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# Design and Testing of Sandwich Structures with Different Core Materials

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The purpose of this study was to design a light-weight sandwich panel for trailers. Strength calculations and selection of different materials were carried out in order to find a new solution for this specific application. The sandwich materials were fabricated using vacuum infusion technology. The different types of sandwich composite panels were tested in 4-point bending conditions according to ASTM C393/C393M. Virtual testing was performed by use of ANSYS software to simplify the core material selection process and to design the layers. 2D Finite element analysis (FEA) of 4-point bending was made with ANSYS APDL (Classic) software. Data for the FEA was obtained from the tensile tests of glass fiber plastic (GFRP) laminates. Virtual 2D results were compared with real 4-point bending tests. 3D FEA was applied to virtually test the selected sandwich structure in real working conditions. Based on FEA results the Pareto optimality concept has been applied and optimal solutions determined.

*Keywords*: sandwich structures, 4-point bending tests, FEA, virtual testing, multicriteria optimization.

## 1. INTRODUCTION

Sandwich composites have high strength to weight ratio (which results in increase of payload, provides greater range and/or reduced fuel consumption), extended operational life, lower maintenance cost (due to less corrosion, and resistance to marine boring organisms), as well as a range of integrated functions, such as thermal and sound insulation, excellent signature properties, fire safety, good energy absorption, directional properties of the face sheets enabling optimized design and production of complex and smooth hydrodynamic surfaces [1].

Simple theories exist to predict bending deflections of low cost sandwich plates with a line load and specific support conditions [2]. Several studies were focused on the competing collapse mechanisms for simply supported sandwich beams with composite faces and a PVC foam core subjected to three point bending [2, 3]. Map of failure modes or collapse mechanism depending on the core thickness or materials with prediction of collapse loads was studied in [3].

Micromechanical analysis with experimental validation is used to construct parametric and probabilistic model. With this method the influence of randomness of the manufacturing process can be discarded in respect to the mechanical properties [4].

Numeric modeling and experimental test have been completed to prove effect of shear keys to improve stiffness and in plane shear strength properties of composite sandwich panels [1].

The problem considered is consisting of the following objectives: the mechanical properties of the sandwich structure (tensile strength, elongation at break, maximum stress at break) are subjected to maximization and the cost of the materials subjected to minimization. The multicriteria optimization problem has been formulated and solved by applying multicriteria analysis techniques [5 – 8] and genetic algorithms [9 – 12].

The main goal of the current study is to develop a new composite material with optimal physical and mechanical properties.

## 2. EXPERIMENTAL

### 2.1. Preparation of GFRP for tensile test

The reinforcement fibres for glass fibre reinforcement plastics GFRP are supplied in fabrics/mats. In Chopped Strand Mat (CSM) the orientation of relatively short fibre strands (~60 mm) is random and the used binder agent is in form of powder or emulsion. Rowing mats are made of long fibre strands, arranged in bundles with little or no twist and joined in fabric form with stitching. To improve the resin flow properties in vacuum infusion process the CSM mats are used in combination of rowing mats or layer of polypropylene fibres which are stitched together.

The prepared GFRP laminates consisted of following materials:

- The three layers of balanced stitched biaxial roving mat 0°/90° ($3 \times 600$ g/m$^2$) reinforcement were used to prepare GFRP laminate with polyester resin (413-568) matrix by vacuum infusion process.
- To obtain the shear modulus of the GFRP laminate, the balanced stitched biaxial roving mat –45°/+45° ($3 \times 600$ g/m$^2$) reinforcement were used to prepare GFRP laminate with polyester resin (413-568) matrix by vacuum infusion process.
- The second laminate was prepared in vacuum infusion process. The polyester matrix resin 413-568 was reinforced with three layers of flow mat consisting of three layers of fibres: 450CSM/210PP/450CSM (in total $3 \times 1110$ g/m$^2$).

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After post-curing the laminates at the room temperature the rectangular tensile specimens according to ISO 527-4 (25 mm × 250 mm) were milled by 3D CNC milling machine.

## 2.2. Preparation of sandwich panels for 4-point bending test

Sandwich panel consists typically of two GFRP facings and a lightweight thicker core material. The most common core materials are structural foams and wood products. Foams based on polyvinyl-chloride (PVC), high-density polyethylene (HDPE), polyethylene-therephtalate (PET) polyurethane (PUR), polymethyl-methacrylate (PMI), and others. The most important mechanical properties of reinforcement filling materials are the compressive strength, shear modulus and shear strength at failure. Stiffness and strength increases with the density of core material (see Table 1). The used technique for specimens manufacturing was vacuum infusion. Firstly the mould was cleaned, and the vacuum tape was placed in the edges of the mould, then 2 layers of wax were applied and dried for polishing. The complete set of reinforcement plies (see Table 2) with core material were applied to the mould, the peel ply, vacuum and resin injection tubing with connectors and finally the vacuum film were placed on top mould and vacuum drawn. The resin was then transferred via piping/hoses from a container of premixed resin by the suction created by the vacuum. It is important that the gel time is sufficiently long so that the resin has time to infuse the whole mould before it gels.

**Table 1.** Material specification of the sandwich panel

| Material | Mass of 1m$^2$, kg | Layer thickness, mm |
|---|---|---|
| Gelcoat GS | 0.6 | 0.5 |
| Flowmat 450/210/450 | 1.1 | 1.5 |
| Biaxial 0/90, 600g | 0.6 | 1.0 |
| Flowmat 450/210/450 | 1.1 | 1.5 |
| Core (PET 20 mm)<br>80 kg/m$^3$ | 1.60 | 20.0 |
| Flowmat 450/210/450 | 1.1 | 1.5 |
| Polyester resin | 3.9 | – |
| Total | 10.0 | 26.0 |

The three different sandwich panels were manufactured according to materials specification in Table 1. The three different core materials were used (PET and HDPE having density of 80 kg/m$^3$, PMI having density of 52 kg/m$^3$).

## 2.3. Mechanical testing of composites

### 2.3.1. Tensile testing of GFRP laminate

The mechanical properties of experimentally manufactured sandwich composite materials were tested. Mechanical properties of the GFRP laminate are mainly defined by tensile strength of the material. The tensile strength of the composite materials strongly depends on the adhesion strength between the matrix and reinforcement material. Tensile tests of composite plastic materials were performed according to standard EN ISO 527-4:2000. During this process the mechanical properties, such as tensile strength, elongation and modulus of elasticity were determined. Specimens for tensile tests were prepared according to EN ISO 527-4:2000 type 2 (rectangular without end tabs). The cross-sections of the specimens were measured with calibrated calliper gauge with measurement accuracy of 0.01 mm. The axial extensometer with the gauge length of 50 mm (travel +50 % to –10 %), was used to measure axial strain in the specimen. Servo hydraulic testing machine Instron 8800 was used to conduct the testing. Bluehill 2 software was used. The tensile tests were performed with loading rate 2 mm/min with a tolerance of ± 20 %.

### 2.3.2. Bending tests of sandwich panels

For testing the bending strength and stiffness of sandwich panels the 4-point bending test are typically used. The different types of sandwich composite panels are tested in 4-point bending conditions according to ASTM C393/C393M. 4-point bending tests were performed by using electro-mechanical testing system Instron 5866 (PV005688) equipped with the video extensometer and Bluehill software. The principal scheme of 4-point bending test is described in Fig. 1, where: *P* is the load, *S* is the distance between supports, *L* is the span. The span of the lower supports was 560 mm and upper supports 100 mm.

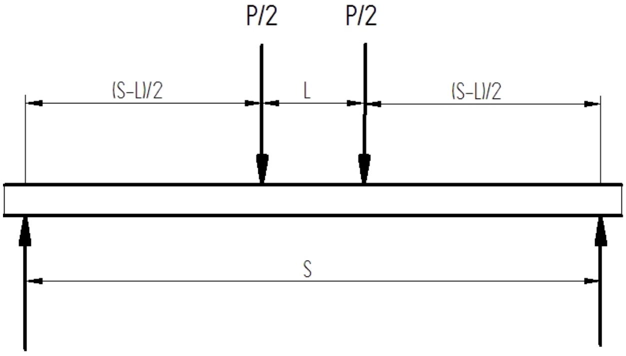

**Fig. 1.** Loading scheme in 4-point bending

## 2.4. Finite element model of sandwich panel

FEM procedures have been successfully employed in research studying the performance of composite structural sandwiches [13 – 15]. Generally a complex failure criterion is used to assess the performance of sandwich structure, e. g. Hou failure criteria [24] or Hashin failure criteria [25]. However, in this study von Mises stress in facings and shear stress in core are chosen to assess the strength of the sandwich. The end application of this development is not strength critical. Failure will not have catastrophic consequences.

Finite element analysis subjected to 4-point bending was conducted with ANSYS APDL v12.1 software. A plane strain 2D assumption was used. Parametric 2D elements with eight nodes (plane183) were chosen to model the sandwich test specimen [16]. Linear orthotropic material model was used to define laminate properties (defined by elastic modulus $E$, Poisson´s ratio $\upsilon$ and shear modulus $G$). Linear isotropic material model was used to define core properties (defined by elastic modulus $E$ and Possion´s ratio $\upsilon$). Mechanical properties of used core materials and GFRP facings and are presented in Table 2 and Table 3 respectively.

**Table 2.** Mechanical properties of core materials [18 – 21]

| Core material | Thick-ness, mm | Density, kg/m$^3$ | Comp-ressive strength (perpen-dicular to the plane), MPa | Shear strength (parallel to the plane), MPa | Shear modulus (parallel to the plane), MPa |
|---|---|---|---|---|---|
| Atlas PUR F | 20 | 60 | 0.6 | 0.55 | 6.5 |
| Atlas PUR F | 20 | 80 | 0.95 | 0.7 | 11 |
| Atlas HDPE | 20 | 100 | 1.3 | 0.9 | 17 |
| Atlas HDPE | 20 | 80 | 0.8 | 0.6 | 13 |
| PET AC80 | 20 | 80 | 1.0 | 0.6 | 20 |
| PMI 51IG-F | 20 | 52 | 0.9 | 0.8 | 19 |
| PVC H60 | 20 | 60 | 0.9 | 0.76 | 20 |
| PVC H80 | 20 | 80 | 1.4 | 1.15 | 27 |

## 2.5. Optimal design of sandwich panel

In order to improve mechanical properties of the sandwich structure the design optimization has been performed. The aim is to design the sandwich structure with maximum stiffness/strength properties while keeping minimal expenses. Behaviour of the different strength characteristics of the sandwich structure has been analyzed and the maximum stress was selected as optimality criterion i. e. the aim is to find out a configuration of the sandwich structure providing highest failure load. Certain similarity in behaviour of the stiffness/strength characteristics has been observed (proportional relations). An alternative concurrent optimality criterion is the cost of the sandwich structure.

Thus, the multicriteria optimization problem considered can be formulated as

$$F_1(\bar{x}) = \sigma_{\max} \to \max, \quad F_2(\bar{x}) = Cost \to \min, \tag{1}$$

subjected to linear constraints applied to the design variables vector $\bar{x}$

$$x_i \le x_i^*, \quad -x_i \le x_{i*}, \quad i = 1,\ldots,n, \tag{2}$$

and non-linear constraints applied to the maximum deflection of the sandwich $w_{\max}$, maximum stresses of the each layer $\sigma_k$ as

$$w_{\max}(\bar{x}) \le w^*, \tag{3}$$

$$\sigma_k(\bar{x}) \le \sigma_k{}^*. \tag{4}$$

In (2) – (4), the indexes * refer to the upper limit value of the corresponding variable.

The objectives (1) are normalized by taking use the following non-dimensional functions

$$f_1(\bar{x}) = \frac{\max F_1(\bar{x}) - F_1(\bar{x})}{\max F_1(\bar{x}) - \min F_1(\bar{x})}, \tag{5}$$

$$f_2(\bar{x}) = \frac{F_2(\bar{x}) - \min F_2(\bar{x})}{\max F_2(\bar{x}) - \min F_2(\bar{x})}. \tag{6}$$

Obviously, both concurrent objectives $f_1(\bar{x})$ and $f_2(\bar{x})$ are subjected to minimization and the Pareto optimality concept can be applied.

## 3. RESULTS AND DISCUSSION

### 3.1 Tensile test results

To determine the required mechanical properties of the laminates used in facings of sandwich material, the tensile tests were performed.

Elastic modulus was calculated according to standard ISO 527. Longitudinal elastic modulus $E_x$ and transverse elastic modulus $E_y$ values were obtained from tensile tests (see Table 2 and Fig. 2).

As E-Glass fiber properties are similar in 0° and 90° directions, then $E_x = E_y$. Same idea is used for determining the $E_z$ value for CSM. It was assumed to be 50 % of the polyester resin elastic modulus [17]. Poisson's ratios $\nu$ of facing materials were obtained from tensile tests (see Table 2).

Shear modulus ($G$) for E-Glass fiber was calculated according to standard ASTM D3518. E-Glass fiber shear modulus was obtained from tensile tests with ±45° test specimens. As fiber properties are same in $x$- and $y$-direction, then $G_{xz} = G_{yz}$. As CSM aligned with 45° fibers is not available, shear modulus was obtained from literature [22, 23].

**Fig 2.** Tensile test of the GFRP laminate

**Table 3.** Mechanical properties of GFRP laminates

| E-Glass fibre 0°/90°, GPa | | CSM, GPa | |
|---|---|---|---|
| $E_x$ | 19100 | $E_x$ | 9400 |
| $E_y$ | 19100 | $E_y$ | 9400 |
| $E_z$ | 1800 | $E_z$ | 1800 |
| $\nu_{xy}$ | 0.11 | $\nu_{xy}$ | 0.26 |
| $\nu_{yz}$ | 0.30 | $\nu_{yz}$ | 0.33 |
| $\nu_{xz}$ | 0.30 | $\nu_{xz}$ | 0.33 |
| $G_{xy}$ | 2900 | $G_{xy}$ | 2200 |
| $G_{yz}$ | 1600 | $G_{yz}$ | 800 |
| $G_{xz}$ | 1600 | $G_{xz}$ | 800 |

Mechanical properties presented in the Table 2 are important data for performing virtual 2D bending tests with ANSYS software.

### 3.2. Bending test results

The flexural strength and stiffness of the three sandwich panels which had similar GFRP facings and different core materials (see Table 1) were determined. 4-point bending tests showed that the sandwich panel which had PMI foam core (see Table 4, Fig. 3) achieved best results as regards to stiffness.

**Table 4.** Average results of the 4-point bending test

| Core material | Max force, kN | Global modulus of Elasticity, GPa | Deflection (mm) | Flexural stress, MPa |
|---|---|---|---|---|
| PET | 2,1 | 2.4 | 48.2 | 17 |
| HDPE | 2.3 | 2.1 | 64.1 | 19 |
| PMI | 1.6 | 2.5 | 26.1 | 13 |

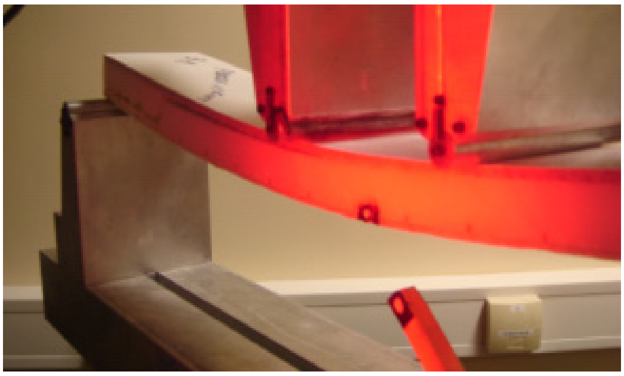

**Fig. 3.** Shear failure of sandwich panel with PMI core in 4-point bending test

The cost of PMI foam exceeds 5-times the cost of HDPE and PET foams. Thus, the second option for core material selection is PET foam having lower flexural stiffness, similar global modulus of elasticity and higher flexural strength than PMI. The cost of PMI foam exceeds 5-times the cost of HDPE and PET foams. Thus, the second option for core material selection is PET foam having lower flexural stiffness, similar global modulus of elasticity and higher flexural strength than PMI.

**Fig. 4.** Shear failure of sandwich panel with PET core in 4-point bending test

### 3.3. FEA model validation

For FEA model validation the results of 4-point bending tests and virtual testing have to be compared. As it follows from the Tabel 5 for the sandwich panels with PET and PMI foam the deflection rates obtained by real and virtual tests are quite similar differentiating only by 3 % – 6 %, as the shear modulus of these foams (see Table 2) are in same range 19 MPa – 20 MPa. Regarding the sandwich panel with HDPE foam (80 kg/m$^3$) the deflection rate obtained by real testing is differencing almost 40 % from virtual result. It can be explained by relatively low shear modulus (11 MPa) and buckling with plastic deformation of the tested panel.

**Table 5.** Comparison of the real and virtual 4-point bending test results

| Type of core material | Maximal deflection obtained by testing, mm | Maximal deflection obtained by FEA, mm | Shear stress of the core material obtained by FEA, MPa |
|---|---|---|---|
| PET | 34.2 | 32.0 | 0.97 |
| HDPE | 69.9 | 41.5 | 0.94 |
| PMI | 30.0 | 30.9 | 0.94 |

### 3.4. FEA analysis results

The sandwich materials were loaded with 2000 N force (1000 N per single loading nose). First support point had both horizontal and vertical directions fixed and second support had only vertical direction blocked. Meshing density was set to the element size with 1 mm edge length.

Von Mises stress distributions in facings are depicted in Fig. 5 and Fig. 6 respectively.

The values of the von Mises stress on lower facing are significantly higher than that in upper facing. The distribution of the xy-shear stress is depicted in Fig. 7.

After number of tests with nine core materials with different thicknesses (15, 18, 20 mm) combined with different number of biaxial reinforcement layers (1 – 6) in the GFRP laminate. It was noticed that all core and sheet material combinations had a failure occurring firstly in core due to shear stresses exceeding the limit value. The obtained FEA analysis results were used for optimal design of sandwich panel. The problem considered is consisting of the following objectives: the mechanical properties of the sandwich structure (tensile strength, elongation at break, maximum stress at break) are subjected to maximization and the cost of the materials subjected to minimization. The material and production costs were calculated for each design of sandwich panel.

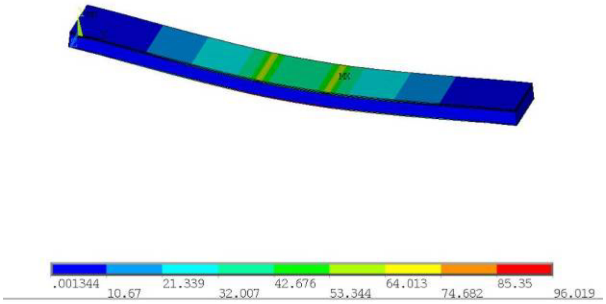

**Fig. 5.** Stress distribution in GFRP upper facing.

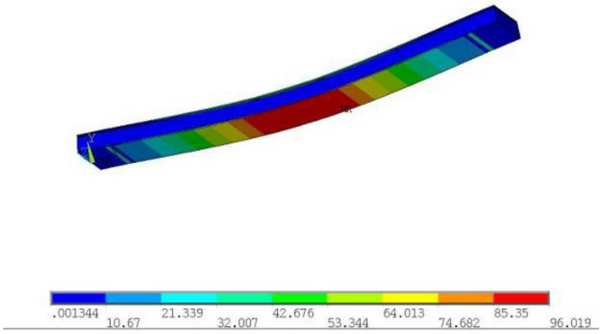

**Fig. 6.** Stress distribution in GFRP lower facing

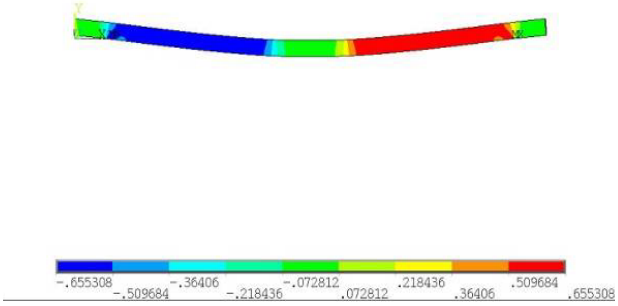

**Fig. 7.** Shear stresses in core material

### 3.5. Pareto frontier

Repetitive evaluation of the objective function $f_1(\bar{x})$ and nonlinear constraints (3)–(4) during optimization procedure is time consuming. For that reason, the FEA has been performed for fixed set of design variables and on the basis of obtained numerical results the response surface has been constructed (most commonly used technique to reduce the cost of the computational analysis and /or experimental tests). In the current study the artificial neural network (ANN) has been employed for response surface modeling. The surface constructed by the use of ANN does not normally contain the given response values (similarity with least-squares method in this respect). An approach proposed is based on the use of the MATLAB neural network toolbox (two layer network with one hidden layer). The Pareto front of the maximum stress and cost of the sandwich structure is given in Fig. 8.

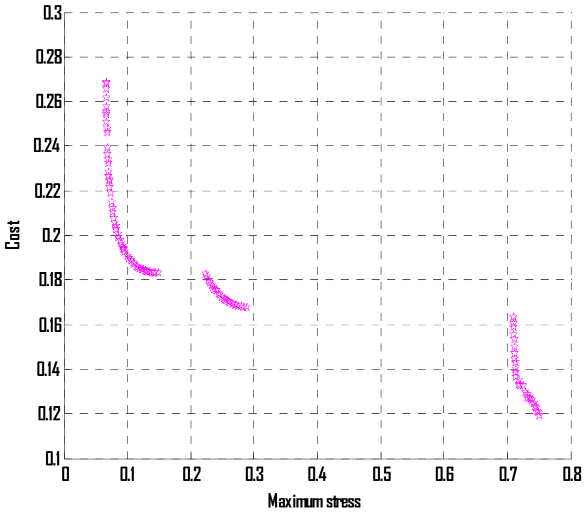

**Fig. 8.** Maximum stress vs cost of the sandwich structure

First note, that the minimum values of the objective function $f_1(\bar{x})$ in Pareto front correspond to maximum values of the original stress function $F_1(\bar{x})$ (see formulas (1), (5)). Pareto front depicted in Fig. 8 contains discontinuities and is made up from three parts corresponding to sandwich structures with different values of the maximum stress and cost. Obviously, the Pareto front can be made less gradual by design of neural network model, but this is not the target desired. Main aim is to provide as much information as possible for decision making i. e. for selection optimal point on Pareto front. Points before sudden rise of the cost function seem most appropriate. However, all points in Pareto front are optimal (Pareto optimality) and final decision depends on particular case.

## 4. CONCLUSIONS

Optimal design of the light-weight sandwich panel has been performed. Different combinations of the core material and layer thicknesses are considered. The study involves experimental investigation and numerical simulation for determining mechanical properties of the layer materials of the sandwich structure. In order to reduce computational time the metamodeling technique has been employed (ANN). Finally, relying upon the obtained response surface the Pareto optimality concept is applied and optimal solutions are determined. It can be concluded that:

- the solution appears more sensitive with respect to core material selection than core layer thickness (it was assumed that the total thickness on the sandwich structure remains unchanged, i. e. core thickness can decrease with increasing facing layers thickness);
- the use of certain expensive core materials like PMI leads to sudden increase in cost, but does not provide significant improvement of the mechanical properties; thus in most of cases use of such core materials is not reasonable;

– the sensitivity of the solution with respect to design variables is times higher in points neighbouring the discontinuity points of the Pareto front.

In future studies, the sensitivity analysis needs special attention. Based on ANN model used, the closed form analytical expressions can be derived for computing the sensitivities with respect to design variables.

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