0^2}{(r_0 + x)^2 - r_0^2} + \mu_c\right] + 1 + \frac{2\delta_0}{d}\right\}^2 - 1}{(n-1)i_{corr}} \quad (4)$$

where d is the diameter of reinforcements; x is the thickness of concrete cover; k is the correction factor considering that corrosion products can fill into the cracks; f_{tk} is the standard tensile strength of concrete; E_{cef} is the effective elasticity modulus of concrete. $E_{cef} = E_c/(1.0 + \varphi)$, where E_c is the elasticity modulus of concrete, and φ is the creep coefficient of concrete; δ_0 is the thickness of capillary cavity between reinforcement and concrete; $r_0 = d/2 + \delta_0$; μ_c is the Poisson ratio of concrete; n is the volume expansion ratio of corrosion products; and i_{corr} is the corrosion electric current density.

3.1.2.3 Step Three: durability improvement measures and maintenance plan

Coatings, mineral admixtures, as well as electrochemical techniques are among the most frequently used durability improvement methods. Studies [39] showed that adequate mineral admixtures can increase the concrete's resistance to chloride penetration. The Code [23] and the Guide to Durability Design and Construction of Concrete Structures [40] also recommend the best dosage of admixtures for concrete structures in specific environment. For example, fly ash (FA) should be no less than 30% (wt. of cement, same below) if it's the only admixture; and blast furnace slag (SL) should be no less than 50%; while the most effective amount of silica fume (SF) is approximately 5%.

Coatings can be used on either concrete or reinforcements to block the penetration of harmful ions. Usually, coatings are low-permeable organic paint, such as the epoxy coating for reinforcements or concrete. Corrosion resistant coatings can prolong T_D of concrete structures effectively and conveniently.

Electrochemical techniques can remove the chloride ions in concrete by connecting the reinforcements to an anode outside to form a current circuit[41]. It usually takes 8~12 weeks for the electrochemical chloride extraction (ECE) treatment to have a favorable effect. Based on ECE treatment, bidirectional electro-migration (BE) can simultaneously move corrosion inhibitors into the concrete and provide longer protection [42].

Combined utilization of durability improvement methods also has favorable effects in extending structures' service life. Different combinations not only add up to different durable service lives, but also different LCCs, which is another major concerns of the stakeholders. Thus, it is important to conduct the LCC evaluation to meet the economic objective.

3.1.3 Economic Evaluation- Level 3

LCC is a comprehensive indicator for structural economic efficiency evaluation. Traditional engineering cost usually refers to the initial cost only, while LCC contains the costs associated with not only design and construction, but also the operation, maintenance, failure, as well as demolition. Several studies[43] showed that although design stage accounts for only 5%~7% of the total LCC, the decisions made can determine the allocation of 70%~80% of the future costs. In other words, initial design for structural reliability and durability can significantly affect the future costs. Based on the life-cycle stages of a structure, the LCC can be computed as[44][45]:

$$LCC = C_{ds} + C_{con} + C_{op} + C_{mt} + C_f + C_{dm} \tag{5}$$

where C_{ds} is the design cost, including the cost of site investigation, research and design; C_{con} is the construction cost; C_{op} is the operation cost, considering the energy and water consumption, as well as other investments during operation stage; C_{mt} is the maintenance cost in terms of the direct and indirect cost of maintenance actions; C_f is the failure cost in terms of the direct and indirect cost caused by structure failure[46]; and C_{dm} is the demolition cost, including the costs demolition, landfill and recycling.

Generally, direct cost considered herein refers to the money spent directly on engineering activities, while the indirect cost is related with the deficiency or loss of structural functionality[47]. For instance, bridge failure can paralyze the traffic network, induce time loss to the commuters who travel through it, and economic loss to regional industry. These losses are considered as indirect costs.

3.2 Green Design Objectives

3.2.1 Environmental Evaluation- Level 4

Indicators in this level are associated with controlling the harmful environmental impacts caused by structural activities in a life-cycle context. Analytic Hierarchy Process (AHP) is used to set up the indicator system by dividing it into five classifications, namely Category, Aspect, Attribute, Sub-attribute and Indicator[48]. For bridges, the environmental evaluation mainly focuses on the energy system, water system and construction materials, as shown in Table 1. The life-cycle power consumption is the main concern in energy system of bridges. For water system, designers are supposed to measure the water consumption, as well as the potential water pollution caused by engineering activities. When it comes to construction materials, the utilization of recyclable, environmental-friendly, local and natural materials is encouraged.

In the evaluation of the environmental impacts, qualitative indicators are needed. Utility theory[49][50][51] can be used to depict the decision makers' value on multiple attributes. In this paper, fuzzy comprehensive evaluation (FCE) method is applied to deal with qualitative evaluations. The evaluation factor set is

$$\boldsymbol{U} = \{u_1, u_2, ..., u_n\} \tag{6}$$

where u_i is the ith evaluation indicator, i=1, 2, …, n. The evaluation value set is

$$\boldsymbol{V} = \{v_1, v_2, ..., v_n\} \tag{7}$$

where v_i is the evaluation score for u_i. v_i=1, 2 or 3, where 1 point represents the least green performances, and 3 points represents the greenest ones. For example, 1, 2 and 3 points can represent large, medium and small electric power consumption, respectively. Weight factors are allocated to each evaluation factor to reach a comprehensive score, and the weight vector is

$$\boldsymbol{A} = \{a_1, a_2, \ldots, a_n\}^T \tag{8}$$

where a_i is the weight factor for u_i, and $\sum a_i = 1$. Consequently, the evaluation result vector is

$$R = \boldsymbol{V} \cdot \boldsymbol{A} \tag{9}$$

3.2.2 Users' and Social Evaluation- Level 5

Civil infrastructure systems not only affect the environment, but also the users, investors, construction workers and social groups. AHP and FCE are used to conduct users and social evaluation process.

Generally, users are under the most direct and significant effects of engineering activities. Structures are supposed to provide safety and comfort to the users. For investors, structures' life-cycle cost/ benefits is the main concern. Designers should provide green, feasible and concise structural solutions, while also maximize the economic efficiency. A safe and healthy working environment is the basic requirement for engineering workers. Thus, proper construction management and construction plans are necessary. Although social groups are not directly related to structures, they are still affected by the existence of structures and relevant engineering activities. Hence, public feedback channels should be established to collect complaints and advices from the society. Basic indicators for users' and social evaluation of bridge structures are presented in Table 1.

3.2.3 Sustainability Evaluation- Level 6

The sustainability criteria are considered within the design process to minimize the long-term structural impacts on the global environment and ecosystem. The consumption of nonrenewable resources, the disturbance to the atmosphere and the damage to ecosystem are considered. For example, the production of construction materials consumes abundant nonrenewable raw materials and fossil fuel. Meanwhile, the emissions from engineering activities have harmful influence on atmosphere and global climate. The ecological exploitation on and around construction site should also be under control. Similarly, representative qualitative design indicators are set up to evaluate the sustainability of structural design and structural activities, as shown in Table 1.

Disturbance to the atmosphere mainly refers to the emission of noxious gases, such as greenhouse gas, acid gas and HCFCs. Specifically, carbon emission is widely adopted as one of the major quantitative indicators for gas emissions, and the life-cycle CO_2 emission ($LCCO_2$) of a bridge structure can be computed as[52]

$$LCCO_2 = CE_{con} + CE_{mt} + CE_{dm} \tag{10}$$

where CE_{con} is the carbon emission of construction, including emission of material production, machine operation and power consumption during construction; CE_{mt} is the carbon emission of maintenance and repairmen, including emissions of relevant materials and work machines; and CE_{dm} is the carbon emission of demolition, including the emission of demolition, landfill and the emission deduction of material recycling. The carbon emission of the *i*th life-cycle stage (e.g., construction, maintenance and demolition) [52] is

$$CE_i = \sum_j A_j \alpha_A + \sum_k M_k \alpha_M \tag{11}$$

where A_j is the workload of *j*th engineering activity; M_k is the consumption of *k*th construction material; and α is the carbon emission factor associated with different works and materials. Sustainability evaluation of a bridge structure can base on the combination of $LCCO_2$ and other qualitative indicators.

4 Illustrative Example

The proposed Hierarchical Life-Cycle Design Approach is applied to a cap beam of a reinforced concrete highway bridge in marine-atmosphere environment. The designed service life is 100 years. The beam is supported by two columns with center distance of 7.5m, and holds a 15m deck. Forces are transferred to the beam through two bearings with the central distance of 6.9m. The main cross-section of the beam is 1.5m × 1.5m, and the total length is 15m. The structure layout and load condition are shown in Figure 3.

Level 1: Safety and reliability design

For internal stress analysis, special attention should be paid to the critical locations along the span of the beam, such as the bearing points, loading points and the mid-span, as shown in Figure 3. Concrete and reinforcement strength level and the thickness of concrete cover are taken as design variables with notations shown in Table 2. The design process is based on the Code for Design of Concrete Structure[53]. Analysis results indicate that the biggest positive moment occurs at the mid-span of the beam, and the biggest shear happens near the left bearing. Considering solution **iv-*C*** as an example, its cross-sections near the bearing and loading points require the highest reinforcement ratio, with 6940mm^2 for both top and bottom reinforcements.

Level 2: Durability design

- **Step One: structural requirements**

Based on the environmental classification in the Code [23] and the Guide [40], the following requirements are proposed toward the cap beam:

①Minimum reinforcement level should be HRB400, minimum concrete level should be C50; ② thickness of concrete cover should be no less than 60mm; ③maximum water cement ratio is 0.36; ④ mineral admixtures are recommended, and the integrated use of multiple anti-corrosion strategies is recommended. Thus, the range of solution alternatives is narrowed down by excluding concrete level **i** and **ii** (i.e., C30 and C40), reinforcement level ***A*** (i.e., HRB335), concrete cover thickness ***a*** and ***b*** (i.e., 40mm and 50mm).

- **Step Two: durable service life prediction**

In step two, initial T_D is investigated. Relative parameters and T_D are presented in Table 3[54][55]. Results indicate that solutions with higher concrete level and thicker cover tend to have longer T_D.

- **Step Three: durability improvement measures and maintenance plan**

The effect of mineral admixtures, coatings and electrochemical techniques are investigated in this section, with corresponding notations and effects shown in Table 4. The mineral admixtures can change the chloride diffusion coefficient of concrete, as shown in the following equations[56]:

$$D(t) = D_{28}\left(\frac{t_{28}}{t}\right)^m \tag{12a}$$

$$m = 0.2 + 0.4(\%FA/50 + \%SL/70) \tag{12b}$$

$$D_{SF} = D_{PC} \cdot e^{-0.165 \cdot \%SF} \tag{12c}$$

where $D(t)$ is the chloride diffusion coefficient at time t; D_{28} is the chloride diffusion coefficient at 28d (t_{28}); m is the diffusion decay index; D_{SF} is the chloride diffusion coefficient of concrete with SF; D_{PC} is the chloride diffusion coefficient of Portland cement; and $\%FA$, $\%SL$ and $\%SF$ is the mass percentage of fly ash, slag and silica fume to all cementitious materials, respectively.

Several reports[23][40] stated that the effect of epoxy coating for reinforcements could last at least 20 years, depending on the thickness and bonding strength of the coating. Epoxy coating[57][58] for concrete is also an effective way to insulate chloride intrusion, which can provide protection for at least 10 years. Silane soakage[59][60]is effective for around 15 years.

After 8~12 weeks of ECE treatment, chloride ions around the reinforcement could reduce by nearly 80% [61] [62]. With the help of corrosion inhibitor in BE treatment, the T_D could be prolonged for at least 5 more years [42][63].

For solutions using single durability improvement measure, T_D are listed in Table 5. The T_D under the combined utilization of multiple techniques are also calculated, which lead to the following conclusions:

- Increasing the thickness of concrete cover is an effective way to improve durability;
- When applied alone, coatings show the best durability improvement effect, followed by mineral admixtures and electrochemical techniques;
- The combination of ER and concrete coatings have the strongest resistance to chloride ions; and
- The combination of mineral admixtures and other durability improvement strategies makes highly effective anti-corrosion measures.

Based on the T_D prediction, users and designers can choose the durability improvement methods accordingly. For example, given that the users require an initial T_D of at least 50 years, then the combined utilization of different durability improvement measures is inevitable, and Table 6 shows several eligible solutions. In order to reach the designed service life of 100 years, it is assumed that the component should remain uncracked for at least 75 years. Thus, durability maintenances should be performed regularly based on the conditions presented in Table 4. Corresponding maintenance costs are analyzed in Level 3.

Level 3: Economic evaluation

Life-cycle cost is investigated in this section to evaluate the economic efficiency of solutions. It is assumed that the bridge structure does not fail within the designed service life, so the failure cost is not considered herein. Meanwhile, in order to meet the requirements of designed service life and to predict the future costs, a maintenance plan should be determined based on the initial design solution. Unit cost of construction materials, durability improvement techniques and construction works are presented in Table 7, collected from various dealers and contractors. The future costs are transferred to present value by a monetary discount rate of 2% and an inflation rate of 1.2%. To make a comparison, the total costs of construction and maintenance in present value are divided by T_D to reach an average annual cost, as listed in Table 8. The following conclusions are obtained:

- Concrete coating is the most economical method, and also perform well when combined with ER;
- 50% SL shows better durability effect and higher economic efficiency than 30% FA; and
- Although electrochemical measures can extensively prolong structures' service life, their unit costs are too high to be economical.

The indirect costs of the maintenances include the user cost and the socioeconomic cost[64]. In order to quantify the indirect cost, more detailed information of the investigated bridge is required, such as its location in transport network, average daily traffic volume (ADTV), regional economy, regional industry, etc. Thus, a qualitative analysis of indirect cost is conducted.

For this illustrative example, using electrochemical techniques can cause a higher indirect cost. Electrochemical measures need to keep the component steady and soak it with electrolyte [62]. Furthermore, concrete surface strength drops temporarily during the operation, making the lane closure or speed limit unavoidable during the work period. Painting coatings, on the other hand, have less strict requirements. The application of new coating can take place even when the structure is in service. So, electrochemical measures show no advantage on both direct and indirect cost aspects. In light of this, the solutions associated with electrochemical measures are eliminated. Among all available solutions, six with relatively lower average annual cost are selected, as the values in bold in Table 8.

Level 4: Environmental evaluation

With respect to the environmental evaluation of the reinforced concrete bridge, special attention is paid to the energy system, water system and construction materials. Evaluation factor set is $\boldsymbol{U_E} = \{u_1, u_2, u_3, u_4\}$. u_1 and u_2 represents the electricity consumption and water consumption during construction, respectively, with 1, 2 and 3 points for large, medium and small consumption, respectively; u_3 means the recycling rate of construction materials, with 1, 2 and 3 points for small, medium and large recycling rate, respectively; and u_4 means the pollutant emission level of material, with 1 to 3 points for the most to the least emissions. The weight vector for evaluation factors is assumed $\boldsymbol{A_E} = \{0.25, 0.25, 0.25, 0.25\}^T$. The environmental evaluation results $R_E = \boldsymbol{V_E} \cdot \boldsymbol{A_E}$ are listed in Table 9.

Herein, a simple fuzzy evaluation is conducted. Given additional expert information, more detailed evaluation can be conducted.

Level 5: User's and social evaluation

Users' and social evaluation considers the needs of users, investors, construction workers and social groups. In this example, focus is mainly placed on the evaluation from investors and engineering workers. Thus, the evaluation factor set is $\boldsymbol{U_U} = \{u_1, u_2, u_3\}$, where u_1 means the life-cycle economic efficiency, with 1 to 3 points for the least to the most economic solutions; u_2 is the construction feasibility, with 1 to 3 points for the hardest to the easiest construction work; and u_3 means the life-cycle workload of engineering workers, with 1, 2 and 3 points for large, medium and small amount of work, respectively. The weight vector for users' and social evaluation is set to be $\boldsymbol{A_U} = \{0.4, 0.3, 0.3\}^T$. The environmental evaluation results $R_U = \boldsymbol{V_U} \cdot \boldsymbol{A_U}$ are listed in Table 9. Since the life-cycle economic efficiency has the largest weight among all three evaluation factors, the evaluation results show almost the same trends as in the case of LCC evaluation.

Level 6: Sustainability evaluation

For sustainability evaluation, the consumption of nonrenewable resources, disturbance and damage to the atmosphere and the impacts on ecosystems are discussed. Several qualitative indicators and $LCCO_2$ are used herein to evaluate the sustainability performance.

The evaluation factors for sustainability are defined as $\boldsymbol{U_S} = \{u_1, u_2, u_3\}$, where u_1 is the consumption of fuels, with 1 to 3 points for the maximum to minimum consumption; u_2 is the utilization of environmentally-friendly materials or recycled materials, with 1 to 3 points for minimum to max application; u_3 is the $LCCO_2$, with 1 to 3 points for the highest to the lowest emission of carbon dioxide. The weight vector for sustainability evaluation is $\boldsymbol{A_S} = \{0.3, 0.2, 0.5\}^T$. The evaluation results are computed as $R_S = \boldsymbol{V_S} \cdot \boldsymbol{A_S}$.

The life-cycle carbon emission of the cap beam mainly comes from the construction and maintenance stages. In the construction stage, the production and transportation emission of construction materials, as well as the emission of construction work are considered. Similarly, the carbon emission of maintenance material, transportation and maintenance work are considered in maintenance stage. Carbon emission factors for various construction materials, energy and construction procedures are presented in Table 10[65] [66][67][68][69]. The carbon emission of solutions are computed as in Table 9. The following conclusions are drawn:

- Carbon emission in construction stage is dominated by the consumption of cement, so solutions with higher cement replacement rate (i.e., higher admixture dosage) emit less carbon dioxide;
- The solution with the lowest maintenance frequency emits the least carbon dioxide in maintenance stage, so the improvement of initial durability can reduce the future carbon emission; and
- Since u_3 is allocated with the biggest weight, so the solution with less carbon emission gets higher scores in the sustainability evaluation.

Comprehensive Green Evaluation

Finally, all the remaining solutions are scored considering the environmental, users' and social, and sustainability objectives, respectively. Assuming the weight vector for three green objectives $\boldsymbol{A}=\{1/3,1/3,1/3\}^T$, a synthetic green evaluation is obtained for all solutions. Relevant results are presented in Table 11.

Results indicate that solutions with higher cement replacement rate get higher green marks. Since the combination of multiple admixtures can improve durability and replace a large proportion of cement, it shows a significant advantage on environmental, sustainable and economical objectives. In general, the solutions with higher concrete strength level, thicker concrete cover, and more initial anti-corrosion measures are likely to get higher green scores.

5 Discussion

5.1 Comparison between Hierarchical LCD and Traditional Structural Design

Current structural design process mainly focuses on the safety and reliability design. Only critical projects facing severe environmental actions will move one step further to take the durability requirements into account. Investors' attention is still focused on the initial cost of a project, neglecting the possible future cost caused by durability deficiency and structural failure. While, the proposed Hierarchical LCD Theory combines the traditional structural design with durability design, economic efficiency design and green design. Thus, a comparison between the Hierarchical LCD and traditional structural design is conducted in Table 12. Solution **iii-*c*-FA** is a typical solution under traditional structural design, which satisfies the safety and reliability design, and complies with the structural requirements in durability codes. The solution **iv-*c*-FA-SC** is a result based on Hierarchical LCD method.

The checked item (√) means relevant requirement is considered or satisfied, and the crossed item (×) refers to the opposite.

As indicated in Table 12, solution **iii-*c*-FA** fulfills the safety and basic durability requirements. But, it does not apply any anti-corrosion measures. Consequently, it fails to remain uncracked for 75 years as required above. Since traditional structural design does not consider future maintenance plans, the structure is left unprotected in the severe environment and will gradually deteriorate to an unaccepted level. Restorations should be conducted at these moments by replacing the degraded component. Although it has lower initial cost, the average annual cost is much higher due to repeated restoration, as shown in Figure 4. Another negative effect of the repeated restorations is associated with the $LCCO_2$, since more construction materials and construction works are needed.

The solution designed based on Hierarchical LCD method shows advantages in wide range of aspects. It can maintain the demanded structural performance with less intervention for a longer time. Although it is built with higher initial cost, the total cost induced by future maintenance activities is much less. What's more, green design process guarantees better environmental and sustainable performance, as well as higher users' and social satisfaction.

Overall, Hierarchical LCD is a more comprehensive design method considering life-cycle requirements.

5.2 Sensitivity Analysis of the Weight Factors

Weight factors may have significant effects on the evaluation results. In fuzzy evaluation, weight factors are determined by experts according to their previous project experience, which is unavoidably subjective to some degree. So, different sets of weight factors are tested to investigate their effect on the evaluation results, as shown in Table 13. The values in bold are relatively higher green marks.

It is concluded that solutions with the higher scores in R_E, R_U and R_S tend to have better green performance regardless of the change of weight factors. Additionally, the solutions with the highest green design scores also show comprehensive advantages in the durability and economic design, which means that the durability, economic efficiency and green performance of a structure are interdependent, and that Hierarchical LCD method is able to find out design solutions that are favorable in wide range of aspects.

6 CONCLUSIONS

This paper proposes a new LCD approach comprehensively considering the aspects of safety and reliability, durability, economic efficiency, environmental impacts, users' and social satisfaction and sustainability. In order to settle a reasonable and logical clue for the LCD, the design objectives are arranged hierarchically into six levels.

Level 1 performs structure safety and reliability design. Initial durability design and durability improvement measures are proposed in Level 2 to maintain structures' durable service life. With respect to Level 3, LCCs of various solutions are assessed to identify the most economic ones. The green objectives proposed herein mainly focus on the structural effects on environment, users and society, as well as global ecology, and corresponding indicators are set up in Level 4~6.

A reinforced concrete coastal highway bridge is investigated to illustrate the practical application of the proposed hierarchical LCD method. Quantitative analysis is performed for the structural safety, durability and economic efficiency design. With respect to the green objective, most of the relevant indicators are qualitative. By using fuzzy comprehensive evaluation, solutions get their integrated green evaluation scores. Results indicate that solutions with higher concrete strength level, thicker concrete cover, and more initial durability measures are more likely to have better durability, economic efficiency and green performance.

According to the comparison between traditional design and hierarchical LCD method, the latter is able to obtain solutions with better durability, economic efficiency and green performance. The sensitivity analysis indicates that the structural durability, economic efficiency and green performance are interrelated. The hierarchical LCD method is able to obtain the solutions that meet the requirements in major design aspects.

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