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Pilot test on a developed GFRP bridge deck

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Abstract

In this paper, an optimum design technique is developed which can be applied to bridge decks based on FRP materials with more complex objective functions and constraints than those of existing materials. The proposed optimum design technique is applied to determine optimum geometry for bridge decks and properties of the FRP material by carrying out three-dimensional numerical modeling. In addition, FRP deck modules have been produced using the pultrusion method after considering the proposed optimum cross-section shape and property of the material, and several tests have been performed to validate the performance of the developed GFRP deck.

Keywords: Glass fibers; Mechanical testing; Debonding

1. Introduction

The apparent advantages of FRP (fiber reinforced plastics) composites over the conventional structural materials may be attributed to their superior strength and stiffness. In particular, the excellent durability of the FRPs has made it a favorable material for structures in severe service conditions. Hence, the material properties of FRP structural components should be included in the designs to meet its specific requirements and service conditions.

Over the last two decades, numerous studies have been conducted for structural optimizations, and most of them are related to the practical applications for the tractable engineering problems. To date, many standard structural optimization algorithms are available, but a greater number of design variables and constraints are required in the structural optimization process. If the number of design variables and constraints are increased, a great deal of structural analysis is required in the optimization process.

Theoretical and practical applications of the structural optimization are well summarized by Cohn and Dinovitzer [1]. Burnside et al. [2] proposed an optimization process for the FRP bridge decks having the cellular- and stiffened-box geometries. An optimal structural shape of the FRP beams, having a wide-flange section, has been presented by Qiao [3]. In his studies, the stacking sequence, volume ratios, number of ply, and the ply angle of FRPs are considered as the major design variables. Based on the CLT (classical lamination theory), Mantell and Heiness [4] have also proposed an optimization procedure for a GFRP (glass fiber reinforced plastics) composite box beam. Recently, an optimum design of a precast FRP system was proposed by Salem [5] and Choi et al. [6].

This paper presents the optimum design and analysis on the GFRP deck with a hollow cross-section. An optimum design algorithm, associated with an improved GA (genetic algorithm) based on index technique suitable for optimization of the GFRP deck, has been developed. Therefore, the optimum cross-section and physical properties of the GFRP deck module with a hollow

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cross-section have been proposed. In addition, the performance of the GFRP deck module has been verified by the means of the pultrusion method on test samples.

2. Formulation of optimization

The thickness of upper/lower flange (t_1, t_2), thickness of web (t_3), slope angle of web ($\alpha_1 \sim \alpha_3$), height of deck (H), and interval between webs (B) are assumed to control the geometric section shape of GFRP deck as shown in Fig. 1. In this case, it is assumed that the interval between the webs equals the distance from the half position of web height to the center. Moreover, additional optimum processes have been conducted to determine the number of ply, stacking sequence, ply angle and fiber volume ratio to simultaneously satisfy optimum geometry and physical properties.

In the case of FRP material pattern in the flange, unidirectional roving and random mats or continuous strand mats are applied to resist tension and compression. Also, in cases where the web needs to resist shear deformation in the decks, ±45° woven mats are added to material components of flange. Tables 1–3 provide geometric design variables of the cross-section, properties of FRP material, and the boundary of physical properties, respectively. An objective function is selected to minimize the volume of a FRP structural system in Eq. (1).

$$\text{Minimize} \sum_{i=1} (W_i \times t_i) \times L_i \tag{1}$$

where W, t, and L are the width, thickness and length of components within the section, i.e., flanges and webs. The subscript i represents the index for each component.

The constraints are classified into two parts: side constraint and behavior constraint. The minimum thickness has been specified by design standards as the side constraint. The behavior constraint refers to the limitation of stress, deflection, and buckling strength. Behavior and serviceability constraints of FRP deck are based on a number of previous studies (i.e., [7–11]), and constraint due to manufacturing technology of pultrusion method has been also included.

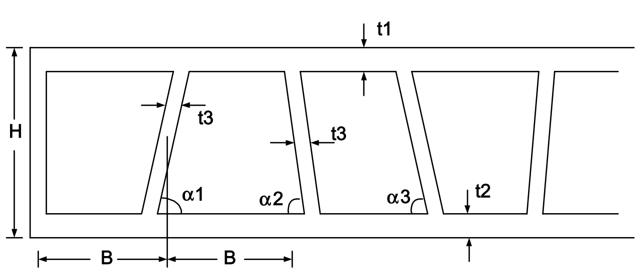

Fig. 1. Thin-walled cellular section.

Table 1
Geometric design variables of GFRP deck

Description	Symbol	Range
Web interval	B	80–230 mm
Height	H	100–250 mm
Thickness of upper flange	t_1	8–23 mm
Thickness of lower flange	t_2	6–21 mm
Thickness of web	t_3	6–21 mm
Slope angle of web	α	60–130°

Table 2
Properties of FRP material

Material	Description	Value
Glass fiber	Tensile strength, f_{glass} (MPa)	3500
	Elastic modulus, E_{glass} (MPa)	73,500
	Shear modulus, G_{glass} (MPa)	29,400
	Poisson's ratio, ν_{glass}	0.25
	Density (gr/cc)	2.54
Vinylester	Tensile strength, f_{glass} (MPa)	77
	Elastic modulus, E_{glass} (MPa)	3910
	Shear modulus, G_{glass} (MPa)	1428
	Poisson's ratio, ν_{glass}	0.366
	Density (gr/cc)	1.15

3. Optimization algorithm

Practical optimum design problems may be characterized by the mixed continuous discrete variables, and by the discontinuous and non-convex design spaces. If standard nonlinear programming techniques are used for these types of problems, they will be inefficient and computationally expensive. In most cases, these techniques may give a relative optimum value that is close to the starting point [12]. On the other hand, the optimization procedure based on the GAs may efficiently exploit the historical information to speculate on new search points with the improved performance. Therefore, a GA-based optimization procedure was developed and coded as a computer program. A concise flow of the overall optimization procedure is illustrated by a flowchart as demonstrated in Fig. 2. As shown in the Figure, three-dimensional structural computations are carried out by a commercial finite element analysis package, ABAQUS [13]. The S4R element, which is suitable for analysis of the FRP structure, is used in the numerical modeling.

To treat the optimization problem more efficiently, the index technique is employed in this study. The modified GA-based solution algorithm with the index technique is shown in Fig. 3. Generally, the GA can be applied to an optimization problem with the non-constraints that are considered as the penalty parameters and maximum of fitness function.