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EXPERIMENTAL VALIDATION OF THE STIFFNESS OPTIMISATION FOR PLYWOOD SANDWICH PANELS WITH RIB-STIFFENED CORE

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ABSTRACT

Current paper deals with stiffness optimisation of silver birch (*Betula pendula* ROTH) plywood rib stiffened hollow core sandwich panels. Such a structural solution has several advantages over conventional plywood boards - weight and material savings are just some of them. However hollow core panels demand special attention to accurate structural design for selected loading scenarios. In order to acquire mechanical behaviour of plywood boards and rib-stiffened panels the ANSYS finite element (FE) calculation code has been employed linked with predefined design of computer experiments. Based on acquired mechanical responses from FE analysis metamodelling technique has been implemented to optimise cross-section parameters of rib stiffened panels. Optimisation results demonstrated that such a strategy allows to obtain an optimum solutions and to substitute conventional thick plywood boards (h>30 mm) with equivalently stiff hollow core sandwich alternative. This could be of particular interest for applications where bending is dominating load case and structure span length is at least 20 times larger than thickness. In such a case weight reduction of plywood hollow-core panels may reach up to 45 %, comparing with conventional plywood boards. Experimental validation of obtained optimal designs confirmed the match between load/deflection curves among conventional and equivalent rib stiffened panel designs. Some slight stiffness deviations observed in tests are mainly caused by geometrical intolerances included in manufactured prototypes.

KEYWORDS: Plywood, sandwich structures, optimisation, metamodelling, ANSYS.

INTRODUCTION

Conventional plywood boards usually are employed as covering surfaces for walls (a thin sheets) or load bearing (thick plates) elements for floor systems in regard of its high stiffness and relatively affordable price for building engineering. However once exceeding a particular thickness limit (at least 30 mm), plywood board becomes cost/weight inefficient structural solutions to be applied in cases of bending load. Therefore it becomes apparent to utilize the "sandwich effect" in order to increase the cross section stiffness/ weight ratio.

Sandwich structures with fibre reinforced skins are widely used in lightweight transport vehicles, like trains, planes, ships and others (Zenkert 1995, Vinson 2005). It allows significantly reduce structure weight and integrate additional interdisciplinary properties like thermal/ acoustic/electromagnetic isolation. In case of hollow core sandwich structures (with ribbed or corrugated core) communication inserts could be placed inside the sandwich. This is especially important for aeronautics, where even minor weight savings allow reducing energy consumption for the lifecycle or allow increasing the maximum payload (Soutis 2005). Similar trend now may be observed also in land transport industry where metal train bodies are being substituted by lighter composite parts with integrated crashworthiness properties (Cameron et al. 2010, Gay and Hoa 2007).

The use of sandwich structures in civil engineering applications like walls and floors is mainly driven by need to integrate insulation properties inside panel core (Kawasaki et al. 2006). Low weight solutions are mainly employed in furniture industry where paper honeycomb cores are widely utilised.

Recently a trend in material research is focused on biodegradable materials and ways to utilize natural product as wood more effectively, reducing manufacturing surplus (Hunt 2004, Beck et al. 2009). Taking into account that plywood manufacturing is one of the most efficient means of wood processing, producing a low CO_2 emission rate comparing to other traditional structural materials, it makes sandwich structures with plywood components especially environmentally friendly.

In case of sandwich structures with different stiffener core types, a cross linking parameters must be introduced in order to optimise the core topology for specific commercial products.

Optimizations of plywood itself and sandwich panels made of it has not been widely studied so far. In contrary there are a wide range of research done on design and optimization of various types of metallic sandwich panel cores, like design of sandwich panels with corrugated core by Valdevit et al. (2006), truss cores by Wicks and Hutchinson (2004), pyramidal by Zok et al. (2004). Rathburn et al. (2005) proposed general methodology for weight optimization of metallic sandwich panels in bending. Banerjee and Bhattacharyya (2011) adopted this methodology for strength-based optimization for plywood sandwich panels with veneer hollow cores. Negro et al. (2011) proposed to use such structure in boatbuilding industry and performed mechanical and acoustic tests for panels made from okoume (*Aucoumea klainean* Pierre) wood.

Sandwich panels with rib stiffened and corrugated core have been numerically investigated by Kalnins et al. (2009). Stiffness-based optimization demonstrated significant weight savings over traditional plywood boards; however this numerical analysis has not been experimentally validated so far.

Main effort in current research is directed towards modeling aspects of plywood panels with rib stiffened core and physical validation of optimized designs. In order to evaluate efficiency of a new design a conventional plywood board is taken as a reference to assess stiffness and weight advantage of sandwich structure with I- stiffener type core. Bending strength or maximum stress level have not been taken as optimization responses due of reason that in engineering applications critical load (usually 1/300 of the span length according building codes for timber structures like Eurocode 5(2004)) is reached much faster than critical stress in face or core. Other reason for stiffness- only optimization is the fact that in practice high scatters of critical load values might be observed due to non-uniform stress distribution and local failure of bond line between face and stiffener.

MATERIAL AND METHODS

Case study of plywood sandwich panels – numerical modelling

The optimization conducted in present paper is based on approximation of mechanical response values acquired from numerical ANSYS commercial code. Similar technique also has been employed to simulate plywood panels with corrugated core by Labans and Kalnins (2011). Initial geometry of the parametrical model is evaluated using 4-node SHELL 181 elements. Geometrical tolerance and virtual loading conditions are kept as close as possible to the test environment at the same time setting some assumptions to make model suitable for computer analysis.

Panel skins and core walls are made out of layered material taking into account stiffness effect due to material orientation in the layer of every single ply in cross-section. Mechanical properties of single veneer largely differs from traditional wood specimens (Wu 2005), therefore they were acquired experimentally performing tension tests in preliminary study (Labans et al. 2010). Birch (*Betula pendula* ROHR) veneers mechanical properties used as input data for sandwich panels are assumed as follows: Young`s modulus in longitudinal direction $E_L$ =17.1 GPa; Young`s 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}=0.49 GPa, v_{LR}=v_{LT}=0.035 and density has been set to 630 kg.m^{-3}. A single layer thickness has been calculated dividing plywood board thickness with layers count. Therefore approximate layer thickness may be assumed as 1.3 mm. In order to forecast the mechanical behaviour of the structure under given loading conditions some manufacturing assumptions need to be considered. Among them should be reduced thicknesses of the cover layers and density fluctuations over the cross section. Outer plies of produced plywood have thickness reduction of nearly 20 % from surface grinding procedure during the manufacturing process. Large divergence of the sandwich panel stiffness caused by thickness variations of the outer plywood layers also was mentioned before (Kljak and Brezović 2007).

A FE mesh for I-core sandwich panel is shown in Fig. 1, where equivalent grid mesh step of 10 mm has been assigned. As an output result of numerical analysis the deflection at the panel mid-span, strains at various locations on outer skins and total volume of the structure have been extracted.

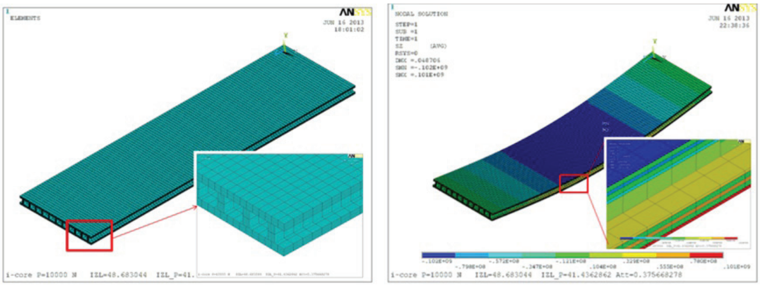

Fig. 1: Numerical model of the panel. a – mesh pattern; b– stress distribution in bending mode.

In order to set the reference values a numerical model of conventional plywood board has been modelled to serve as a reference to compare elaborated optimum sandwich designs. In parallel several traditional boards have been modelled according dimensions of the plywood manufacturer handbook. The actual board thickness usually is smaller than nominal thickness therefore each board thickness and layer number should be verified before the analysis.

Design variables and optimisation

The purpose of the optimisation in current paper is elaborating the optimal cross-section parameters for the sandwich panel to achieve maximal possible reduction of the structural weight. Four design variables for cross section topology have been selected (Fig. 2). All plywood thicknesses are expressed by the number of plies. Thickness increment step for those variables is nominal 2 ply step, correspond to 0/90 manufacturing thickness gradual step. The upper and lower bounds of the variables are summarised in Tab. 1. Bound values is chosen taking into account available plywood thicknesses range and manufacturing restrictions.

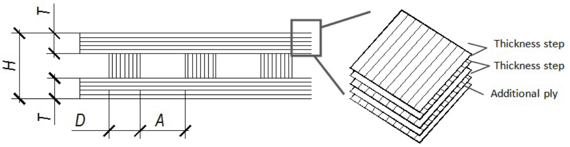

Fig. 2: Design variables for sandwich panel cross-section.

Tab. 1: Design space for deck structure.

Parameter	Lower bound	Upper bound	Increment step	Units
Number of cover plate plies (T)	3	9	2	-
Stiffener plies count (D)	5	23	2	-
Distance between stiffeners (A)	10	80	-	mm
Total section height (H)	30	50	5	mm

The traditional plywood boards have been set as a reference to evaluate sandwich design. Combinations of variables providing the same sandwich stiffness as plywood board at the same time keeping mass lower are within scope. In order to discern sets of variables offering the lowest mass (function extreme) results from 150 numerical analysis trial runs have been processed using metamodelling method. Metamodels replace original responses with approximation function which later can be minimized to find extremes. Design optimization process using metamodels usually consists of three major steps:

1) design of computer experiments,
2) construction of approximation functions that best describes the behaviour of the problem,
3) employing developed metamodels in optimization task or derivation of the design guidelines.

In current research a sequential design based on Means Square error criterion has been evaluated by in house EdaOpt software (Auzins 2004). For common engineering tasks low order global polynomial approximations (for example 2nd order polynomial) have been widely accepted. As they do not require a large number of sample points and are computationally effective. However they fail to approximate most of non-linear model behaviours. In such a case a higher order polynomial could be utilised, but if no special control algorithms are assigned they tend to overfit the data and produce even larger approximation errors.

An alternative approach for polynomial model building which does not assume a predefined set of basis functions has been proposed by Jekabsons (2010) - Adaptive Basis Function Construction. This particular approach allows generating polynomials of arbitrary complexity without the requirement to predefine any basis functions or to set the maximal order of the polynomial (or any other hyper parameters) – all the required basis functions are constructed adaptively. Generally a polynomial model can be defined by a linear summation of basis functions:

$$\hat{y} = \sum_{i=1}^{k} \beta_i f_i(x) \tag{1}$$

where: the coefficients β are calculated by the ordinary least squares:

$$\beta_i = \arg\min_{\beta} \sum_{i=1}^{n} (F(x_{(i)}) - y_{(i)})^2 \tag{2}$$

where: n - the number of available sample points;
$x_{(i)}$ - the input value for the i`th point 0,
$y_{(i)}$ - the response value for this poin,
$f_i(x)$ - basis function which generally can be defined as a product of the input variables each raised to some order:

$$f_i(x) = \prod_{j=1}^{d} x_j^{r_{ij}} \tag{3}$$

where: r_{ij} - the order of the j-th variable in the i-th basis function (a non-negative integer). It should be noted that when all
r_j`s of a basis function become equal to 0, the basis function is equal to 1, thus having the intercept term of the model. The matrix r completely defines all the basis functions in the model – each row corresponds to one basis function with all of its orders. Construction of the model has been performed in an iterative manner, and deleting the basis functions of the model. As a search procedure a modification of the Sequential Floating Forward Selection (Pudil et al. 1994) algorithm has been employed while models are evaluated using the Corrected Akaike's Information Criterion (Hurvich and Tsai 1989).

Specimens and mechanical testing

According to the optimised design three types of sandwich panels have been prototyped to match the stiffness properties of conventional plywood boards. Sandwich components have been made from commercially available plywood sheets where veneers are bonded with the phenol - formaldehyde resin. Skins and stiffeners have been joined together applying poly-urethane resin. After manufacturing process panels were stored in ambient temperature of 20°C and relative air humidity of 50 % for two weeks. Parameters of prototyped plywood panels are summarised in Tab. 2. It should be noted that further weight saving could be reached applying even thinner

Tab. 2: Geometrical properties of the specimens.

Equivalent plywood board thickness (H_b), (mm)	Sandwich panel thickness, (H), (mm)	Surface thickness (T1), (mm)	Stiffener thickness (D), (mm)	Distance between stiffeners (A), (mm)
30	37.5	6.5	6.5	53.5
40	50.3	6.5	6.5	53.5
50	63	9	9	51

plywood however manufacturability and processing would become less effective. In addition, thin plywood sheets may not guarantee sufficient contact area for screw joints.

Further in the text panels with the stiffness equivalent to 30 mm boards has been marked as Panel 1, consequently Panel 2 is stiffness equivalent for 40 mm plywood and Panel 3 for 50 mm thick plywood boards.

Sandwich panels and corresponding plywood boards have been tested in 4-point bending mode according to the EN 789 (2004) standard on INSTRON 8802 the universal testing equipment (Fig. 3). Distance between the supports has been set to 1000 mm and between loading points – 200 mm. During the test deflections have been measured with LVDT at the panel midspan and panels have been tested until deflection ratio of 1/200 which is treated as a serviceability design limit in structural engineering legislation for timber structures Eurocode 5 (2004).

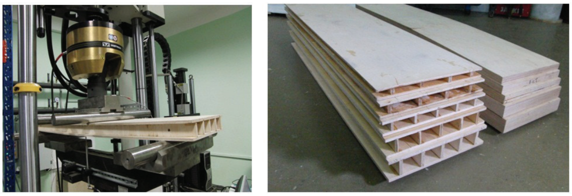

Fig. 3: Test set-up for bending test. Prototyped sandwich panels in comparison with conventional plywood boards.

RESULTS

In order to validate the stiffness properties of the optimised panels and the reference boards, load/deflection curves for each type of panels have been extracted and plotted in Figs. 4 to 6. In all graphs hollow core panels demonstrated slightly higher structural stiffness compared with conventional plywood boards at the same time reducing self-weight at least by 45 % comparing with traditional plywood.

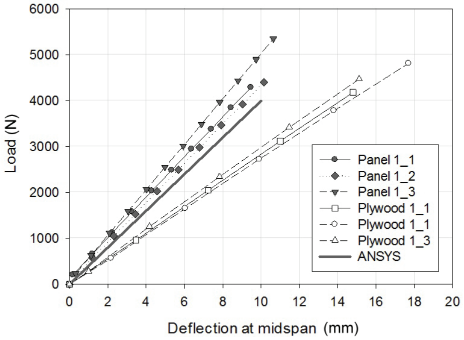

Fig. 4: Load deflection curves for 30 mm plywood and equivalent stiffness sandwich panels.

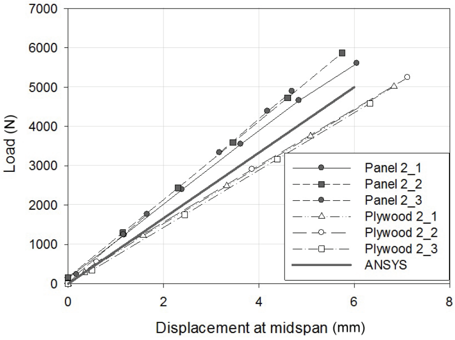

Fig. 5: Load deflection curves for 40 mm plywood and equivalent stiffness sandwich panels.

The largest divergence in absolute deflection values between the sandwich panel and conventional plywood board's has been observed for 30 mm equivalent design and outlined in

Fig. 4. More than 40 % difference between the average deflection at 4 kN load limit is caused mainly by thickness variation in commercially available plywood boards, where actual thickness was more by one millimetre thinner than average given by a plywood producer and implemented in numerical model.

Sandwich panels with the smallest thickness also cause the largest deviations when comparing the deflection at the 4 kN load magnitude. It should be noted that for sandwich panels equivalent to 30 mm plywood board (Panel 1) standard deviation is 0.62 mm from average 8.44 mm.

For the specimens of Panel 2 series difference between sandwich panels and traditional plywood boards does not exceed 30 %. Moreover comparing with previous series, standard deviation of the sandwich panel`s deflections at the same load magnitude is decreased to 0.12 mm. Numerical analysis marked as ANSYS demonstrated slightly conservative results than estimated, matching the mechanical behaviour of the sandwich panels with lowest stiffness.

Finally sandwich panels and plywood boards with the largest thickness demonstrated the smallest scatter of experimental results (Fig. 6). At this range plywood thickness deviation has an inessential effect on stiffness in contrary to the boards with smaller thicknesses. Standard deviation of the sandwich panel`s deflections at 6 kN load magnitude is 0.05 mm (average 3.72 mm).

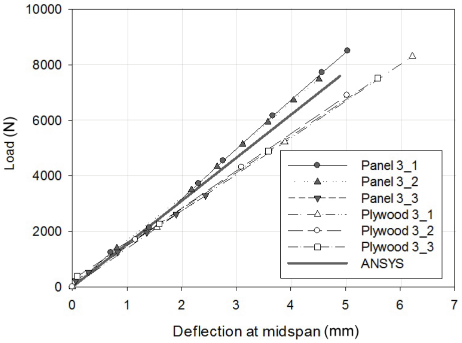

Fig. 6: Load deflection curves for 50 mm plywood and equivalent stiffness sandwich panels.

DISCUSSION

Analysing obtained experimental results it could be noted that applying numerical models and optimisation techniques it is possible to design birch plywood sandwich panels with the same stiffness as conventional plywood boards. Optimisation approach based on Latin hypercube design space filling criteria and metamodelling method is a convenient way to find function extremes (lower panel mass) because it requires small number of trial runs and in contrast to Genetic Algorithm optimisation always gives global maximums and minimums.

However many technological aspects regarding material properties and structure should be preliminary studied, especially influence of the outer plies thickness to the stiffness of the whole panel as mentioned by Kljak and Brezović (2007).

During the examination of sandwich panel prototypes and plywood boards, slight variation in final product thicknesses have been observed leading to discrepancy between numerical and experimental results especially for panels with the smallest thickness. One of the possible solution how to reduce the gap between numerical and experimental results is dividing research process into two steps where numerical model is at first validated with conventional plywood boards and after that sandwich panels are designed and prototyped. In this case close match between numerical and experimentally obtained plywood board stiffness could be reached.

Difference between the mass of the 30 mm thick conventional plywood boards and equivalent stiffness sandwich panels reach 41 %. For the next board thickness step of 40 mm the mass difference is 55 % and for the plywood boards and panels with the largest thickness mass difference is 48 %. The mean density of the rib stiffened panels is approximately 288 kg.m^{-3} which is more than twice less than plywood board density. For comparison all-plywood sandwich panels with honeycomb core from okoume wood (*Aucoumea klaineana* Pierre) has mean density of 205 kg.m^{-3} (Negro et al. 2011), however bending modulus of elasticity for such sandwich panels (mean 2.86 GPa) is significantly lower comparing with sandwich panels from birch wood with the mean bending modulus of 5.59 GPa.

CONCLUSIONS

In present research three configurations of optimal cross-section parameters for the plywood rib stiffened panels have been elaborated and prototyped employing optimization with metamodelling technique where traditional plywood boards have been set as reference for sandwich panel design.

Research confirmed that it is feasible to make rib-stiffened plywood panels to match the same stiffness properties as conventional plywood boards. Experimentally acquired average weight reduction comparing sandwich structure with traditional board was 45 %. Some technological challenge remains, for example, to reach even closer matching properties thickness variations of plywood boards should been foreseen and implemented in design procedure.

Further research will be conducted towards implementing the ply failure characteristics into the simulation model and improving manufacturing technology to reduce scatter of the mechanical properties.

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