The Effect of Beam Curvature on Bending Properties of Sandwich Structures

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Sandwich composites are well known for many years and its place among the construction materials have they deserved mainly due to very good mechanical properties related to their weight. These materials have been a subject for many researches, but very few of them were focused on the behavior of curved constructions in bend with respect to their specific shape (curvature). With increasing number of new materials and resulting possible material combinations, it is necessary to characterize performance of new prepared structures and also evaluate the effect of a shape on the behavior of sandwich constructions with regard to their material composition. Presented paper deals with an investigation of flat and curved beams of sandwich structures, which correspond by their material composition to those, used in transport industry. Specifically, the influence of curvature size on a change of bending properties of structures with specific material composition compared to flat constructions is evaluated. This influence is also investigated in terms of specimen clamping and type of bending test. Obtained results showed that properties of sandwich structures are dependent not only on size of curvature, bud also on core thickness. Moreover, these results can help designers, constructers or technologists with design, dimensioning or production of these materials for specific applications.

Keywords: Sandwich structure, Beam, Curvature, Shape, Bending, Load capacity, Core, Prepreg

1 Introduction

Sandwich panels (Fig. 1) belong to the group of layered composite materials consisting of two facings with identical or different thickness and core. The connection of individual layers is ensured by curing of impregnation resin (when using composite facings) or by addition of third layer between – adhesive. These layered structures are used in practice especially due to their high bending strength and stiffness, high durability and low weight. Because of these properties, they are ideally suited for structural applications mainly in aerospace, automotive and transportation [1,2,3].

The required mechanical and other properties of composite parts are often in practice defined by required values of properties according to the tests specified in technical standards, and also in standards created by individual companies. As an example, standards defined by companies Skoda Transportation and Bombardier can be mentioned, which have to be fulfilled by suppliers of composites into the transport industry. However, most of the mechanical tests are performed on flat specimens where a shape of final layered part is not taken into account. In practice, from the macroscopic point of view a lot of parts consist surfaces of various curvatures or other deviations from planar state [4]. Curved sandwich panels can achieve in certain applications higher values of strength than planar panels, but more often is the case when properties are rather decreased due to the shape factor (curvature). Main cause is the fact that a core of curved sandwich structure transmits transverse forces and also considerable normal stresses. These normal stresses can be a limiting factor in the design of sandwich structures [1, 5].

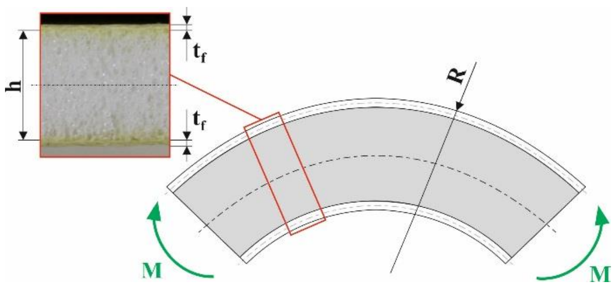

Fig. 1 *Curved sandwich structure in bending*

For example Baba and Thoppul experimentally confirmed that smaller curvature of panel increases bending strength (in four-point bending) compared to the strength of planar panel, and further described that the curvature affects the vibrational behavior of sandwich structures [6]. Smith based on Airy stress function implemented into analytical calculation and subsequent comparison with FEM model describes that circumferential stresses in facings of curved sandwich beams are dependent on the geometry and material parameters as in case of planar beams. This claim is valid in those case where radius of curvature is considerably greater than thickness of the entire sandwich structure. Moreover, Smith found that radial stresses in a core of sandwich curved beams are mainly influenced by the radius of curvature (R), and only minimally by material properties and facing thickness [7,8].

For the production of sandwich panels or layered composite parts, many technologies can be used where only some can be applied for example for honeycomb core structures. Namely, vacuum infusion technology can be used only for parts containing foam or wood cores [9,10,11]. In general, with growing difficulty of part, technology complexity also grows due to rising tools (molds) cost and necessary qualification of operators. As a manufacturing technology for pre-impregnated materials (prepregs), vacuum bagging in combination with resin curing in the oven or autoclave is commonly used. Parts cured by this prepreg technology exhibit identical properties in all sections of the panel without defects and unsaturated areas [12]. Furthermore, in case of all curved panels and parts, the undesirable panel spring-in after demolding from the tool can occur [13].

This research paper is focused on comparison and effect definition of sandwich beam curvature on its bending load capacity in different types of test with respect to sandwich material composition and core dimensions. Moreover, the research discuss the effect of beam clamping regarding its curvature.

2 Experiment

An experiment was divided into several steps, where material selection and production of sandwich panels were performed in cooperation with industry sector. Sample (beam) preparation and mechanical testing were conducted at University laboratories.

2.1 Material Selection and Sample Composition

All further mentioned materials that were used for a production of sandwich structures, were selected with respect to specific area of application – public and rail transport. Materials (structures) used in this industry field have to satisfy increased demands on safety, fatigue resistance and FST (Fire-Smoke-Toxicity) properties. The faces (facings) of all created sandwich structures were made of pre-impregnated fabrics (prepregs) manufactured by Gurit – PH840-300-42. This prepreg is composed of E-glass fabric, impregnated by halogen-free modified phenolic resin. Specific properties can be seen in Tab. 1.

***Tab. 1** Selected properties of prepreg PH840-300-42*

PH840-300-42	
Prepreg areal weight [g/m^2]	**525**
Fabric areal weight [g/m^2]	**296**
Weave style	**8H satin**
Resin content [w. %]	**42**
Curing temperature [°C]	**120 - 160**

In total, three representatives were chosen from wide range of available core materials. The first is polymeric foam AIREX T90.100. This foam with closed cells is prepared from PET (Polyethylene terephthalate), characterized by excellent FST properties and fatigue lifetime, high thermal stability and chemical resistance. Next core material is also foam AIREX C70.55 from crosslinked PVC (Polyvinylchloride) also with closed cells. Main advantages of this foam are excellent chemical resistance, fire retardancy, good impact resistance and high resistance to fatigue. Last used material is COREMASTER honeycomb C2-4.8-48 made of aramid paper (hexagonal cell size 4.8 mm) impregnated by phenolic resin, which has excellent thermal stability and high dimensional stability under heat and also moisture. Tab. 2 shows selected properties of individual core materials.

***Tab. 2** Selected properties of core materials*

	AIREX T90.100	**C2-4.8-48**	**AIREX C70.55**
Density [kg/m^3]	**110**	**48**	**60**
Compressive strength [MPa]	**1.4**	**2.0**	**0.6**
Compressive modulus [MPa]	**85**	**-**	**69**
Shear strength [MPa]	**0.8**	***0.54 – 1.12**	**0.85**
Shear modulus [MPa]	**20**	***23.0 – 37.0**	**22**

* values differ due to honeycomb cell orientation

All described materials were used for a production of planar and curved sandwich beams. Facings were created from two layers of prepreg from each core side (facing thickness t_f = 0.47 mm). For an experiment, where the effect of core material type was investigated, individual cores of 5 mm thickness were used in structures. Subsequently, PET foams

(T90.100) of thickness h = 5, 10 and 20 mm were placed into sandwich structures to evaluate the impact of core thickness on bending properties of curved structures.

2.2 Specimen Fabrication

For the purpose of experiment, laminate mold (Fig. 2) was designed and manufactured comprising two different areas with the defined curvature, on which were subsequently manufactured highly precise curved panels. Curvature of panels is expressed by the ratio of radius R and core thickness h, thus R/h. Specifically, radiuses R_1=200 mm and R_2=400 mm were defined on this mold. Mold design follows all principles applicable to this type of molds. Positive wood model was used for the production of this mold where hand lay-up technology was applied using glass reinforcements impregnated by polyester resin system. Resulting laminate mold was coated with the protective gelcoat, and was fitted with the metal reinforcing frame to increase stiffness of entire mold.

Fig. 2 *Prepared manufacturing laminate mold*

Production of curved panels is in general more complex, thus it was necessary to modify foams of higher thickness (10 and 20 mm). Preforming by mean of heat was sufficient in case of 10 mm thick foam, however 20 mm thick foams were necessarily provided by pre-cut 1 mm thick grooves allowing foam to bend into the required curvature.

According to used materials, vacuum bagging technology was selected for the production of sandwich panels, where the resin in prepreg was cured in oven under the mean of permanent vacuum (0.8 bar). Curing cycles began by gradual temperature increase during 30 minutes to temperature of 130 °C followed by curing itself at this temperature for 2 hours. Individual testing specimens (beams) were cut from produced panel using circular saw.

2.3 Mechanical Testing

Prepared beams of sandwich structures were tested in three-point, and four-point bending in case of both types, planar and curved beams. All bending tests were conducted on a ZWICK 1456 testing machine according to ASTM C393 standard, dealing directly with bending of sandwich structures. Dimensions of testing specimens (beams) were chosen regarding to this standard, equal to 150 x 45 mm. As was described, testing was conducted in three-point (with significant impact of shear) and four-point (area of the constant bending moment - pure bending) beam set up. In both cases, supports distance between each other was set to 150 mm. Distance of acting supports in four-point bending test was set to 50 mm as 1/3 of clamping supports distance. Crosshead speed for both tests was equal to 5 mm/min, and all measurements were conducted at ambient temperature (25 °C). Bending force F_{omax}, representing bending load capacity of sandwich structure was the main parameter evaluated from all measurements.

Individual specimens were tested in three configurations of beam clamping, which are depicted in following figure (Fig. 3). Symbols, given in this figure (0,+,-) correspond to the results description in graphs, where + symbol marks concave clamping, and – symbol convex beam clamping on supports.

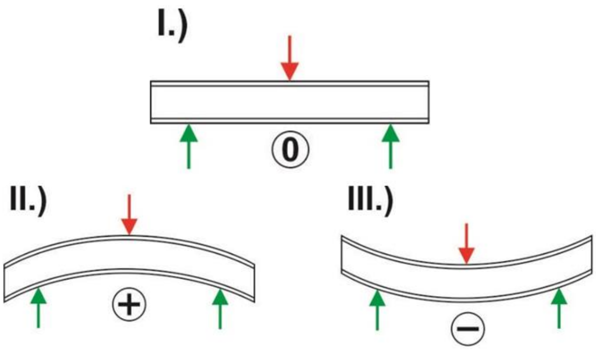

Fig. 3 *Setup of sandwich beams for three point bending*

3 Results and Discussion

The results of maximum bending force that represent bending load capacity of individual beams with selected cores in three-point bending are given in following graph (Fig. 4). As can be seen, structures with foam cores inside show lower load capacity than structures with Nomex honeycomb. Concavely clamped beams (+ symbol) exhibit lower decrease of F_{omax} in all cases in comparison to convexly clamped (- symbol). Curved sandwich structures with Nomex honeycomb show balanced values of evaluated parameter in the case of concavely clamped beams, where significant drop of load capacity by 10% is evident at convexly clamped strongly curved beams (R/h = - 40). Conversely, slight increase of load capacity at concavely clamped beams with PVC foam cores (C70.55) was measured. The highest arise of F_{omax} compared to planar beam by 8.3 % was evaluated for curved beam with ratio R/h = 40. On the other hand, the highest decline of load capacity by almost 25% was measured for an identical beam clamped convexly. This major decline is probably caused by low foam density together with low compressive strength and modulus because only local failure and loss of core stability were observed. Curved sandwich beams consisting T90.100 foam core show also decrease of load capacity, however in all cases are the values better (higher) than those measured for structures with PVC core. The highest drop by 19% was again measured for convexly clamped curved beams. Despite local failure, core shear failure was observed, especially in strongly curved concavely clamped beams (R/h = 40).

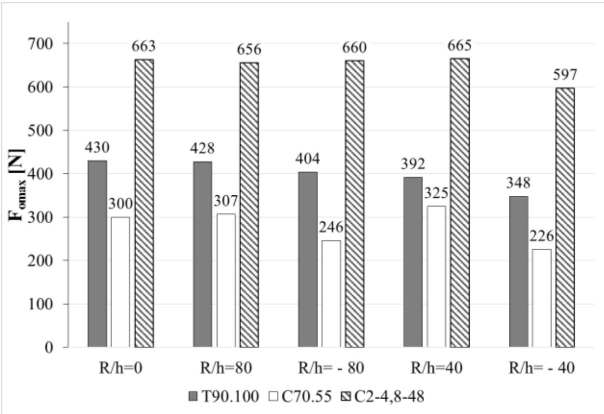

Fig. 4 *Bending load capacity of individual sandwich samples (beams) in three point bending*

Following graph (Fig. 5) depicts results of maximal bending force measured in four-point bending test. In this test configuration, only concavely clamped beams were measured. Without influence of shear stress, which is considerable in three-point bending test, an increase of bending load capacity by 15 % for structures with honeycomb core was measured for both ratio of curvature. Sandwich structures with T90.100 core show decrease of load capacity by 7 % in case of strongly curved beams. Curved structures with C70.55 foam core did not exhibit significant change of load capacity in comparison to the planar structures in this type of bending test (value deviations correspond to measurement errors).

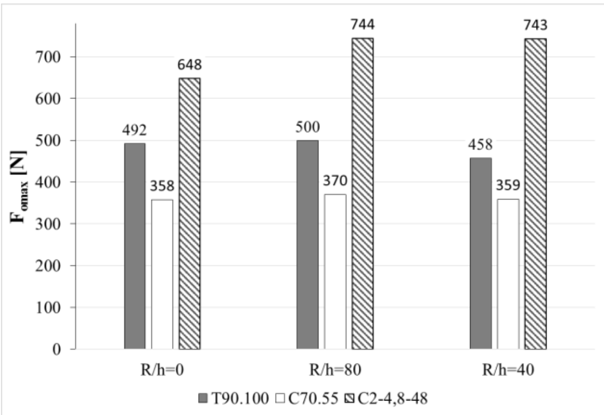

Fig. 5 *Bending load capacity of individual sandwich samples (beams) in four point bending*

Bars in last graph (Fig. 6) correspond to the values of bending load capacity of sandwich structures containing identical core type (foam T90.100), but varying in core thickness. As can be seen, curved structures with core thickness of 10 mm and 20 show an increase of bending load capacity compared to planar structures, thus different behavior than structures with 5 mm thick core. Identically to previous tests, even in case of these thicker core concavely clamped beams, higher values of measured parameters were determined. The highest increase of 20 % was measured for slightly curved concavely clamped beams with 10 mm thick core. The thickest curved structures (with 20 mm core) showed maximal rise of load capacity by 7 % for convexly clamped slightly curved beams.

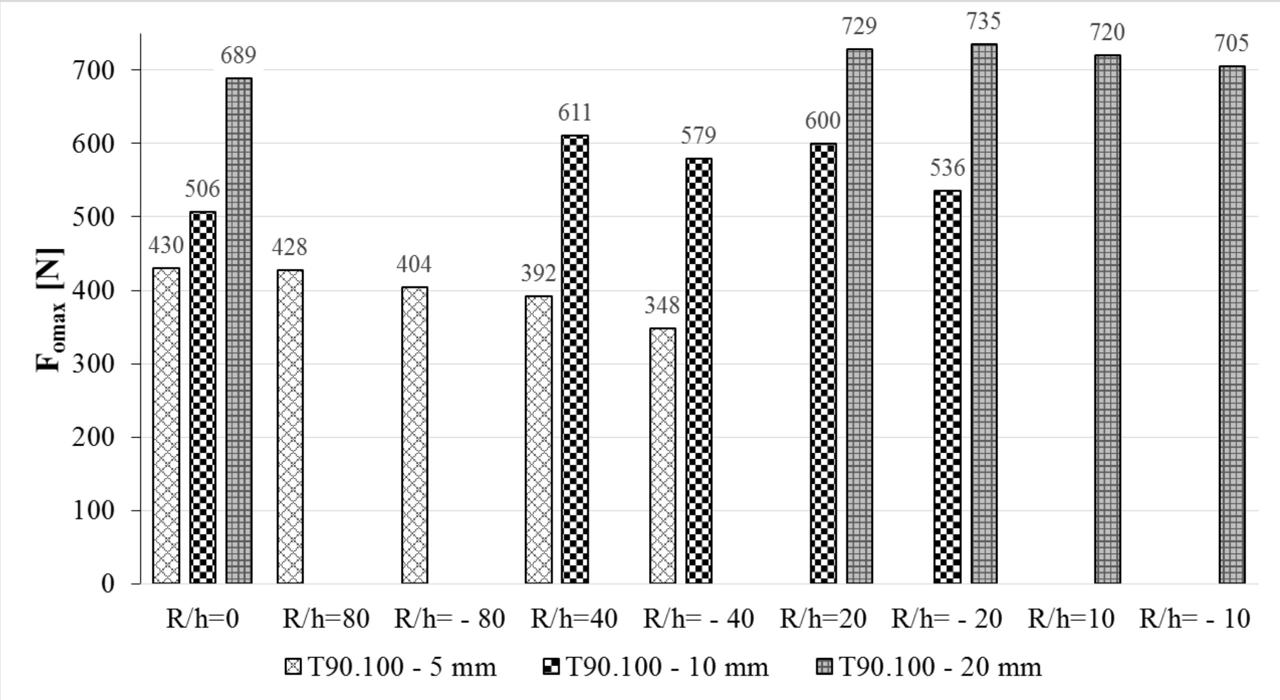

***Fig. 6** Bending load capacity of PET foam core sandwich specimens (beams) in three point bending*

4 Conclusion

In this experimental study, bending load capacity of sandwich structures has been evaluated and results compared with respect to beam shape, material composition, clamping configuration, and beam dimensions. The comparison of foam cores of 5 mm thickness revealed that in test, where beams are subjected to combined loading by bend and shear, these structures show decrease of load capacity with increasing ratio of curvature. On the other hand, honeycomb core sandwich beams exhibit in general higher load capacity and more balanced values compared to foam core beams. Bending behavior of these honeycomb beams in four-point test was characterized by increase of measured parameter due to beam curvature. This is probably caused by higher compressive and shear stiffness of honeycomb core. As is apparent from all these results, curvature together with material composition of sandwich panels may have a significant effect on bending load capacity.

Curved beams with higher thickness cores of same material composition exhibit always higher bending load capacity compared to identical but planar beams. This is apparently caused by a greater ability of thicker core to transfer shear force components from upper to lower facing, and thus prevent local deformation (indentation).

Moreover, research showed that convex curved beams have in nearly all cases lower bending load capacity in comparison to concave beams. This fact should be considered especially during design stage of interior curved panels, for example interior facing panels in trains and buses.

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