THEORETICAL AND NUMERICAL ANALYSIS OF AN ALUMINUM FOAM SANDWICH STRUCTURE

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Abstract: The aim of the research was to develop a new lightweight sandwich structure, which can be used for elements of air containers. The structure consists of aluminum foam core with fiber reinforced composite face-sheets. Nine different laminated glass or/and carbon fiber reinforced plastic face-sheet combinations were investigated. Finite element analysis of the sandwich structures was introduced. Single-objective optimization of the new sandwich structure was achieved for minimal weight. Five design constraints were considered: stiffness of the structure, face-sheet failure, core shear, face-sheet wrinkling, size constraints for design variables. The elaborated composite structure results significant weight savings due to low density.

Keywords: Sandwich structure, Fiber reinforced plastic face-sheet, Aluminum foam core, Structural optimization, Minimum weight

1. Introduction

The purpose of the study is the design of a lightweight structure consists of fiber reinforced plastic face-sheets (nine different laminated glass fiber or/and carbon fiber reinforced plastic face-sheet combinations) and aluminum foam core. The fiber reinforced plastic face-sheets and the core has a small density and high specific stiffness, which can meet the stiffness requirements and reduce the weight of the sandwich structure. The elaborated structural model can be used for manufacturing of walls, floor and roof of containers to fulfill the requirements of shipping and airlines

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carriers. The aim of the application of lightweight containers is to provide a huge savings in weight compared to conventional steel containers, which results in lower fuel consumption of transport vehicles and less environmental damage.

The sandwich structures consist of composite face-sheets and foam core are widely utilized in many engineering applications such as aerospace and automotive applications due to its high performance like bending stiffness and strength to weight ratios [1]. Huang and Alspaugh [2] introduced a method to determine the minimum weight of sandwich beams. The most common applied design constraints related to bending stress, shear stress and deflection, where the face-sheets thickness and the core thickness are design variables. Gibson [3] described an analytical method to find the optimum thickness and density of the foam core sandwich beam to minimize the weight. Gibson and Triantafillou described the way to minimize the weight of a sandwich beam with a foam core. The analysis gave the optimum core and face-sheets thicknesses and the density of the core [4]. In the books of Zenkert and Bitzer several methods and algorithms are described to minimize the weight of sandwich structures with symmetrical and unsymmetrical face-sheets and subjected to bending and torsional stiffness requirement [5]-[6]. Kota and Jarmai show also a very well scalable discrete firefly algorithm. The built in general reduced gradient and evolutionary algorithms of the Excel solver are also compared solving similar problems [7]. Hazim and Jarmai estimate the minimum structural dimensions of robot arms [8]. Many researchers have studied the influence of hybrid composite materials on mechanical properties of the structure [9]. Dong and Davies studied the flexural behavior of hybrid composites consist of glass and carbon fibers [10]. The effect of hybrid observed when the natural fiber reinforced plastics layers built into the conventional sandwich panels with aluminum face-sheets [11]. Lot of algorithms is available for optimization of composite laminated structures [12]. A few studies included the cost of the sandwich structure as a design aim [13].

2. A new sandwich structural model

The newly constructed sandwich structure consists of aluminum (Al) foam core with laminated glass fiber and/or carbon fiber reinforced plastic face-sheets, see *Fig. 1*. The dimensions and weights of the core and face-sheets used in this structure are given in *Table I*. The technical notes of the flexure model program for symmetrical sandwich structures were clarified. The norm of the model is MIL-STD-401B [14].

Fig. 1. Aluminum foam core sandwich structure with laminated composite face-sheets

Table I

Data relating to the structural elements of the investigated sandwich structure

Fibers	Dimension					Density			Weight		
	l	b	h	t_c	t_f	ρ_c	ρ_g	ρ_{cr}	W_{core}	W_{skin}	W_t
Unit	mm	mm	mm	mm	mm	kg/m ³	kg/m ³	kg/m ³	kg	kg	kg
E-glass	1000	100	24	20	2	300			0.6	0.38	1.36
Carbon	1000	100	24	20	2	300	1900	1600	0.6	0.32	1.24
Hybrid	1000	100	24	20	2	300			0.6	0.35	1.30

where l is the length; b is the width of the sandwich structure; ρ_g is the density of the E-glass fiber/epoxy resin laminate; ρ_{cr} is the density of the carbon fiber/epoxy resin laminate; ρ_c is the density of the foam core; t_f is the thickness of the face-sheet; t_c is the thickness of the foam core and h is the total thickness of the sandwich structure. W_{core} is the weight of the foam core; W_{skin} is the weight of the face-sheet; W_t is the total weight of the sandwich structure.

2.1. Aluminum foam core

The foam core is closed cell formed from *Al* alloy. The mechanical properties of the core make it ideal for several applications. These properties include high strength and stiffness to weight ratio and high energy absorption as shown in Table II, [15].

Table II

Data of Cymat A35620SC 030SS stabilized aluminum foam

E	Compressive modulus	1200	MPa
ν	Poisson's ratio	0.33	----
G	Shear modulus	1000	MPa
σ	Compressive strength	4	MPa
τ	Shear strength	1	MPa
ρ	Density	300	kg/m ³

2.2. Laminated fiber reinforced plastic face-sheets

Nine different sandwich constructions were studied, which consist of *Al* foam core with upper and lower skin face-sheets. The laminated glass fiber and/or carbon fiber reinforced plastic face-sheets were symmetrical concerning to the mid-plane of the sandwich structure. Every skin face-sheet composed of 4-layers. The fiber orientation in the face-sheets is having cross ply (0°, 90°) and angle ply $\pm 45^\circ$. Table III includes the mechanical properties of the different composite layers.

E-glass fiber/epoxy resin face-sheets

Three constructions were investigated: *Al* foam core sandwich structure with 4-layers in the upper and 4-layers in the lower skin face-sheets made of fabric of E-glass fiber/epoxy resin with fiber orientation (0°, 90°, 0°, 90°), (0°, 90°, +45°, -45°) and (+45°, -45°, +45°, -45°).

Table III

Mechanical properties of composite materials [16]

Fiber 0°, 90° fabric to loading axis, Dry, Room Temperature, $V_f = 50\%$				
Property	Symbol	E-glass	Carbon	Units
Young's Modulus 0°	E_1	25	70	GPa
Young's Modulus 90°	E_2	25	70	GPa
In-plane Shear Modulus	G_{12}	4	5	GPa
Major Poisson's Ratio	ν_{12}	0.2	0.1	----
Ultimate Tensile Strength 0°	X_t	440	600	MPa
Ultimate Compression Strength 0°	X_c	425	570	MPa
Ultimate Tensile Strength 90°	Y_t	440	600	MPa
Ultimate Compression Strength 90°	Y_c	425	570	MPa
Ultimate In-plane Shear Strength	S	40	90	MPa
Fiber $\pm 45^\circ$ to loading axis, Dry, Room Temperature, $V_f = 50\%$ (fabric)				
Property	Symbol	E-glass	Carbon	Units
Longitudinal Modulus	E_1	12.2	19.1	GPa
Transverse Modulus	E_2	12.2	19.1	GPa
In-plane Shear Modulus	G_{12}	8	30	GPa
Poisson's Ratio	ν_{12}	0.53	0.74	----
Tensile Strength	X_t	120	120	MPa
Compression Strength	X_c	120	120	MPa
In-plane Shear Strength	S	150	310	MPa

Carbon fiber/epoxy resin face-sheets

Three constructions were investigated: *Al* foam core sandwich structure with 4-layers in the upper and 4-layers in the lower skin face-sheets made of fabric of carbon fiber/epoxy resin with fiber orientation (0°, 90°, 0°, 90°), (0°, 90°, +45°, -45°) and (+45°, -45°, +45°, -45°).

Hybrid face-sheets (combination of glass and carbon fiber layers)

Three constructions were investigated: *Al* foam core sandwich structure with 4-layers in the upper and 4-layers in the lower skin face-sheets (outer two layers of carbon and inner two layers of E-glass laminas). The hybrid face-sheet is the combination of carbon fiber and E-glass fiber/epoxy resin laminas with different fiber orientations: (0°, 90°, 0°, 90°), (0°, 90°, +45°, -45°) and (+45°, -45°, +45°, -45°).

3. Finite element analysis of the investigated sandwich structures

In this study, the deflection, skin stress and core shear stress were calculated numerically by using finite element analysis (Digimat-HC) program for 4-point flexural model, where P is the applied load; δ is the deflection of sandwich structure; σ_{skin} is the skin stress and τ_{core} is the core shear stress. Numerical results of the finite element analysis can be seen in (Table IV - Table VI); and in (Fig. 2 - Fig. 4). The introduction

of print screens of the finite element analysis results for all of nine constructions is not possible in this study due to space constraints.

Table IV

Analytical and numerical results for aluminum foam core sandwich structure with E-glass fiber/epoxy resin face-sheets with different fiber orientations (0° , 90° and $\pm 45^\circ$)

E-glass fiber	Numerical results				Optimum results			W_t	$W_{red.}$
Symbol	P	δ	σ_{skin}	τ_{core}	$t_{c\ opt}$	$t_{f\ opt}$	W_{min}		
Unit	N	mm	MPa	MPa	mm	mm	kg	kg	%
$0^\circ, 90^\circ, 0^\circ, 90^\circ$	1000	9.877	25.6	1.08	23.224	0.998	1.076	1.36	20.88
$0^\circ, 90^\circ, \pm 45^\circ$	1000	10.949	28.4	1.18	23.244	1.012	1.081	1.36	20.51
$\pm 45^\circ, \pm 45^\circ$	1000	12.597	25.1	1.36	23.224	0.984	1.070	1.36	21.32

Table V

Analytical and numerical results for aluminum foam core sandwich structure with carbon fiber/epoxy resin face-sheets with different fiber orientations (0° , 90° and $\pm 45^\circ$)

Carbon fiber	Numerical results				Optimum results			W_t	$W_{red.}$
Symbol	P	δ	σ_{skin}	τ_{core}	$t_{c\ opt}$	$t_{f\ opt}$	W_{min}		
Unit	N	mm	MPa	MPa	mm	mm	kg	kg	%
$0^\circ, 90^\circ, 0^\circ, 90^\circ$	1000	3.746	26.6	0.54	21.204	1.110	0.991	1.24	20.08
$0^\circ, 90^\circ, \pm 45^\circ$	1000	4.281	29.3	0.57	21.204	0.998	0.955	1.24	22.98
$\pm 45^\circ, \pm 45^\circ$	1000	5.502	26.4	0.67	19.183	0.970	0.886	1.24	28.54

Table VI

Analytical and numerical results for aluminum foam core sandwich structure with hybrid face-sheets with different fiber orientations (0° , 90° and $\pm 45^\circ$)

Hybrid	Numerical results				Optimum results			W_t	$W_{red.}$
Symbol	P	δ	σ_{skin}	τ_{core}	$t_{c\ opt}$	$t_{f\ opt}$	W_{min}		
Unit	N	mm	MPa	MPa	mm	mm	kg	kg	%
$0^\circ, 90^\circ, 0^\circ, 90^\circ$	1000	5.185	37.6	0.66	23.224	1.181	1.110	1.30	14.61
$0^\circ, 90^\circ, \pm 45^\circ$	1000	5.461	39.6	0.68	23.224	1.279	1.144	1.30	12.00
$\pm 45^\circ, \pm 45^\circ$	1000	9.708	30.9	1.07	23.224	1.096	1.080	1.30	16.92

4. Minimum weight optimization of the investigated sandwich structure

The optimization method for the newly constructed sandwich structure (*Fig. 1*) was elaborated. The fibers orientation in the face-sheets is having angles of cross ply 0° , 90° and angle ply $\pm 45^\circ$. The optimal design variables were face-sheet thickness t_f and core thickness t_c to minimize the weight of the sandwich structures, Eqs. (1)-(3). During the optimization five design constraints were taken into consideration, Eqs. (4)-(8). The equations of the optimization problem are listed below [17]. The classical lamination theory and Tsai-Hill criteria of the first ply failure used to calculate the mechanical

properties of the laminated face-sheet [18]. The constraints of the optimization problem are stiffness, face-sheet failure, core shear, face-sheet wrinkling.

Fig. 2. Numerical results by using (Digimat-HC) program; flexural model of the sandwich structure consists of E-glass fiber/epoxy resin face-sheets (0° , 90° , 0° , 90°) with Al foam core

Fig. 3. Numerical results by using (Digimat-HC) program; flexural model of the sandwich structure consists of carbon fiber/epoxy resin face-sheets ($\pm 45^\circ$, $\pm 45^\circ$) with Al foam core

The sandwich structure stiffness, the maximum load of face-sheet failure, core shear and skin wrinkling for every core thickness and face-sheet thickness were calculated.

With all these data, for every step, the minimum face-sheet thickness was calculated that accomplishes the load defined and the stiffness required, Eq. (4). The software calculates the minimum weight condition for the sandwich structure, which corresponds to the face-sheet thickness and the core thickness. This software is a modified version of the software in the composite sandwich optimizer 2017, GitHub, Inc [19]. The program was developed to fit with the flexure model. The results of numerical (Digimat-HC) program were used as inputs to achieve the desired results (maximum deformation δ_{max} and maximum load P_{max}).

Fig. 4. Numerical results by using (Digimat-HC) program; flexural model of the sandwich structure consists of hybrid face-sheets (0° , 90° , $+45^\circ$, -45°) with Al foam core

4.1. Total weight objective functions

Weight of E-glass fiber/epoxy resin face-sheets with aluminum foam core:

$$W_t = W_f + W_c = 2 W_g + W_c = 2 \rho_g t_g lb + \rho_c t_c l. \quad (1)$$

Weight of carbon fiber/epoxy resin face-sheets with aluminum foam core:

$$W_t = W_f + W_c = 2 W_{cr} + W_c = 2 \rho_{cr} t_{cr} lb + \rho_c t_c lb. \quad (2)$$

Weight of hybrid face-sheets with aluminum foam core:

$$W_t = W_f + W_c = 2(W_g + W_{cr}) + W_c = 2(\rho_g t_g lb + \rho_{cr} t_{cr} lb) + \rho_c t_c lb. \quad (3)$$

4.2. Design constraint

Constraint for the stiffness of the sandwich structure:

The minimum stiffness of sandwich structure $(EI)_{min}$ was calculated by using given data from and numerical results (Digimat-HC) (δ and P).

$$(EI)_{min} = \frac{P l^3}{B_3 \delta} \leq D = \frac{E_f t_f h^2 b}{2}, \quad h = t_c + t_f. \quad (4)$$

Constraint for face-sheets failure

$$P_{act} \leq P_{ff} = \frac{\sigma_f b t_f h}{B_1 l}. \quad (5)$$

Constraint for core shear

$$P_{act} \leq P_{cs} = \frac{\tau_c b h}{B_2}. \quad (6)$$

Constraint for face-sheet wrinkling

$$P_{act} \leq P_{wr} = \frac{b t_f h}{2 B_1 l [E_C G_C E_f]^{1/3}}. \quad (7)$$

Size constraint for design variables

$$10 \text{ mm} \leq t_{c \text{ opt}} \leq 100 \text{ mm}, \quad \text{and} \quad 0.1 \text{ mm} \leq t_{f \text{ opt}} \leq 5 \text{ mm}, \quad (8)$$

where $B_1 = \frac{1}{8}$, $B_2 = \frac{1}{2}$, $B_3 = \frac{768}{11}$, and $P_{act} = 1000 \text{ N}$ (Simply supported, flexural model).

4.3. Results of the optimization

The final results are optimum core thickness ($t_{c \text{ opt}}$), optimum face thickness ($t_{f \text{ opt}}$) and minimum weight (W_{min}) as shown in (Table IV - Table VI) and (Fig. 5 - Fig. 7). The optimization results of all 9 constructions are not possible in this study due to space constraints.

Fig. 5. Theoretical results by using MATLAB program, flexure model, the sandwich structure consists of E-glass fiber/epoxy resin face-sheets ($0^\circ, 90^\circ, 0^\circ, 90^\circ$) with *Al* foam core

Fig. 6. Theoretical results by using MATLAB program, flexure model, the sandwich structure consists of carbon fiber/epoxy resin face-sheets (+45°, -45°, +45°, -45°) with Al foam core

Fig. 7. Theoretical results by using MATLAB program, flexure model, the sandwich structure consist of hybrid face-sheets (0°, 90°, +45°, -45°) with Al foam core

5. Evaluation of the results

5.1. Numerical results in case of different types of laminated composite face-sheets

According to the numerical results of sandwich structures with aluminum foam core and different types of composite face-sheets, as shown in (Table IV - Table VI) and (Fig. 2 - Fig. 4), the deflection and core shear stress of the sandwich structures with

carbon fiber/epoxy resin face-sheet are less than the deflection and core shear stress of the sandwich structures with hybrid and E-glass fiber/epoxy resin face-sheet respectively, because of the carbon fiber having higher stiffness-to-weight ratio compared to E-glass fiber. The skin stress of the sandwich structures with E-glass fiber/epoxy resin face-sheet is less than the skin stress of the sandwich structures with carbon fiber/epoxy resin and hybrid face-sheet respectively, because of the E-glass fiber having high strength-to-weight ratio and more flexible compared to carbon fiber.

5.2. Numerical results in case of different fiber orientations of composite layers

The numerical results of sandwich structures with aluminum foam core and different fiber orientations of composite face-sheets cross ply (0° , 90°) and angle ply ($\pm 45^\circ$) are the following: the deflection and core shear stress of the sandwich structures with face-sheet fiber orientation (0° , 90° , 0° , 90°) are less than the deflection and core shear stress of the sandwich structures with face-sheets fiber orientation (0° , 90° , $+45^\circ$, -45°) and fiber orientation ($+45^\circ$, -45° , $+45^\circ$, -45°) respectively, because of the fiber with cross ply orientation (0° , 90° , 0° , 90°) having higher young modulus of elasticity and stiffness compare with angle ply ($+45^\circ$, -45° , $+45^\circ$, -45°). The skin stress of the sandwich structures with fiber orientation ($+45^\circ$, -45° , $+45^\circ$, -45°) of face-sheet are less than the skin stress of the sandwich structures with fiber orientation (0° , 90° , 0° , 90°) and fiber orientation (0° , 90° , $+45^\circ$, -45°).

5.3. Theoretical results in case of different types of laminated composite face-sheets

According to the theoretical results, as shown in (Table IV - Table VI) and (Fig. 5 - Fig. 7), the weight of the sandwich structures with carbon fiber/epoxy resin face-sheet is smaller than the weight of the sandwich structures with E-glass fiber/epoxy resin and hybrid of face-sheets.

5.4. Theoretical results in case of different fiber orientations of composite layers

According to the theoretical results of sandwich structures with aluminum foam core and different fiber orientation of composite materials face-sheet cross ply (0° , 90°) and angle ply $\pm 45^\circ$, the weight of the sandwich structure with fiber orientation ($+45^\circ$, -45° , $+45^\circ$, -45°) of face-sheet is less than the weight of the sandwich structures with fiber orientation (0° , 90° , 0° , 90°) and fiber orientation (0° , 90° , $+45^\circ$, -45°).

6. Conclusions

The aim of the study was to develop a new sandwich structure, which can be used for manufacturing of walls, floor and roof of lightweight containers. The aim of the application of lightweight containers is to provide significant weight savings compared to conventional steel containers, which results in lower fuel consumption of transport vehicles and less environmental damage.

The new sandwich structure consists of aluminum foam core with upper and lower composite face-sheets. Nine different laminated glass fiber or/and carbon fiber

reinforced plastic face-sheet combinations were investigated. In the study the finite element analysis of the investigated sandwich structures was introduced.

The optimization method was also elaborated for the new sandwich structure. The objective function was the total weight of the structure and five design constraints were taken into consideration, which were the following: total stiffness of the structure; face-sheet failure; core shear; face-sheet wrinkling and size constraint for design variables.

Single-objective optimization of the new sandwich structural model was achieved for minimal weight. In the case study the optimal structure, which ensures the minimal weight of the sandwich structure is a carbon fiber/epoxy laminated face-sheet with 4 layers, with fiber orientation (+45°, -45°, +45°, -45°) and *Al* foam core, which thickness is 19.183 mm. This optimal *Al* foam sandwich structure provides 28.54% weight saving compared to the original structure.

It can be concluded based on the results of the research, that the application of the elaborated sandwich structure can be suggested in those applications where weight saving is the most important design aim.

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