PRELIMINARY OPTIMIZATION OF HYBRID FRP-CONCRETE BRIDGE SYSTEMS

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Abstract: *Most of the bridges in the world are built of concrete and steel. Therefore, they are vulnerable to damage from environmental factors. It is a major challenge to build bridge systems that have long-term durability and low maintenance requirements. A solution to this challenge may be to use new materials or to implement new structural systems. Fiber reinforced polymer (FRP) composites have continued to play an important role in solving some of persistent problems in infrastructure applications because of its high specific strength, light weight, and durability. In spite of all these advantages, FRP composites have higher initial costs than conventional materials used in infrastructure application. To overcome this obstacle and to make the best use of materials, this study focused on the optimization of a hybrid FRP-concrete structural systems previously developed by the author. An optimization scheme based on the optimality criteria and a simplified analysis method using the transformed plate formulation to represent the structural system is implemented. The optimization scheme reduced the weight of the hybrid superstructure by approximately 35 % from the initial design.*

Keywords: fibre reinforced polymer; hybrid system; optimization; bridge superstructure.

I. INTRODUCTION

Because of their superior material properties—such as high specific stiffness, high specific strength, high corrosion resistance, light weight, and durability—FRP composites have come to play an important role in solving some of the most persistent problems in infrastructure applications.

In spite of all these advantages, FRP composites have higher initial costs than conventional materials used in infrastructure application. To overcome this obstacle and to make the best use of materials, the idea of combining FRP composites with conventional construction materials such as steel and concrete has been considered by several researchers. Alnahhal et. al. (2008) developed and tested one-quarter-scale model of an 18-m long hybrid concrete-FRP bridge superstructure. The results clearly indicate that the use of FRP in combination with concrete has led to stiffness enhancements of over 35%.

Optimization is a very crucial process when dealing with FRP composites because of their high initial cost. Optimization methods can be generally classified in two categories, deterministic and probabilistic. Mathematical programming methods are most prevailing of the first category. Evolutionary algorithms are widely used class of probabilistic methods and in particular evolutionary programming, genetic algorithms and genetic programming. Deterministic methods can be subdivided into two categories, classical solutions of constrained and unconstrained systems, and numerical search techniques. The classical tools are used for finding the maxima and minima of a function. In general, the numerical techniques start with an initial design and proceed in small steps intended to improve the value of the objective function. Structural optimization has been a topic of interest for over 100 years. As far back as 1890, Maxwell (1890) established some theorems related to rational design of structures, which were further generalized by Michell (1904). Schmit (1960) applied non-linear programming to structural design. Another approach based on optimality criteria were introduced in the late 1960's. Venkayya (1971) proposed an optimality criterion whereby the minimum-weight of structure is the one in which the strain energy density is constant throughout the structure.

Optimization of composite structures has gained a lot attention in recent years to reduce the cost and weight of such structures. Ply orientation, ply thickness, stacking sequence, and geometrical variables were usually used as design variables. Several researchers investigated the optimum structural design of FRP structural systems. Fukunaga and Vanerplaats (1991) performed optimum minimum weight design of laminated composite panels under strength and displacement constraints. They used linear approximation for the stress components and displacement components; transformed design variables with respect to the layer angles were also introduced to reduce the nonlinearity between the strength constraints and the layer angles. He et al. (2003) investigated an approach using genetic algorithms to minimize the weight of structural components by simultaneously changing the cross sectional shape and ply orientation of the FRP laminates. Many researchers have applied optimization techniques to the design of composite structures based on mathematical programming methods or optimality criteria methods. Fukunaga (1991) optimized the structural strength by tailoring the layer orientation angle and layer thickness. Aref (1999) investigated an approach using the optimality criteria method combined with the Ritz solution of the transformed plate to minimize the weight of FRP deck system by changing the layer thickness. Other researchers extended their studies to multi-objective optimization. For example, Adali et al. (1996) used the objective weighting method for the pre-buckling, buckling, and post-buckling optimization of laminated plates. Spallino et al. (2002) developed a multi-objective optimal design methodology based on evolution strategies and game theory approach.

The optimality criterion is applied in this study to develop a preliminary optimization algorithm for the hybrid FRP-concrete bridge superstructure system.

II. OPTIMALITY CRITERIA FORMULATION

Optimality criteria presented in this section was based on derivation by Venkayya (1989) and Khot (1981). The optimization problem takes the general form:

Minimize:

$$f(x) = f(x_1, x_2, ..., x_n) \qquad (1)$$

Subjected to the constraints:

$$g_j(x) \geq 0, \qquad j = 1, ..., n_m \qquad (2)$$

$$h_k = 0, \qquad k = 1, ..., n_l \qquad (3)$$

where $f(x)$ is the objective function of n variables, g_j are inequality constraints, n_m is the number of inequality constraint; h_k are the equality constraints, and n_l is the number of equality constraints.
The Kuhn-Tucker conditions (Venkayya, 1989; Khot, 1981) state the necessary conditions for a local minimum x^* of the constrained problem using Lagrange multipliers $\lambda_1^*, ..., \lambda_{n_m}^*$, that is:

$$g_j\left(x^*\right) \geq 0 , \qquad j = 1, ..., n_m \qquad (4)$$

$$\lambda_j^* \; g_j\left(x^*\right) \geq 0 , \qquad j = 1, ..., n_m \qquad (5)$$

$$\lambda_j^* \geq 0 , \qquad j = 1, ..., n_m \qquad (6)$$

$$\frac{\partial f}{\partial x_i} - \sum_{j=1}^{n_m} \lambda_j^* \frac{\partial g_j}{\partial x_i} = 0 , \qquad i = 1, ..., n \qquad (7)$$

The necessary condition for a local minimum of the optimization problem with a single constraint can be reformulated as

$$\frac{\partial f}{\partial x_i} - \lambda_j \frac{\partial g_j}{\partial x_i} = 0 , \qquad i = 1,....., n \qquad (8)$$

Now Eq. 8 above can be written as

$$\lambda = \frac{\partial f}{\partial x_i} \Big/ \frac{\partial g}{\partial x_i}, \qquad i = 1, ..., n \qquad (9)$$

In the case of a nonlinear objective function or nonlinear constraints with respect to the design variables, an approximate value of the Lagrange multiplier can be obtained from

$$\lambda = \left[\frac{1}{g_o} \sum_{i=1}^{n} x_i \frac{\partial g}{\partial x_i} e_i^{1/\eta} \right]^{\eta} \qquad (10)$$

and

$$g_o = g + \sum_{i=1}^{n} x_i \frac{\partial g_j}{\partial x_i} \qquad (11)$$

where η is a resizing parameter that controls the step size, and e_i is the ratio of the sensitivity derivatives of the constraints and the objective function and cab be written as

$$e_i = \frac{\partial g}{\partial x_i} \Big/ \frac{\partial f}{\partial x_i}, \quad i = 1, ..., n \qquad (12)$$

This was based on imposing a condition on the constraint to be critical at the resized design (Haftka et al. 1990).When the objective function or constraint is nonlinear with respect to the design variables, a resizing scheme was required to change the size of the design variables until the objective function has converged. The resizing techniques adopted in this study can be written as

$$x_i^{new} = x_i^{old} (\lambda e_i)^{1/\eta}, \qquad i = 1, ..., n \qquad (13)$$

The resizing steps were repeated until the objective function has converged.

III. HYBRID FRP-CONCRETE BRIDGE SUPERSTRUCTURE SYSTEM

In this study, the optimality criteria method presented in the previous section was employed to optimize a hybrid FRP-concrete bridge superstructure previously developed by the author. The hybrid bridge superstructure system consists of trapezoidal FRP cell units surrounded by an FRP outer shell forming a bridge system. Each trapezoidal section consists of two layers of laminates: the inner tube laminate and the outer tube laminate. A thin layer of concrete is placed in the compression zone. Concrete is confined by GFRP laminates which provide protection from environmental exposure. Moreover, the concrete layers reduce the local deformation of the top surface of the bridge under concentrated loads. Webs of the box section were designed at an incline to reduce shear force between sections. According to Ashby (1990), thin walled box sections are the most efficient structural forms for beams. For this study, the bridge superstructure was designed as a simply-supported single span one-lane bridge with a span length of 18.3 m. Geometrical parameters of this bridge system were determined by detailed finite element analyses. FEA was used to verify the structural behavior of this hybrid bridge superstructure. *Figure 1* shows a cross section of the hybrid bridge superstructure system. Advantages of this bridge superstructure include: (1) corrosion resistance; (2) initial cost reduction due to the effective use of concrete; (3) lightweight;

(4) reduction of local deformation under concentrated loads that is found to be a problem in all-composite bridges; and (5) high quality control and a short construction period due to pre-fabrication.

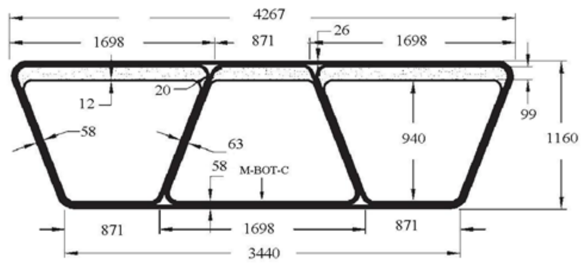

FIGURE 1 CROSS SECTION OF THE HYBRID FRP-CONCRETE SUPERSTRUCTURE (DIMENSION IN MM)

IV. OPTIMIZATION PROCEDURE FOR HYBRID FRP-CONCRETE BRIDGE SUPERSTRUCTURE SYSTEM

One of the most important reasons for optimizing FRP composites is to reduce the structural weight. It was assumed herein that the cost is directly related to the weight of the bridge. Therefore, the weight of the hybrid bridge system was used in this study as the objective function with a modification to account for the difference in cost between concrete and GFRP. The weight of concrete was ignored in this study.

The design variables of a hybrid-FRP bridge system include: bridge geometry, number of cells, ply orientation, stacking sequence, ply thickness, and concrete thickness. The design variables were limited in this study to the thickness of the plies in the inner, outer, and most outer tube laminates of the proposed bridge system; the other design variables have pre-assigned values.

Design of a bridge system must be subjected to both stiffness and strength constraints based on the AASHTO specifications (2007). However, since the design of FRP bridge systems is stiffness-driven, a single constraint on the maximum vertical deflection was imposed. The deflection limitation suggested by AASHTO LRFD is

$$\delta_{req.} = \frac{L}{800} \quad (1)$$

where L is the span of the bridge.

The basic optimality criteria algorithm was implemented in a computer program to perform the optimization of the proposed hybrid systems. The flow chart in *Fig. 2* summarizes the main steps presented in this section.

V. NUMERICAL RESULTS

The preliminary optimization procedure presented in the previous section was employed to optimize the hybrid- FRP bridge superstructure. Just the weight of the FRP composites was used as the objective function. The change in weight over the weight of the previous step was used to check for convergence for a specific tolerance. The tolerance used in this study is 0.0001. The rate of convergence depends on the parameter η. The value of η used in this study is 2.

Following the AASHTO LRFD specifications, the bridge was subjected to design truck load when checking the serviceability limit of the bridge. The location of design truck load was arranged to obtain the maximum deflection. The impact load (IM) was applied to the truck design load and was taken as 33 % of design truck load in our case. The design variables were limited to the thickness of the plies in the inner, outer, and most outer tube laminates. The optimization scheme reduced the weight of the superstructure by 35 % from the initial design.

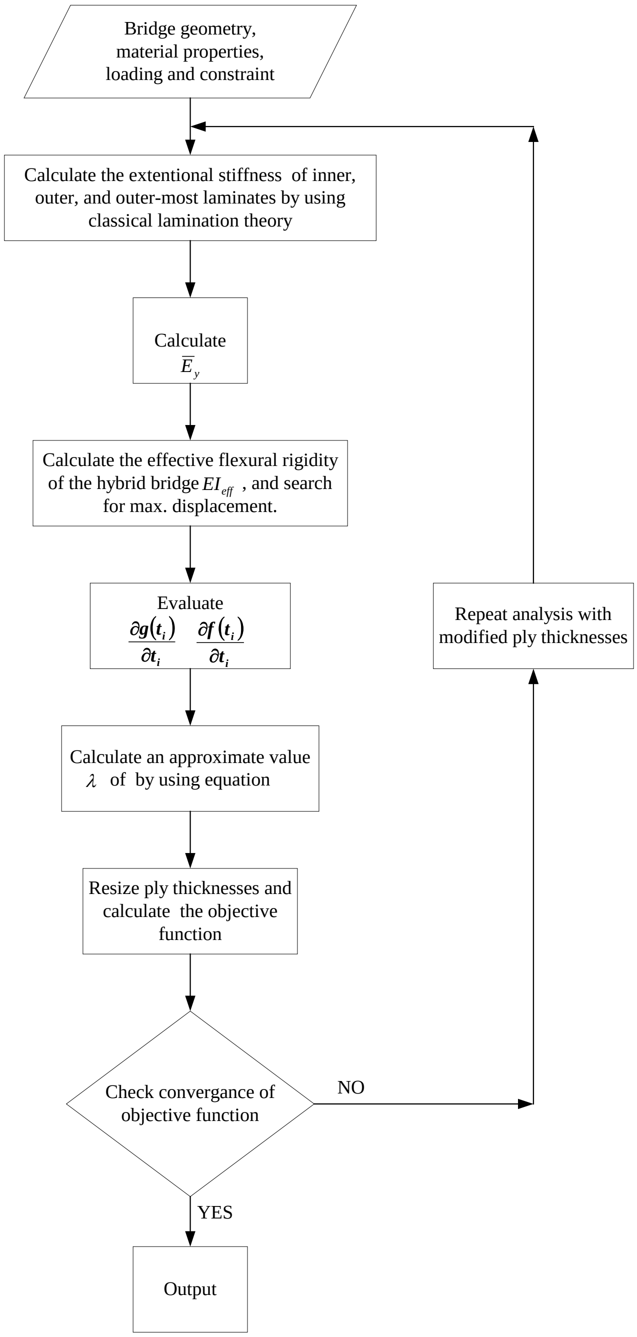

FIGURE 2 FLOW CHART FOR OPTIMIZATION PROCEDURE

VI. CONCLUSIONS

One of the most important reasons for optimizing a hybrid bridge system is to reduce its initial cost. An optimization scheme based on the optimality criteria and a simplified analysis method using the transformed plate formulation to represent the structural system was implemented in this study. Since the design of hybrid bridge systems is stiffness-driven in this study, the maximum allowable deflection was used as a constraint in the optimization design procedure. In this study, we limited the design variables to the thickness of the plies in the inner, outer, and most outer tube laminates of the proposed bridge system. The optimization scheme reduced the weight of the hybrid superstructure by approximately 35 % from the initial design.

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