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Optimization of structural elements of transport vehicles in order to reduce weight and fuel consumption

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Abstract. In global competition manufacturing companies have to produce modern, new constructions from advanced materials in order to increase competitiveness. The aim of my research was to develop a new composite cellular plate structure, which can be primarily used for structural elements of road, rail, water and air transport vehicles (e.g. vehicle bodies, ship floors). The new structure is novel and innovative, because all materials of the components of the newly developed structure are composites (laminated Carbon Fiber Reinforced Plastic (CFRP) deck plates with pultruded Glass Fiber Reinforced Plastic (GFRP) stiffeners), furthermore combines the characteristics of sandwich and cellular plate structures. The material of the structure is much more advantageous than traditional steel materials, due mainly to its low density, resulting in weight savings, causing lower fuel consumption and less environmental damage. In the study the optimal construction of a given geometry of a structural element of a road truck trailer body was defined by single- and multi-objective optimization (minimal cost and weight). During the single-objective optimization the Flexible Tolerance Optimization method, while during the multi-objective optimization the Particle Swarm Optimization method were used. Seven design constraints were considered: maximum deflection of the structure, buckling of the composite plates, buckling of the stiffeners, stress in the composite plates, stress in the stiffeners, eigenfrequency of the structure, size constraint for design variables. It was confirmed that the developed structure can be used principally as structural elements of transport vehicles and unit load devices (containers) and can be applied also in building construction.

Keywords: optimal design; composite cellular plate; minimal weight; minimal cost; multi-objective optimization

1. Introduction

Due to the growing market competition and rapidly changing customer demands, enterprises have to improve their efficiency and focus on cost reduction and profitability. Manufacturing activities of production companies have to be adjusted from time to time to fit changing customer and market demands in order to maintain and increase their competitiveness.

New materials, advanced structures, constructions and new innovative production technologies are needed during the manufacturing of final products for such companies. Research and development activity and structural optimization are also keys for competitiveness.

To meet the requirements of the growing market competition the transport vehicles have to be not only cost-effective and of high quality, but at the same time environmentally friendly, because it supports sustainable freight transportation.

The aim of my research was to develop a new composite cellular plate structure which can be widely used for structural elements of road, rail, air and water transport vehicles (e.g. for a road truck trailer body, rail car body, aircraft fuselage and wings, ship floor).

The research is novel and innovative, because on the one hand all materials of the components of the newly developed structure are fiber reinforced plastic composites, on the other hand the new model combines the characteristics of the sandwich and cellular plate structures.

These advanced materials are much more advantageous than traditional steel materials. The reason of it is that the application of composite materials instead of metals provides mainly significant weight savings due to their low density. Therefore, the application of composite structures reduces weight in transport vehicles, which results in higher speed, lower fuel consumption and less environmental damage. Based on the above-mentioned characteristics, these fiber composites are widely used recently in the automotive industry in passenger cars.

Additional advantageous characteristics of these composite structures are e.g. high strength, corrosion resistance, high bending stiffness, good thermal insulation, good vibration damping and aesthetic appearance.

Due to the weight savings they provide, these composite structures can also be widely applied in the future also in the freight transportation industry as structural elements of transport vehicles or as elements of unit load devices (e.g. air freight containers (ULD), shipping containers); furthermore, in the architectural industry as civil infrastructure applications and for building construction (e.g. structural elements of industrial buildings, warehouses, and bridge decks).

In the study the newly developed composite cellular plate structural model is introduced and investigated. It is constructed from two laminated *CFRP* deck plates and

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numerous longitudinal pultruded *GFRP* square hollow section beams (Fig. 1).

The goal of the research is to introduce a real example, the optimal construction of a given geometry of a structural element of a road truck trailer body is defined by single- and multi-objective structural optimization.

Therefore, the optimization procedure is also elaborated; the mass and cost objective functions and seven design constraints (maximum deflection of the total structure, buckling of the composite deck plates, buckling of the stiffener webs, stress in the composite deck plates, stress in the stiffeners, eigenfrequency of the structure and size constraint for design variables) are introduced.

The Flexible Tolerance Optimization method is used in the single-objective optimization and the Particle Swarm Optimization method in the multi-objective optimization process.

Depends on the application field of the composite structure the designer has to define that the minimization of the cost or the minimization of the mass is the preferred design aim during the multi-objective optimization. Therefore, the ratio of the cost- and mass objective functions has also to be defined. (For example in case of the airplane the weight saving is more important design aim, on the contrary in case of mass production of building elements the cost is more frequented aim.)

It can be concluded, that the developed composite structure can principally be applied in the freight transportation industry as structural elements of transport vehicles and structural elements of unit load devices and be applied also in building constructions for bridges and building elements.

2. Literature review

- The new structural model I developed is constructed from laminated *CFRP* deck plates and longitudinal pultruded *GFRP* stiffeners.

There are a lot of books and articles dealing with the micro- and macromechanics of fiber reinforced laminated composite plates and the theory of design procedures (Barbero 1999, Jones 1993, Houmat 2018), but the main barrier to the widespread application of fiber reinforced plastic (*FRP*) constructions is the lack of simplified practical design guidelines.

Fiber reinforced laminated composites are constructed of thin layers stacked together. Laminated plates are utilized in various industries instead of metals due to their light weight and high strength (Ferreira *et al*. 2016, Peng *et al.* 2010).

Pultruded fiber reinforced plastic profiles are being increasingly used in more and more constructions due to their advantageous characteristics, e.g. in civil architectural applications (Correia *et al*. 2015, Hollaway 2010).

- The newly developed structural model introduced in the recent study combines the characteristics of the sandwich and cellular plates.

Fiber reinforced plastic sandwich structures are constructed from *FRP* face sheets and a low-density core material (e.g. foam or honeycomb). The advantages of *FRP* sandwich constructions are high strength-to-weight and stiffness-to-weight ratios, rapid on-site assembly and design versatility.

Design procedures as well as applications of composite sandwich structures have been widely studied in the literature (Vinson 2001, Zenkert 1995). The optimal design of sandwich structures results in high strength and stiffness as well as low weight and cost of constructions (Noor *et al*. 1996, Craig 2012).

Composite cellular plate structures are more capable of withstanding higher external loads compared to their original counterparts. Adding stiffeners to thin composite plates increases their stiffness and results in a higher critical buckling load. Composite cellular structures are geometrically more complex than monolithic structures and have a very complicated behavior.

The design procedure, material and shape optimization of composite cellular structures are much more complex compared to traditional homogenous metal structures due to their orthotropic or anisotropic nature. A number of studies deal with optimizing stiffened cellular composite plates (Wang *et al*. 2017, Liu *et al*. 2008, Rao and Lakshmi 2012, Lakshmi and Rao 2012).

- Several scientific articles have been published in the topic of optimizing laminated composite plates and composite structures. Some of these involve objective functions, constraints and design variables (Nikbakt *et al*. 2018, Sohouli *et al*. 2017, Gillet *et al*. 2010, Marannano and Mariotti 2008).

The most frequently investigated objective functions are weight, load carrying capacity, deflection, frequency, laminate sequence, etc. (Kalantari *et al*. 2017, Blasques and Stolpe 2011, Barkanov *et al.* 2016, Borri and Speranzini 1993, Rajasekaran 2010). Other studies in the literature deal with the optimization procedures of composite structures including optimization algorithms (Nikbakt *et al*. 2018, Vo-Duy *et al.* 2017, Lakshmi and Rao 2013, Liao and Chiou 2006, Rao and Arvind 2007).

3. Characteristics of fiber reinforced composites

A composite is a material made from two or more different constituent materials, which has significantly advantageous properties compared to the characteristics of its individual constituents. The fiber composite consists of the following parts: a strengthening phase and a basic matrix. The strengthening phase is typically fiber, which provides the high strength of the composite. Fibers are embedded in the matrix, which holds fibers and protects fibers from destructive environmental conditions.

There are many types of fibers and matrix materials. The number of the possible combinations of these materials is infinite, which provides adequate composite materials for a wide variety of different structural applications.

Based on the above mentioned characteristics it can be concluded that the fiber reinforced plastic composites are much more advantageous than traditional metal materials since they have high strength, low density, good corrosion and chemical resistance, fatigue resistance, good thermal

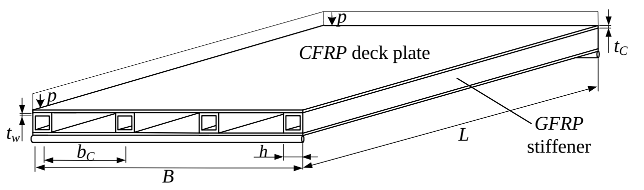

Fig. 1 Composite cellular plate structure

insulation, high bending stiffness, good vibration damping, good design versatility (huge choice of materials and geometrical options is available), ease of fabrication and installation, and aesthetic appearance.

Due to these advantageous properties fiber composites are widely used in many industries e.g. the space, military, automotive, construction, machine and chemical industry.

4. The developed new composite cellular plate model

The new structural model I developed is novel, because all the materials of the components of the new structure are fiber reinforced plastic composites providing significant weight savings. The structure is constructed from laminated *CFRP* deck plates and longitudinal *GFRP* stiffeners (Fig. 1).

The reason for the material selection of the deck plate is that the carbon fiber reinforced plastic (*CFRP*) is one of the most widely used materials in engineering application due to its high strength-to-weight ratio and relatively low cost.

The reason for selecting the glass fiber reinforced plastic (*GFRP*) pultruded beam as the other structural component is that the production technology of the pultruded carbon sections is more complex than in the case of glass fibers, and the *GFRP* also provides the required strength-to-weight ratio and the cost of glass fibers is lower compared to carbon fibers.

The developed model is also novel, because this new structural model combines the characteristics of the sandwich and the cellular plates. Generally, the sandwich plates have face plates made of metal or fiber reinforced plastic (*FRP*) plates, and their core is usually made of foam or honeycomb. The cellular plates consist of metal face plates and metal stiffeners welded into the face plates.

The novelty of the investigated new multi-cellular composite plate is that it is constructed from laminated carbon fiber reinforced plastic deck plates with longitudinal pultruded glass fiber reinforced plastic stiffeners. The connection between the beams and deck plates is adhesive bonding.

The goal of the study is the single- and multi-objective structural optimization of the newly developed structural model, which is a given geometry of an element of a road truck trailer body (Fig. 1).

The fiber volume fraction of a layer in a laminated deck plate is 61%, the matrix volume fraction is 39%. All of the fibers are arranged in the longitudinal direction. Plates assembled using adhesive bonding to the flanges of the pultruded *GFRP* square hollow section profiles.

The investigated structure is simply supported.

Table 1 Geometrical parameters and specific costs of different pultruded GFRP profiles

h [mm]	25	30	30	38	38	40	40
t_w [mm]	2.5	2.5	5	3	4	5	6
Cost [€/m]	5.7	6.4	19.7	10	12.5	14.3	19.8
h [mm]	50	50	50	50	60	60	60
t_w [mm]	3	4	5	6	4	5	8
Cost [€/m]	14.3	17	17.2	19.9	19.9	24.7	29
h [mm]	75	75	100	100	100	100	
t_w [mm]	6	9	5	6	8	10	
Cost [€/m]	36.6	37.4	36.2	40.8	52.3	71.1	

Uniformly distributed loading of $3.5 \cdot 10^{-3}$ N/mm^2 acts on the surface of the composite cellular plate structure. The length of the structure is L = 2250 mm, the width of the structure is B = 2000 mm (e.g. element of a road truck trailer body).

The material parameters of a *CFRP* layer: the thickness of a layer t^* = 0.2 mm; the Young's moduli $E_x = E_C$ =120 GPa, E_y = 9 GPa; the density ρ_C = 180 g/m^2; the Poisson's ratios ν_{xy} = 0.25, ν_{yx} = 0.019.

The material parameters of a pultruded *GFRP* stiffener: the Young's modulus E_G =40 GPa; the density $\rho_G = 2 \cdot 10^6$ g/m^3. Table 1 includes the geometrical parameters and specific costs of different pultruded *GFRP* square hollow sections.

5. Structural optimization

5.1 Objective functions

The main aim of the research is to elaborate the optimization procedure of a newly developed construction. The cost objective function used in the optimization process includes the sum of the material costs of the structural elements and manufacturing costs. The mass objective function is formulated based on the mass of the *CFRP* deck plates and the *GFRP* stiffeners.

5.1.1 Cost objective function

The cost objective function K can be formulated as the sum of the material costs of the structural elements (cost of *CFRP* plates: K_{CFRP}; cost of *GFRP* stiffeners: K_{GFRP}; cost of adhesive bonding: K_{Adh}) and manufacturing costs (cost of heat treatment of *CFRP* plates: K_{Heatt}; cost of manufacturing: K_{Manuf})

$$K = K_{CFRP} + K_{GFRP} + K_{Adh} + K_{Heatt} + K_{Manuf}$$
$$K = 2(nk_{CFRP}) + n_s k_{GFRP} L + n_s k_{Adh} hL + 2nk_{Heatt} + \quad (1)$$
$$+k_f \left[n14_{\min} + n_s 26_{\min} + 110_{\min} \right]$$

where: n is the number of *CFRP* layers; n_s is the number of stiffeners; h is the height, L is the length of the stiffeners; k_{CFRP} is the specific material cost of the *CFRP* layers; k_{GFRP}

is the specific material cost of the pultruded stiffeners; k_{Adh} is the specific material cost of the adhesive bonding; k_{Heatt} is the specific heat treatment cost of the *CFRP* laminates; k_f is the specific fabrication cost.

In our case the specific material cost of a *CFRP* layer is 31.047 €/layer. The specific material costs of the *GFRP* profiles are given in Table 1. The material cost of the adhesive bonding is 55 €/tube (380 ml) which is sufficient for bonding of 4 m^2 surface.

The heat treatment cost is depending on the type of resin matrix and the volume of laminated plates. In our case this cost can be calculated as a function of layer numbers and a specific heat treatment cost. The specific cost of the heat treatment is 1.05 €/layer.

The specific fabrication cost (k_f) is 0.6 €/min. The total fabrication cost (as the function of time [min]) is the sum of the cost required for the manufacturing of the deck plates ($n \cdot 14_{min}+110_{min}$), the cutting cost of the pultruded profiles ($n_s \cdot 6_{min}$) and the cost of the assembly of the structural elements ($n_s \cdot 20_{min}$). The time associated with manufacturing of the deck plates consists of the time needed for the press form preparation, cutting of the layers, layer stacking and final working. The above mentioned manufacturing activities are defined based on my practical experience.

The design variables of the optimization are the number of layers (n) of the laminated plates, the number of the *GFRP* stiffeners (n_s) and the height (h) and thickness (t_w) of the stiffeners.

5.1.2 Mass objective function

The total mass of the structure is the sum of the mass of structural components:

$$m = 2\rho_C\left[BL(nt^*)\right] + n_s\rho_G\left[L(4ht_w - 4t_w^2)\right] \quad (2)$$

where: ρ_C is the density of the *CFRP* layers; ρ_G is the density of the pultruded stiffeners; the mass of the adhesive bonding can be neglected.

5.2 Design constraints

Seven design constraints were considered in the optimization: maximum deflection of the total structure, buckling of the composite deck plates, buckling of the pultruded stiffener webs, stress in the composite plates, stress in the stiffeners, eigenfrequency of the structure and size constraint for design variables.

5.2.1 Deflection of the total structure

$$w_{max} = \frac{5p\,L^4}{384(E_C I_C + E_G n_s I_G)} + \frac{5\Delta M\,L^2}{48(E_C I_C + E_G n_s I_G)} \le \frac{L}{200} \quad (3)$$

where: I_C, I_G are moments of inertia of the deck plate and the stiffener; E_C, E_G are reduced modulus of elasticity of the plate and Young's modulus of the pultruded stiffener.

There is a relative movement between the structural components, which can be defined as a function of the differences in predicted stresses in the middle of the stiffeners and the plates. Due to this difference in stress ($\Delta\sigma$) there is a difference in the equivalent applied moment (ΔM). So the second part of the Eq. (3) is an additional deflection resulted by sliding of components.

5.2.2 Buckling of CFRP plates

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

where: b_c is the plate width between the stiffeners; σ_{max} is the maximal stress in the lamina; E_x, E_y, G_{xy} are laminate moduli; ν_{xy}, ν_{yx} are Poisson's ratios. (Barbero 1999)

5.2.3 Buckling of the webs of GFRP profiles

$$\frac{h}{t_w} \le 42\sqrt{\frac{235E_G}{240E_{Steel}}} \quad (5)$$

where: E_G, E_{Steel} are Young's moduli of elasticity of *GFRP* and *Steel.*

5.2.4 Stress in the CFRP deck plates

The moment acting on the total structure is distributed on the structural components. $X_C M$ is the part of the total moment acting on deck plates, $X_G M$ is the part of the total moment acting on *GFRP* stiffeners.

$$\frac{X_C M}{I_C}\cdot\frac{h+nt^*}{2} \le \sigma_{Call} \quad (6)$$

where: $X_C = \frac{E_C I_C}{E_G n_s I_G + E_C I_C}$; $M = \frac{pL^2}{8}$; $\sigma_{Call} = \frac{\sigma_T}{\gamma_C}$ is the allowable stress; $X_C M$ is the moment acting on the deck plate; σ_T is the tensile strength of composite lamina; γ_C is a safety factor (=2).

The stress due to the transversal bending moment can be neglected because of the relatively high number of stiffeners.

5.2.5 Stress in the GFRP stiffeners

$$\frac{X_G M}{n_s I_G}\cdot\frac{h}{2} \le \sigma_{Gall} \quad (7)$$

where: $X_G = \frac{E_G n_s I_G}{E_G n_s I_G + E_C I_C}$; $X_G M$ is the moment acting on the stiffener; σ_{Gall} is the allowable stress.

5.2.6 Eigenfrequency of the structure

$$f_1 = \frac{\pi}{2L^2}\sqrt{\frac{10^3(E_G I_G + E_C I_C)}{m}} \ge f_0 \quad (8)$$

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

5.2.7 Size constraints for design variables

$$16 \le n \le 32 \qquad 4 \le n_s \le 20$$
$$25 \le h \le 100 \qquad 2.5 \le t_w \le 10 \quad (9)$$

The above mentioned 4 physical limitations on the design variables [mm] taking economical and manufacturing aspects into consideration.

5.3 Methods applied during the optimization

Single-objective optimization of the newly developed structural model was achieved for both minimal cost and minimal weight by the Flexible Tolerance Optimization method, while multi-objective optimization was achieved by the Particle Swarm Optimization method.

5.3.1 Flexible Tolerance Optimization method

The Flexible Tolerance Optimization (FTO) method is applied during the single-objective optimization process.

This is a constrained random search method (Himmelblau 1972). The FTO algorithm improves the value of the objective function because it uses information provided by feasible points and near-feasible points. The near-feasibility limits are gradually becoming more restrictive as the search proceeds toward the solution of the task, until in the limit only feasible *x* vectors will be accepted.

$$\text{Minimize: } f(x)$$
$$\text{Subject to: } \Phi^{(k)} - T(x) \geq 0 \qquad (10)$$

where $\Phi^{(k)}$ is the flexible tolerance criteria for viability at stage *k* of the search; *T(x)* is a positive function for equality and/or inequality constraints.

5.3.2 Particle Swarm Optimization method

Particle Swarm Optimization (PSO) method is applied during the multi-objective optimization.

The PSO algorithm (Kennedy 1997) models the exploration of a problem space by a population of individuals. The success of the individuals depends on their searches and their peers. The social behavior of birds is mimicked during the method. Individual birds exchange information about their location, velocity and fitness, and the behavior of the flock is then influenced to increase the probability of migration to regions of high fitness.

The method is derivative free and able to find the global optimum of the objective function. Constrained problems can be simplified using penalty functions. The normalized weighting method is also used to analyze the weight of the cost objective and mass objective functions in the optimization.

$$f(x) = \sum_{i=1}^{r} w_i f_i(x) / f_i^0 \qquad (11)$$

where

$$w_i \geq 0 \quad \text{and} \quad \sum_{i=1}^{r} w_i = 1$$

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

6. Numerical results of single-objective optimization

6.1 Cost optimization

Cost saving is an important design aim of composite structures due to the high cost of composite materials. Table

Table 2 Result of cost optimization

Number of layers n [pieces]	Optimal discrete stiffener numbers and dimensions h_{Al} [mm]	t_w [mm]	n_s [mm]	Cost K [€]
16	**60**	**4**	**16**	**2224**
18	60	4	14	2244
20	60	4	12	2264
22	60	4	11	2347
24	60	4	9	2367
26	60	4	8	2449
28	60	4	7	2532
30	60	4	6	2615
32	60	5	5	2750

Table 3 Result of mass optimization

Number of layers n [pieces]	Optimal discrete stiffener numbers and dimensions h_{Al} [mm]	t_w [mm]	n_s [mm]	Mass m [kg]
16	60	4	16	90.43
18	60	4	14	85.61
20	60	4	12	80.78
22	60	4	11	79.99
24	60	4	9	83.23
26	60	4	8	74.38
28	60	4	7	73.58
30	**60**	**4**	**6**	**72.79**
32	60	4	6	76.03

2 shows the result of cost optimization of the investigatednew composite cellular plate structure based on the cost objective function (Eq. (1)) and design constraints (Eqs. (3)-(9)).

The obtained optimal numbers and geometries of the *GFRP* stiffeners and the total costs for case of different numbers of layers (16-32 pieces) of the deck plates are as follows:

It can be concluded based on the obtained results that the increasing number of *CFRP* layers causes significant increasing of the total cost of the structure. The optimal structure which ensures the minimal cost is a laminated *CFRP* deck plates with 16 layers and 16 pieces of 60×60×4 mm pultruded *GFRP* stiffeners.

6.2 Mass optimization

The most advantageous characteristic is that the application of composite structures provides significant weight savings. Table 3 shows the result of mass optimization of the investigated structure according to the mass objective function (Eq. (2)) and design constraints (Eqs. (3)-(9)).

Table 4 Result of multi-objective optimization

Weights of objective functions Cost-Mass	n [pieces]	h_{Al} [mm]	t_w [mm]	n_s [mm]
0-100% weight	30	60	4	6
20-80% weight	30	60	4	6
40-60% weight	30	60	4	6
50-50% weight	26	60	4	8
60-40% weight	26	60	4	8
80-20% weight	20	60	4	12
100-0% weight	16	60	4	16

The obtained optimal numbers 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 3.

The result of weight optimization is that the minimal mass of the structure was obtained in case of the 30-layered *CFRP* deck plates with 6 pieces of 60x60x4 mm *GFRP* stiffeners.

7. Numerical results of multi-objective optimization

Multi-objective optimization was achieved by Particle Swarm Optimization method. During the optimization the normalized weighting method were used to analyzed the weight (importance) of the cost- and mass objective functions.

Depends on the application field of the composite structure the designer has to define that the minimization of the cost or the minimization of the mass is the preferred design aim. Therefore, the ratio of the cost- and mass objective functions has also to be defined.

Table 4 shows the result of the multi-objective optimization of the investigated structure. The obtained optimal number of layers of the deck plates, the number and geometries of the stiffeners are summarized in the table in case of different weights of objective functions.

In the 1st column of Table 4 the first number of weights shows the importance of the cost objective function in percentage, the second number shows the weight of the mass objective function during the multi-objective optimization.

It can be concluded based on the results of the multi-objective optimization (Table 4) that if the importance of the mass saving (mass objective function) is increasing, the number of the layers in the deck plates will be increasing, which require smaller number of stiffeners.

If the cost minimization is more important design aim, the number of the layers in the deck plates can be reduced, but more stiffeners will be needed.

8. Possible application fields of the newly developed structural model

- **Automotive industry** (the research introduced in this study primarily focuses on this application field) – **structural elements of road, rail, water and air transport vehicles,** e.g. road truck trailer bodies, rail car bodies, ship floors, aircraft fuselages and wings. The most important advantageous characteristics of the applied composite materials are low density resulting in weight savings and significant fuel savings, high strength, good vibration damping, corrosion and chemical resistance, and easy assembly.
- **Freight transportation industry – structural elements of unit load devices,** e.g. air freight containers (ULD) and shipping containers. The most important advantageous characteristics of the applied composite materials are their low density resulting in weight savings and significant fuel savings, high strength, good vibration damping, corrosion and chemical resistance, and easy assembly.
- **Architectural industry – building construction,** e.g. structural elements of factory buildings, warehouses **and other civil infrastructure applications,** e.g. bridge decks. The most important advantageous characteristics of the applied composite materials are their low weight, high strength, good thermal insulation, corrosion and weather resistance, aesthetic appearance, and easy assembly.

9. Conclusions

Manufacturing activities of production companies have to be adjusted from time to time to fit changing customer and market demands in order to maintain and increase their competitiveness. Therefore, new materials, advanced structures, constructions and innovative production technologies are needed during the manufacturing of final products.

The aim of my research was to develop a new complex composite structural model that can be primarily used for structural elements of road, rail, air and water transport vehicles (e.g. road truck trailer bodies, rail car bodies, deck plates of airplanes, and ship floors).

The research is novel and innovative, because on the one hand all materials of the components of the newly developed structure are fiber reinforced plastic composites, on the other hand the new model combines the characteristics of the sandwich and cellular plate structures.

This composite structure is much more advantageous than traditional steel constructions. The most advantageous characteristic is that the application of composite structures provides significant weight savings due to their low density. Therefore, the composite materials are reducing weight in transport vehicles, which results in higher speed, lower fuel consumption and less environmental damage.

Additional advantageous characteristics of these composites are e.g. high strength, good corrosion and chemical resistance, good thermal insulation, good vibration damping, good design versatility (a huge choice of materials and geometrical options is available), and the ease of fabrication and installation.

In the study it was confirmed by numerical example (real example: structural optimization of a given geometry of an element of a road truck trailer body) that the developed structure can be applied primarily in case of structural elements of transport vehicles due to the weight savings resulting by low density of the composite construction.

The result of my research was the development of a new composite cellular plate structure which is constructed from two laminated *CFRP* deck plates and a number of longitudinal pultruded *GFRP* square hollow section beams.

Single-objective optimization of the new structural model was achieved for both minimal cost and minimal weight by the Flexible Tolerance Optimization method. Multi-objective optimization was achieved by the Particle Swarm Optimization method. Seven design constraints were considered: maximum deflection of the total structure, buckling of the composite deck plates, buckling of the stiffener webs, stress in the composite deck plates, stress in the stiffeners, eigenfrequency of the structure and size constraint for design variables.

The result of the single-objective optimization: during the optimization the number of layers of the deck plates and the number of stiffeners and geometrical parameters of the stiffeners were determined for given structural geometries and loading conditions in order to construct an optimal structure. It can be summarized based on the structural optimization that the increasing number of deck layers causes a significant increase in the total cost.

In the case study the optimal structure which ensures the minimal cost is a laminated deck plate with 16 layers and 16 pieces of 60×60×4 mm pultruded stiffeners (Table 2). The result of weight optimization was that the minimal mass of the structure was obtained in case of the 30-layered deck plate with 6 pieces of 60x60x4 mm stiffeners (Table 3).

The result of the multi-objective optimization: depends on the application field of the composite structure the designer has to define that the minimization of the cost or the minimization of the mass is the more important design aim. Therefore, the ratio of the cost- and mass objective functions has also to be defined.

In the case study the results of the multi-objective optimization (Table 4) were obtained. The optimal composite cellular plate structure (Table 4) was defined (the number of layers of the deck plates, the number and geometries of the stiffeners) in case of different weights of the cost- and the mass objective functions (0%-100%, 20%-80%, 40%-60%, 50%-50%, 60%-40%, 80%-20%, 100%-0%) depending on that the importance of minimization of the cost or the mass of the structure.

It can be concluded, that the goal of the research was achieved, because the optimal construction of a given geometry of a structural element of a road truck trailer body was defined by single- and multi-objective structural optimization.

It can be summarized based on the results of the study, the application of the elaborated fiber reinforced plastic composite cellular plate structures is suggested in those applications where weight saving is the primary design aim, for example the structural elements of road, rail, air and water transport vehicles, civil infrastructure applications, and building construction in the architectural industry, and the structural elements of unit load devices (e.g. containers) in the freight transportation industry.

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