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MASS MINIMIZATION OF COMPOSITE SANDWICH FLOORS

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Abstract: *The purpose of this study was to develop a new optimization method for a completely FRP composite vehicle floor construction. Combinations of four different FRP layers (phenolic resin with woven glass fibres, epoxy resin with woven glass fibres; epoxy resin with woven carbon fibres; hybrid composite) and FRP honeycomb core were investigated during the optimization process. The face sheets comprised varying layers with cross-ply, angle-ply, and multidirectional fibre orientations. The mechanical behaviours of the structure have been considered as design constraints: stability, stress, deflection, stiffness, skin wrinkling, intracell buckling, and shear crimping were all taken into account during the optimization process. The Nonlinear Generalized Reduced Gradient (GRG) Algorithm of the Excel Solver software was used to solve the single-objective mass optimization.*

Keywords: *fibre-reinforced plastic, optimization*

INTRODUCTION

There are many requirements, particularly for vehicles, such as low mass; easy and safe manoeuvrability; high speed; cost-effective operation; and safe transportation (e.g., reliability, crashworthiness) [1]. Crashworthiness is a crucial requirement for vehicles. Vehicles can crash due to human error or technical failure. To avoid structural failures, vehicle design has always been a top priority. With the application of materials or structures, which increase energy-absorbing, vehicle crashes can be reduced [2].
The use of advanced composite materials in the design and manufacture of vehicle structural elements, such as the floor, can meet the previously mentioned requirements for vehicles. This is because composites have more advantageous properties than traditional materials [3]. Composite materials have reduced mass. Furthermore, composite structures are strong, have good vibration damping, are resistant to corrosion and chemicals, are fire resistant, and have good thermal insulation [4].

There are two parts of the FRP composite: (1) resins (matrix) and (2) fibres (strengthening component). The composite materials' strength is provided by the fibres. The fibres are protected by the matrix. There are numerous fibre and matrix phase options available [5].

1. OPTIMIZATION

A single-objective mass optimization method has been developed that considers nine design constraints: buckling, deflection, skin wrinkling, shear crimping, face sheet stress, stiffness, core shear stress, and intracell buckling. The Nonlinear Generalized Reduced Gradient Algorithm of the Excel Solver software was used to solve the optimization.

a. The new structure

The new plate is made up of an FRP honeycomb core and various types of face sheets, including phenolic resin with woven glass fibre, epoxy resin with woven glass fibre, epoxy resin with woven carbon fibre, and hybrid composite layers (combined layers of epoxy resin with woven glass fibre and epoxy resin woven with carbon fibre), with various fibre orientations: cross-ply, angle-ply, and hybrid composite layers combined, see Figure 1. The floor panel of a vehicle is l = 1500 by b = 825 mm in size and self-supporting, with no external support frames except around the floor's edges. The floor plate deforms by w_{max} = 10 mm. The uniformly distributed pressure is p = 1500 kg/m^2 with 4.5g acceleration (see Table 1). The boundary conditions of the floor plate are simply supported, and l/b=1.8.

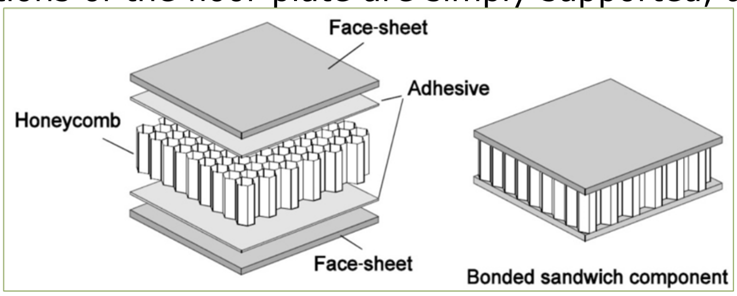

Figure 1: Honeycomb core sandwich plate construction

FRP sandwich plates were created to be lightweight with a high stiffness-to-mass ratio. The sandwich plates were made up of three layers: two (upper and lower) FRP face sheets and, between them, a honeycomb core. The three layers bonded together with an adhesive. Due to the distance between the face sheets, its stiffness is high and can bear more significant force, and the sandwich plate's light mass is caused by the honeycomb core's lightweight. The composite honeycomb core's design properties make it ideal for various industrial applications (see Figure 1).

b. Face Sheets of the Sandwich Plate

Figure 2 shows the three composite laminated plate classes used in this paper. Table 1 displays the facing materials’ mechanical properties. The face sheet layers are manufactured by Hexcel Composites Company.

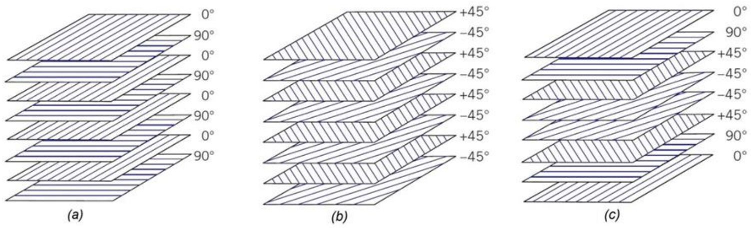

Figure 2: Face sheets, composite laminates angles

Laminate composite lay-ups Cross-ply (a), angle-ply (b), and multidirectional (0°, 90°, and 45°).

Table 1. Material properties of different FRP layers

Type of Layers	Tens./Compr. Strength (MPa)	Tens./Compr. Mod. of Elasticity (GPa)	Poisson's Ratio (−)	Cured Ply Thickness (mm)	Mass/Ply (kg/m^2)
Epoxy Resin Woven Carbon Fiber	800/700	70/60	0.05	0.3	0.45
Epoxy Resin Woven Glass Fibre	600/550	20/17	0.13	0.25	0.47
Phenolic Resin Woven Glass Fiber	400/360	20/17	0.13	0.25	0.47

c. Sandwich Plate's Honeycomb Core

The honeycomb core is standard hexagonal and is now available in metallic and composite materials (see Figure 1). Table 2 shows the engineering properties of the FRP honeycomb core. Hexcel Composites Company manufactures the honeycomb core.

Table 2. Engineering properties for FRP honeycomb core [50].

Characteristics		Plate Shear				Compression	
Dens.	Cell Dimension	Long. Direction		Transv. Direction		Stabilized	
		Strength	Modulus	Strength	Modulus	Strength	Modulus
(kg/m^3)	(mm)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)	(MPa)
104.12	6.35	4	159	2.28	90	8.14	828

2.SINGLE-OBJECTIVE OPTIMIZATION METHODS

The objective function is the total mass of the sandwich structure

$$W_t = W_f + W_c = 2\,\rho_f lbt_f + \rho_c lbt_c \tag{1}$$

where $t_f = N_l t_l$; indexes: *f*—face; *c*—core.

$$W_t = W_f + W_c = 2(W_{f,g} + W_{f,cr}) + W_c = 2(\rho_g N_g t_g + \rho_{cr} N_{cr} t_{cr})lb + \rho_c lbt_c \tag{2}$$

The design variables are the core thickness t_c of the composite honeycomb and face sheet thickness t_f for the sandwich plate floor, which is limited:

$$1 \text{ mm} \le t_c \le 100 \text{ mm} \tag{3}$$

$$0{,}5 \text{ mm} \le t_f \le 2 \text{ mm} \tag{4}$$

where $t_f = N_l t_{fl}$; N_l—number of layers in the laminate; t_{fl} —thickness of one layer.

The design constraints are as follows

- *The bending stiffness* constraint for the sandwich plate of the vehicle floor with composite material face sheets is

$$D_{11,x} = \frac{D_{11}}{1 - \nu_{12}^f\ \nu_{21}^f} \geq D_{min} = \frac{K_b p l^4}{\delta} \quad (5)$$

where $D_{11} = 0.5 d^2 A_{11}^f + 2D_{11}^f + 2dB_{11}^f$, $\nu_{12}^f = A_{12}^f / A_{22}^f$, $\nu_{21}^f = A_{12}^f / A_{11}^f$, and $d = t_f + t_c$.

- *The shear stiffness* of the sandwich plate is

$$\tilde{S}_{11} = \frac{d^2}{t_c} \frac{E_c}{2\,(1 + \nu_c)} \quad (6)$$

The calculated stiffness of the sandwich plate should be greater than the minimum stiffness, computed using the data presented in Tables 1 and 2.

The deflection constraint is as follows

$$\delta_{max} \geq \delta = \frac{K_b p l^4}{D_{11,x}} + \frac{K_s p l^2}{\tilde{S}_{11}} \quad (7)$$

The maximum deflection of the sandwich plate of the vehicle floor δ_{max} that is provided in Table 1 should be higher than the calculated deflection δ.

- *The skin stress* constraint is

$$\sigma_{f,x} \geq \sigma_f = \frac{M}{d t_f b} \quad (8)$$

$\sigma_{f,x}$—yield strength of the FRP face sheets in the x direction; σ_f—calculated skin stress.

- *The core shear* stress constraint is

$$\tau_{c,y} \geq \tau_c = \frac{F}{db} \quad (9)$$

$\tau_{c,y}$—shear stress of the composite honeycomb core in the transverse direction; τ_c—calculated core shear stress.

- *The facing stress* constraint is:

$$\sigma_{f,y} \geq \sigma_f = \frac{P}{2 t_f b} \quad (10)$$

$\sigma_{f,y}$—yield strength of the composite face sheets in the y direction; σ_f—calculated facing stress.

- *The buckling constraint* is:

$$P_{b,cr} = \frac{\pi^2 D_{11,x}}{\beta l^2 + \frac{\pi^2 D_{11,x}}{\tilde{S}_{11}}} \geq \frac{P}{b} \qquad (11)$$

$P_{b,cr}$—computed load at critical buckling occurs; P/b—load per unit width.

- *The shear crimping* constraint is:

$$P_{cr} = t_c G_c b \geq P \qquad (12)$$

where $G_c = G_w$; P_{cr}—computed load at which shear crimping occurs; P—load utilized.

- *The skin wrinkling* constraints are:

$$\sigma_{wr,cr} = 0.5 \sqrt[3]{E_{f,x}\, E_c\, G_c} \geq \sigma_{f,x} \qquad (13)$$

where $G_c = G_L$.

$$\sigma_{wr,cr} = 0.5 \sqrt[3]{E_{f,y}\, E_c\, G_c} \geq \sigma_{f,y} \qquad (14)$$

where $G_c = G_W$.

$$P_{wr,cr} = 2\sqrt{D_{11}^f \frac{E_c}{(t_c/2)}} \geq \frac{P}{b} \qquad (15)$$

where $E_{f,x} = A_{11}^f(1 - \nu_{12}^f \nu_{21}^f)/t_f$, $E_{f,y} = A_{22}^f(1 - \nu_{12}^f \nu_{21}^f)/t_f$, and $E_f = \sqrt{E_{f,x} E_{f,y}}$.

The limit stress for skin wrinkling $\sigma_{wr,cr}$ is higher than the yield strength of the skin in the x direction $\sigma_{f,x}$ and in the y direction $\sigma_{f,y}$.
$P_{wr,cr}$—load at which skin wrinkling occurs; P/b—load per unit width.

- *The intracell buckling* constraint is:

$$\sigma_{fib,cr} = \frac{2E_f}{(1 - \nu_{12}^f \nu_{21}^f)} \left[\frac{t_f}{s}\right]^2 \geq \sigma_{f,y} \qquad (16)$$

where $E_f = \sqrt{E_{f,x} E_{f,y}}$; $\sigma_{fib,cr}$—stress at which intracell buckling would happen; $\sigma_{f,y}$—yield strength of the skin material.

3.RESULTS—CASE STUDY FOR THE OPTIMIZATION OF VEHICLE FLOOR

The optimization results for the single-objective function include: W_{min}—minimum mass; $t_{c,opt}$—optimum core thickness; $t_{f,opt}$—optimum thickness of face sheets. The single-objective optimization technique decreased the mass objective function utilizing the Excel Solver program (GRG Nonlinear

Algorithm) for FRP face sheets and the FRP honeycomb core (hexagonal shape).

Table 3 shows the optimal results of the mass objective function for the sandwich plate of the vehicle floor consisting of a composite honeycomb core with composite face sheets obtained utilizing the Excel Solver program (GRG Nonlinear Algorithm).

Table 3. Theoretical results for a sandwich plate of the vehicle floor.

Type of Face Sheets:	Layers' Number and Fiber Orientations:	W_{min} kg	$t_{f,opt}$ mm	$t_{c,opt}$ mm
(1) Phenolic woven glass fibre	4 (0°, 90°, 90°, 0°)	22.133	1	136
(2) Epoxy woven glass fibre	4 (0°, 90°, 90°, 0°)	22.133	1	136
(3) Epoxy woven carbon fibre	**2 (0°, 90°)**	**14.486**	**0.6**	**95**
(4) Hybrid composite	4 (0°, 90°, 90°, 0°)	15.475	1.1	85

The bolted numbers show the best solution with the minimum mass.

4.CONCLUSION

A new optimization was made for a total FRP composite— the face sheets and the honeycomb core are FRP composite materials—sandwich structure. The optimal material constituents and structure of the vehicle floor can be determined by an optimization method, which provides minimal mass. The following design constraints have been considered: deflection, face sheet stress (bending load and end loading); stiffness; buckling; core shear stress; skin wrinkling, intracell buckling, and shear crimping. The optimal material constituents of the FRP face sheets were defined from four different types of FRP layers (epoxy resin with woven carbon fibres, phenolic resin with woven glass fibres; epoxy resin with woven glass fibres; hybrid composite layers).

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