Fuzzy Optimization of a Prestressed Concrete Bridge System Considering Cost, Aesthetics and Seismic Safety

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This paper proposes a rational, systematic and efficient multicriteria fuzzy optimum design method for a large-scale prestressed concrete bridge system that is developed combining suboptimization concept, introduction of measure membership functions for relative evaluation of all objective functions and fuzzy decision-making techniques. The proposed design method is applied to an optimum design problem of a large-scale prestressed concrete bridge system in which three objectives; total construction cost, aesthetics and seismic safety of the bridge system are taken into account. The rationality, systematic design process and efficiency of the proposed design method are demonstrated.

Key Words : fuzzy optimization, prestressed concrete bridge, cost, aesthetics, seismic safety

1. Introduction

The practical structural design problem involves several different characteristic objective functions such as economy, functionality, serviceability, maintainability, safety and aesthetics with the surrounding situation of construction site. Conflicts can arise between these objectives, for example, economy versus safety and serviceability. Moreover, the value of each objective function has to obtain the client and/or general consent and satisfy the designer's preferences and design emphases. Furthermore, the relative evaluations among different characteristic objectives have some tolerance or fuzziness. Therefore, the designers are always forced to seek for the best-compromise solution rationally by relatively evaluating these different characteristic objectives satisfying design requirements. This optimum decision-making problem can be recognized as a multicriteria optimum design problem with fuzziness.

Since the present concept of multicriteria optimization is originated by Parato in 1896, numerous contributions have been done in the field of optimization theory, operation research, control theory and engineering design. In the structural optimization field, the literatures have been appearing since the late 1970's and the solution methods are reviewed by Eschenauer et al [1], Osyczka [2] and Koski [3] [4].

The multicriteria optimization problems have been solved by two stage process, namely, generation of Pareto optima and decision-making process using Pareto optima. The Pareto optima have been generated using different methods, namely, linear weighting method, minimax approach and use of distance function, constraint method and so on. The decision-making is done by interactive methods, choice by comparisons, a priori fixed parameters and so on. However, no comprehensive multicriteria optimum design method has been developed which can deal with most of the psychological characteristics to be considered in the design process, such as fuzziness, design emphases, designer's preferences, general and/or client consent and so on.

In the field of optimum design of prestressed concrete structure, the optimum design problem considering single objective has been studied considerably, however, a quite few study has been done on the multicriteria optimum design problem of prestressed concrete structures. Lounis and Cohn [5] have studied on the multicriteria optimum design problem of prestressed concrete structures in which cost and initial camber are taken into account as the objectives and the optimum solution is determined using Pareto optima and trade-off approach.

This paper proposes a rational, systematic and efficient multicriteria fuzzy optimum design method for a large-scale prestressed concrete bridge system which is developed combining suboptimization concept, introduction of measure membership functions for relative evaluation of all objective functions and fuzzy decision-making techniques. The proposed design method is applied to an optimum design problem of a large-scale prestressed concrete bridge system in which three objectives; total construction cost, aesthetics and seismic safety of the bridge system are taken into account. The rationality, systematic design process and efficiency of the proposed design method are demonstrated.

2. Proposed multicriteria fuzzy optimum design method

In this paper, a multicriteria fuzzy optimum design method for a large-scale structural system which is developed combining suboptimization concept, introduction of measure membership functions and fuzzy decision-making techniques. The proposed optimum design method is conducted by the following design process.

At the first step of the design process, the design variables to be dealt with in the optimum design problem of structural system are classified into two sets by taking into account the significance and the degree of contributions of each design variable to each objective function. The design variables which affect to all objectives significantly are classified as the common design variables X_c and the design variables to be dealt with only in the optimization process of individual objectives are termed as the objective oriented design variables X_o. In this study, it is assumed the objective oriented design variables of each objective are exclusive of those of other objectives. The objective functions are also classified into two sets, namely, a set of design parameter objectives f_p and another set of objectives to be suboptimized subject to the various design conditions f_o. The design parameter objectives f_p specify discretely the design conditions for optimization problems of the objectives to be suboptimized f_o.

At the second step, the optimization of the objectives to be suboptimized are conducted for all combinations of discrete values of the common design variables X_c and the design parameter objectives f_p.

Then, at the third step, the measure membership functions of objectives to be suboptimized f_o are introduced by taking into account relative evaluation of the corresponding suboptimized data of f_o for all discrete design conditions, fuzziness involved in decision-making process, the client and/or general consent, designer's preferences and design emphases. The measure membership functions of the design parameter objectives f_p are also introduced considering the significance of values of f_p.

At the fourth step, the membership functions of sub-optimized relationship of all objective functions with respect to a certain common design variable for the discrete design conditions are introduced using corresponding measure membership functions as datum.

At the fifth step, the optimum values for a certain common design variable for the discrete design conditions are specified by the other discrete common deign variables and the discrete design parameter objectives are determined by the weighted operator method in which the relative weights of the objective functions are determined by the client and/or general consent, designer's preferences and design emphases of the structural system.

The optimum values of one of remaining common design variables or one of design parameter objectives for discrete conditions specified by the other discrete common design variables and the other design parameter objectives are obtained by introducing a continuous membership function which is derived by arranging the results obtained in the previous step. This procedure is iterated until all optimum values of common design variables and the design parameter objectives are obtained. At the final step of this procedure, we can obtain the global optimum value of the final common design variable or final design parameter objective.

The global optimum values of other common design variables and other design parameter objectives can be determined by a backward interpolation process using the previously derived relationships.

The global optimum values of objective oriented design variables $X^g_{o,opt}$ can be determined by suboptimizing f_o for the set of the global optimum values of common design variables $X^g_{c,opt}$ and design parameter objectives $f^g_{p,opt}$.

The proposed multicriteria fuzzy optimum design method is applied to an optimum design problem of a large-scale prestressed concrete three-span continuous bridge system in which the total construction cost, the aesthetics and the seismic safety of the bridge system are considered as objectives. The details of the proposed optimum design method is described in the following sections.

3. Primary optimum design problem of the prestressed concrete bridge system

3.1 Bridge system

The bridge system considered in this paper consists of a three-span parabolic shape prestressed concrete box girder (superstructure) and four RC piers and RC pile foundations (substructure) as shown in Fig. 1. The bridge has a total length of 200m and a width of 14m. The superstructure is elevated 30m from the top of the RC foundations. The geological condition of construction site is assumed that a bearing layer with N value 30 exists underneath a 10-m depth sand layer with N value 10.

3.2 Objective functions

In the multicriteria fuzzy optimum design problem of the prestressed concrete bridge system, the total construction cost of the bridge system f_t to be minimized, the aesthetics f_a to be maximized and the seismic safety of the bridge system f_l to be maximized are dealt with as the objective functions. As it has been experienced at the huge earthquake like Hanshin-Awaji great earthquake in Kobe 1995, the collapse of piers and foundations of the bridge system at urban area causes huge damages not only the direct collapse of the bridge system itself but also the tremendous secondary damages caused by the blockages of traffic flows. However, if the bridge system is constructed in the country site or mountain site, the secondary damages caused by the collapse of piers and foundations might be smaller than that at urban area. For this reason, the magnitude of the safety parameter to be used for the design of the substructure is very significant design parameter from the viewpoint of maximization of the seismic safety of the bridge system, in other words, minimization of total social losses caused by the collapse of the bridge system, and then the value of the safety parameter f_s for the design of the substructures is dealt with as the objective function instead of the direct use of f_l.

For the reason that the safety parameter f_s affects so much to the total construction cost, we define f_s as a design parameter objective and other two objectives, the total construction cost f_t and the aesthetics f_a are dealt with as the objectives to be suboptimized dealing with the objective oriented design variables for discrete design conditions which are specified by the primary design constraints and discrete values of the safety parameter f_s.

3.3 Design variables

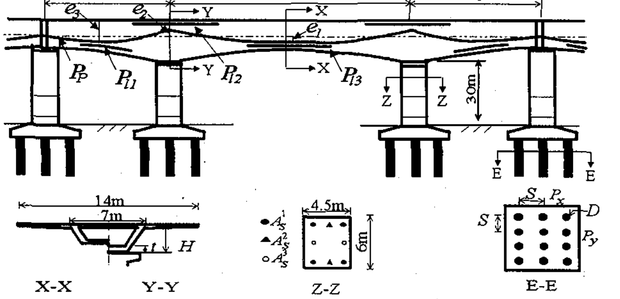

Fig.1 Design variables of a three-spans continuous prestresssed concrete box girder bridge system

In the prestressed concrete bridge system shown in Fig. 1, the girder height is assumed to be varied parabolically at the center span and side spans and it takes the value H at intermediate supports and $H/2$ at the end supports and the center of center span. Since the span ratio Sr ($=l_1/l_2$) and girder height H affect significantly two objectives of the total construction cost and the aesthetics, Sr and H are dealt with as the common design variables $\boldsymbol{X}_c$ of the bridge system, namely, $\boldsymbol{X}_c=[Sr, H]^T$.

In the suboptimization of the superstructure, the parabolic prestressing force P_p, linear partial prestressing forces P_{l1}, P_{l2} and P_{l3}, thickness of the bottom slab of box section t and tendon eccentricities of parabolic prestressing e_1, e_2 and e_3 as shown in Fig. 1 are dealt with as the design variables. These design variables affect only to the construction cost of the superstructure. Therefore, we deal with these design variables as objective oriented design variables $\boldsymbol{X}_{sup}$ which belong to construction cost of the superstructure, namely, $\boldsymbol{X}_{sup}=[P_p\ \boldsymbol{P}_l, \boldsymbol{e}, t]^T$, where $\boldsymbol{P}_l=[P_{l1}, P_{l2}, P_{l3}]^T$, $\boldsymbol{e}=[e_1, e_2, e_3]^T$.

The substructure of the prestressed concrete bridge system consists of four rectangular shape RC piers and four RC pile foundations as shown in Fig. 1. In the pier optimization, each pier is assumed to consist of three segments with same width and depth, and these values are determined as constants from the aesthetic viewpoint. Then only the reinforcement areas $\boldsymbol{A}_{s\,jk}=[A_{sjk}^1, A_{sjk}^2, A_{sjk}^3]^T$ in each pier segment shown in Fig. 1 are dealt with as the design variables, in which j is the number of the RC pier segment ($j = 1, 2, 3$) and k is the number of the RC pier ($k = 1, 2, 3, 4$).

In the suboptimization problem of rectangular RC pile foundation, number of the RC piles in the direction of the bridge axis P_x and the number in the perpendicular direction P_y, diameter of pile D and spaces of piles S in each pile foundation are dealt with as the design variables (see Fig. 1). These design variables affect only to the construction cost of the substructure, therefore, we deal with these design variables as objective oriented design variables $\boldsymbol{X}_{sub}$ which belong to the construction cost of the substructure, namely, $\boldsymbol{X}_{sub} = [\boldsymbol{A}_s, \boldsymbol{P}_x, \boldsymbol{P}_y, \boldsymbol{D}, \boldsymbol{S}]^T$, where $\boldsymbol{A}_{s\,jk}=[A_{sjk}^1, A_{sjk}^2, A_{sjk}^3]^T$, $\boldsymbol{P}_x=[P_{x1}, P_{x2}, P_{x3}, P_{x4}]$, $\boldsymbol{P}_y=[P_{y1}, P_{y2}, P_{yk}, P_{y4}]^T$, $\boldsymbol{D}=[D_1, D_2, D_3, D_4]^T$, $\boldsymbol{S}=[S_1, S_2, S_3, S_4]^T$.

3.4 Formulation of the multicriteria optimum design problem of the prestressed concrete bridge system without fuzziness

Using the terminology defined in the previous section, the multicriteria optimum design problem of the prestressed concrete bridge system in which no fuzziness is taken into account is formulated as follows,

find	$Sr, H, \boldsymbol{X}_{sup}, \boldsymbol{X}_{sub}$, which	
minimize	$f_t(\boldsymbol{X}_{sup}, \boldsymbol{X}_{sub}, Sr, H, f_s) = W_{sup}(\boldsymbol{X}_{sup}, Sr, H)$ $+W_{sub}(\boldsymbol{X}_{sub}, Sr, H, f_s)$	(1)
maximize	$f_a(Sr, H)$	(2)
maximize	f_s	(3)
subject to	$g_j(\boldsymbol{X}_{sup}, Sr, H) \le 0 \quad j=1,\dots,q_{sup}$	(4)
	$g_k(\boldsymbol{X}_{sub}, Sr, H, f_s) \le 0 \quad k=1,\dots,q_{sub}$	(5)

where g_j and g_k are, respectively, design constraints of the superstructure and the substructure and q_{sup} and q_{sub} are, respectively, number of design constraints for suboptimization of the superstructure and the substructure.

4. Suboptimization of the total construction cost and the aesthetics of the bridge system

As described in section 3.2, we deal with f_s as a design parameter objective and it specifies discrete design conditions. Then the suboptimization problems on the total construction cost f_t and the aesthetics f_a are solved for every combination of discrete values of H, Sr and f_s.

4.1 Discrete combinations of Sr, H and f_s

In order to obtain the minimum total construction costs of the bridge system, we solve the suboptimization problem of construction cost of the superstructure for every combination of discrete values of Sr and H and suboptimization problem of construction cost of the substructure for every combination of discrete values of Sr, H and f_s. As the discrete values of common design variables, span ratios Sr = 0.5, 0.61, 0.75, 0.92 and girder heights at the interior support H = 4.5m, 5.0m, 5.5m, 6.0m, 6.5m, 7.0m, 7.5m, 8.0m, 8.5m are considered. As the discrete values of parameter objective, the safety parameter of the substructure f_s= 1.0, 1.2, 1.4, 1.6, 1.8 are taken into account.

4.2 Suboptimization of construction cost of the superstructure for discrete combination of Sr and H

(a) Design constraints

In the suboptimization of the superstructure, stress and cracking constraints in the serviceability limit state and flexural-strength and ductility constraints in the ultimate limit state specified by the ACI code are taken into account.

(b) Construction cost of the superstructure

Since the values of f_s affects only to the construction cost of the substructure, the suboptimization process of construction cost of the superstructure is conducted for every combination of discrete values of Sr and H. The construction cost of the superstructure for the given combination of discrete Sr and H, W_{sup} ($\boldsymbol{X}_{sup}$, Sr, H), can be calculated as the summation of the cost of prestressing tendon and the cost of concrete, namely,

$$W_{sup}(\boldsymbol{X}_{sup}, Sr, H) = C_p A_p(P_p) + \sum_{i=1}^{m}[C_p A_p(P_l) l_{ei}(e) + C_c A_{gci}(t) l_i] \tag{6}$$

where $A_p(P_p) = P_p / f_{pe}$, $A_p(P_l) = P_l / f_{pe}$. f_{pe} is the allowable tensile stress of prestressing tendon. $l_{ei}(e)$ and l_i are, respectively, the length of prestressing tendon in the ith girder element and the length of the ith girder element. A_{gci} is the cross-sectional area of concrete of the ith girder element. C_p and C_c are, respectively, the relative unit costs of prestressing tendon and concrete, and assumed as 6130800 /m^3 and 24000 /m^3, respectively. These relative unit costs are estimated including the constant (initial) expenditure also. m is the number of girder elements.

(c) Primary suboptimization problem and suboptimization algorithm of the superstructure

By considering the design variables, design constraints and the total construction cost of the superstructure described above, the primary suboptimization problem for the discrete combination of Sr and H can be formulated for the superstructure as

$$\begin{array}{lll} \text{find} & \boldsymbol{X}_{sup}\ [=P_p, \boldsymbol{P}_l, \boldsymbol{e}, t]^T, \quad \text{which} & \\ \text{minimize} & W_{sup}(\boldsymbol{X}_{sup}, Sr, H) & \\ \text{subject to} & g_j(P_p, \boldsymbol{P}_l, \boldsymbol{e}, t) \le 0 & j = 1, \ldots, q_{sup} \quad (7) \end{array}$$

The suboptimization problem described above is solved by an optimal structural synthesis method combining the convex approximation concept and a dual method (Fleury and Braibant [6], Ohkubo and Asai [7]). Utilizing the convex and linear approximation concept, the objective function and behavior constraints are, respectively, approximated by the first-order terms of Taylor series expansions with respect to the direct design variables or the reciprocal design variables. The first-order partial derivatives of behavior constraints with respect to the primary design variables are calculated by the forward-difference method. The above approximate subproblem is solved by the dual method in which the separable the Lagrangian function is minimized with respect to the primary design variables and maximized with respect to the Lagrange multipliers (dual variables). At the minimization process, the primary design variables are improved by simple expressions derived from stationary conditions of the separable Lagrangian function. Then, at the maximization process, the dual variables are improved by a Newton-type algorithm. The minimum cost of the superstructure, optimum P_p, $\boldsymbol{P}_l$, t, $\boldsymbol{e}$ can be determined by iterating the above approximate formulation and min.-max. process of the separable Lagrangian function.

4.3 Suboptimization of the construction cost of the substructure for discrete combination of Sr, H and f_s

The three-span continuous prestressed concrete box girder (superstructure) is supported by four piers and four pile foundations (substructure) as shown in Fig. 1, therefore, the suboptimization of the substructure should be conducted for each pier and its pile foundation separately.

The bridge system is subjected to dead load (DL), live loads (LL) and horizontal force ($F(\alpha)$) caused by the horizontal acceleration (α) due to an earthquake motion. In this paper it is assumed that the magnitude of horizontal force acting to the top of the ith pier, $F(\alpha)_i$, is calculated by,

$$F(\alpha)_i = \alpha \cdot R_{\sup i} \tag{8}$$

where $R_{\sup i}$ is the vertical reaction of the ith pier due to the dead load of the superstructure.

In this paper, the safety parameter f_s is considered as the parameter objective and α is assumed to be a function of f_s and calculated by

$$\alpha(f_s) = 0.2 \cdot f_s \tag{9}$$

This value $\alpha(f_s) = 0.2$ for $f_s = 1.0$ is determined as the standard value of horizontal acceleration by referring the Seismic Design Code Specification for Highway Bridge (Japan Road Association [8]).

(a) Design constraints of a RC pier

A RC pier consists of three segments, and the width, depth and height of each segment are assumed to be the same from aesthetic viewpoint. In the suboptimization problem of the kth segment of the RC pier for the combination of discrete Sr, H and f_s the ultimate limit state constraints g_{kj} under vertical force and bending moments due to horizontal forces in the directions of the bridge axis (q=1) and perpendicular to the bridge axis (q=2) at an earthquake are taken into account (Japan Road Association [8]).

(b) Construction cost of a RC pier segment

The construction cost of the kth segment of the jth RC pier W_{pkj} for the discrete Sr, H and f_s can be calculated as the summation of costs of concrete and reinforcement of the segment.

$$W_{pkj}(A^1_{skj}, A^2_{skj}, A^3_{skj}, Sr, H, f_s) = C_s \sum_{i=1}^{3} A^i_{skj} l_{kj} + C_c A_{pckj} l_{kj} \tag{10}$$

where $A_{s\,kj}^{\;i}$ (i=1,2,3) and A_{pckj} are, respectively, areas of steel reinforcements and concrete. l_{kj} is the length of the kth segment of the jth pier. The relative unit costs of steel reinforcement C_s and concrete C_c are assumed, respectively, as 110000/m^3 and 24000/m^3.

(c) Primary suboptimization design problem of the RC pier segment

By considering the design variables described in 3.3 and design constraints in 4.3 (a), the primary suboptimization design problem can be formulated for the kth segment of the jth RC pier as

$$\begin{array}{lll} \text{find} & A_{s\,kj}^{\;1},\ A_{s\,kj}^{\;2},\ A_{s\,kj}^{\;3}, \quad \text{which} & \\ \text{minimize} & W_{p\,kj}(A_{skj}^{\;1}, A_{s\,kj}^{\;2}, A_{s\,kj}^{\;3}, Sr, H, f_s) & \\ \text{subject to} & g_{kqj}(A^1_{skj}, A^2_{skj}, A^3_{skj}, Sr, H, f_s) \le 0 & q=1,2 \quad (11) \end{array}$$

The suboptimization problem of the above RC pier segment is also solved using the dual method described in 4.2 (c).

(d) Design constraints of a RC pile foundation

A RC pile foundation consists of a rectangular concrete footing and P_xxP_y piles. In the suboptimization problem of the RC pile foundation, the constraints on bearing or tensile capacities of piles are taken into account as design constraints (Kokubu et al. [9]). The side constraint that ensures the minimum pile space is also considered.

(e) Construction cost of the RC pile foundation

The construction cost of the RC pile foundation for the discrete combination of Sr, H and f_s $W_f(D, S, P_x, P_y, Sr, H, f_s)$, can be calculated as the summation of the costs of concrete footing and piles.

$$\begin{aligned} &W_f(D, S, P_x, P_y, Sr, H, f_s) = \\ &C_{fc}A_{fc}(D, S, P_x, P_y)h + C_{pc}A_{pc}(D)P_xP_yl_p \end{aligned} \tag{12}$$

The relative unit costs of concrete for footing C_{fc} and pile C_{pc} are assumed, respectively, as 24000 /m^3 and 30000 /m^3. $A_{fc}(D, S, P_x, P_y)$ and $A_{pc}(D)$ are, respectively, bottom area of the rectangular concrete footing and cross-sectional area of pile. l_p is the pile length. h is the average height of concrete footing.

(f) Primary suboptimization problem of the RC pile foundation

By considering the design variables described in 3.3, the design constraints in 4.3 (d) and the construction cost in 4.3(e), the primary suboptimization problem can be formulated for each RC pile foundation as

find	D, S, P_x, P_y which		
minimize	$W_f(D, S, P_x, P_y, Sr, H, f_s)$		(13)
subject to	$g_{pq}(D,S,P_x,P_y,Sr,H,f_s) \leq 0$	$q=1,2,3$	(14)
	$g_{fr}(D,S,P_x,P_y,Sr,H,f_s) \leq 0$	$r=1,2$	(15)

The above suboptimization problem of the RC pile foundation is solved quite simply and easily by applying a systematic iterative and comparing process for discrete sets of the design variables ***D, S, P$_x$, P$_y$***.

4.4 Summarization of the suboptimized data of f_t with respect to H for every discrete Sr and f_s

The suboptimization processes of the superstructure and the substructure described in 4.1~ 4.3 are conducted for all discrete combinations of Sr, H and f_s within their comparable ranges described in 4.1. The minimum total construction cost for a discrete set of Sr, H and f_s, $f_{t,min}$ (X_{sup}, X_{sub}, Sr, H, f_s), is calculated by the following expression,

$$f_{t,min}(X_{sup}, X_{sub}, Sr, H, f_s)=W_{sup}(X_{sup}, Sr, H) + \sum_{j=1}^{4}\sum_{k=1}^{3} W_{pkj}(A_{skj}, Sr, H, f_s) + \sum_{j=1}^{4} W_{fj}(D_j, S_j, P_{xj}, P_{yj}, Sr, H, f_s) \quad (16)$$

By arranging the minimum total construction costs of the bridge system obtained by (16) for all discrete combinations of Sr, H and f_s, the relationships between the minimum total construction cost of the bridge system and H for every discrete Sr and f_s are introduced. Fig.2 shows two examples of this relationship for Sr=0.61, f_s=1.2 and Sr=0.75, Sr =1.2.

4.5 Suboptimization of the aesthetics of the bridge system

The aesthetics of the bridge system is affected so much by many factors such as combination of values of common design variables Sr and H, harmony in color of the bridge system with surrounding situation of construction site and so on, but objective oriented design variables X_o and the safety parameter f_s do not affect so much to the evaluation of the aesthetics of the bridge system. Therefore, in this study, the preparation of the perspective views of the bridge system for all discrete combinations of common design variables Sr and H using reasonable material and tools is considered as the suboptimization process of the aesthetics of the bridge system.

5. Relative evaluation of all objective functions f_t, f_a and f_s

In this optimum design problem, three different characteristic objectives are considered and relative evaluation of these objectives has some tolerance or fuzziness. Considering these characteristics of design problem the fuzzy decision-making techniques are adopted for the determination of the global optimum solution as described in 2. As the first step of mutual evaluation of the objectives, we introduce the measure membership functions for all objectives.

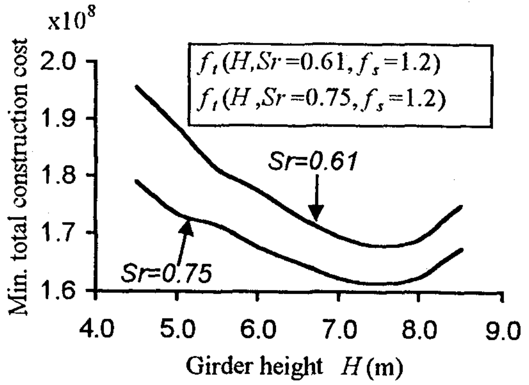

Fig. 7 Relationships between mini. total construction cost and H for Sr=0.61,f_s=1.2 and Sr=0.75,f_s=1.2

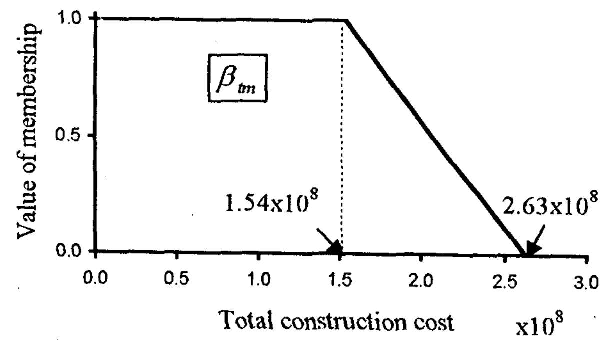

Fig.3 The measure membership function of the total construction cost

5.1 Introduction of the measure membership function of the minimum total construction cost β_{tm}

The measure membership function of the total construction cost β_{tm} is introduced by inspecting the budget limitation for the total construction cost and the range of variation of the suboptimized minimum total construction costs of the bridge system for all discrete sets of common design variables Sr, H and the safety parameter f_s. In this introduction process of measure membership function, the designer's preferences, design emphases, client and/or general consent are also to be satisfied. We decided that the smallest value, 1.54×10^8, and the largest value, 2.63×10^8, among the suboptimized minimum total construction cost for all discrete set of Sr, H and f_s have, respectively, the maximum and the minimum membership values, namely, 1.0 and 0.0, and the membership value is varied linearly for the total construction costs between the maximum and the minimum values. The measure membership function is then introduced as that shown in Fig.3.

5.2 Introduction of the measure membership function of the aesthetics: β_{am}

The measure membership function of the aesthetics objective β_{am} is introduced by evaluating relatively aesthetics of perspective views of the bridge system for all discrete combinations of common design variables Sr and H which are prepared in the suboptimization process of the aesthetics of the bridge system in 4.5. As the measure membership function of the aesthetics of the bridge system the membership function shown in Fig.4 is assumed, in which the bridge system with Sr=0.61, H=6.5m is decided as the most beautiful bridge system giving the best harmony with surrounding situation of construction site.

5.3 Introduction of the measure membership function of the seismic safety of the bridge system: β_{lm}

As described in 3.2 the total social damages caused by the collapse of structural system due to an earthquake are significantly depend on the characteristics of the construction sites such as urban area, country site and mountain site. If the bridge system is constructed in urban area, the seismic safety of the bridge system has to be greater than these for country site and mountain site. In the practical design problem, the measure membership function of the seismic safety is to be determined by evaluating the total social loss caused by the failure of the structural system designed with seismic safety f_l. In this study, it is assumed that the bridge system designed with f_s=1.0 might cause twice much of social loss compare with that of the bridge system designed with f_s=1.8. Then, the membership value of the bridge system designed with f_s=1.0 is assumed to be 1/2 of that of the bridge system designed with f_s=1.8. The social losses caused by the failures of the bridge systems designed with f_s=1.2, 1.4, 1.6 are assumed to be linearly proportional to f_s. Therefore, the measure membership function of seismic safety of the bridge system β_{lm} is introduced as that shown in Fig. 5.

5.4 Modification of the measure membership functions of f_t with respect to β_{lm}

It is clear that if the seismic safety (safety parameter) is specified as the small value it makes total construction cost of the substructure economical, however, the probability of collapse of the bridge system increases and in consequence the secondary damages caused by the collapse of the bridge system might be increased. Therefore, from the viewpoint of the minimization of total damages due to an earthquake the measure membership function of the total construction cost of the bridge system $\beta_{tm}(f_t)$ has to be modified with respect to the seismic safety of structural system. In this study, the modified measure membership functions of the total construction cost for discrete $\tilde{f}_s$, $\lambda_{tm}(f_t, \tilde{f}_s)$ is assumed to be obtained by multiplying $\beta_{lm}(\tilde{f}_s)$ to $\beta_{tm}(f_t)$. The modified measure membership functions $\lambda_{tm}(f_t, f_s)$ are shown in Fig.6. Meanwhile, the membership function of the aesthetics is not affected by the safety parameters, therefore, the measure membership function of the aesthetics β_{am} is not necessary to be modified by β_{am}.

5.5 Introduction of membership functions of suboptimized objectives

(a) Introduction of membership functions of the total construction cost with respect to H for every discrete Sr and f_s

The membership function of the minimum total construction cost with respect to girder height H for the kth discrete span ratio Sr_k and the jth discrete safety parameter f_{sj}, $\mu_t(H, Sr_k, f_{sj})$, can be introduced using the modified measure membership function of the total construction cost corresponding to the jth discrete safety parameter f_{si} (see Fig.6) and suboptimized minimum total construction costs for all discrete combinations of H_i (i=1,..,9), Sr_k and f_{sj}. Fig. 7 shows

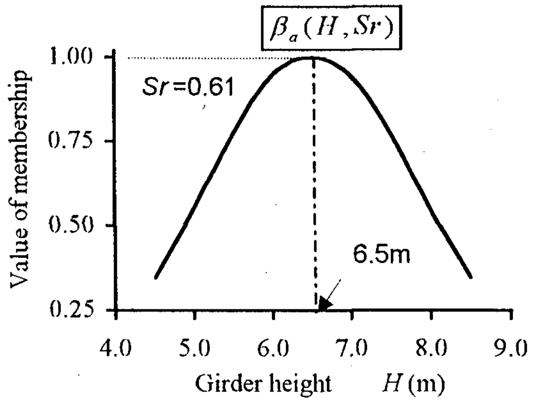

Fig.4 The measure membership function of the aesthetics of the bridge system

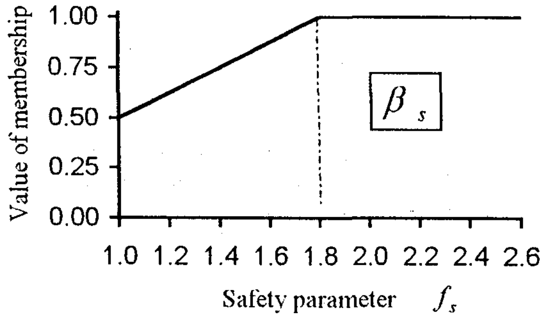

Fig.5 The measure membership function of the seismic safety of the bridge system

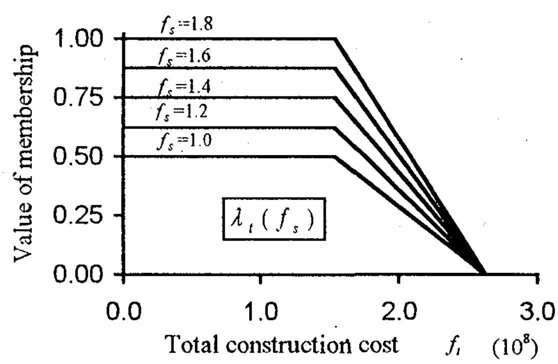

Fig.6 Modified measure membership functions of the total construction cost at every discrete f_s

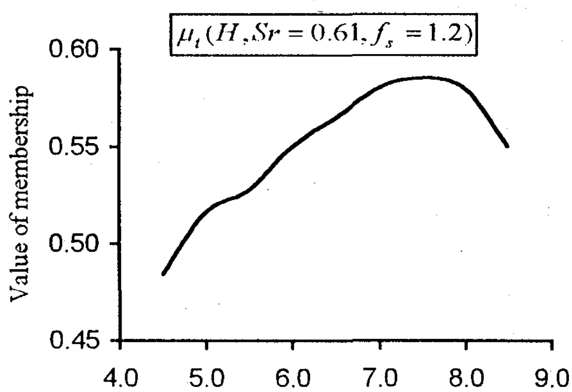

Fig. 7 Membership function of the mini. total construction cost with respect to H for Sr=0.61, f_s=1.2

the membership function of the total construction cost with respect to girder height H for Sr=0.61 (=Sr_k) and f_s=1.2 (=f_{sj}). The membership functions stated above are introduced for every combination of discrete Sr_k and f_{sj} ,where k=1,..,4 and j=1,..,5.

(b) Introduction of membership functions of the aesthetics with respect to H for all discrete Sr

The membership function of the aesthetics with respect to girder height H for the kth discrete span ratio Sr_k, $\mu_a(H, Sr_k)$, is introduced by evaluating relative aesthetics of perspective views of the bridge system with girder height H_i (i=1,..,9) for Sr_k referring to the measure membership function of the aesthetics β_{am} as datum (see Fig.4). The membership functions of the aesthetics with respect to girder height H for every discrete span ratio Sr=0.5, 0.61, 0.75 and 0.92 are shown in Fig.8.

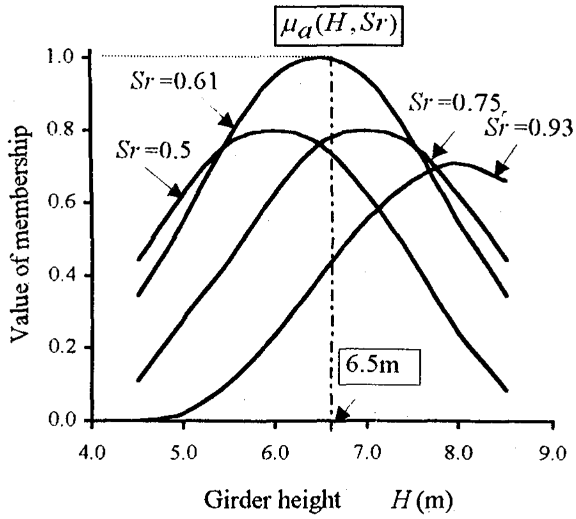

Fig. 8 Membership functions of the aesthetics w. r. t. the girder height H for Sr=0.5, 0.61, 0.75, 0.93

6. Determination of the global fuzzy optimum solution

In the previous sections, we introduced the membership functions of the minimum total construction cost with respect to H for all discrete span ratios Sr and the safety parameter f_s and the aesthetics with respect to H for discrete Sr. Then, using these membership functions, we can determine the fuzzy optimum girder heights H_{opt} for each combination of discrete span ratios Sr and discrete safety parameters f_s by the weighted operator method with assumed weight ratio. Then we can introduce the relationship between maximum value of membership at the optimum girder height H_{opt} and span ratio for every discrete f_{sj} (j=1,..,5). The optimum span ratios for every discrete f_s can be obtained by searching the maximum values of the relationships. The maximum membership values for every discrete f_{sj} (j=1,..,5) are summarized with respect to the safety parameter f_s, and the global optimum safety parameter $f^g_{s,opt}$ can be obtained by searching the maximum membership value in the relationship. The final global optimum values of the objective oriented design variables $X^g_{o,opt}$ can be determined by suboptimizing f_o for the set of the global optimum values of common design variables $X^g_{c,opt}$ and design parameter objectives $f^g_{s,opt}$.

6.1 Determination of the optimum girder heights for every discrete span ratio Sr and the safety parameter f_s

In the weighted operator method, membership functions of the minimum total construction cost and the aesthetics are multiplied, respectively, by the normalized corresponding relative weights W_t and W_a, where W_t+W_a=1.0. These relative weights are determined by the client and/or general consent, the designer's preferences and design emphases of the structure. In this paper, these weights are assumed as W_t=0.6 and W_a =0.4. Then, the weighted maximum membership value $\mu_{k,opt}$ and the corresponding optimum girder height $H_{kj,opt}$ for the kth span ratio Sr_k and the jth safety parameter f_{sj} can be determined by the following expression of the weighted operator method. Fig.9 shows the determination process of eq.17 for Sr_2 =0.61 and f_{s2} =1.2. The max. ($W_t\mu_t + W_a\mu_a$) is obtained as 0.66 for H=7.2m.

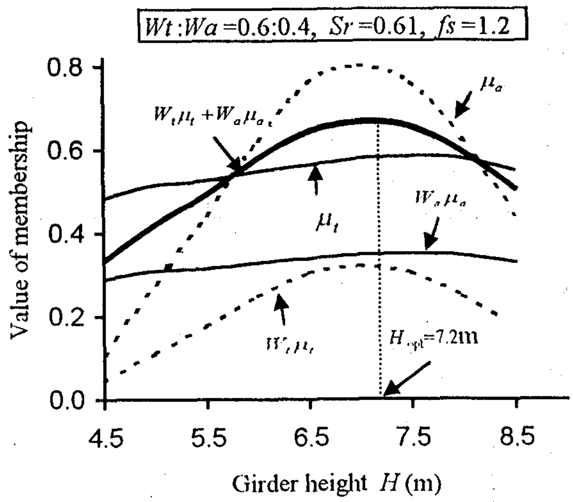

Fig. 9 Determination of maximum membership value and optimum H by the weighted operator method

$$\mu_{k,j,opt}(H_{k,j,opt}, Sr_k, f_{sj}) = \max\{W_t\mu_t(H, Sr_k, f_{sj}) + W_a\mu_a(H, Sr_k)\} \quad (17)$$

6.2 Determination of optimum span ratios for every discrete safety parameter objective f_{sj}

The relationships between weighted maximum membership values $\mu_{k,j,opt}(H_{k,j,opt}, Sr_k, f_{sj})$ (k=1,...,4) and span ratio Sr for discrete f_{sj} can be introduced for every discrete safety parameter f_{sj} (j=1,..,5). In Fig. 10 the relationship for f_{s2} = 1.2 is depicted and the optimum span ratio Sr_{opt} is determined as Sr_{opt} =0.64 which gives the maximum weighted membership value. The optimum span ratios Sr_{opt} for every discrete safety parameter f_{sj} (j=1,..,5) can be obtained by the same process.

6.3 Determination of the global fuzzy optimum safety parameter $f_{s,\,opt}$

By arranging the safety parameter and corresponding values of $\max(W_t\mu_t + W_a\mu_a)$, we can introduce the relationship between maximum membership values $\mu_{j,opt}(Sr_{j,opt}, f_{sj})$ and the safety parameter f_{sj} (j=1,..,5). The relationship introduced is shown in Fig.11 and the global optimum safety parameter $f^g_{s,opt}$ is determined as $f^g_{s,opt}$ =1.57 that has the maximum value μ_{opt} in the $\mu_{j,opt}(f_{sj})$ (j=1,...,5) and f_s relationship as shown in Fig.11.

6.4 Determination of the final global optimum values of Sr, H, $\boldsymbol{X}_{sup}$ and $\boldsymbol{X}_{sub}$

The global optimum span ratio Sr^g_{opt} =0.65 for $f^g_{s,opt}$=1.57 can be determined using already established relationship between weighted maximum membership values and span ratio for two discrete $f_{s\,j}$ which are nearest to $f^g_{s,opt}$. The global optimum girder height H^g_{opt}=7.28m for Sr^g_{opt} and $f^g_{s,opt}$ can be determined using relationship between maximum values and the girder height for two discrete set of $f_{s\,j}$ and Sr_j which are nearest to $f^g_{s,opt}$ and Sr^g_{opt}.

The exact global optimum values of X_{sup} and X_{sub} for Sr^g_{opt}, H^g_{opt} and $f^g_{s,opt}$, $\boldsymbol{X}^g_{sup}$ and $\boldsymbol{X}^g_{sub}$ are determined by the suboptimization processes of the superstructure and the substructure described in 4. The global optimum values $\boldsymbol{X}^g_{sup}=[P_p\ \boldsymbol{P_l},\ \boldsymbol{e},\ t]^T$ and $\boldsymbol{X}^g_{sub}$ = $[\boldsymbol{A_s},\ \boldsymbol{P_x},\ \boldsymbol{P_y},\ \boldsymbol{D},\ \boldsymbol{S}]^T$ are, respectively, given in Table 1,2 and 3.

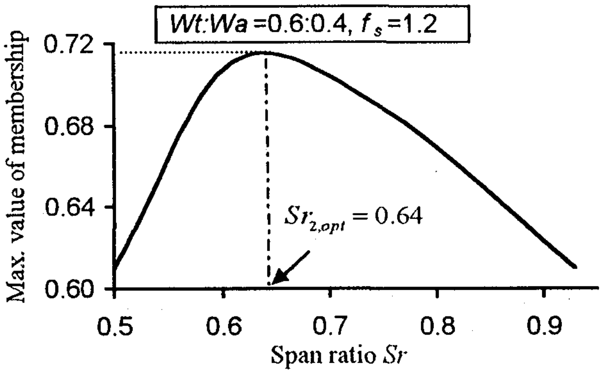

Fig. 10 Determination of optimum Sr_{opt} for f_s=1.2

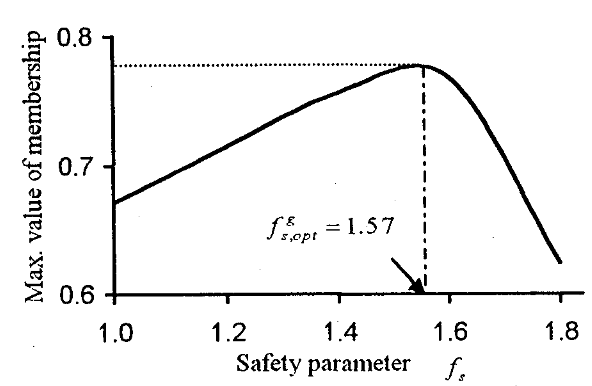

Fig. 11 Determination of the global optimum f^g_s

Table. 1. Global optimum values of P_p, P_l, e and t of superstructure

P_p (kN)	P_l(kN)			e (m)			t (m)
	Pl_1	Pl_2	Pl_3	e_1	e_2	e_3	
18828	332	8562	2828	1.46	0.42	1.71	0.52

Table. 2. Global optimum values of A_1, A_2 and A_3 of RC pier

	Segment 1	Segment 2	Segment 3
	A_1. (cm^2)	A_2. (cm^2)	A_3.(cm^2)
	A_1^1, A_1^2, A_1^3	A_1^1, A_1^2, A_1^3	A_1^1, A_1^2, A_1^3
P1, P4	43.9, 43.0, 76.3	76.3 , 73.4, 76.4	92.6, 88.3, 92.6
P2, P3	58.7, 54.2, 58.7	132, 98.2, 132	172 , 141, 172

P1 P4: Pier and foundation of end support *P2 P3*: Pier and foundation of outer support

Table. 3. Global optimum values of D, S, P_x, and Py of RC footing

	D (m)	S (m)	Px	Py
P1, P4	1.1	3.2	2	5
P2, P3	1.2	3.4	3	4

7. Conclusions

The following conclusions can be drawn from this study.

1. For the reason that all discrete combinations of design conditions specified by the design parameter objectives and common design variables are taken into account and the corresponding suboptimized data of all objectives are evaluated in the determination process of the global optimum solution, the proposed design method is applicable to any types of convex and nonconvex multicriteria optimization problems.

2. The proposed design method can easily involve the fuzziness in the decision-making process, the designer's preferences and design emphases by defining and modifying the measure membership functions and relative weights of each objective function appropriately on the basis of the suboptimized data for each objective and the relative emphases of the objectives. The proposed design method, therefore, has a great flexibility for the decision-making process with fuzziness.

3. By classifying the design variables into the set of common design variables and the set of objective oriented design variables considering the effects of each design variable to all objective functions, the suboptimization process of complex structural system for discrete set of common design variables and determination process of the global optimal solution can be carried out quite rationally and systematically.

4. The measure membership function of each objective function can be introduced rationally by comparing the relative evaluation of exactly suboptimized data of each objective function including design condition, general consent, client consent, designer's preferences, design emphases of the structural system and fuzziness of the decision-making.

5. Introduction of the measure membership functions of each objective function makes the relative evaluations of the suboptimized data rationally and easily, and the determination process of the global optimum solution quite systematically.

6. The values of membership functions of each objective for all discrete combinations of common design variables and design parameter objectives can be evaluated reasonably by comparing the relative significance of the suboptimized data referring to the corresponding measure membership functions as datum.

7. The weighted operator method can take into account easily the relative significance of various characteristic objectives, general consent, client consent, designer's preferences and design emphases of the structure.

8. To sum up, the proposed multicriteria fuzzy optimum design method can determine the global optimum solution of a practical large scale structural system rationally, systematically and efficiently considering the total construction cost, the significance of the aesthetics and the seismic safety of structural system, fuzziness involved in the decision-making process, general and client consent, designer's preferences, design emphases of structural system.

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