NUMERICAL VERSUS EXPERIMENTAL INVESTIGATION OF PLYWOOD SANDWICH PANELS WITH CORRUGATED CORE

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ABSTRACT

In the present research, an investigation of the mechanical behaviour of plywood sandwich panels, consisting of plywood surfaces and corrugated plywood core, has been performed using the finite element analysis in ANSYS code. For evaluation purposes, the results from finite element simulations were verified with experimental strain and deflection measurements performed using actual sandwich panels in 4-point bending test set-up. A good correlation between numerical and experimental results has been achieved. Using the validated finite element model of sandwich panel an optimization procedure has been developed to identify the best combinations for cross section parameters leading to optimal weight/ stiffness designs. A number of design guidelines have been drawn to establish the optimal panel configurations for given span length and corresponding load carrying abilities.

Key words: finite element analysis, 3D sandwich structures, metamodeling, optimizations

INTRODUCTION

The Nordic and the Eastern European countries have one of the largest territories of forests where export of sawn timber and wood products like plywood and various chipboards take a significant part in the national export structure. Also bearing in mind the historical wood research traditions in Latvia it makes a good background for new wood based product development. One of the promising directions in new products research and development may be considered lightweight sandwich structures with reduced structural weight and load bearing capacities close to the traditional engineering materials like plywood. Such solution offers material with high specific strength - strength/ density ratio is much higher than in solid wood case. Plywood sandwich panels consisting of plywood surfaces and corrugated plywood core may become an adequate alternative for thick traditional plywood boards in several fields like surface and maritime transport demanding reduced weight and sufficient load bearing capacity. Moreover, considerable wood resource savings, thus solving environment issues, also could be reached using such solutions. However, some scientific effort is required to develop a functional product with optimal cross-section parameters.

Traditionally wood products have been analyzed with simple analytical assumptions and approved with extensive experimental testing. Such assumption restricts the variety of structural applications and imposes restraints on structural weight saving. In contrary numerical simulations based on the finite element method (FEM) can deliver time saving tailored plywood structural solutions with potential of easy change design requirements. To simulate the plywood behaviour and to optimize the complicated multilayer material structure FEM commercial code ANSYS (2009) has been utilized. FEM analysis using commercial codes has been considered as industrial standard for aerospace and car industry in order to reduce the required physical experiments in prototype development process. Employing of parametrical the model in the development process allows saving time in design optimisation using the metamodeling technique and elaboration of design guidelines to tailor the customer requirements.

To use this design method a detailed parametrical model validated with physical tests is needed. Considering that plywood is modelled as multilayer material consisting of veneers composed in several layers with different orientation of fibres, the mechanical and physical behaviour of laminate is largely dependant upon the performance of each individual material layer and its bonding (Wu et al, 2005). This is why it is important to determine the material unidirectional properties to create an accurate parametrical model for structural plywood boards.

A governing mechanics of corrugated structures has been described and methods compared in source (Luo et al., 192). More recent publications describe the analysis of corrugated structures by FEM (Mackerle, 2005; Gilchrist et al., 1999) and computer codes based on FEM usage (Hudson et al., 2010), good correlation between experimental and numerical results was found approving the efficiency of FEM for structural design. FEM analysis and experimental tests on wood based panels with corrugated core (wood fibreboard) were performed by (Hunt, 2004) to show the potential of 3D wood fibreboards. Sandwich plywood panels with rib-stiffened and corrugated core have been investigated by (Zudrags et al., 2009) with the aim to increase plywood specific stiffness. Optimisation procedures using stiffness and weight ratio for plywood sandwich panels with rib-stiffened core were described in (Kalnins et al., 2009).

The aim of this paper is to validate the numerical model of plywood sandwich panel with experimental results and applying metamodeling methodology to develop the optimisation procedure.

MATERIALS AND METHODS

FEM modelling

For numerical simulation of the bending tests a FEM commercial code ANSYS v.11 (2009) has been applied. A parametrical model of the panel was created with variable cross section parameters and bending loading set up options. Corrugate V-core plywood sandwich panel has been modelled according to the EN 789 (2004) test set-up by using ANSYS 4-node shell element SHELL 181. It has been assumed that each ply has thickness of 1.3 mm and transversal isotropic material properties (Figure 1, 2).

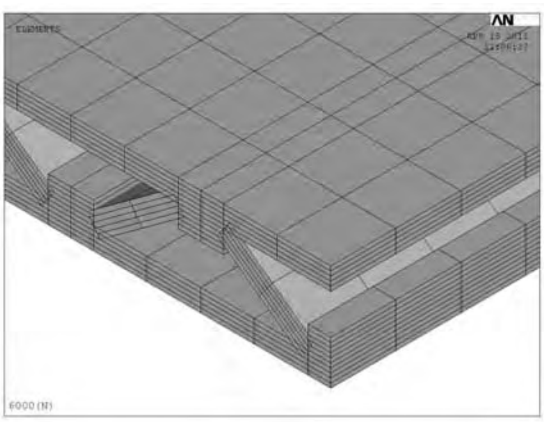

Figure 1. Finite element laminate mesh thought the panel cross section.

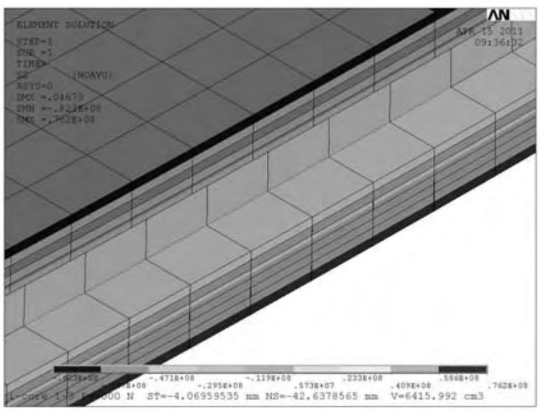

Figure 2. Stress distribution in sandwich structure.

Numerical model geometry was created to mach the panel dimensions according to the manufacturing tolerance where the thickness of outer plies has been reduced by 20%.

The mechanical properties used in the numerical model were obtained in the previous study (Labans et al, 2010) and summarized in Table 1.

Table 1

Veneer mechanical properties

Name of the elastic property	Symbol	Optimal values
Modulus of elasticity in fibre direction	E_x	17 GPa
Modulus of elasticity perpendicular to fibre direction	E_y	0.5 GPa
Poisson ratio in fibre direction	P_{xy}	0.35
Poisson ratio perpendicular to fibre direction	P_{yx}	0.03
Shear modulus	G	0.7 GPa
Density	R_o	600 kg/m^3

Corrugate core roundups are required in the manufacturing process; however, including them in the numerical model is not reasonable (Figure 3).

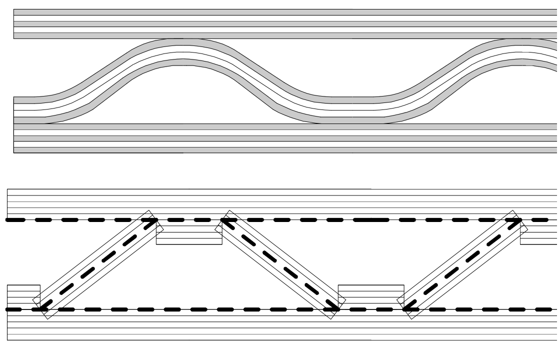

Figure 3. Manufactured cross section of sandwich panel (upper); numerical ANSYS model (lower).

Metamodelling procedure

In industrial applications, in order to reduce the development time involving the high precision simulations, the metamodels also called surrogate models can be constructed to replace the original response with the approximation functions (Kalnins et al,. 2009). The design optimization process using metamodels usually consists of three major steps: 1) design of computer experiments 2) construction of approximation functions that best describe the behaviour of the problem 3) employing developed metamodels in the optimization task or derivation of the design guidelines.

Table 2

Cross section design variables

Parameter	Nomenclature	Lower limit	Upper limit	Increment step	Units
Number of cover plate plies	***P1***	3	7	2	-
Total section height	***P2***	30	50	5	mm
Number of plies in corrugate section	***P3***	3	5	1	-
Corrugated ply angle	***P4***	30	60	-	deg

In the current research a sequential design based on the Means Square error criterion has been evaluated by EdaOpt software (Auziņš et.al 2007). A total of 125 points for four design variables have been evaluated.Four design variables have been used to describe different cross section parameters, in particular number of plies in upper ***P1*** and corrugate plates ***P4***, the total section height ***P2*** and the angle between the upper plate and the corrugate core ***P3*** as displayed in Figure 4. The design boundaries for the variables are given in Table 2. As response parameters acquired during the numeric calculations are maximum deflection at the midspan ***U***, normal stress at the midspan ***σ*** and the tension strain in outer ply ***ε***.

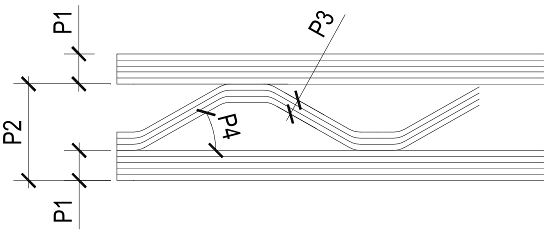

Figure 4. Variable cross section parameters.

The span length of the four point loading model was kept constant; however, the width of the panel has been linked with the corrugated ply angle parameter ***P4***. This constraint assures that the acquired results for different topology models would be comparable, as the width parameter and corrugate topology have linear dependency. This means that the acquired response values were multiplied with the coefficient $\boldsymbol{k_r}$ characterizing relation of the actual panel width against the standard width of the panel of 300 mm.

Experimental investigation

Three sandwich panels with corrugated core have been tested in 4-point bending set up according to EN-789 (Figure 5) at the Riga Technical University, Institute of Materials and Structures (IMS). The average length of the panels is 1200 mm, width – 300 mm, and thickness 30 mm, width of one corrugate wave – 75 mm. Surfaces plate manufactured of 5-layer plywood and corrugate core from corrugated 4–layer symmetrical plywood sheet where the outer plies are parallel to the cover plate longitudinal axis. All panels have been tested up to 22 mm deflection which corresponds to approximately 40 % of the critical load for this type of specimens. Deflections under the symmetrical loading conditions have been recorded with extensometer at the midspan, strains on outer surfaces measured using strain-gauges (produced by HBM).

Figure 5. Sandwich panel in 4-point bending test set-up on INSTRON 8802.

For two panels strains were measured on both sides of the outer surfaces and also in several positions on the corrugate core panel surfaces. In total 14 strain-gauges were used to cover one panel. On the other hand, for the third panel strain measurements were taken only on the cover plate outer surfaces with 6 strain-gauges.

RESULTS AND DISCUSSION

Validation of the numerical model

To validate the numerical model of the plywood sandwich panel, experimental strain and deflection measurements have been compared with the response values extracted from the numerical simulations. The numerical and experimental deflection curves are compared in Figure 6.

One can note that the load deflection curves have linear behaviour, indicating the elastic deformation of the panels. The numerical results practically match the experimental load/deflection values. The vertical line is added to the graph in order to identify the deflection limit state (5% of span length) prescribed by structural safety codes.

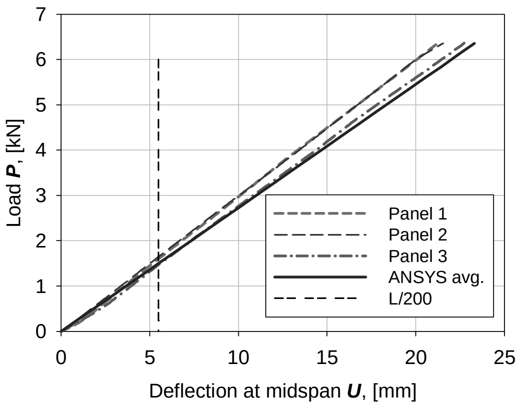

Figure 6. Load/deflection curves of sandwich panels.

The load/ strain curves are shown in Figure 7. Curves with negative strain values are obtained from strain-gauges attached to the upper surfaces of the cover panels or in the compressed zone. In the same way the curves with the positive strain values are obtained from sandwich panel bottom surfaces. Likewise to the previous figure, the numerical values are close to the experimentally obtained ones. The load/ strain curves derived from the strain gauges attached at the corrugated core surface are summarized in Figure 8. The shear strain values obtained by numerical modelling are higher than the experimental values in average by 10-15 %. This could be explained by inaccurate positioning of the strain values, because strains should be measured in 45 degrees angle toward the panel longitudinal axis. Precise measuring angle probably was not reached or maximal strains were positioned at a different angle because of not precise veneers orientation in plywood sandwich production.

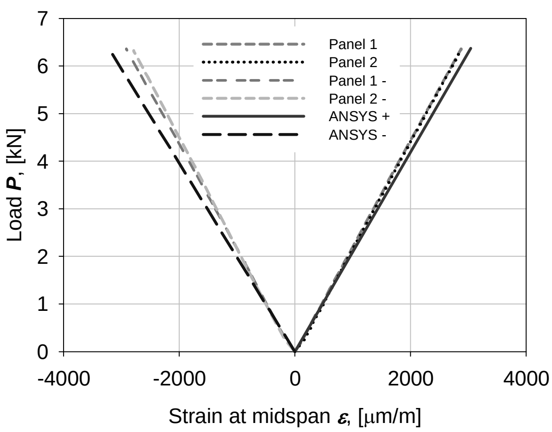

Figure 7. Load/ strain curves on the sandwich panel outer plates.

It has been concluded from the verification study that the parametrical model elaborated in ANSYS code matches the mechanical behaviour of the sandwich panel observed in the experimental tests.

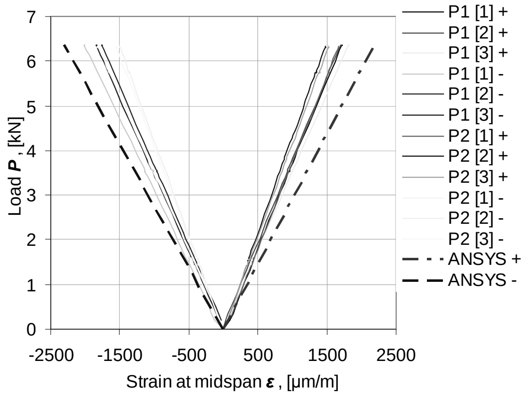

Figure 8. Load/ strain curves on sandwich panels corrugated core surface.

It may be recommended to utilize such model for metamodeling based optimisation procedure.

Optimisation results

During the optimization procedure the maximum stiffness and volume ratio combinations have been obtained for the given parametrical variables and normalized versus homogeneous plywood panel (Table 3).

Table 3

Optimal plywood sandwich parameters sorted according to homogeneous panel geometry

Variable	Set1	Set 2	Set 3	Set 4	Set 5
P1	3	5	5	3	3
P2	0.03	0.035	0.04	0.045	0.05
P3	5	5	3	5	5
P4	60	60	60	60	60
Vs,cm^3	3966	6600	5580	5300	5360
Vs-Vp,%	55	37	53	61	64
Us-Up, %	22	14	30	35	42
Total, %	33	23	23	26	22

The sandwich panel volume parameter has been marked as ***Vs*** in contrary to the homogenous plywood volume as ***Vp***. Respectively ***Us*** and ***Up*** – deflections for sandwich panels and plywood panels of the same thickness. To estimate the efficiency of the cross section parameters deflections and volumes of the sandwich panels were compared with the homogenous plywood values. The difference between the sandwich panel and pure plywood volume has been divided by the sandwich panel volume to acquire volume reduction (%) using sandwich structure. A similar action has been used to assess the deflection values for both structural types. The parameter ***Total*** stands for the difference between the volume gain and deflection loss (%). In average a total gain value in

comparison with homogenous plywood is 25 %.
In order to graphically assess the influence between the parametrical variables, the 3-D influence graphs have been constructed to show the dependencies with the deflection and strain response values (Figures 9, 10, 11). It may be evident that the cross section height parameter has the most sensitivity to decrease both the global and local deflection of the sandwich panel.

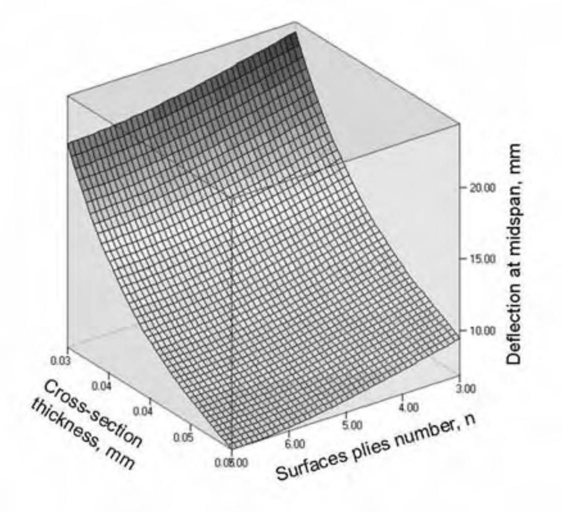

Figure 9. Panel thickness/ outer plies number versus panel deflection at the midspan graph.

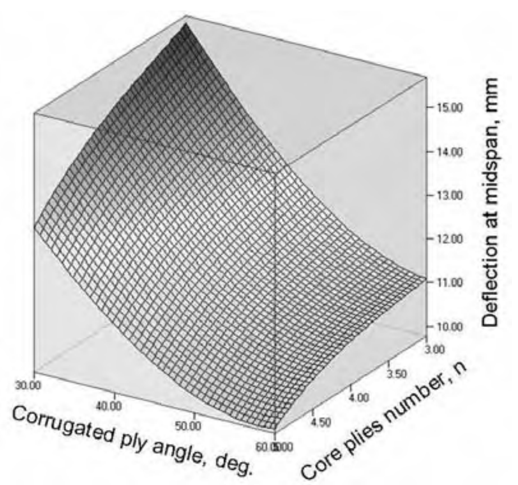

Figure 10. Number of plies in corrugate section / corrugated ply angle versus panel deflection at the midspan graph.

A general trend could be estimated from Figure 10 that panel deflection is largely dependent on the corrugated ply angle parameter ***P4***. The panel stiffness is more sensitive towards the change of the angle than the core plywood thickness. However, some combinations with a smaller angle also should be considered in case of manufacturing difficulties of plywood structures with small bend radius.

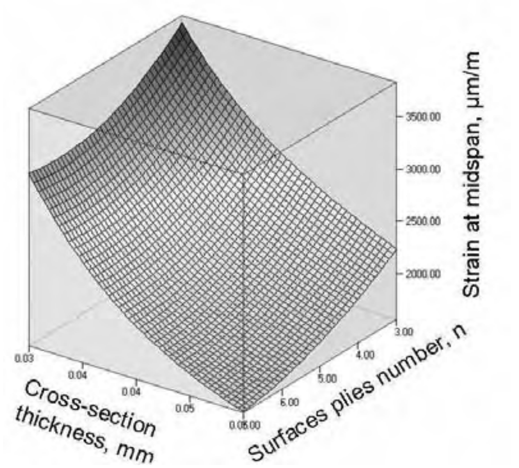

Figure 11. Panel thickness/ outer plies number influence graph on elastic strain.

For the sandwich panel of each thickness with optimal cross section parameters design guidelines were evaluated for better demonstration of the load bearing capacity at different span length (Figure 12).

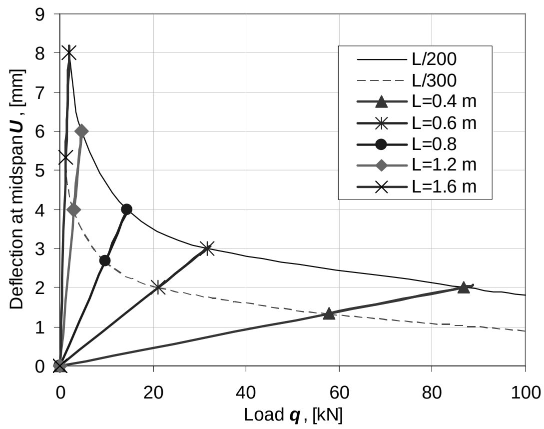

Figure 12. Acceptable load / deflection graph for panels with 30 mm thickness, 3-layer surfaces and corrugated ply angle 60^0.

One may notice that the load bearing capacity decreases exponentially by increasment of the span length. For other panels the span/ limit load graphs have been constructed as well to assess the load carrying possibilities for panels with different cross-section parameters.
The ultimate load values for sandwich panels could range up to large plastic strain limit state –in this particular case strain up to 5000µm/m. This may be stated as the current strain limit determined analysing the material properties and physical tests for similar type panels. The limit load values largely depend on the span length parameter, thus for every sandwich panel thickness a separate graph has been drawn.

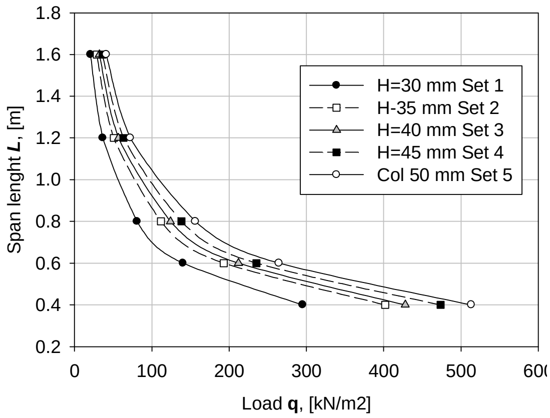

Figure 13. Ultimate load/span graph. Restriction-load values causing major plastic strains leading to material destruction (ε_{max}=0.005).

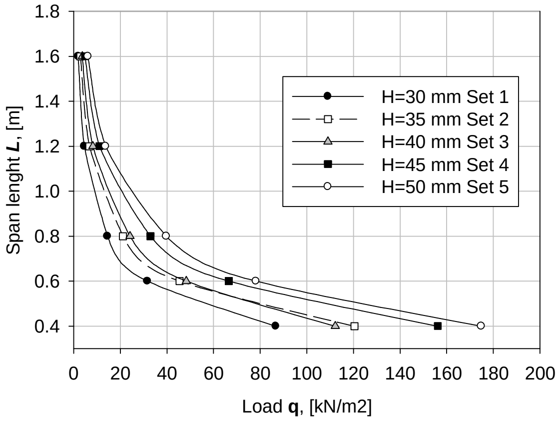

Figure 14. Load /span length graph for deflection limit 5 % of span length.

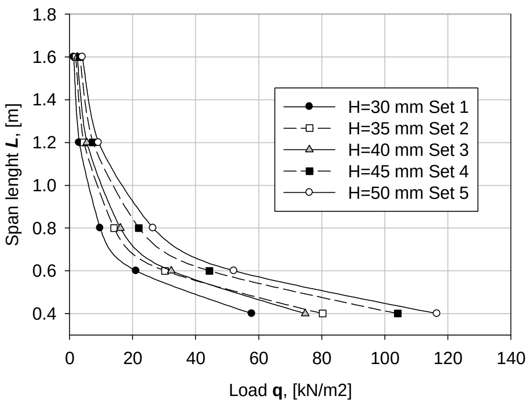

Figure 15. Load /span length graph for deflection limit 3.3 % of span length.

Similar load/span curves have also been constructed to determine the sandwich panel load bearing capacity up to the specific deflection limit (Figure 14, 15). The deflection limit has been set to 5 % which correspond to 1/200 of the span length, in same manner 3.3 % correspond to ratio of 1/300 of the span length.

Using the acquired design guidelines it is possible to easy assess the efficiency of sandwich structures comparing them with homogenous plywood and foresee deformation values at various loading and span length. For example, it is clearly seen that a sandwich panel with 40 mm total thickness is not as economically efficient as a panel with 30 mm total thickness at small span lengths (0.4-0.6 m).

CONCLUSIONS

During the present investigation of plywood sandwich panels with corrugated core, multilayer numerical models with variable cross section parameters have been evaluated and verified with the experimental results. The acquired numerical results were compared with the experimental results acquired by testing of three manufactured panel prototypes in 4-point bending set up according to EN-789 and a good agreement between the experimental and the numerical results has been acquired.

It has been concluded that the corrugated panel stiffness is largely dependent on the corrugated ply angle. The best results acquired from the optimisation procedure indicated the 60^0 corrugate plate angle, however, this value may not be possible to achieve by manufacturing restraints.

The optimisation results demonstrate that in some combinations of design variables the sandwich panels could be up to 40 % weight effective comparing with homogeneous plywood panels with the corresponding height, by losing only 10-20 % of the load carrying capacity.

Based on the optimisation results the design guidelines were constructed for a limited amount of considered panel configurations delivering the optimal cross section parameters, within the given deflection and maximal strain limits.

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