DTU Library

Temperature-dependent changes in thermoplastic sandwich core properties and failure mechanisms using four-point tests with short specimens

Horn, Alexander; Berggreen, Christian; Gomez Meisel, Edgar Arturo; Legarth, Brian Nyvang

Published in:
Proceedings of ECCM21 – 21st European Conference on Composite Materials

Publication date:
2024

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Horn, A., Berggreen, C., Gomez Meisel, E. A., & Legarth, B. N. (2024). Temperature-dependent changes in thermoplastic sandwich core properties and failure mechanisms using four-point tests with short specimens. In Proceedings of ECCM21 – 21st European Conference on Composite Materials: Material and Structural Behavior - Simulation & Testing (Vol. 3, pp. 1318-1322). European Society for Composite Materials.

Temperature-dependent changes in thermoplastic sandwich core properties and failure mechanisms using four-point tests with short specimens

A. Horn[1], C. Berggreen[1], E. A. Gomez Meisel[1] and B. N. Legarth[1]

Department of Civil and Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
Email: alhor@dtu.dk, Web Page: https://construct.dtu.dk/
Department of Civil and Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
Email: cber@dtu.dk, Web Page: https://construct.dtu.dk/
Department of Civil and Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
Email: eagme@dtu.dk, Web Page: https://construct.dtu.dk/
Department of Civil and Mechanical Engineering, Technical University of Denmark, DK-2800 Kgs. Lyngby, Denmark
Email: bnle@dtu.dk, Web Page: https://construct.dtu.dk/

Keywords: thermoplastic, sandwich, honeycomb, four-point bending, core shear failure, low temperature, aircraft application

Abstract

Because of the emerging need for sustainable materials in the aircraft industry a promising composite material group is remeltable thermoplastic sandwich composites. To secure the useability of these sustainable thermoplastic composite materials, it is irrevocable to gain sufficient insight into the performance of these materials under versatile environmental conditions. In this investigation, the core properties, such as the ultimate core shear strength, the shear stiffness, and the associated failure mechanisms, at different temperatures are investigated by a four-point bending test series.

This series of tests can be seen as a step towards precise material characterization to ensure the development of a sustainable material alternative for structural aircraft parts, without compromising safety and reliability. Furthermore, critical aspects could be identified for prospective investigations.

1. Introduction

In order to the challenge of improving sustainability of structural airplane parts thermoplastic composite materials are a promising material alternative. In opposite to conventionally used thermoset based materials, such as epoxy or phenolic resin, thermoplastic materials will not receive irreversible chemical reactions. Due to that, thermoplastics can be remelted or restored to the flowable state. This ability offers new methodologies regarding recycling processes as well as other process options and new maintenance possibilities.

Sandwich materials have become standard material configurations, for designing parts with excellent strength-to-weight ratios. Their low mass compared to homogenous or stiffened structures as well as their high durability and reliability keeps them attractive for different industrial applications even beside the aerospace industry.

The aerospace industry is obliged to adhere to strict safety regulations. Sandwich materials in structural airplane parts, such as the shells of the vertical rudder, are continuously researched and improved to handle all the different conditions, which can appear during operation. One of the most critical aspects is the low temperature prevailing at flight altitude. Even at temperatures down to -55°C the sandwich material needs a good mechanical performance to ensure safety and reliability. To investigate the feasibilty of replacing conventional sandwich materials with more sustainable thermoplastic-based solutions it is important to investigate differences and similarities respectively of this promising material type compared with the conventionally used.

2. State of the Art

The two shells of a conventional rudder are both sandwich panels with two corresponding skin sheets on the outer surface. These sheets, also known as face sheets, are usually made of high-performance fiber-reinforced laminate. The high performance is reached by a fabric of carbon fibers embedded in an epoxy matrix. The face sheets are supported by a low-density core material. This low density is realized by using an aramid fiber paper material (known under the trade name Nomex®) coated with phenolic resin and arranged in a characteristic honeycomb geometry. To gain the so called sandwich effect, all corresponding layers has to be connected with each other, usually by an adhesive film. A general structure of sandwich materials is shown in figure 1. The major load case a sandwich material is supposed to, is bending. The bending deflection can be separated in a pure bending-related part and shear-related part. The amount of shear related effects for homogenous materials is very small and can be neglected. By using a low-weight core material the sandwich deformation gains an increasing amount of shear-related phenomena, which have to be considered.

The simplified first order shear deformation theory is highly coupled with two assumptions. The first is that the elastic modulus of the face sheets E_f should be much higher than the one of the core material E_c.

$$E_c << E_f \tag{1}$$

The second assumption is that the height of the core material t_c should be higher compared to the thickness of the face sheets t_f.

$$t_f << t_c \tag{2}$$

If both assumptions are fulfilled the stress contribution inside the material can be approximated like it is shown in figure 2. The bending stresses are just carried by both face sheets. The bending stresses inside the core material can be neglected. The shear load is completely carried by the core material because the face sheets are thin enough to not build up notable shear forces [1].

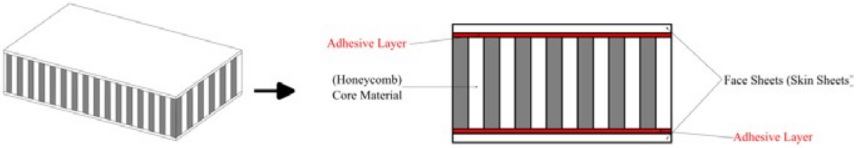

Figure 1. Sketch of general (honeycomb) sandwich structure

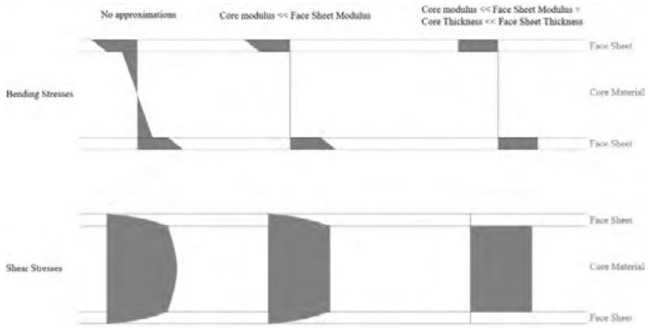

Figure 2. Approximated stress contributions

The mechanical properties of the face sheet laminate can be calculated well by using classical lamination theory (CLT). Also fiber reinforced composites consisting of thermoplastic matrix materials are already existing and are offered by the industry (e.g. by Toray Industries, Inc. or the Danish company Comfil ApS).

The honeycomb core material investigated in this approach is different from the conventional ones even beyond the material type. A specific production process also known as ThermHex process [2] realizes a semi-open folded honeycomb structure, characterized by two main differences [3]. Figure 3 shows schematically the folding process. Every row of cells obtain due to the continuous process covers, which are alternately pronounced on the upper and lower sides. This covers acting as additionally connection zones, therefore they increase the area of the core-face interface. Due to that characteristic, some known analytical calculation methods e.g. according GIBSON and ASHBY are not applicable for this core type [4]. The second difference related to conventional honeycomb cores is that the double cell walls are not connected over the complete surface. While conventionally produced cores are corrugated, stacked and connected over the full surface of double cell walls by an additional adhesive film, the folded structure just have connected zones at the upper and the lower area of the cells.

Another notable advantage of a sandwich material, which is completely thermoplastic-based, is the possibility to renounce the adhesive film for the core-face interface and realize the connection by a welding process instead.

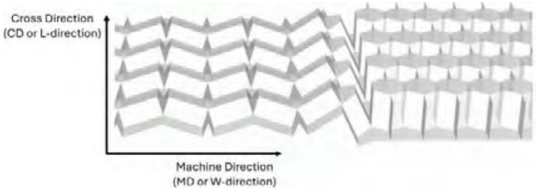

Figure 3. Process of semi-open folded honeycomb core (extracted and customized from [2])

3. Methodology

The focus for a promising material choice with respect to the use as aircraft structural part felt on two thermoplastic polymers as base material. Samples made of Polyetherimide (PEI) and Polphenylene Sulfide (PPS) were produced and provided by the company Econcore. Both polymers, regardable as high-performance thermoplastics, are characterized by a glass transition temperature, which is higher than the required operation temperature for structural airplane parts [5]. Furthermore they are less complicate to process caused by a lower melting point than other comparable high-performance thermoplastics. The core-face interface was realized in case of PPS with a welded connection. On the opposite, the PEI material is bonded together by using a thermoplastic adhesive layer.

As a first investigation to gain information about critical mechanism related to this type of sandwich materials a conventional four-point bending was chosen. In order to minimize the face sheet related proportion of the flexural rigidity and to provoke a core shear failure the decision of short sample design with a span length of 270mm was taken. The load introduction distance was 100mm. The bending test setup is located in a climatic chamber able to realize a temperature of -55°C. Tests were performed at low temperature as well as room temperature.

Three different basics are focused to compare. The first is a investigation of the failure mode, namely if the expected failure mode of core shear failure appears and if it is typically characterized. Second basic is the calculation of the ultimate core shear strength according ASTM C393 [6]. The standard prescribes a core shear failure for a properly determination. Another comparable core related property is the core shear stiffness. In order to determine it, the curvature in the area supposed to pure bending between the load introduction points was monitored by a digital image correlation system (DIC). To realize this, tracking dots are applied at the outer edges of the face sheets. With help of the curvature, the flexural rigidity can be calculated. With respect to the displacement the samples obtaining during the experiment as well as the known flexural rigidity, the shear stiffness can be calculated. Figure 4 shows the test setup inside the climatic chamber. Support point as well as load introduction points are supported by rotational bearings. To increase the load introduction surface additional load pads are applied. This helps to prevent local indentation phenomena. Figure 5 shows exemplarily a loaded test sample, where the for the DIC required tracking points as well as reference index respectively is shown.

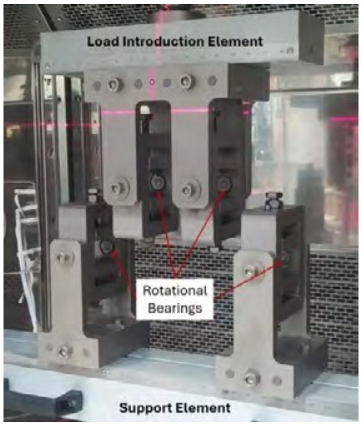

Figure 4. Four-point bending test setup

Figure 5. Loaded four-point bending test setup with PEI sample

4. Results

Figure 5 as well as figure 6 showing exemplarily the load-displacement behavior of PPS sandwichs and PEI sandwichs respectively. Due to the highly orthotropic character of honeycomb material a separation of properties with respect to the production direction and the transversal direction must be performed. The solid lines showing the low temperature tests, which can be directly compared with experimental results at room temperature visualized by dashed lines. Regarding the slopes, the curves are comparable with each other. An influence of low temperature effects the absolute force which is reached during the tests. However, all samples are subjected to a certain amount of variation, which causes that also these values are quite comparable.

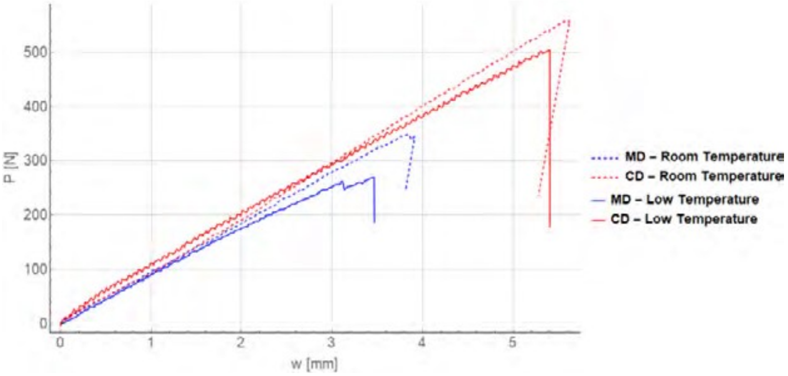

Figure 5. Exemplarily load-displacement curves of PPS

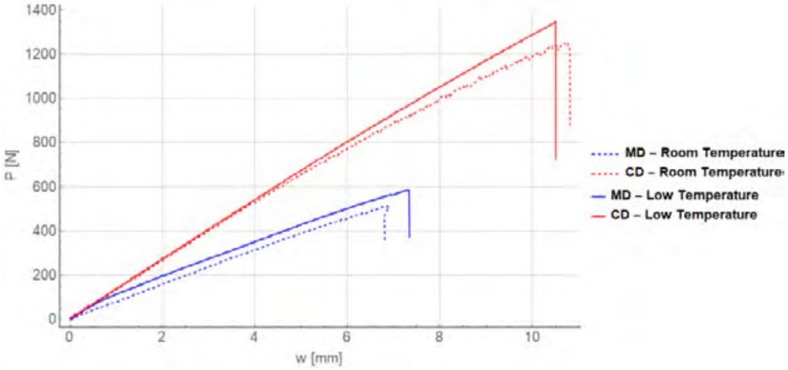

Figure 6. Exemplarily load-displacement curves of PEI

It is to note that the numerous values between both material types should not be compared directly because of differences in the geometry as well as the core density. A meaningful comparison is just possible within one material configuration between room temperature and low temperature.

In opposite to the numerous values, the failure mechanisms are representative for both material configurations and can be compared qualitatively. A buckling of the cell walls, initiating a critical failure of the core material is observable at all tested samples. The figures 7 and 8 are showing characteristic core shear failures of both material types. The shear crack is as expected in an approximate 45° angle. It is conspicuous that a development of the shear crack underneath the face sheets is observable. This phenomenon is more pronounced at low temperatures and independent of the type of core-face interface.

Figure 7. Core Shear Failure of PPS Sandwich

Figure 8. Core Shear Failure of PEI Sandwich

5. Discussion and Conclusion

The expectation of a more brittle behavior at low temperatures of -55°C was confirmed during the experiments. However, for a first investigation are these effects acceptable. All samples are supposed to a certain amount of variation, so that the results remain comparable independently of the test temperature. This also confirmes the promising character of PPS and PEI.

All in all, PPS shows a more brittle failure at lower loads than PEI, which is confirmed by lower values of the ultimate core shear strength in production direction at low temperatures. Due to increased brittleness at low temperatures, the relatively small connection zones between the double cell walls are supposed to fail earlier. A decreased shear stiffness can also be associated with this phenomena. It is planned that the PPS will additionally be modified and optimized regarding this brittle behaviour by a choice of certain additives.

The cell wall buckling as main driver of a critical core shear failure could be observed for both material types. It was observed that the failure starts in the immediate vicinity of the face sheets. The secondary source of a critical failure is the collapse of the core-face interface. Especially this phenomena will be investigated further to gain a more detailed knowledge about the failure mechanism and the associated useability of thermoplastic sandwich solutions for structural airplane parts.

Acknowledgments

Special thanks to all project partners of the work package EcoRudder of the Horizon Europe - Clean Aviation project FASTER H2 for a lot of knowledge exchange. Especially, the provision of test samples by Econcore was highly appreciated.

References

[1] D. Zenkert. *The Handbook of Sandwich Construction.* 1997
[2] Honeycomb cores for lightweight sandwich panels (Online), https://thermhex.com/ (Available at 07/05/2024)
[3] J. Pflug. *Continuously Produced Honeycomb Core Materials.* Leuven: Arenberg Doctoral School Dissertation. 2018
[4] L. Gibson and M. Ashby. *Cellular Solids - Structure and Properties.* Cambridge University Press 1997
[5] G. Wypych. *Handbook of Polymers*. Elsevier, 2016
[6] ASTM C393/C393M – 20, *Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure* 2020