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EXPERIMENTAL AND NUMERICAL THREE-POINT BENDING TEST FOR SANDWICH BEAMS

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Abstract

The article deals with an experimental investigation of mechanical properties of sandwich beams obtained from bending tests. The tested specimens consisted of foam or honeycomb core and face sheets made of aluminium alloys, plywood or composite material. The face sheets and the core were bonded with glue material. Beams of different dimensions, namely beam width, as well as core and face sheets thickness, were tested. Three point bending tests were carried out, which mid span deflections of the beam versus applied force were recorded. Experimental test results were compared with simulations on the basis of finite element method. The full, non-linear analysis, taking into account large displacements and using contact elements was performed. The obtained results are presented in load-deflection diagrams. Some conclusions concerning ultimate loads and failure behaviour of tested beams made of different materials have been derived.

Keywords: *numerical simulation, bending tests, composite materials, sandwich beams, honeycomb*

1. Introduction

For years, sandwich constructions consisting of different materials have been widely used in many applications in which lightweight materials are desirable, e.g. for structures such as rocket, vehicle frame, aerospace construction or aircraft. Typical and dangerous problems raising in sandwich structures are interfacial debonding between core and outer sheet (face) as well as application of concentrated forces.

Mines and Alias [10] presented experimental results of progressive collapse of polymer composite sandwich beams. The investigated sandwich was composed of a foam core and glass epoxy skins. Additionally for comparable purposes, a two-dimension numerical simulation of these beams was conducted in code Abaqus. Authors of work [1] dealt with plastic collapse modes of sandwich beams. They investigated experimentally and theoretically, aluminium alloy foam with cold-worked aluminium face sheets. Deshpande and Fleck [4] investigated sandwich beams built of truss core and either solid or triangulated face sheets in aluminium-silicon alloy and in silicon brass. The authors revealed that due to optimisation performance truss core sandwich beams are substantially lighter than sandwich beams with a metallic foam core. An experimental study of selected static properties for composite material was carried out in paper [3]. The authors examined widely properties of materials assigned for manufacturing ballistic product. To attain static mechanical properties for different composites obtained in different physical and chemical conditions they performed tensile test, hardness test, bending test and delamination test. Wang and McDowell [15] analysed a metal honeycomb sandwich beam/torsion bar under combined loadings. Due to studies, it turned out that the relative contributions of honeycomb core to torsion and bending resistances vastly depend on a configuration of cell walls. Manalo and Aravinthan in [9] took research into behaviour of glued composite sandwich beams in flexure. The considered block representing a new generation of composite sandwich structure was built of the polymer face sheets reinforced with glass fibre and a high strength phenolic core material. The obtained results in an experiment and using the fibre model analysis indicated a good agreement. Authors of [11] investigated the large deflections of slender ultralight sandwich beams with a metallic foam core under transverse loading by a flat punch. They proposed a unified yield criterion for metallic sandwich structures considering the effect of core strength. On the other hand, they derived analytical solutions for the large deflections of fully clamped and simply supported metallic foam core sandwich beams under transverse loading. Comparisons of the present solutions with experimental results were presented and good agreements were found. Works [6] and [7] show data with respect to material properties of foam and its behaviour under impact condition. Authors performed experimental tests for various velocity of pendulum. In the next paper [2], authors analysed sandwich material using tension, compression and 4-point bending tests. Experimental data were compared with numerical analyses performed in Abaqus tool. Obtained results were similar in elastic range of material (before appearing of delamination).

In the presented article, three-point bending tests of sandwich beams were carried out experimentally and in some cases numerically as well. Investigated sandwich specimens were composed of core as honeycomb or foam and of face sheets as aluminum alloy or plywood. The main goal of presented bending test was to assess a behaviour of sandwich specimens and determine their properties needed to design the real structures in an industry.

2. Introduction to theory of sandwich beams

The theory of three-layered beams has been developed by Plantema [12], Stamm and Witte [14] and by Romanów [13]. It is based on the concept of “zig – zag” cross-section line [8]. Equations of equilibrium describing behaviour of the sandwich beams subjected to uniformly distributed load q take the following form [13]:

$$\begin{aligned} &-2B^{*}\lambda\ddot{\overline{U}}-2G_{c}(-b\overline{U}+b\lambda \mathrm{K}_{b}\dot{W})=0 \\ &-2G_{c}(b\dot{\overline{U}}-b\lambda K_{b}\ddot{W})-2D^{*}\ddot{\ddot{W}}+q=0 \end{aligned}, \tag{1}$$

where:

$\overline{U}=\dfrac{u_1-u_2}{2}$,

u_i = displacement of i-th facesheet middle surface, $\dot{\overline{U}}\equiv\dfrac{d\overline{U}}{dx}$, $\dot{W}\equiv\dfrac{dW}{dx}$, $\ddot{W}\equiv\dfrac{d^2W}{dx^2}$, $\ddot{\ddot{W}}\equiv\dfrac{d^4W}{dx^4}$,

$B^{*}=Ebt$, $D^{*}=\dfrac{Ebt^3}{12}$, $\lambda=c+t/2$, $K_b=\dfrac{tgh(pc)+t/2}{\lambda}\approx 1$ for slender beams (where, $p=\dfrac{\pi}{L}\sqrt{\dfrac{1-2\nu_c}{2(1-\nu_c)}}$ and tgh(pc) $\approx$pc) [13],

G_c – shear modulus of core,
q – unit force uniformly distributed on the beam (in this case q=0),
E – Young’s modulus of face sheet,
W – deflection of the beam,

2c – total height of core,
b – width of the beam
t – thickness of single face sheet.

The total beam deflection can be expressed as a sum:

$$W = W_m + W_s \tag{2}$$

where W_m is deflection due to bending and W_s is a deflection due to shear force. Relations between sectional forces (bending moment M and shear force Q) and deflections are:

$$\begin{gathered} M = -B_w \ddot{W}_m \\ Q = \overset{*}{S} W_s \; ; \; \overset{*}{S} = 2 G_c b \lambda \end{gathered}, \tag{3}$$

where $B_w = \frac{1}{2} Etb(2c+t)^2$.

Subsequently, solution of simultaneous equation (1) for the beam subjected to three-point bending (concentrated force F applied in the half-length L (see Fig. 2) leads to the following expression of the maximum deflection [13]:

$$w_{\max} = \frac{FL^3}{48B_w} + \frac{3FL^3Et(2c+t)}{24B_wG_c}. \tag{4}$$

In Fig. 1, displacements and sectional forces in the cross-section of three-layered beam are presented [13].

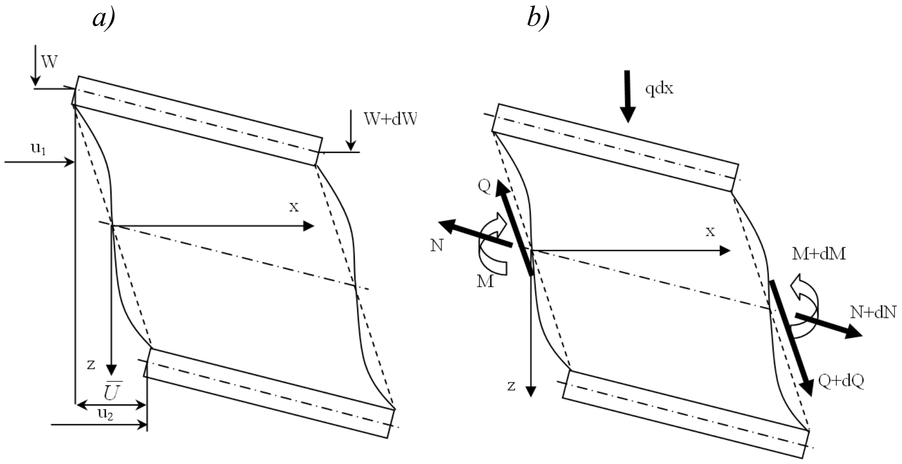

Fig. 1. Deformation pattern (Fig. 1a) and sectional forces (Fig. 1b) in three-layered infinitesimal beam element [13]; N – normal force, Q – shear force, M – bending moment, q – unit force, $u_{1,2}$ – displacements of face sheets, W – deflection (displacement in 'z' direction)

Analysis can be led in the elastic-plastic or elastic-shear yielding range of material work for face sheets and core. In case of core, shear yield stress τ_Y^c determines point of failure, but in case of face sheets – yield stress σ_Y^f limits the region of face sheets work.

Depending on the magnitude of τ_Y^c and σ_Y^f, three types of mechanism of failure of sandwich beam with foam core can appear [5]:

- yielding of face sheets (Fig. 2), when $\sigma_Y^f >> \sigma_Y^c$,
- core shear, when $\sigma_Y^f << \tau_Y^c$ – in this case, two plastic regions can be produced near shear force and two near support (Fig. 3),
- indentation, when $\sigma_Y^f / \sigma_Y^c \cdot t_1^2 << l^2$ – in this case, four plastic regions appear near point of shear force application (Fig. 4).

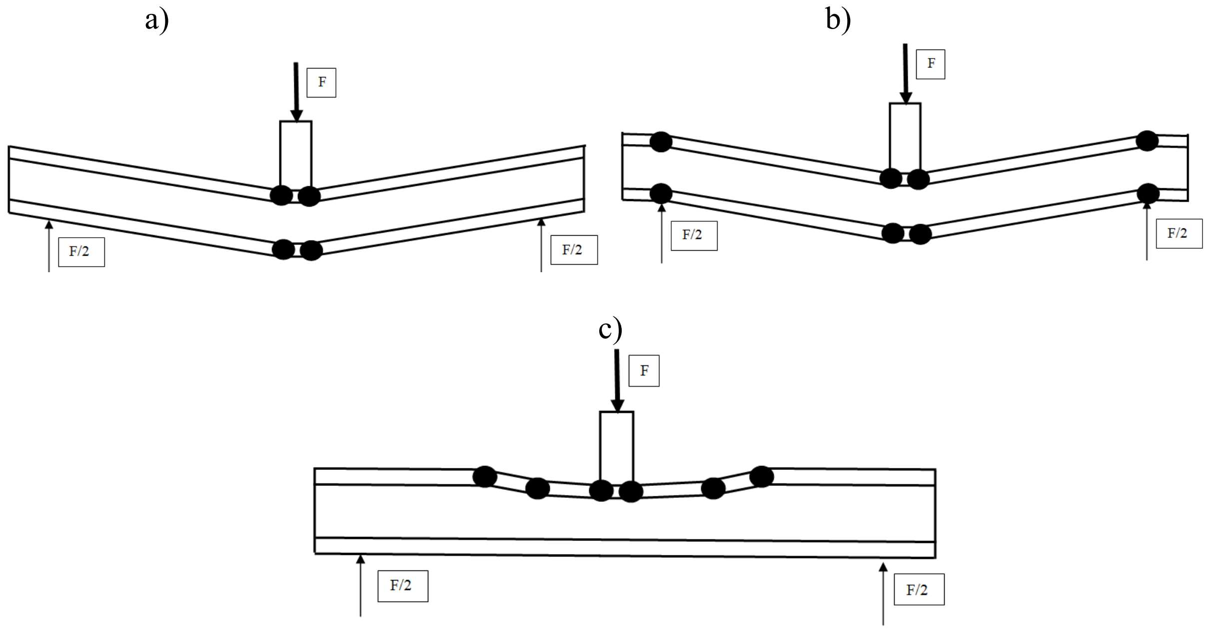

Fig. 2. Model of beam failure (black circles mean region of plasticity) a) due to face sheets plasticity near stamp, b) due to of face sheets plasticity stamp and support and c) due to face sheet indentation

3. Test conditions

In general, for the experimental study, 32 series with different material configuration have been taken into consideration but in this article, it was limited to the most interesting series (See Tab. 1). Each series consists of four specimens made of the same materials. The outer dimensions as well as the thickness of face sheets and core of each series could differ from each other as given in Tab. 1. Carrying out the three-point tests, span of supports was kept at the same magnitude – 500 mm. The core and face sheet were bonded together with an adhesive material. The configuration of investigated specimens was designed and manufactured in the manner, which allowed one to assess behaviour of entire sandwich beam as well as successive parts of specimen including the type of adhesive.

Tab. 1. Description of each series

Ser. No	Face sheet 1/ thickness [mm]	Face sheet 2/ thickness [mm]	Core	h (average) [mm]	Average width [mm]	Kind of applied glue
1	Plywood/ 3	Plywood/ 3	Honeycomb	36	52	GRP CRYSTIC 2-420PA (*)
2	FOREMAX FGE137 (**)/1	FOREMAX FGE137 / 1	Honeycomb	29	49	GRP CRYSTIC 98-78PA (***)
3	Plywood/ 3	Plywood/3	Honeycomb HP	21	51	GRP CRYSTIC 2-420PA
4	Al/2	Al/2	Honeycomb	20	50	GRP CRYSTIC 2-420PA
6	Al/2	Al/2	Honeycomb HP	20	50	Dow VORAMER™ (****)
16	FOREMAX FGE137/1	FOREMAX FGE137/1	Foam PCV	29	48	GRP CRYSTIC 2-420PA
18	FOREMAX FGE137/1	FOREMAX FGE137/1	Honeycomb	29	54	GRE MGS L 135
20	Al/1	Al/1	Foam	32	51	Dow VORAMER™
21	Al/1	Al/1	Honeycomb	18	50	CRESTOMER 1152PA (*****)
24	Al/1	Al/1	Foam	28	51	CRESTOMER 1152PA

Legend
(*) GRP CRYSTIC 2-420PA – polyester glue,
(**) FOREMAX FGE137 – composite material composed of glass fibres and epoxy or polyester matrix,
(***) GRP CRYSTIC 98-78PA – polyester paste,
(****) Dow VORAMER™ – polyurethane binder,
(*****) CRESTOMER 1152PA ticsotropic material based on unsaturated urethane acrylic embedded in styrene.

4. Numerical models

In numerical approach to reflect real conditions of experimental study, full nonlinearities were employed: complete material characteristics and contact elements. Each simulation was conducted using implicit method incrementally in code Ansys 14.5.

Numerical analyses of three-point bending were conducted for beams with honeycomb (Fig. 3a) and foam (Fig. 3b) cores. All beams were prepared as 3-dimensional sandwich beams: face sheets and foam were modelled as solid blocks, but honeycomb core as shell structure.

In analysis, to solve static bending problem in elastic-plastic range of material, first order types of finite elements were used: 4-node Shell181 with 3 translational and 3 rotational degrees of freedom and 8-node Solid185 with 3 translational degrees of freedom.

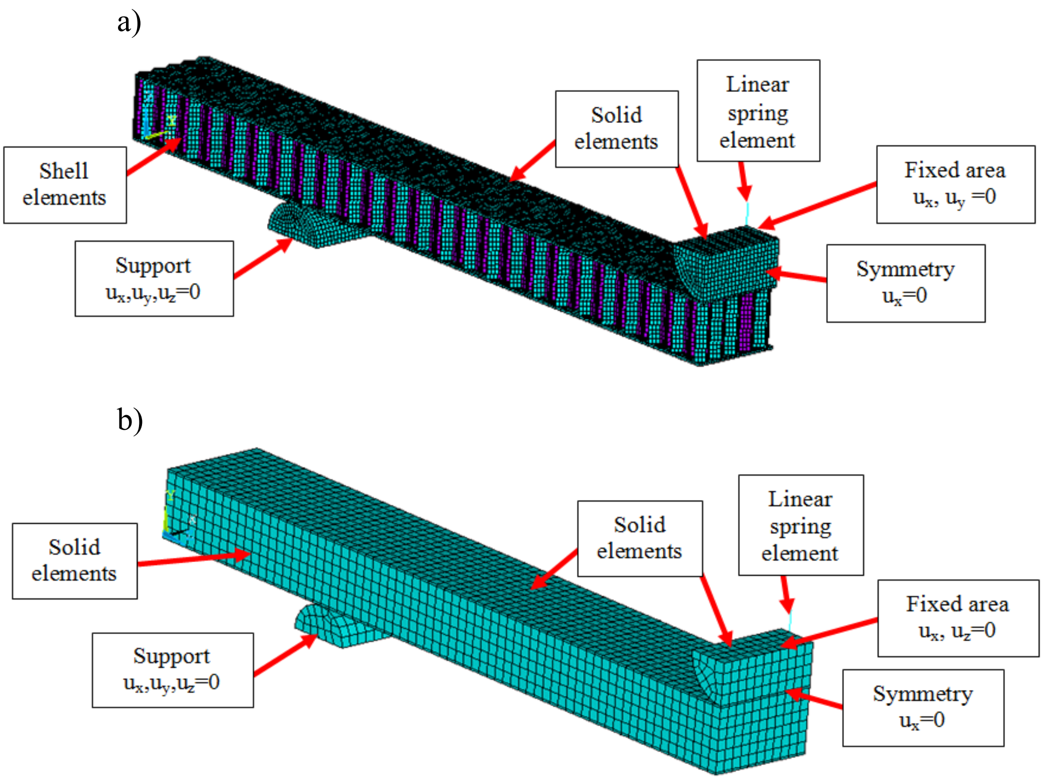

Fig. 3. Numerical models and boundary conditions for a) beam with honeycomb core and 2 face sheets and b) for beam with foam core and 2 face sheets

Because bending test is enforced with transverse force, it must be transferred to the stamp using flexible spring element. To assure uniform distribution of force to stamp, constraint equation conditions (coupling of degrees of freedom) were applied.

For foam core and for honeycomb core were taken multi-linear model or Ogden model and bilinear model (Young modulus 20 MPa, yield stress 20 MPa, secant modulus 1 MPa), respectively. For aluminium face sheets, bilinear material model was chosen (Young modulus of 70 GPa, yield stress of 200 MPa, secant modulus of 10 MPa).

The material properties of components of the sandwich beam given by manufacturers have been determined in Tab. 2. Some data especially of glue properties were difficult to be determined.

5. Results and discussion

In these sections, the results of empirical three-point bending test are presented mainly. In diagrams of series 20 and 21, the results of numerical computations were also added. While each testing, bending force, and displacement of the specimen, in the middle of the span (where the force was applied), was recorded. The obtained curves for each series have been displayed in Fig. 4-8. The maximum forces as well as average forces for given series were set out in Tab. 3.

Tab. 2. Material properties for each components of investigated beams

Component of beam	Properties / Material kind	Young's modulus [GPa]	Poisson's ratio [-]	Density [kg/m^3]	Ultimate stress in tension [MPa]
Cores and face sheets	foam	0.045-0.080	0.5	20-80	0.3-1.3
	Foam HP	0.06-0.090	0.5	90	0.6-2
	Honeycomb (sheet)	20	0.4	1900	200
	Honeycomb PCV (sheet)	25	0.4	1900	200
	Aluminium alloy	70	0.4	2700	220
	Plywood	5	0.4	600	40
	FOREMAX FGE137	20	0.4	1900	200-400
Glues	GRP CRYSTIC 2-420PA	3.7-7.5	n/d	1100	44-108
	CRYSTIC 98-78 PA	3.0-3.2	n/d	1300	30- -32
	GREMGS L 135	2.9-3.2	n/d	1140-1180	68-80
	CRESTOMER 1152PA	n/d	n/d	n/d	26

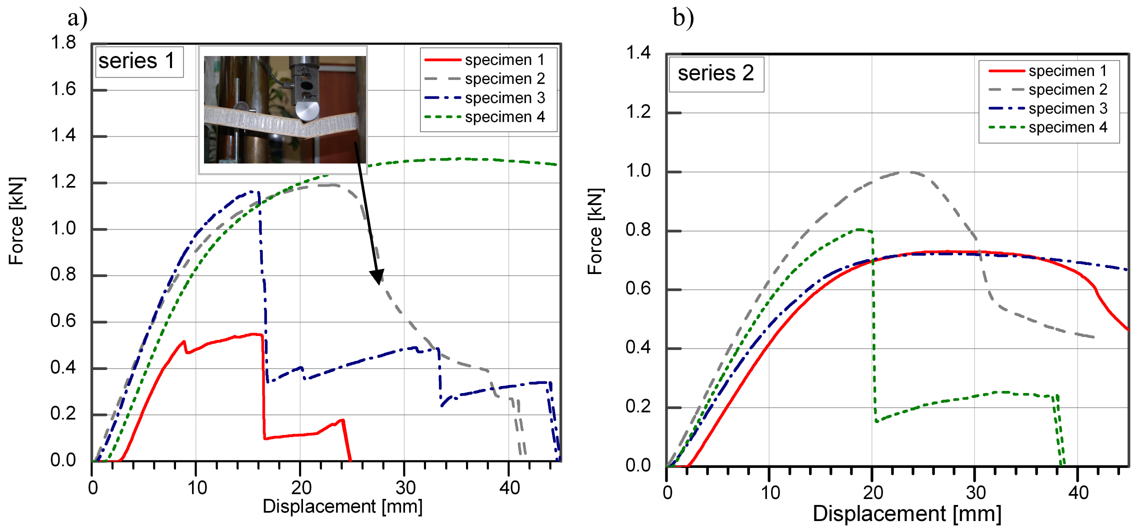

Fig. 4. Displacement vs. force for a) series 1 and b) series 2

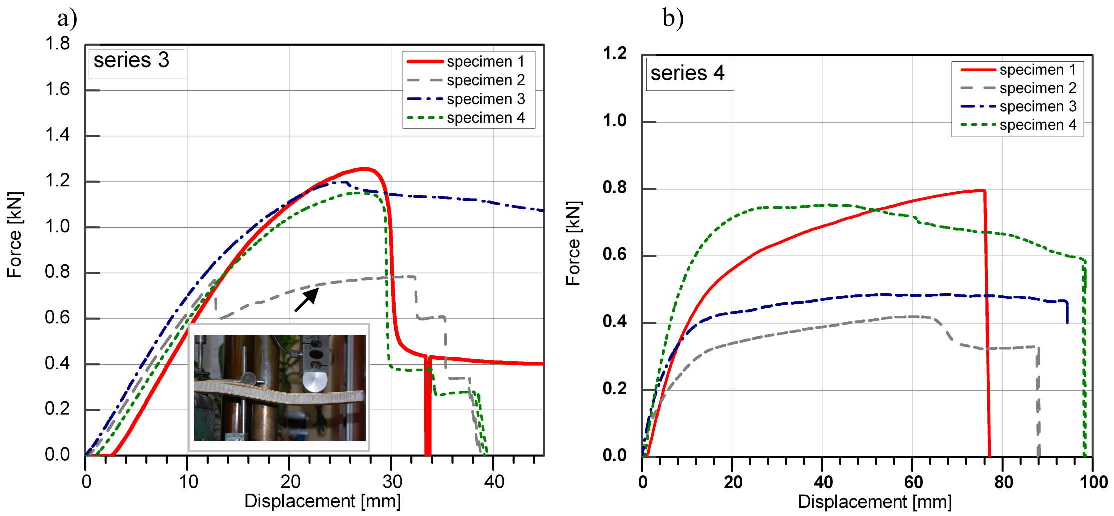

Fig. 5. Displacement vs. force for a) series 3 and b) series 4

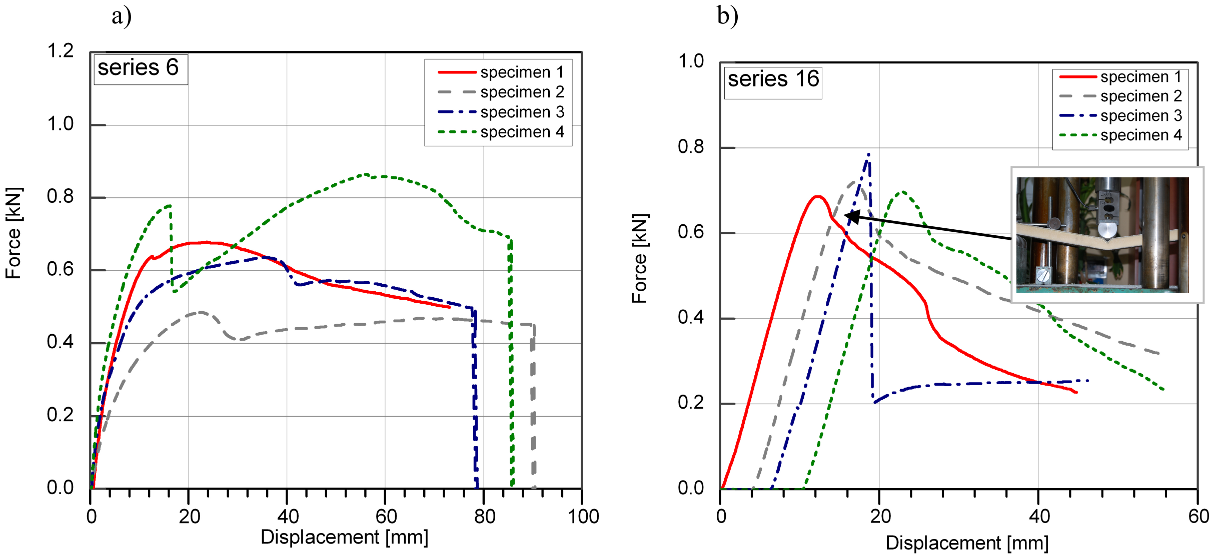

Fig. 6. Displacement vs. force for a) series 6 and b) series 16

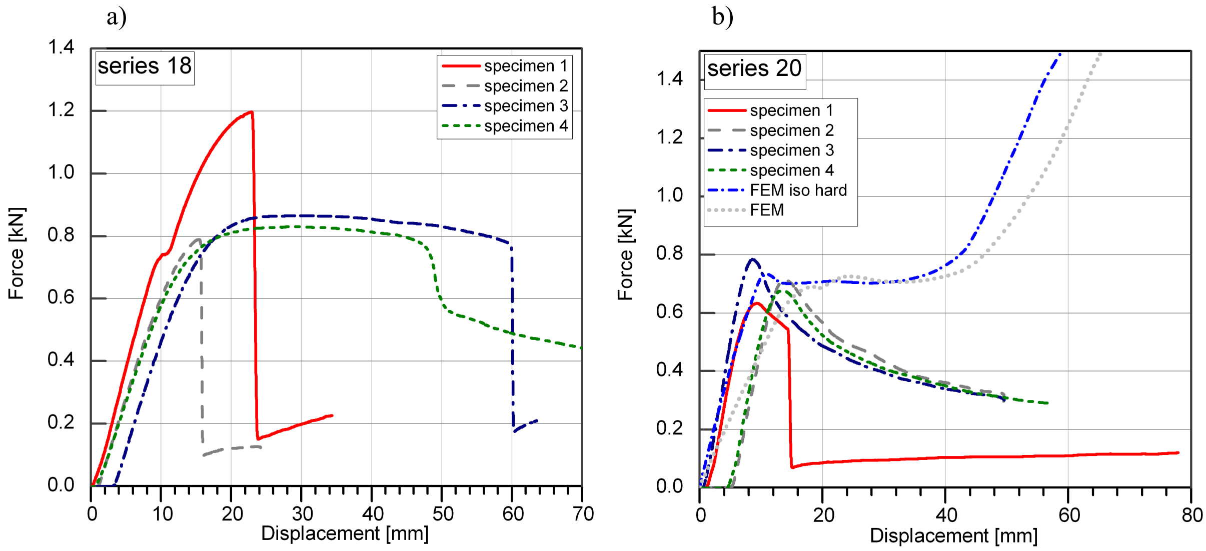

Fig. 7. Displacement vs. force for a) series 18 and b) series 20

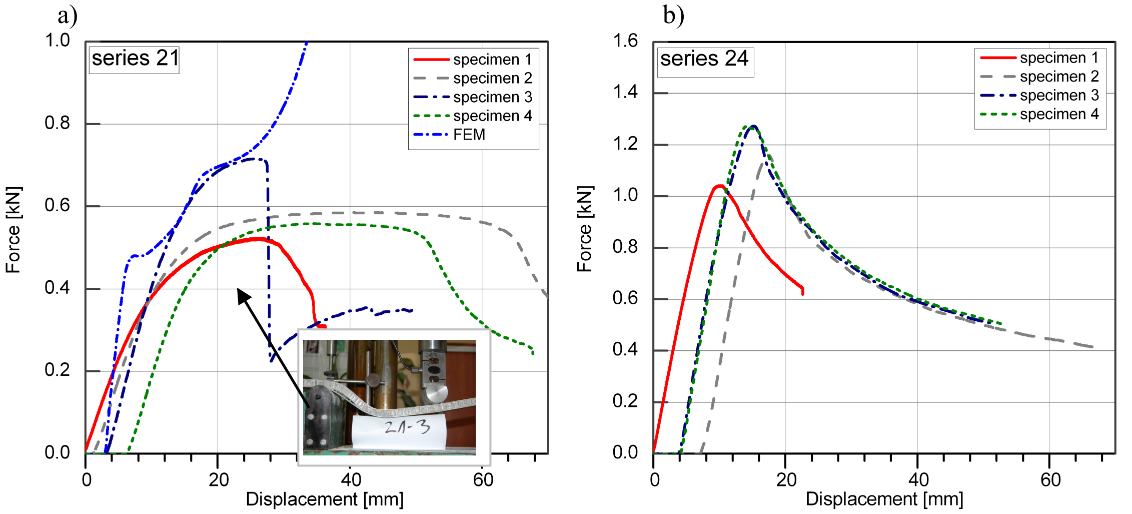

Fig. 8. Displacement vs. force for a) series 21 and b) series 24

Tab. 3. Maximum forces and average forces obtained in each series

No. series	Maximal value of force [kN]				Average force [kN]	Standard deviation	Remarks
	1	2	3	4			
1	1.34	1.19	1.17	0.57	1.07	0.34	– weak repeatability of obtained curves as well as maximal recorded forces, – maximum values of loads registered on diagrams results mainly from ply-wood strength,
2	0.73	1.01	0.72	0.82	0.82	0.13	– maximal observed forces on similar level, – fracture of specimen follows in core ,
3	1.26	0.78	1.21	1.15	1.10	0.22	– maximal forces are almost the same, – failure of specimens due to fracture facesheets, – in specimen 2 was observed delamination,
4	0.78	0.42	0.48	0.76	0.61	0.19	– obtained characteristics differ from each other, – in 3. specimen was observed delamination,
6	0.68	0.48	0.64	0.84	0.66	0.15	– average repeatability of received curves and different recorded forces, – failure of specimens due to debonding, – weak conjunction of face sheets and core,
16	0.69	0.72	0.77	0.7	0.72	0.04	– strongly comparable maximal forces and obtained curves, – failure of specimens due to local damage of face sheet, – applied adhesive ensured right connection between a foam and face sheet,
18	1.19	0.78	0.86	0.82	0.91	0.19	– different maximal forces and other shapes of obtained curves, – failure of specimens due to delamination or failure of honeycomb, – weak connections between a foam and face sheet can be observed,
20	0.64	0.72	0.77	0.68	0.70	0.06	– similar maximal obtained forces, – failure of specimen 1 due to delamination, – other failure of specimens observed during tests was caused by local strong deformation,
21	0.52	0.58	0.72	0.56	0.60	0.09	– maximum obtained forces differ slightly each other, – failure of specimens due to delamination or the local core damage,
24	1.05	1.12	1.28	1.28	1.18	0.12	– maximum forces are comparable as well as curves, – failure of specimens due to local face sheet damage, – right connections of core and face sheets were ensured.

Taking a look at all diagrams obtained in a framework of this article, it can be stated:

- average forces recorded during bending test for considered specimens ranged from about 0.6 kN up to 1.18 kN,
- comparing series 1 (Fig. 4a) with series 3 (Fig. 5a) it was observed that thinner specimens (thickness specimens of 21 mm) with core built of honeycomb HP can endure almost the same maximal forces as for thicker sandwich (thickness specimens of 36 mm) with usual honeycomb core. In both mentioned cases face sheets as well as adhesives applied in experiment were the same,
- the connections between aluminium and honeycomb were usually insufficient (in major cases was noticed delamination – series 6, Fig. 6a),
- comparison of the honeycomb core (exemplary series 2 – Fig. 4b) with the foam core (exemplary series 16 – Fig. 6b) shows that recorded limit forces seemed the same, but shapes of curves differed from each other,

- for sandwiches composed of face sheets made of a plywood (series 1, 3 – Fig. 4a and 5a), the failure of specimens usually followed in major cases cracking of lower face sheet. Thus, the kind of a core application mattered only slightly,
- the all obtained results in numerical way were generally comparable with empirical experiment, especially for series 20 (Fig. 7b) where foam core was applied. Focusing on further part of curve it is seen a discrepancy because in real specimen some aspects of failure or debonding which in numerical model is difficult to take into consideration, took place. The real failure curves do not display a final range of indentation, which was the case in FE simulation. Furthermore, in implemented numerical model for specimens with honeycomb core apparently stiffness was overestimated, what was observed in series 21 (Fig. 8a),
- analysis of mean values of maximal forces allows moreover to specify quality of connection between core and face sheets as it can be noticed for series 20,
- in case of the beams with foam cores, indentation phenomenon usually appeared. In case of beams with honeycomb core, indentation or delamination phenomena were often observed.

6. Conclusions

The presented work concerning the three-point-bending tests was targeted to assess possibilities of different materials applications in real sandwich structures. The discussed structure built of those sandwich materials was considered and designed to be mounted on the vehicle floor in order to hold the seats for the passengers' conveyance. These types of materials are nowadays very desired with respect to their lightweight and their moderate strength.

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