DETERMINATION OF THE CHARACTERISTICS OF A SANDWICH STRUCTURE WITH COMPLEX 3D SHAPE

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Abstract
A recently developed glass fibre reinforced PU-foam sandwich panel is mechanically characterized in the current research. Due to the in situ formation of the different components of the sandwich structure, specific experimental techniques are required for this purpose. Compression testing on the complex foam core and tensile testing on milled samples of the skin revealed the stiffness of both sandwich components. The thickness of the sandwich skins was determined by image processing of CT-scans. This thickness was shown to decrease with an increasing density of the complex foam core. Finally the obtained data and models were used to develop a simple software tool to predict the bending stiffness of the sandwich panel with an accuracy of +/-10%. Moreover the software tool identifies possible future material developments.

1. Introduction

The main principle applied in sandwich structures is to base the material distribution in the structure on the occurring stresses created by the design load. In most cases, this design load is a central or distributed load, causing the sandwich panel to bend. In order to optimize the bending resistance of the sandwich panel without increasing the weight significantly, sandwich structures combine thin but stiff materials at the outer layers of the panel with a less stiff but lightweight material in the core of the sandwich panel [1,2].

Typical examples of these materials are aluminium or fibre reinforced plates as skin material and honeycomb, balsa wood or synthetic foams as core material. In some cases, an additional adhesive layer is required to bond the different materials. The combination of lightweight design with high load bearing capacities makes sandwich structures highly efficient. For this reason, a lot of applications can be found in automotive, aerospace and sports.

The currently investigated sandwich structure was developed by the International Development Centre of Recticel and is best described as a glass fibre reinforced polyurethane foam sandwich panel [3]. The production process of this sandwich panel is schematically shown in figure 1.

The stack of the sandwich panel consists of a flexible open cell polyurethane-foam (1) with a glass fibre mat on top and bottom of it (2 & 3). This stack is placed in an open mould (4 & 5) after which a spraying robot applies the reaction mixture of a rigid closed cell PU-foam (6) on top of the stack. The reaction mixture is a low viscosity fluid and spreads itself throughout the stack. When the mould is closed, the reaction mixture starts to foam and cure. In this way, the different components are joined and produce a solid sandwich panel.

Figure 1. Illustration of the sandwich panel production process (left) interior side of a car door made from the presented glass fibre reinforced PU-foam sandwich panel with a PU imitation leather surface finishing (right).

The most important advantage of this sandwich panel is the ability to make products with a complex 3D shape. While most sandwich panel products are restricted to flat plates, the current production process allows complex shapes like the interior side of a car door (figure 1). Moreover, inserts and surface finishing layers like imitation leather can readily be incorporated in the same production process.

The production process and characteristic build-up of the presented sandwich panel poses however some difficulties to characterize the different components of the sandwich panel. Since the glass fibre reinforced PU-foam skins and the complex foam core are formed in situ, their mechanical properties cannot be measured in advance and prevents pre-production predictions of the mechanical performance of the sandwich panel. This problem is addressed in the current research by applying different experimental and calculation methods.

First, the stiffness of the sandwich panel core is determined by means of compression tests, while tensile tests on milled samples were used to measure the stiffness of the skins. The thickness of the sandwich skins was determined by an image processing algorithm on CT-scan data. The collected data was used in a simple software tool to predict the bending stiffness of the sandwich panels.

2. Experimental methods

2.1. Compression testing

The stiffness of the complex foam used as core material in the sandwich panel, was determined by means of compression tests. For this purpose, large plates of the complex foam were produced without the glass fibre reinforcement layer. Samples with a size of 20x30x30mm were cut out of the large plates. Since the cells of the closed cell foam have a cell size on the order of 200µm, the prepared samples are large enough to avoid interfering sample size effects [4]. All samples were tested in the rise direction of the foam and according to ASTM standard D1621-04a [5].

The influence of two parameters was investigated: the cell size of the open cell foam constituent and the density of the rigid closed cell foam, which possesses a free rise density of 40kg/m³. The density of the latter foam was controlled by varying the overpack ratio in the mould. In case an overpack ratio of two is applied during the production, the density of the foam will be 80kg/m³.

2.2. CT-based skin thickness determination

In order to measure the skin thickness of different sandwich panels, a CT-sample containing multiple specimens was prepared (Figure 2, Table 1). The use of CT imaging allows a virtual 3D reconstruction of a piece of the sandwich panels. Subsequently, the skin thickness can be determined by means of an image processing algorithm developed by Kuppinger et al. [6].

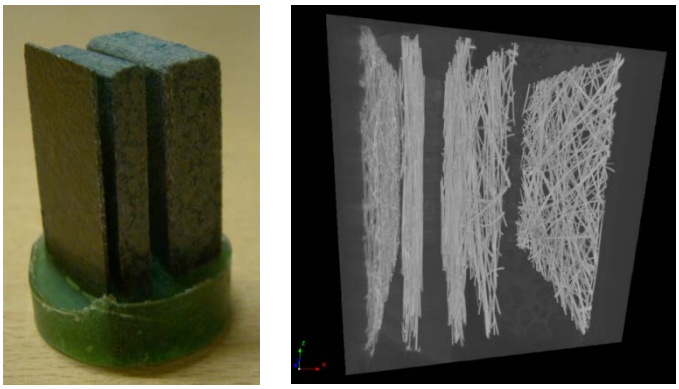

Figure 2. CT-sample of three different glass fibre reinforced PU composites embedded in a resin base (left), 3D reconstruction of the scanned CT-sample (right). The different glass fibre layers can be distinguished in this 3D reconstruction.

	Material	H [mm]	Weight [g/m²]	ρ_{foam} [kg/m³]	Overpack** [-]	Skin	t_f [µm]
1	Separate skin	0,65	535	477	12	-	650±48
2	Sandwich panel 1	4,50	1390	209	5,2	Top	1110±50
						Bottom	1250±85
3	Sandwich panel 2	9,10	1778	146	3,6	Top	1225±65
						Bottom	1495±25

**free rise foam density = 40kg/m³

Table 1. Summary of the materials embedded in the resin base for CT visualization. The order of the materials in the table correspond to the left to right order in figure 2.

In short, the algorithm projects the different slices of CT-scan into a single image and performs the Euclidean distance transformation on the binarized projected image. Since the skin final thickness is sensitive to the selected black/white threshold value, the results will be presented as a function of this threshold value. The reported skin thickness is based on the standard deviation of the results and a visual quality inspection of the binarized image. A more detailed description of the image processing algorithm can be found in the paper by Kuppinger et al. [6].

2.3. Tensile testing

Tensile specimens of the glass fibre / PU-foam skins were extracted from the sandwich panels by milling the opposite skin and core away up to a final thickness of 2mm. This thickness is

larger than the actual skin thickness and was chosen to avoid damaging the glass fibre reinforcement during the milling step. When the tensile test are performed, the stiffness of the additional PU-foam layer was neglected with respect to fibre reinforced layer.

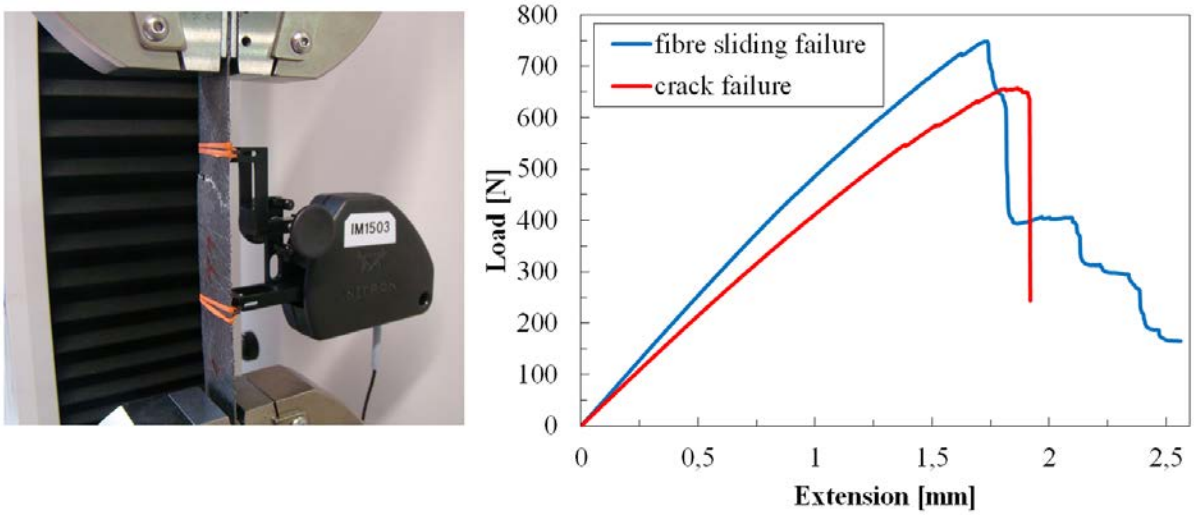

Figure 3. Experimental tensile set-up on CompoLite™ skins. An extensometer is attached to the specimen to measure the elongation of the specimen (left). Typical load-extension curves recorded during tensile testing of CompoLite™ skin material (right)

Tensile samples were produced out of two different sandwich panels with a different height and areal weight (table 2). A difference was made between the top and bottom side of the panels during production and the 0° and 90° direction of the glass fibre mat with respect to the production direction of the glass mat.

Material	Weight [g/m²]	Tests	Abbreviation
CompoLite™ 7mm	1990	Top side 90°	T90
		Bottom side 90°	B90
CompoLite™ 10mm	2310	Top side 0°	T0
		Bottom side 0°	B0
		Top side 90°	T90
		Bottom side 90°	B90

Table 2. Tensile test specimens to determine the stiffness of the CompoLite™ sandwich panel skins.

The tensile experiments were conducted according to ASTM D 3039-76 [7] and 2mm thick aluminium end tabs were used to ensure a good load introduction to the specimens. Both stiffness and strength values will be reported.

3. Results & discussion

3.1. Compression testing

The dependency of the stiffness of the complex foam on its relative density is shown in figure 5. As evidenced in this figure, no significant difference is observed with respect to the cell size of the open cell foam constituent. Therefore, all experimental stiffness values, regardless of the cell size of the open cell foam, were fitted to the Gibson & Ashby power law model [2].

The value of the exponent in this model is very close to two. This indicates that the bending of the cell edges of the closed cell foam is the dominating deformation mechanism and no additional stiffness is obtained from the cell faces.

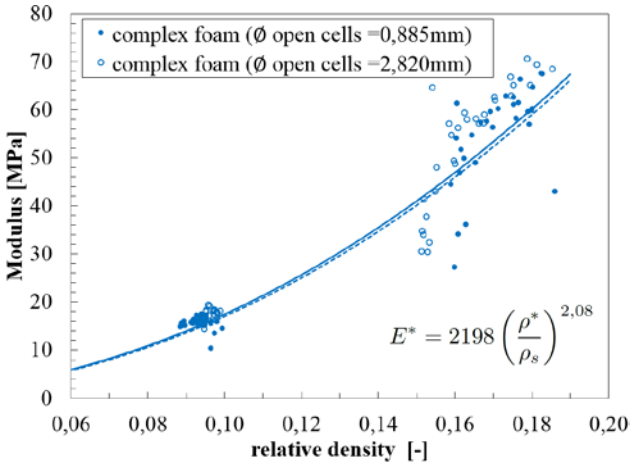

Figure 5. Stiffness of the complex foam as a function of the relative density and the cell size of the open cell foam constituent. The experimental results are fitted to the Gibson & Ashby power law model.

3.2. CT-based skin thickness determination

The skin thickness of the separately produced GF/PU composite plate as a function of the black/white threshold values, is presented in figure 5. Based on the aforementioned criteria, the skin thickness of the composite plate was found to be 618µm. This value was validated by micrometre measurements on a 30x20cm large plate. The obtained thickness in this way was 650µm with a standard deviation of 49µm. Similar measurements on the small 2x2cm CT sample yielded a thickness of 600µm. The small difference between the experimental thickness values and the result of the image processing algorithm, confirms the validity of the latter method.

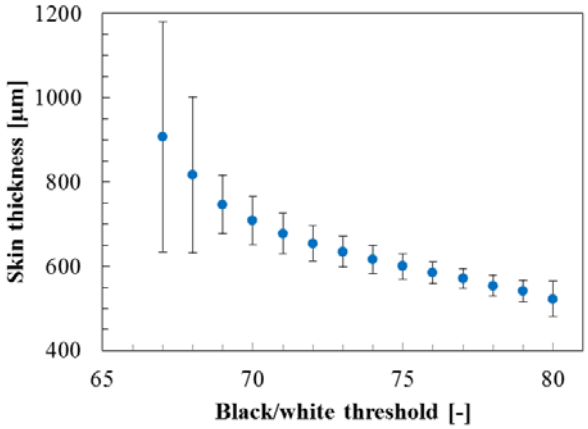

Figure 5. Skin thickness of a separately produced GF/PU composite as a function of the applied black/white threshold in the image processing procedure.

The skin thickness of two sandwich panels is shown as a function of the black/white threshold value in figure 6. The resulting average skin thickness values are reported in table 2. The skins of sandwich panel 1 are thinner compared to the skins of sandwich panel 2. This difference is explained by the higher overpack ratio in the first sandwich panel. The higher the overpack is, the higher the pressure build up will be inside the mould during the production

process and the more the fibre reinforcement will be compacted in the skins. This mechanism yields a lower skin thickness at higher foam densities.

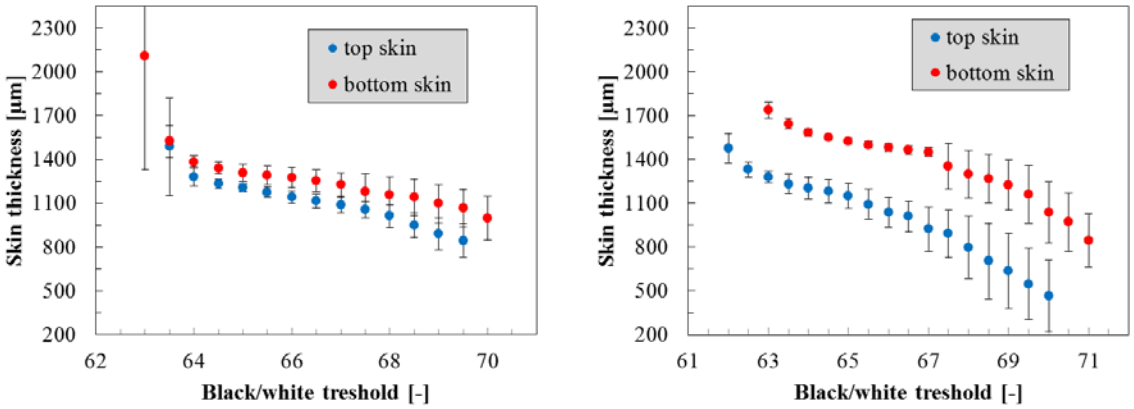

Figure 6. Skin thickness of two CompoLite™ sandwich panels of different height: 4,5mm (left) and 9,1mm (right). The 'top' and 'bottom' name in the legend refers to the position of the skins during the production of the sandwich panel.

For both sandwich panels, the bottom skins are thicker than compared to the top skins. The difference between both skins is smaller for sandwich panel 1. These observations are explained by the difference in sandwich panel height. The higher the sandwich panel is, the more distance the liquid reaction mixture has to cover to spread itself through the complete stack thickness. This process results in a lower amount of reaction mixture at the bottom compared to the top side and eventually leads to a higher skin thickness at the bottom side of the sandwich panel. The thicker the panel is, the more pronounced this effect will be.

A final remark is on the accuracy of these measurements. Although the CT-scan has a resolution of 10µm, the current procedure and results are not able to report skin thickness values with an accuracy of 10µm. The values reported in table 2 are only valid for the small CT-sample areas. When a large number of samples at random locations of a large plate would be taken, a higher standard deviation is expected. This is illustrated by the different average thickness values of the separately produced skins when measured on the small CT sample or a larger plate.

Moreover, because of the expected local thickness variations, the differences between top and bottom side of the sandwich panel might become insignificant. For these reasons it is probably more correct to neglect the difference between both sides and state that the average skin thickness of sandwich panels 1 and 2 is respectively 1,18mm and 1,38mm.

3.3. Tensile testing

The strength and stiffness results of the CompoLite™ skins are shown in figure 7. No significant difference between the top and bottom side can be identified. When all results in the 90° direction are compared, no significant difference between both sandwich panels can be observed as well. The small existing difference is attributed to the higher foam density of the sandwich panel with a height of 10mm.

There is however a significant difference between the 0° and 90° direction. When the stiffness values of 10mm thick sandwich panel are averaged per orientation, the skins possess a 38% higher stiffness in the 0° direction. These results contradict the initial assumption of a

completely random distribution of the glass fibre orientation. This should be taken into account during the design phase of the sandwich panels.

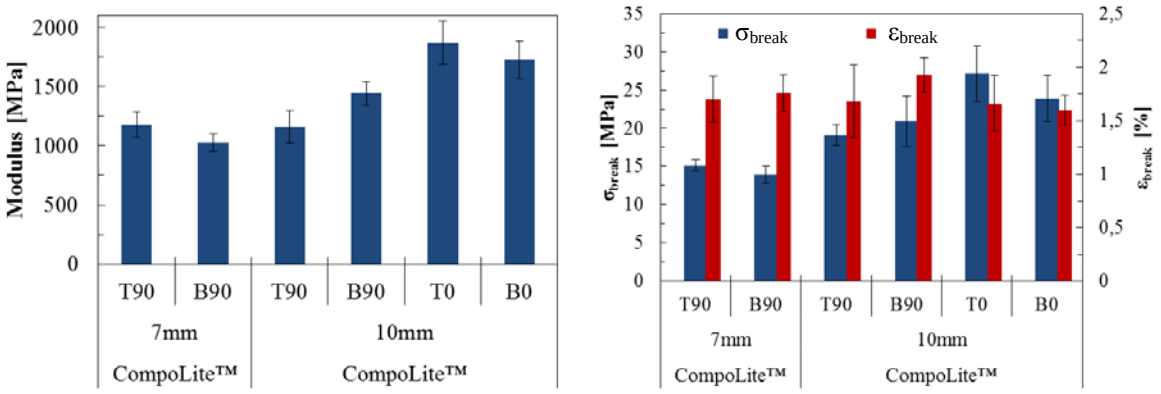

Figure 7. CompoLite™ skin stiffness and strength as a function of sandwich height, position and orientation. The stiffness and stress values were normalized against an average fibre volume fraction of 5,21%.

The maximum attainable stress of the sandwich skins shows a similar behaviour as the stiffness results, figure 7. Due to the higher degree of fibre orientation in the 0° direction compared to the 90° direction, the skins are capable of bearing the highest stresses in the former direction.

The strains at which the maximum stresses occur seem to be independent of the orientation, position in the sandwich panel and the height of the sandwich panel. This can be explained by the low fibre volume fraction (5 - 7%) in the skins. Due to these low volume fractions, the maximum strain will be determined by the PU-foam properties, which do not depend on the investigated factors.

3.4. Prediction of the homogenised bending stiffness

The homogenised bending stiffness, E_h of the CompoLite™ sandwich panels is calculated by:

$$E_h = \frac{2E_{skin}t_{skin}^3 + 6E_{skin}t_{skin}d^2 + E_{core}t_{core}^3}{h^3} \quad (1)$$

Where E is the stiffness, t is the thickness of the skin or core, h is the total height of the sandwich panel and d is the distance between the neutral lines of the complete sandwich and the skin [1]. The stiffness of the skin was calculated by the standard longitudinal, transversal and empirical (eq. 2) rules of mixture.

$$E_{skin} = \frac{3}{8}E_{long} + \frac{5}{8}E_{transv} \quad (2)$$

Since this model assumes a completely random fibre orientation, it does not predict an orientation dependent stiffness as observed in the tensile experiments.

The experimental results regarding the foam core stiffness, skin thickness and skin stiffness were used in the equations (1) and (2) to predict the homogenised bending stiffness of the CompoLite™ sandwich panels. Although these models are simple, they predict the bending stiffness of industrially produced sandwich panels with an accuracy of +/-10%.

Moreover, the influence of the areal weight of the fibre reinforcement and the skin thickness on the bending stiffness can be investigated by these models. The influence of these parameters is presented in figure 8. The green areas in the graphs show the current production windows. It is clear that a higher areal weight of the fibre reinforcement or thinner skin is beneficial for the bending stiffness of the sandwich material. When changes are made to the production process to fulfil these requirements, the porosity and drapeability of the fibre reinforcement as well as the flexibility of the open cell foam spacer, need to be taken into account to ensure the production of complex 3D-shaped sandwich panels.

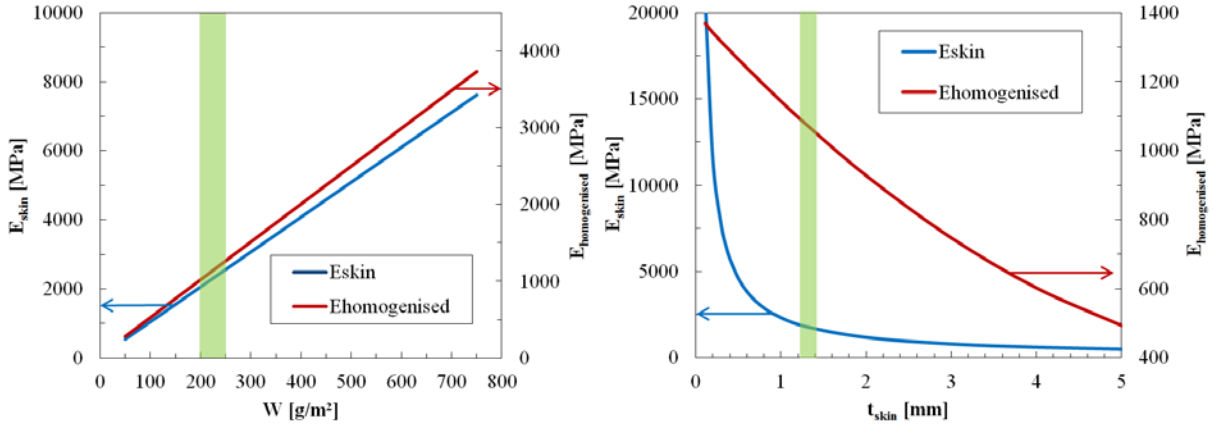

Figure 8. Influence of the areal weight of the glass fibre reinforcement (left) and skin thickness (right) on the stiffness of the skin and the homogenized bending stiffness of the CompoLite™.

4. Conclusions

This paper presents a simple model to predict the homogenised bending stiffness of a glass fibre reinforced PU-foam sandwich panel. This model is based on the experimental characterization of the PU-foam core stiffness as a function of density, the stiffness of the GF/PU-foam skins and the CT-scan based determination of the skin thickness. Since the skin of the sandwich panel is formed in situ, a post-production characterisation method was developed to determine the latter property. The simple model is however not able to capture the observed orientation dependency of the skin stiffness. Despite this, future material and production process developments can be guided by the presented approach.

References

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