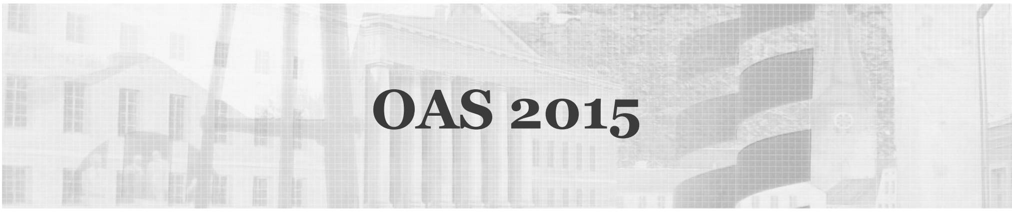

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Evaluation of plywood sandwich panels with rigid PU foam-cores and various configurations of stiffeners

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Abstract. Current paper deals with numerical analysis and optimisation of the mechanical and thermal behaviour of rib-stiffened sandwich panels with plywood and PU foam core constituents. The effect of the skin and rib thicknesses and core density on mechanical and thermal properties has been analysed. Sandwich panel stiffness and of effective thermal conductivity were acquired by means of numerical models in ANSYS software. Parametrical optimisation of the cross section dimensions and material properties was performed to found the best trade-off between stiffness, structural weight and thermal properties. Comparing optimised sandwich structures with tradition plywood boards it is possible to found equivalent stiffness sandwich panels with weight reduction up to 35% and effective thermal conductivity of 0.029 W/m·k (reference to 0.12 for solid plywood board). In addition Pareto optimality front between structure weight and stiffness (comparing to solid plywood) and effective thermal conductivity has been constructed.

Keywords: *plywood sandwich structures, weight optimisation, stiffness, thermal conductivity.*

1. Introduction

Widely used in all fields of engineering plywood boards has good mechanical properties/weight ratio comparing with other conventional materials like steel or reinforced concrete. However for thick plywood boards there is still significantly high density and corresponding costs to other board materials. Large thickness plywood boards are especially ineffective as large span decking structures. In such case sandwich concept of replacing solid core to lightweight and cost effective stiffener/foam core could serve as useful alternative to reduce weight and cost of the inner layer material. Most extensive theoretical base on sandwich design is summarised in great detail [1, 2].

Considering that there is several design variables for sandwich panel cross-section, the optimization allows to track the most efficient combinations of these variables. Advantages of stiffness and weight optimisation for sandwich panels with weak foam cores are described in several research articles [3–5]. Optimisation of the rib-stiffened panels without any core filler is given in previous research by Labans and Kalnins [6] where clear weight saving of more than 60% comparing with reference plywood boards has been achieved. In additional optimisation results were experimentally validated by making 4-point bending tests on panel prototypes. Novel contribution to design and optimisation of plywood based sandwich panels also has been provided in several recent articles [7, 8, 9].

In current research foam core was introduced mainly to address one shot manufacturing process of the sandwich panels with rib-stiffened core. Additional benefits of the foam core filler are improved shear rigidity of the core and consistent quality of sound/vibration and thermal insulation. Therefore trade-off between mechanical and thermal properties should be found.

2. Materials and methods

2.1. Numerical modelling

Mechanical and thermal responses have been acquired by the means of numerical models based on Finite Element Method (FEM). Commercial software ANSYS [10] has been employed for this purposes. Combined shell and solid element types have been combined for stiffness calculations with 4-node SHELL181 elements and 8-node SOLID185 elements. For the purposes of further validation of the shell elements 4-point bending load appliance scheme were applied with the distance between load appliance points of 300 mm and distance between supports of 1100 mm (distances according to EN789[11]). Simply supported boundary conditions were applied at the nodes of both sandwich panel ends. Nodes with coupled vertical displacement were used for simulating of linear bending loads. Multi-layered element structure involves taking into account stiffness effect due to material orientation in the layer of every single ply in given cross-section. Approximate thickness of one layer is 1.3 mm. Mechanical properties of plywood veneer determined in previous study [12] are as follows elastic modulus in longitudinal direction $E_L = 17$ GPa; elastic modulus in radial and transversal direction $E_R = E_T = 0.5$ GPa; shear modulus $G_{RT} = 0.04$ GPa, $G_{LR} = G_{LT} = 0.7$ GPa; Poisson's ratio $v_{RT} = 0.5$ GPa, $v_{LR} = v_{LT} = 0.035$ and density of $630\ \mathrm{kg/m^3}$. Mesh density with cube size of 10 mm has been assigned to the structure as shown in Fig. 1.

a) b)

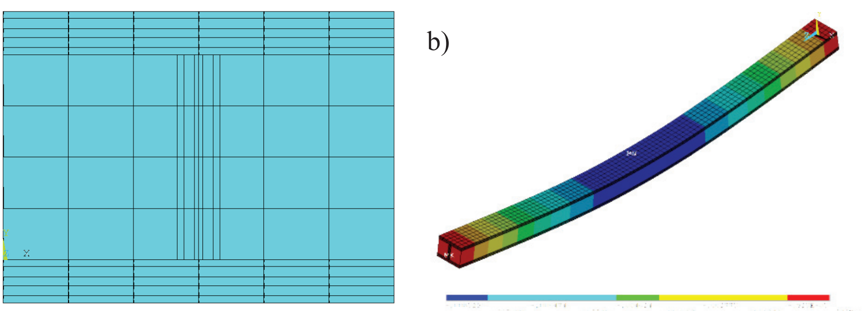

Fig.1. a) - mesh pattern and b) - deformed shape of the panel section.

As a foam filler rigid PU foam has been applied. Rigid PU foams are one of the most effective thermal insulation material available on market with thermal conductivity of $18 - 28$ mW/(m·K) [2, 13]. Low thermal conductivity, closed-cell structure, low water adsorption and moisture permeability, and relatively high compressive strength make this material competitive with polystyrene foams (XPS and EPS) despite higher price [10]. The linear relation between modulus of elasticity and density is given in Fig. 2c.

Thermal model of the cross-section numerically represented in 2D model with PLANE55 elements. Steady state analysis with loads applied as temperature on lower and upper nodes of the mesh. Mesh pattern and heat flow is also shown in Fig. 2.

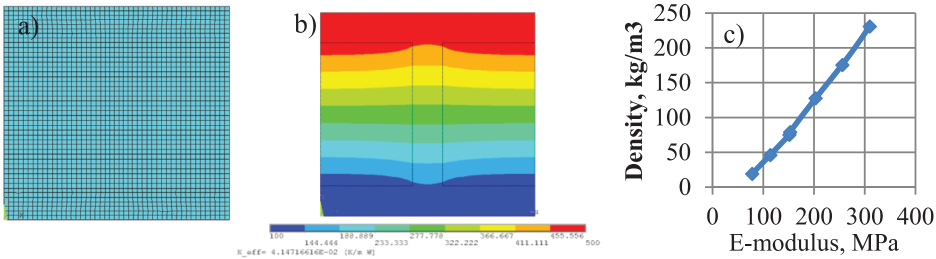

Fig.2. a) - mesh pattern; b) -nodal temperatures at thermal equilibrium; c) – density and modulus of elasticity curve.

As the result of the thermal simulation – the sum of heat flow magnitudes from base nodes are extracted and thermal conductivity k is calculated by Fourier's law (1):

$$k = \frac{d \cdot q''}{A \cdot \Delta T} \tag{1}$$

where d is thickness of the sandwich, q''- heat flux, A- sandwich base area and ΔT temperature difference between upper and lower plate.

2.2. Optimisation

The cross section of a corrugate panel has been characterised with five design variables (Table 1). Separate parameter assigned for core density P_5, which has linear relation with foam mechanical properties.

The design space and parametrical increment for the variables are given in Table 1. In the case of plywood core, core wall thickness is expressed by the number of plies. Acquired response parameters resulting from numerical calculations are maximum deflection at the middle of span and mass of the panel calculated by means of densities. Effective thermal conductivity has been extracted by running the same design of experiments exclusively for thermal 2D model.

Table 1. Design variables.

Parameter	Lower bound	Upper bound	Step	Units
Number of surface plies - P_1	3	7	2	-
Number of stiffener plies – P_2	3	7	2	-
Stiffeners distance– P_3	10	80	10	mm
Total section height – P_4	30	70	-	mm
Foam E-modulus – P_5	75	300	-	MPa

In the present research a sequential space filling design based on Latin Hypercube with Means Square error criterion has been evaluated by the in house EdaOpt software [14]. All responses have been approximated employing Adaptive Basis Function Construction (ABFC) approach proposed by [15].

3. Results and discussion

3.1. Equivalent stiffness sandwich panel design

For efficient evaluation mechanical and thermal properties of sandwich panels were compared with conventional plywood boards. It is commonly known that sandwich panel thickness could be raised to increase bending stiffness without any significant weight penalty. Therefore in the first optimisation step combinations of variables have been selected. This guarantee deflection restrain not to over exceed values obtained from numerical analysis of conventional plywood board. Relative mass indicator is obtained dividing sandwich panel mass by mass of plywood board of the same stiffness.

Table 2. Optimised sandwich panels in comparison with conventional plywood.

	Equivalent of 30 mm plywood	**Equivalent of 40 mm plywood**	**Equivalent of 50 mm plywood**
Cross-section parameter values	$P_1 = 5; P_2 = 3; P_3 = 56; P_4 = 33; P_5 = 75$	$P_1 = 5; P_2 = 5; P_3 = 74; P_4 = 48; P_5 = 75$	$P_1 = 5; P_2 = 3; P_3 = 68; P_4 = 63; P_5 = 75$
Relative mass, %	47.8	40.9	32.3
Relative thermal conductivity, %	28.3	25.1	21.4

Analysing results summarised in Table 2 it could be stated that advantage of sandwich panels increases gradually by increasing thickness. Due to exploitation considerations surface thickness of the sandwich panel with 33 mm section height has been raised to 5 layer. For all sandwich panels types the most efficient strategy to increase stiffness is by increasing the section height using 3-layer stiffeners and foam filler with low density. In case of the sandwich panel with the largest section height, variables P_3 and P_4 reached the boundaries of design space. Therefore it has been considered useful to run the same optimisation task for sandwich panels with foam core only (without stiffeners). Results of this optimisation are shown in Table 3.

Table 3. Optimised sandwich panels (without stiffeners) in comparison with solid plywood.

	Equivalent to 30 mm plywood	**Equivalent to 40 mm plywood**	**Equivalent to 50 mm plywood**
Cross-section parameter values	$P_1 = 5; P_4 = 34; P_5 = 75$	$P_1 = 5; P_4 = 53; P_5 = 75$	$P_1 = 5;\ P_4 = 70;\ P_5 = 121$
Relative mass, %	47.1	34.1	35.5
Relative thermal conductivity, %	25.3	21.7	24.7

From both types of sandwich structures it is clearly seen that increasing section thickness is more efficient than raising density and thus mechanical properties of the foam. In the last column of Table 3 foam properties were increased due to the reason that section height variable reached upper boundary.

3.2. Pareto optimality front

Overall efficiency of plywood sandwich panels has been demonstrated by formulating 3D Pareto optimization problem where maximization of relative stiffness ΔS is done simultaneously by minimizing the relative mass ΔM and relative thermal conductivity ΔK of the panel (Fig. 3 and 4). Relative values is acquired dividing numerically calculated conventional plywood board deflection and thermal conductivity with corresponding values of sandwich panel with the same length and thickness, under the same loading conditions. Relative mass is acquired by dividing sandwich panel mass with solid plywood panel mass.

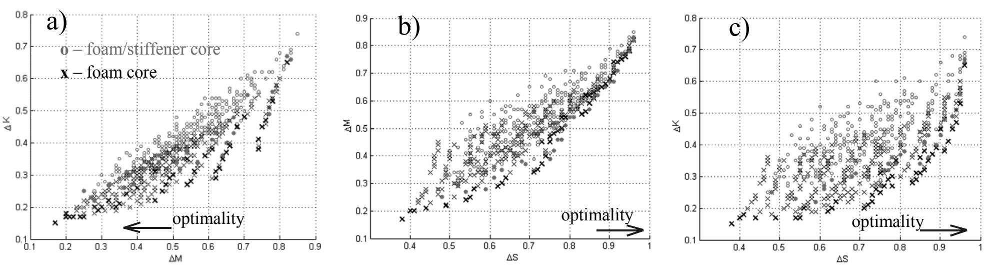

Fig. 3. Graphic representation of Pareto optimality between each of two responses.

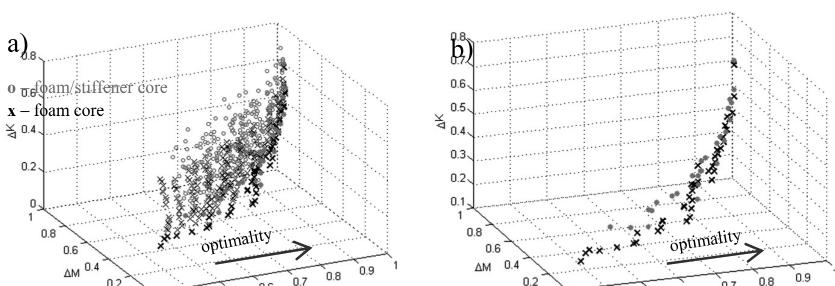

Fig. 4. Graphic representation of Pareto optimality between three responses a) – all data points; b) –only points on Pareto front.

From Fig. 3 and 4 it is seen that both core types has similar stiffness/mass ratio. Most of the marked points (pints on the Pareto front) in Fig. 3b have matching positions. However sandwich panels with foam core has better relative thermal conductivity and stiffness and mass ratio (Fig. 3b, Fig. 3c). Pareto front of sandwich panels with without stiffeners is significantly closer to optimality point.

4. Conclusions

Performing parametrical optimisation on sandwich panels with plywood surfaces and PU foam core the optimal combinations of the variables granting the same stiffness as for plywood reference panel have been found. The largest mass and thermal conductivity benefits has sandwich structures with highest cross-section thickness. Solid plywood board with thickness of 50 mm could be successfully replaced by the same stiffness sandwich panel with 63 mm thickness, but possessing only 32.3% of the reference panel`s mass and approximately 5-fold decreased effective thermal conductivity. Due to the fact that PU foam, made of renewable components, has linear modulus/density ratio increment of sandwich thickness is more efficient than use of higher density foam core.

Pareto optimality front for all three numerical responses has been constructed to assess field of possible optimisation outputs. General trend observed in Pareto front shows that sandwich panels with foam core filler outperform panels with additional stiffeners especially comparing effective thermal conductivity.

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