INVESTIGATION OF WOOD BASED PANELS WITH PLYWOOD AND GFRP COMPOSITE COMPONENTS

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ABSTRACT

The current research aims to extend the existing knowledge about weight reduction of wood based panels with plywood faces and glass fibre reinforced plastic (GFRP) stiffeners, where experimental prototypes have been analysed and optimized utilizing ANSYS finite element code and design of computer experiments. The initial study demonstrated that replacing homogeneous core of plywood boards with corrugated glass fibre composite hollow core it is possible to reach up to 65 % weight reduction at the same time keeping stiffness unchanged.

Key words: finite element analysis, glass fibre composites, plywood, metamodelling, optimization

INTRODUCTION

It is generally well known that oriented fibre composite materials have advantages over traditional isotropic materials when concerning lightweightning of the load bearing structures in transport or civil engineering. Densities of laminate materials are usually lower than those of traditional materials like steel and plastics, besides orientation of fibres could be tailored according to the main load directions. In some cases a more efficient result could be achieved combining several types of fibre reinforced laminates to gain cost advantage (Zhang, 2012) or improve the resistance under specific load cases (Akhbari, 2008). Mostly glass and carbon fibres are compounded together to improve the product stiffness without major cost increasing while other combinations of fibre composites are not widely studied. However, taking into account that mechanical properties of a wood layer (veneer) integrated in the plywood structure are closer to glass fibre fabric laminate than a clear wood specimen, it makes reasonable to combine these two materials for overall benefit in lightweight structure design. Typical modulus of elasticity for glass laminate made of plain woven fabric and epoxy resin is about 18-24 GPa. The same property for veneer subjected to hot pressing and adhesive impregnation is only little lower 14-17 GPa.

In such a way disadvantages of one material component could be compensated by advantages of the other material. Thin glass fibre reinforced plastic (GFRP) layers could be applied for parts requiring complicated geometrical shapes and large bending angles; in opposite plywood sheets could successfully substitute GFRP for straight surfaces requiring increased thickness to prevent local damage. This concept could be further developed replacing thermo reactive laminates made from epoxy resin with glass fibre/ polypropylene woven fabric capable of one shot manufacturing process by hot pressing and demonstrating great potential as future material for transport structures (Zīke, 2011).

The current research deals with investigation of 3D structural sandwich panels made of plywood skins and corrugated glass fibre laminate core.

One of the possible applications for similar structures is offered by Hudson (Hudson, 2010) where rail vehicle floor arrangement consisting of the main structural panel with a corrugated core covered with thinner sandwich-type plates has been optimized to find the best trade-off between the floor mass and price per unit. Optimisation employing mechanical responses acquired by numerical models is one of the most efficient ways of advance necessary structure qualities, because large numbers of cross-section parameters are not allowing making sufficient quantity of experimental prototypes or makes such an approach too expensive.

Previous scientific research in optimisation of corrugated sandwich structures mainly covers isotropic materials where the governing mechanics of corrugated structures has been described and methods compared like in research of \Luo et al., (1992).

Meanwhile several papers deal with corrugated structures from wood origin materials. Hunt (2004) performed experimental tests and FEM analysis for 3D wood fibreboards, confirming the potential of a corrugated structure as an easy producible component for lightweight panels. FEM analysis of conventional corrugated paper structures, used in packaging applications, (Rahman, 2004) demonstrated significant buckling load dependency on adhesive mechanical properties. Sandwich plywood panels with a rib-stiffened and corrugated

core have been investigated by Zudrags et al. (2009) with the aim to increase plywood specific stiffness. Optimisation procedures using the stiffness and weight ratio for plywood sandwich panels with rib-stiffened core were described in the previous study (Kalnins et al., 2009). Also the mechanical behaviour of sandwich panels with a corrugated plywood core has been investigated (Labans, 2011). It has been noted that corrugated structure has a potential for replacing traditional plywood boards, however, birch veneer is not suited for corrugated structure forming with a small section height (<50 mm). Also thin corrugated plywood core could be applied for large span panels (L > 5 m) for civil engineering purposes where stability of the core is provided by foam matrix (Sliseris, 2011).
The aim of this research is to study feasibility of manufacturing GFRP/plywood sandwich panels, their mechanical properties in comparison with traditional plywood boards. Applying validated numerical model bending stiffness of panels has been optimized employing the metamodelling technique to find ways of reducing the structure's mass.

MATERIALS AND METHODS

FEM solution

Mechanical bending responses of the sandwich panel have been acquired by a numerical model made in ANSYS finite element code (2009). In order to accelerate the finite element analysis geometry of the structure has been modelled with SHELL 181 elements. Reaching short calculation times it is especially important to bear in mind that same model will be further employed for parametrical optimisation with several hundreds of trial runs. Loading and boundary conditions have been modelled in accordance to the EN789 (2004) standard with two linear loads near the centre of the panel assigned to coupled sets of nodes. The mesh step for the final model has been assigned to 10 mm

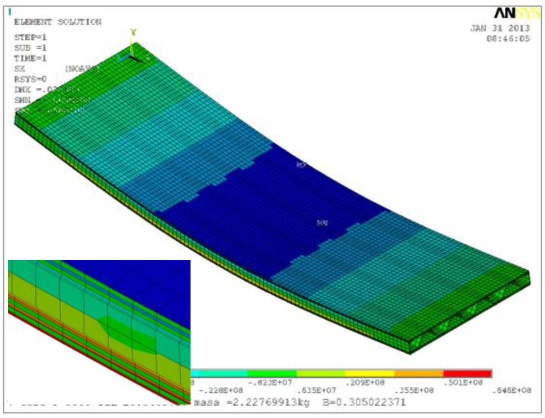

Figure 1. Distribution of stresses along longitudinal axis of the panel

(Figure 2). The model is considered of multilayered nature of plywood where single veneer properties (shown in Table 1) have been assigned to odd number of plies. The thicknesses of the upper plies has been reduced by 20 % according to manufacturing tolerances at plywood industry. The corrugated core has been modelled with only one 0.8 mm thick woven textile layer with the properties summarised in Table 1.

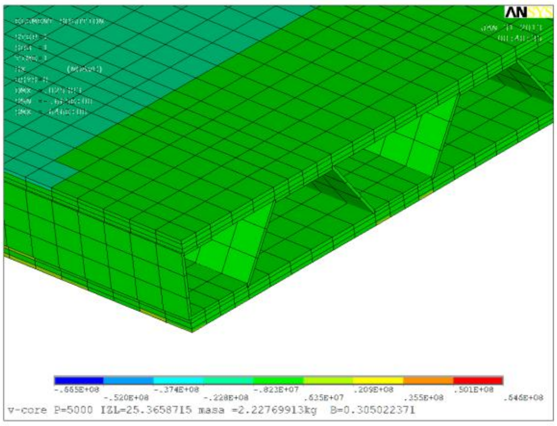

Figure 2. Mesh of the corrugated core

Table 1

Properties of panel materials

Name of the elastic property	Symbol	Mechanical properties	
		Veneer	GFRP
Modulus of elasticity in fibre direction	E_x	17 GPa	18 GPa
Modulus of elasticity perpendicular to fibre direction	E_y	0.5 GPa	18 GPa
Poisson's ratio in fibre direction	P_{xy}	0.35	0.35
Poisson's ratio perpendicular to fibre direction	P_{yx}	0.03	0.35
Shear modulus	G	0.7 GPa	3.2 GPa
Density	R_o	680 kg/m^3	1400 kg/m^3

Experimental investigation

Experimental prototypes for bending tests have been manufactured in a two step process at first creating the corrugated core from 5 layers of plain woven glass fibre fabric and epoxy resin. In the result of vacuum pressing a laminate structure with average thickness of 0.8 mm has been acquired. At the second step plywood surfaces have been attached to the corrugated core with the same epoxy resin. Three panels with the same geometrical parameters have been manufactured and tested in 4-point bending set up according to the EN 789 standard using INSTRON 8802 servo-hydraulic testing rig (Figure 3.)

Figure 3. Bending set-up on INSTRON 8802

Deflections under the symmetrical loading conditions have been recorded with LVDT extensometer at the midspan of the panel. The geometrical properties of the prototype panels are shown in Table 2 marked as reference.

Metamodelling procedure

Regarding the ability to improve the efficiency of simulations and optimization of the designs requiring computationally expensive algorithms metamodelling techniques have been widely employed in engineering applications. Metamodels also called surrogate models can be constructed to replace the original response with the approximation functions, therefore significantly increasing the optimisation/design time (Kalnins et al, 2009).

The design optimization process employing metamodels usually consists of three major steps: 1) design of computer experiments 2) construction of approximation functions that describe the behaviour of the problem more appropriate 3) employing the developed metamodels for the optimization or the derivation of the design guidelines.

In the present research a sequential space filling design based on Latin Hypercube with Means Square error criterion has been evaluated in-house EdaOpt software (Auzins, 2007). 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 the basis functions has been proposed by (Jekabsons, 2010). The Adaptive Basis Function Construction (ABFC) approach allows generating polynomials of arbitrary complexity without the requirement to predefine any base functions or to set the maximal order of the polynomial (or any other hyper parameters) – all the required basis functions are constructed adaptively.

Table 2

Cross section design variables

Parameter	Label	Reference	Lower limit	Upper limit	Increment step	Units
Number of cover plate plies	***P1***	5	3	7	2	-
Total section height	***P2***	28.4	30	50	-	mm
Core wall thickness	***P3***	0.8	1	2.5	-	mm
Corrugated ply angle	***P4***	45	30	60	-	Deg
Glue line width	***P5***	20	10	40	-	mm

The cross section of the corrugated panel has been characterised with five design variables (Figure 4) corresponding to the thicknesses of skins **P1**, core layer **P3**, overall thickness **P2** and glue line **P5** width. A separate parameter is assigned for the corrugated core angle **P4** as displayed in Figure 4. The design space and parametrical increment for the variables are given in Table 2. The core wall thickness has been restricted to 1 millimetre in order to avoid local buckling. The acquired response parameters resulting from the numeric

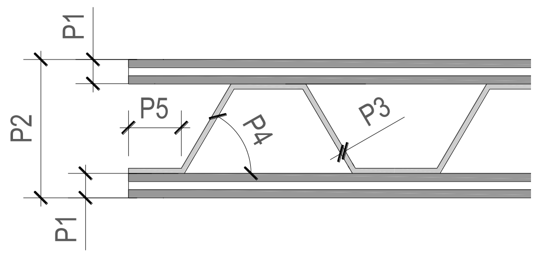

Figure 4. Variable cross section parameters

calculations are the maximum deflection at the midspan ***U*** and mass of the panel ***M*** calculated by means of densities of plywood and GFRP. 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** and corrugate attachment zone width **P5**. This constraint assures that the acquired results for different topology models would be comparable, as the width parameter and deflection magnitudes have linear dependency in the elastic region. This means that the acquired response values (numerical output) were multiplied with the coefficient k_r characterizing the relation of the actual panel width against the standard width of the panel of 300 mm.

RESULTS AND DISCUSSION

Validation of numerical model

The test load/deflection curves have been compared with the numerical results from ANSYS as shown in Figure 5 in order to validate the numerical model accuracy. The numerical and experimental curves have been compared to the experimental ones in the region of elastic mechanical behaviour of the panel until the load magnitude up to 5000 N. Large scatter of the experimental results could be observed between the panel 1.1 and 1.1, 1.3. A possible cause of such a large scatter could be the non-uniform quality of the bond line between the skins and the core. Moreover, the numerical results using ANSYS code are within domain of the experimental load/deflection curves closer to the panels 1.1 and

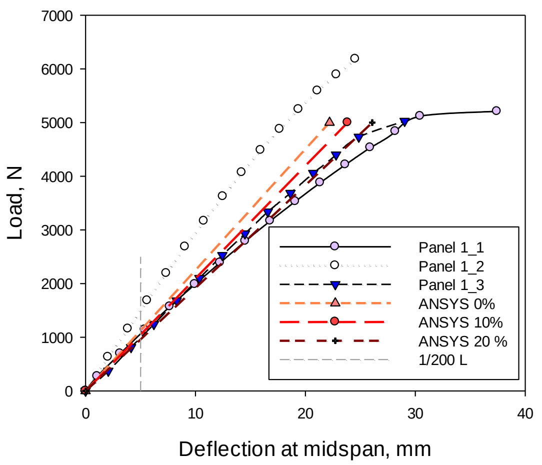

Figure 5. Load/deflection curves of sandwich panels

1.3. Depending on the upper ply thickness reduction additional ANSYS plots have been added indicating the models with 0, 10 and 20% upper ply thickness reduction. It has been set to default, that a model with 10 % thickness reduction is further most appropriate in optimisation tasks.

The vertical line is added to the graph in order to identify the deflection limit state (0.5% of span length) prescribed by the structural design codes as (Eurocode 5 , 1994). It could be 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.

Optimisation of initial design

Improving of the cross–section design for the prototype was considered as the initial step of the optimisation. The aim of optimization was to minimize the mass of the panel. Combinations of cross section topology parameters have been selected to guarantee deflection not over exceeding those original values obtained from the initial designs. The parameters of optimal and initial designs are displayed in Table 3. One could notice that the lower mass in the optimised structure is achieved by slightly increasing the overall thickness by 1.5 mm and a larger corrugated core angle equal to 60 %. The mass of the optimised panel is decreased by 10 % comparing with the initial prototype.

Table 3

Initial and optimised design of the panels

Panel characteristics	Initial design	Optimal Design
Cross-section parameter values	P1=3; P2=0.0284; P3=0.0009; P4=52; P5=0.011	P1=3; P2=0.03; P3=0.001; P4=60; P5=0.02
Load, N	5000	5000
Deflection, mm	29.84	26.43
Mass, kg	2.29	2.08
Absolute mass, %	100.0	90.3

Sandwich panels compared to traditional plywood

One of the best ways how to evaluate the efficiency of sandwich panels is to compare them with traditional wood based plate materials as plywood. Employing the same optimisation approach but constituting deflection restraints to those of full plywood boards, sandwich configurations with stiffness equivalent to traditional plywood could be found. Deflection values of plywood boards have been acquired by a layered numerical model with the assigned material properties from Table 1. Detailed summary of a sandwich panel design versus full plywood cross-section is listed in Table 3. It could be seen that self weight of the sandwich panels in general terms is at least two times lower comparing to a plywood board with corresponding stiffness. Sandwich panels are most efficient comparing with plywood boards the thicknesses of which exceeds 30 mm. In order to keep the sandwich design rational at conventionally large plywood board thicknesses (>40 mm) the overall sandwich panel cross-section height should be raised above the bounds of this variable stated in Table 2. However, in that case special attention to buckling stability should be paid.

Table 3

Equivalent stiffness boards

Nominal plywood thickness	Mass, kg		Differ. %	Deflection at 5kN, mm	Parameters of sandwich panel				
	Sandwich panel	Conventional plywood			P1	P2	P3	P4	P5
24	2.03	4.68	56.62	33.50	3	30.26	1.00	30.00	20.00
30	2.05	5.58	63.26	17.26	3	41.60	1.00	30.00	15.94
35	2.41	6.83	64.71	10.38	3	50.00	1.79	30.00	5.00
40	3.12	7.76	59.79	7.80	5	50.00	1.00	42.62	11.06
45	3.27	8.77	60.89	6.01	5	50.00	1.30	65.00	15.00

Optimal designs based on Pareto optimality

In order to assess the most effective combinations of design variables of the sandwich panel cross section in line with plywood boards with similar total thickness, the Pareto optimality problem has been formulated where maximization of the relative stiffness ΔK is performed simultaneously minimizing the relative mass ΔM of the panel. Relative stiffness is acquired by dividing the numerically calculated conventional plywood board deflection value by the results of the sandwich panel at the same length and thickness configurations assuming that both numerical models have the same loading configurations. Moreover, the relative mass is acquired by dividing the sandwich panel mass by full plywood panel mass. Once the relative stiffness ***ΔK*** is close to 1, this indicates that the sandwich panel stiffness is similar to the stiffness of the plywood board. At the same time the parameter ***ΔM*** close to 1 means that the sandwich panel mass is reaching the mass of the full-cross section panel. The results of Pareto optimality are outlined graphically in Figure 6. The points on Pareto front line are marked with darker colour.

One may observe that average difference between the relative mass and stiffness is 30 %. For example, the sandwich panel which total volume bay is as low as 50 % of full plywood board maintaining 80 % of conventional plywood stiffness. Increasing the GFRP core wall thickness is possible to reach configurations where the sandwich panel stiffness is equivalent to the plywood board stiffness at the same time with 25 % reduced self weight. The acquired results serve as a tool for effective assessment of the bearing capacity of sandwich panels with a GFRP corrugated core.

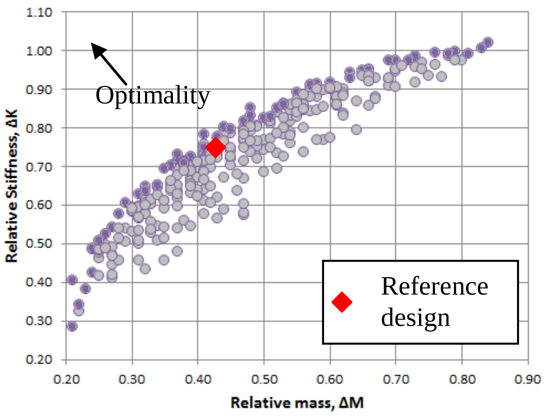

Figure 6. Pareto optimality between relative stiffness and mass

CONCLUSIONS

Several wood based sandwich panels with plywood skins and a corrugated GFRP core were prototyped and the stiffness properties evaluated in 4-point bending. The acquired mechanical responses served as means of validation of the numerical model. It has been confirmed that the numerical model has an ability to predict the mechanical behaviour of the panels in the region of linear elasticity where the calculated results are within scatter of the experimental load/deflection curves. Moreover, it has been recognised that deviation of the plywood upper plies thicknesses, as a result of surface grinding, has significant influence on the sandwich panel overall stiffness. Therefore it should be considered designing sandwich structures with plywood components.

The optimisation results demonstrated that the initial design of the corrugated core could be slightly improved, reducing the structural weight at the same time keeping the initial stiffness by increasing the angle of the corrugated layer. However, such a design makes manufacturing more complex. Once comparing the sandwich panel

design with conventional plywood board it may be concluded that the sandwich structure could be up to 65 % weight effective in bending load case up to the serviceability limit state. Pareto plot between the relative stiffness and mass indicates the region of the most efficient combinations where utilising the GFRP corrugated core is the most reasonable in order to match the conventional plywood board stiffness.
A similar design methodology could be further extended for optimisation of one shot thermoplastic composites with glass fibre reinforcement.

Additional experimental work is required to reduce the scatter of the experimental results in such a way improving the accuracy of the numerical model.

Acknowledgements

This study has received the support from the European Commission through the large-scale integrating collaborative project MAPPIC 3D - number 263159-1 and entitled: One-shot Manufacturing on large scale of 3D up graded panels and stiffeners for lightweight thermoplastic textile composite structures.

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