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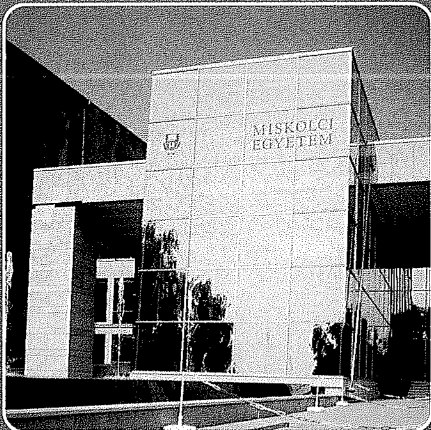

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3.3 Optimal Design of a Composite Cellular Plate Structure

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Abstract

This study shows single and multi-objective optimization of a new complex structural model [laminated carbon fiber reinforced plastic (CFRP) deck plates with aluminium (Al) stiffeners] which is depicted in Figure 1. The structure was designed for both minimal cost and minimal weight. Design constraints on maximum deflection of the total structure, buckling of the composite plates, buckling of the Al webs, stress in the composite plates, stress in the Al stiffeners and eigenfrequency of the structure are considered in the calculation. The flexible tolerance method was used in the single objective optimization and particle swarm algorithm in the multiobjective optimization process.

Keywords: *optimal design, composite cellular plate, cost calculation*

1 Introduction

Sandwich structures utilize the advantages of different structural components. These components can have different structural configurations (e.g. plates or beams) or different material properties (e.g. density or damping coefficients). In the design of layered beams, plates and shells, one can exploit the different beneficial characteristics of these components. Prime examples are orthotropic sandwich structures, which have a high ratio of bending stiffness to density. Hence they are often used in light-weight structures.

Recent literature reviews (Noor & Burton & Bert 1996, Vinson 2001) highlight the significant effort directed at the design, analysis, and applications of sandwich structures. Examples include a bending theory for sandwich beams with thick faces in Stam & Witte (1974). Notable work is reflected by the book of Zenkert (1995). The optimum design of specialized welded sandwich panels for ship floors was treated in Jármai et al (1999), while a five layer beam was analysed and optimized in Farkas & Jármai (1998, 2003). This beam consists of a rubber layer, two aluminium profile beams and two CFRP deck layers.

In the present study a new structural model is investigated. Sandwich plates have deck layers made of metal or FRP (fiber reinforced plastic) plates, and their inner layer is usually made of foam or honeycomb. On the other hand, cellular plates consist of metal deck plates and metal stiffeners welded into the deck plates. Our new structural model combines the sandwich and cellular plates, since it has FRP deck plates and two or more aluminium square hollow section stiffeners riveted into the deck plates. So it is a new combination of materials, stiffeners and fabrication technology.

The multi-cellular sandwich plate is constructed from number of longitudinal Al (aluminium) square hollow section beams and two laminated CFRP deck plates (Fig.1). The connection between the beams and deck plates is effected through riveting. This type of sandwich plate can be applied in many engineering load carrying structures such as ship floors, bridges, airplanes, building floors, etc.

The main aim of the present study is to work out an optimum design procedure for such a structural model. In doing so, design constraints are formulated on the buckling strength of the compressed deck plate, the local buckling of the aluminium square hollow section plate elements, stress in the composite plates and in the Al stiffeners, deflection of the simply supported beams as well as the eigenfrequency of the structure subjected to distributed pressure acting at the total surface.

In order to achieve cost savings in the design stage, a cost function is formulated on the basis of material and fabrication cost analysis. The mass function used in the optimization process includes the sum of the mass of CFRP plates and beams. Mathematical programming methods for constrained function minimization are an integral part of the procedure. The flexible tolerance method (Farkas & Jármai 1997) is used for the determination of the optimal dimensions of the structural model.

2 A new cellular sandwich plate model

The sandwich plate model under consideration is depicted in Figure 1. The *CFRP* plates are constructed from laminated layers. The fiber volume fraction is 61% and the matrix volume fraction is 39%. All of the fibers of a layer and laminate are arranged in the longitudinal direction. Plates are riveted to the upper and lower flanges of the aluminium square hollow section (*SHS*) profiles.

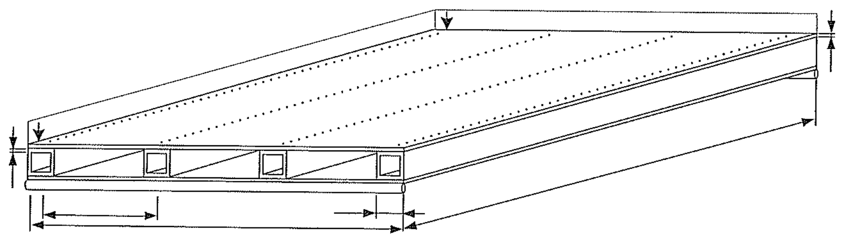

Figure 1. Cellular sandwich plate structure.

The structure is simply supported, and a uniformly distributed loading of $3{,}5 \cdot 10^{-3}$ N/mm^2. (p = 7 N/mm line pressure) acts on the total surface of the structure. The dimensions of the structure are: L = 2250 mm, B = 2000 mm.

The material parameters of a pre-impregnated *CFRP* layer are given as follows: the thickness of a layer t^* = 0,2 mm, the longitudinal Young's modulus $E_x = E_c$ = 120 GPa and the transverse modulus E_y = 9 GPa. The specific mass of the *CFRP* plate ρ_c = 180 g/m^2, and Poisson's ratios ν_{xy} = 0,25 and ν_{yx} = 0,019.

3 Objective functions and constraints

3.1 *Cost function*

The structure is optimized with respect to minimum cost K, which can be formulated as the sum of the material and manufacturing costs (Farkas & Jármai 1997), i.e.

$$f(x) = K = K_{CFRP} + K_{Al} + K_{heat\ treatment} + K_{manufacturing}$$

$$K\,(€) = 2\cdot(n\cdot 31{,}047) + k_{Al}\,[n_s\,(\rho_{Al}\,4\,h_{Al}\,t_w\,L)] + 2\cdot n\frac{525}{528} + k_f\,[n\cdot 14_{min} + $$

$$+\, n_s\cdot 26_{min} + 110_{min}] \tag{1}$$

where n represents the number of *CFRP* layers, n_s the number of stiffeners, ρ_{Al} the density of the *Al* profile, h the height and t_w thickness of the SHS *Al* profiles.

The main contribution to the material cost arises from the raw material for the composite plates. In our case this cost reached 31,047 €/layer. The cost of the *Al* profile is 4,94 €/kg. The specific fabrication cost k_f=0,6 €/min. The cost of heat treatment depends on the volume of deck plates to be heat treated and type of resin matrix. In our case these cost components can be calculated as a function of layer number and plate dimension. Heat treatment cost of a manufactured 220x1200x2mm *CFRP* plate is known, so compared to it the cost of the examined plates based on volume can be calculated. The resulted ratio can be seen in Eq. (1).

The total fabrication cost (as the function of time [min]) is the sum of the cost required for the manufacturing of the *CFRP* plates ($n\cdot 14_{min}+110_{min}$), the cutting cost of the *Al* profiles ($n_s\cdot 6_{min}$) and the total assembly costs ($n_s\cdot 20_{min}$). The time associated with manufacturing of the *CFRP* plates consists of the time lost in press form preparation, layer cutting, layer sequencing and final working. Final assembly consists of drilling of the *CFRP* plates and the *Al* profiles, and also riveting. Drilling of the holes is an implicit function of the number of layers. The design variables are the height h and thickness t_w of the SHS *Al* profiles, the number of layers n of the *CFRP* plates and the number of stiffeners n_s. The fiber orientation is fixed for all layers (0°) as described earlier.

3.2 *Mass function*

The total cost of the structure is the sum of the *CFRP* and *Al* components:

$$m = 2\,\rho_c\,[B\,L(\,n\,t^*)] + n_s\,\rho_{Al}\,[L\,(4\,h_{Al}\,t_w - 4\,t_w^2)] \tag{2}$$

where t^* is the thickness of a laminate.

3.3 *Constraints*

3.3.1 *Deflection of the total structure*

$$w_{max} = \frac{5p\,L^4}{384(E_c I_c + E_{AL} n_s I_{AL})} + \frac{5\Delta M\,L^2}{48(E_c I_c + E_{AL} n_s I_{AL})} \leq \frac{L}{200} \tag{3}$$

where: I_c, I_{Al}: moment of inertia of the *CFRP* plate and *Al* profile,

E_c, E_{Al}: reduced modulus of elasticity of the *CFRP* lamina and Young's modulus of *Al* profile.

There is the effect of the relative movement between the components, and is expressed as a function of the differences in predicted stresses in the middle of *Al* profile and *CFRP* plate. Due to difference in stress ($\Delta\sigma$) there is a corresponding difference in the equivalent applied moment (ΔM). So the second term of the equation is the additional deflection due to the sliding.

3.3.2 *Composite plate buckling* (Barbero 1999)

$$\left(\frac{b_c}{nt^*}\right) \le \sqrt{\frac{\pi^2}{6\sigma_{max}\left(1-\nu_{xy}\nu_{yx}\right)}\left[\sqrt{E_x E_y}+E_x\nu_{xy}+2G_{xy}\left(1-\nu_{xy}\nu_{yx}\right)\right]} \tag{4}$$

where b_c: plate width between stiffeners, σ_{max}: maximal stress in the *CFRP* lamina E_x, E_y, G_{xy}: laminate moduli, ν_{xy}, ν_{yx}: Poisson's ratios.

3.3.3 *Web buckling in the Al profiles* (Farkas & Jármai 1997)

$$\frac{h_{Al}}{t_w} \le 42\sqrt{\frac{235E_{Al}}{240E_{Steel}}} \tag{5}$$

where: E_{Al}, E_{Steel}: Young's modulus of elasticity of *Al* and *Steel.*

3.3.4 *Stress in the composite plates*

The moment acting on the total structure is distributed on the components of the structure. X_cM is the part of total moment which is acting on composite plate, $X_{Al}M$ is the part of total moment which is acting on stiffeners.

$$\frac{X_c M}{I_c}\cdot\frac{h_{Al}+nt}{2} \le \sigma_{Call} \tag{6}$$

where: $X_c = \dfrac{E_c I_c}{E_{Al} n_s I_{Al} + E_c I_c}$; $M = \dfrac{pL^2}{8}$; $\sigma_{Call} = \dfrac{\sigma_T}{\gamma_c}$: allowable stress, X_cM: moment acting on composite plate, σ_T: tensile strength of composite lamina, γ_c: safety factor (=2)

Because of the high number of stiffeners in the case of optimum design, the stress due to the transversal bending moment can be neglected.

3.3.5 *Stress in the Al stiffeners*

$$\frac{X_{Al} M}{n_s I_{Al}}\cdot\frac{h_{Al}}{2} \le \sigma_{Alall} \tag{7}$$

where: $X_{Al} = \dfrac{E_{Al} n_s I_{Al}}{E_{Al} n_s I_{Al} + E_c I_c}$; $\sigma_{Alall} = \dfrac{f_y}{\gamma_{Al}}$: allowable stress, X_AM: moment acting on *Al* tube, f_y: yield stress of *Al*, γ_{Al}: safety factor (=2)

3.3.6 *Eigenfrequency of the total structure*

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{10^3(E_{Al}I_{Al}+E_k I_k)}{m}} \ge f_0 \tag{8}$$

m: weight/unit length of the structure [kg/m], f_0: limitation for eigenfrequency (50 Hz)

Eigenfrequency constraint was not taking into consideration during the optimization, but the optimal structure parameters obtained after the optimization were checked and in all cases satisfied the inequality constraints.

3.3.7 *Size constraints for design variables*

$$
\begin{aligned}
10 &\leq h_{Al} \leq 100 \\
2 &\leq t_w \leq 6 \\
16 &\leq n \leq 32 \\
7 &\leq n_s \leq 20
\end{aligned}
\qquad (9)
$$

These represent physical limitations on the design variables [mm], taking economical and manufacturing aspects into consideration.

3.4 *Flexible tolerance optimization method*

Flexible tolerance optimization method was used during the optimization process.

This method is a constrained random search technique. The Flexible Tolerance algorithm (Himmelblau 1982) improves the value of the objective function by using information provided by feasible points, as well as certain nonfeasible points termed near-feasible points. The near-feasibility limits are gradually made more restrictive as the search proceeds toward the solution, until in the limit only feasible x vectors are accepted.

4 Numerical results of single objective optimization

4.1 *Cost optimization*

Cost saving can be a prime design aim of sandwich structures because the composite materials are very expensive. Table 1. shows the result of cost optimization of the analyzed structure based on the cost function (Eq. 1) and design constraints (Eqs. 3-9). The obtained continuous optimal number and geometries of the stiffeners and total costs for case of different numbers of layers (16-32 pieces) are as follows:

Table 1. Result of cost optimization

Number of layers	*Optimal discrete stiffener numbers and dimensions*			Cost
n [pieces]	h_{Al} *[mm]*	t_w *[mm]*	n_s *[mm]*	[€]
16	60	2.5	15	1730
18	60	2.5	14	1841
20	60	2.5	12	1919
22	55	2.5	11	2014
24	55	2.5	10	2126
26	60	2.5	8	2219
28	50	2.5	8	2340
30	45	2	8	2452
32	45	2	7	2570

It can be summarised based on the obtained results that the increasing number of deck layers causes significant increasing of total cost. The optimal structure is a laminated plate with 16 layers. After continuous optimization a secondary search is necessary to find discrete optimum sizes (standard geometries). The global cost optimum is obtained in case of laminate of 16 layers and 15 pieces of 60x60x2,5 mm stiffeners.

4.2 *Mass optimization*

Table 2. shows the result of mass optimization of the examined structure according to the mass function (Eq. 2) and design constraints (Eq. 3-9). The obtained continuous optimal number and geometries of the stiffeners for the case of different numbers of layers (16-32 pieces) of *CFRP* deck panels can be seen in Table 2.

Table 2. Result of mass optimization

Number of layers n [pieces]	*Optimal discrete stiffener numbers and dimensions*			Mass [kg]
	h_{Al} *[mm]*	t_w *[mm]*	n_s *[mm]*	
16	60	2.5	15	78.317
18	60	2.5	14	78.064
20	55	2.5	13	73.862
22	55	2.5	11	70.723
24	55	2.5	10	70.8
26	50	2.5	9	68.1
28	50	2.5	8	66.445
30	45	2	8	65.32
32	45	2	7	66.469

The global mass optimum is obtained in case of the 30 layered deck plate. This optimum is a global optimum only for the examined interval of n, but it is clear that the total stiffness of the examined structure can be increased by the continuous increase of the number of layers of the deck panel which causes the reduction of number and geometry of stiffeners. So a lighter structure can be constructed in this way, but the cost of it will be extremely high.

After discretization the optimal structure has 30 layers of deck plates and 8 pieces of 45x45x2 mm stiffeners.

5 Sensitivity analysis

We used sensitivity analysis to determine how sensitive the structure is to changes in the value of the parameters of the model and to changes in the structure of the model. Different values of many parameters were set to see how a change in the parameters causes a change in the optimal structural construction.

At first, design variables were analysed in aspect of sensitivity in case of the 20, 22, 24, 26 layered plate structures.

It can be realised that design variables have no significant effect on value of objective functions. After that we analyzed the other components of the objective functions. We have found that the optimal solution is very sensitive to changing of specific fabrication cost (k_f).

We completed the multiobjective optimization for case of different values (1; 2; 2,5; 3; 4 times higher value) of specific fabrication cost to present the effect of sensitivity.

Table 3. includes the result of Particle Swarm Optimization (PSO) (Farkas & Jármai 2003) completed for 26 layered deck plate structure. During the optimization the normalized weighting method were used to show the weight of the cost- and mass objective functions. The normalized objectives method solves the problem of the pure weighting method e.g. at the pure weighting method, the weighting coefficients do not reflect proportionally the relative importance of the objective because of the great difference on the nominal value of the objective functions. At the normalized weighting method we reflect closely the importance of objectives.

$$f(x) = \sum_{i=1}^{r} w_i f_i(x) / f_i^0 \qquad \text{where } w_i \geq 0 \text{ and } \sum_{i=1}^{r} w_i = 1 \qquad (10)$$

The condition $f_i^0 \neq 0$ is assumed.

Table 3. Result of Particle Swarm Optimization

	weights of objective functions	h_{Al} *[mm]*	t_w *[mm]*	n_s *[mm]*
k_f	100-0% weight	60	2.5	8
	0-100% weight	50	3	9
	50-50% weight	50	3	9
	80-20% weight	50	3	9
$2 \cdot k_f$	90-10% weight	55	3	8
	95-5% weight	60	3	8
	100-0% weight	70	3	7
$2.5 \cdot k_f$	100-0% weight	80	4	6
$3 \cdot k_f$	100-0% weight	85	4	6
$4 \cdot k_f$	100-0% weight	90	4	6

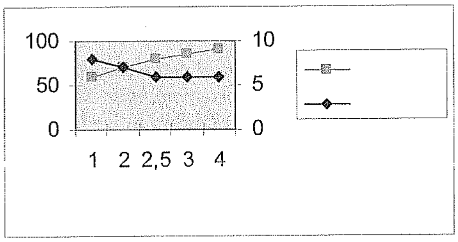

Figure 2. Specific fabrication cost in function of stiffener number and stiffener geometries.

Table 3 includes the optimal structure alternatives for 26 layered deck plate structure. Table summarises the optimal stiffener number and stiffener geometries in case of different value of specific fabrication cost and different weight of objective functions. The first number of weight (2. column of Table 3) represents the effect of cost function in percentage, the second number represents the weight of mass objective function in the multiobjective optimization.

Figure 2 shows the effect of changing of value of specific fabrication cost on optimal stiffener number and stiffener geometries. It can be summarised that the number of stiffeners (n_s) decreases and width of stiffeners (h_{Al}) increases when value of specific fabrication cost increases.

6 Conclusions

A new structural model of a sandwich plate riveted from two aluminium square hollow section rods and two *CFRP* deck plates is investigated by an optimization procedure. In an optimum design procedure the dimensions and number of stiffeners as well as number of layers of sandwich plates are determined, which fulfil the design constraints and minimize the cost and mass. It is shown that significant mass and cost savings can be achieved in the design stage through optimization.

It can be also summarized – based on the mass saving and the disadvantageous extra cost – that the application of fibre reinforced laminates is suggested in those applications where the mass saving is the prime design aim and the cost saving is only secondary. (e.g.: space flight, air-, water- and land vehicles, building parts etc.). Additional advantageous characteristics of these composite structures are the vibration damping and corrosion resistance. Due to the corrosion resistance the surface treatment and painting costs can be neglected which can reduce structural cost significantly.

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