THE INTERFACE OF CFRP FACE SHEETS AND ALUMINUM FOAM CORES IN HYBRID SANDWICH PANELS MANUFACTURED BY A PUR SPRAYING PROCESS

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Abstract
Hybrid sandwich panels with aluminum foam core structures and face sheets made of carbon fiber reinforced plastic (CFRP) were manufactured by means of an automated polyurethane (PUR) spraying process with low pressure during the curing of the resin. Face sheets and core were combined by an integrated interface of PUR foam, which also acts as the face sheet matrix. Prior to the extraction of specimens, the sandwich panels were investigated by X-ray radiography, in order to detect local inhomogeneities. The interfacial properties of face sheets and core structure, determined by the two interlocking foam structures of the PUR matrix and the aluminum core, was characterized by the climbing drum peel test and by optical analysis. The influence of the process parameters, such as the face sheet architecture, the area weight of fibers, the amount of applied PUR and the core cell structure, were investigated. The results show a correlation of the PUR penetration depth and the failure mechanisms occurring in the climbing drum peel test.

1. Introduction

Sandwich structures are lightweight design solutions used in structural applications exposed to bending load or for high energy absorption in crash events [1]. They commonly consist of face sheets of glass fiber reinforced plastic (GFRP) and a core of polyurethane (PUR) foam or paper honeycombs [1–3]. Face sheets of carbon fiber reinforced plastic (CFRP) and core structures of aluminum foam are used for increased impact resistance [4] or specific strength and stiffness [5, 6], as it is done in this paper.

The interface of sandwiches is commonly created by an adhesive, applied either in a liquid state or as a film [1, 6, 7]. The interface owns a significant lightweight optimization potential, as the mass of the applied adhesive usually has a noticeable impact on the relative density [7]. In this paper, the bonding of face sheets and core is realized by foamed PUR, which has a lower density and increases the contact area by penetrating into the sandwich core. For the production of specimens, an automated PUR spraying process was adapted. At Fraunhofer ICT, it is used for research on sandwich structures with GFRP face sheets and honeycomb cores [8, 9]. The pressure applied on the core structure is low, so the core is neither filled with resin nor destroyed by compaction. This process is therefore compatible with open cell cores, in contrast to RTM [5], injection molding [10], or other processes with high pressures [11].

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The mechanical properties of the interface have a significant influence on the behavior of the sandwich panels, which were therefore characterized optically and by the climbing drum peel test. Both procedures are applied in [9], characterizing sandwich panels with GFRP face sheets and paper honeycomb cores.

2. Materials and Methods

2.1. Materials

As core structure, four different types of aluminum foam with different relative density, cell size and cell structure were used. The relative densities were in the range of 5 to 8 %; the cell size varied between 5 and 26 mm. The cell structure included open and closed cell structures, and one type of closed cell panel with the in-plane cell walls removed by sandblasting. A Nomex honeycomb structure impregnated in phenolic resin served as a reference.

The fiber reinforcement of the face sheets consisted of carbon fiber mats, woven with plain weave as well as non-crimp-fabric (NCF), each with biaxial orientation (0° / 90°) and 160 g/m^2 area weight per layer. Sandwich panels with 1 or 2 layers of either woven or NCF fabric per face sheet were produced.

PUR resin supplied by Rühl Puromer GmbH, consisting of the two components isocyanate „PUR 900“and polyol „PUR 569 IT“, was used as the face sheet matrix and interface of face sheets and core.

2.2. Manufacturing of Sandwich Panels

In the automated PUR spraying process used at Fraunhofer ICT [8], resin is applied by a robot directly onto both sides of a dry sandwich assembly. This process requires turning the assembly after the application of PUR on the first side. Fiber misalignment can be caused by this handling process, as the wet fiber mats tend to detach from the core during handling. For this reason, the spraying process was modified in such a way that the assembly it did no longer have to be handled in a wet state: PUR resin, intended for the impregnation of the lower face sheet, was applied directly into the mold. The dry sandwich assembly of core and fiber mats was then placed onto the resin, followed by a second run of the robot applying PUR on the upper side of the assembly. The mold was closed directly after the spraying process, reducing the risk of prematurely cured PUR resin. The infiltration process of the fibers is started at the end of the closing procedure of the mold, by the cavity pressing the PUR resin through the fibers on each surface: A specific amount of excess PUR resin penetrated the outer parts of the aluminum foam core. The curing time was set to 10 minutes, ensuring a fully cured PUR matrix. The PUR foamed while curing, thus creating an interface with a low relative density compared to common adhesives.

The employed PUR spraying robot R-2000iB 175L by FANUC was equipped with a 4-component high pressure mixing nozzle, in which the two PUR-components were tempered to 28±3°C and mixed directly before the application. The mold carrier (600 kN compressing force, pivoting platform) by Kannegiesser, Germany, was equipped with a mold with a cavity of 900 mm x 550 mm with rectangular, plain surface and an adjustable height set to the height of the sandwich core panels (20 mm). As the sandwich core panels measured 350 mm x 250 mm, there was no pressure applied to their sides. The mold was heated to 60 °C. The robot moved on the same path for both spraying runs, applying two straight lines, separated by 160 mm, centered on the sandwich panel and with a distance of approx. 360 mm from the surface. The amount of resin was varied by adjusting the speed of the robot, keeping a constant mixing pressure of 150 bar and PUR discharge rate of 58 g/s for identical PUR properties. Three variations of PUR resin line weight were applied: 75,5 g/m (PUR „C“), 113,3 g/m (PUR „A“) or 226,6 g/m (PUR „B“).

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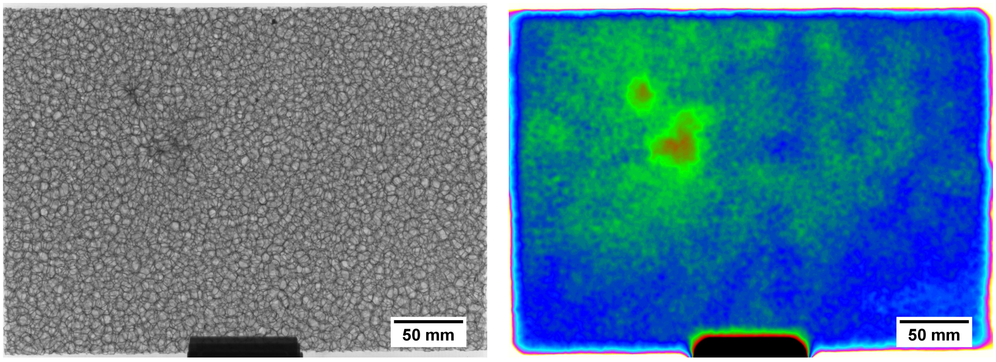
3. Experimental

3.1. Preparation of specimens

The aluminum foam panels were anticipated to show local variations in density, such as spots with accumulations of aluminum or exceptionally large cells. Those spots were observed during manufacturing and could be originated from the production of the foam panels. It was necessary to detect these spots and exclude them from specimen preparation, as they could act as local sources of mechanical failure in test specimens. For this reason, the produced sandwich panels were scanned with X-ray radiography (see fig. 1 (a)) using an Yxlon Y.CT Precision μCT-System. The X-ray tube was operated at an acceleration voltage of 100 kV, using a tungsten transmission target at a current of 0.08 mA. As the face sheet fibers and the PUR absorbed little radiation, they were barely visible in the scan. Therefore, the amount of aluminum per pixel (and thereby the local density) could be approximately correlated to the local grey value. To compensate „regular“accumulations of aluminum, such as cell walls or edges, a median filter of 60 pixels (approx. 10 mm) diameter was applied, using the software ImageJ. A false color table was applied to improve the distinction of small variances of the local grey value (and therefore density). As a result, areas with locally varying densities could easily be detected (see fig. 1(b), red spots in the upper left region) and excluded from the extraction of specimens. Specimens of 75 mm width and 300 mm length were cut out of the sandwich panels using a circular saw.



(a) X-ray scan of sandwich panel (b) Same X-ray scan with applied false color table

Figure 1. Sandwich panel, scanned with X-ray radiography (bottom: mounting bracket).

3.2. PUR penetration depth

The PUR foam simultaneously acted both as the face sheet matrix and as the adhesive. The interface between face sheet fiber mats and the aluminum foam core was created by the penetration of PUR resin through the face sheet into the core structure. While curing, the PUR foamed, inducing a large contact area and interlocking volume with the aluminum cell walls or edges. This PUR penetration volume was assumed to be a reliable characteristic for the strength of the interface. It was represented by the penetration depth as the „volume per area“.

The PUR depth was measured optically by analyzing the side surfaces of the cut specimens. The specimens were photographed with a digital single lens reflex camera aligned in-plane to the specimen sides, at a resolution of approx. 12 px/mm. The illumination was set homogeneously over the specimen side surface. Deformation effects caused by the lens, such as the barrel effect, were removed using the software tool PTLens. Contrary to [9], the PUR surface was marked manually with polygon faces (see fig. 2). An automatic measurement was not possible, as the PUR could not be separated from the core by distinct grey values. The average PUR depth was calculated by dividing the polygon area by its width.

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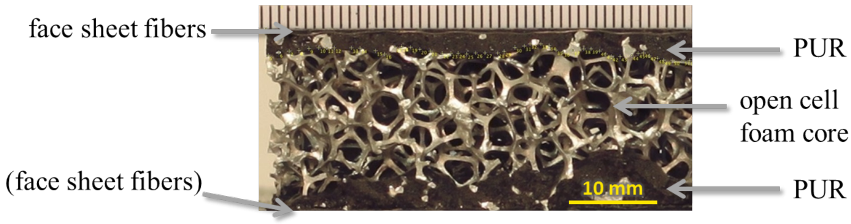

Figure 2. Optical analysis of PUR penetration depth on a specimen with open cell foam core

3.3. Climbing Drum Peel Test

The climbing drum peel test was suitable for characterizing the mechanical properties of the interface of face sheets and core structure, as it is normally used to test adhesives connecting face sheets and core. The test procedure resembled DIN 53295 [12] and ASTM D1781 [13]. The specimen geometry was set to 300 mm x 75 mm, according to the test standards. Thus, the influences of pore size were sufficiently low. The tests were conducted on a Zwick universal tensile testing machine ZMART.PRO with a maximum tensile force of 500 kN and a load cell with a maximum load capacity of 20 kN. Contrary to the test standard, the steel loading straps connecting the drum with the lower flange were replaced by textile straps with sufficient stiffness. This reduced the retracting moment of the drum, which could otherwise cause tilting of the specimen setup and inaccuracies in the recording of the crack propagation.

4. Results

4.1. Influence of processing parameters on PUR penetration depth

Using the described optical method, the influence of several processing parameters was investigated and the resulting PUR penetration depths were compared. For each of the four graphs in fig. 3, one processing parameter was varied, with the other parameters held constant.

Fig. 3(a) shows the PUR penetration depth for a varied setup of face sheets: specimens with each 1 and 2 layers of NCF respectively woven fabric were investigated. All of the sandwich panels were produced with the open cell core type and the PUR amount „A“. Specimens with two layers of 0°/90° non-crimp fabric (NCF) per face sheet show approximately half the PUR penetration depth compared to one single layer of NCF. Compared to one layer of NCF, one layer of woven fibers results a penetration depth only a little higher. Adding a second layer of woven fibers has no influence on the PUR-depth.

In fig. 3(b), the influence of the core structure on the PUR penetration depth is investigated, with all sandwich panels produced with two layers of woven fabric as face sheets and the PUR amount „A“. The values of PUR penetration depth are similar for each core structure.

The influence of the amount of applied PUR to its penetration depth is displayed in fig. 3(c), with all of the specimens being produced with two layers of woven fabric as face sheets and the open cell core type. A larger amount of applied PUR results in a greater PUR penetration depth, indicating a strong influence.

The manufacturing process apparently has an additional influence shown in fig. 3(d): The position of the face sheet inside the mold during manufacturing affects the PUR penetration depth of the specimens. The PUR penetration depth at the „upper“face sheets (located at the top side of the mold) was different from the penetration depth at the „lower“face sheets (located at the bottom side of the mold). For the

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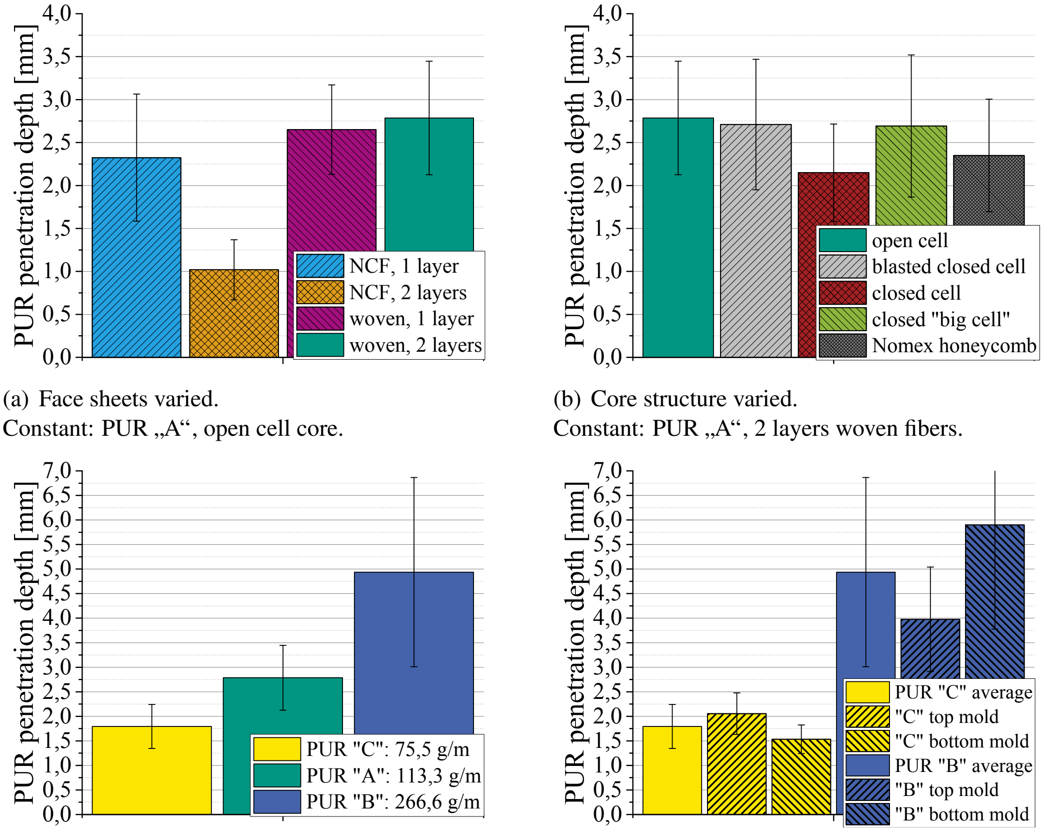
smallest investigated amount of applied PUR („C“), the upper face sheets show a slightly higher PUR penetration depth than the lower face sheets. For the largest amount of applied PUR („B“), the effect is inverted, as the lower face sheets show a higher PUR depth than the upper face sheets.



(a) Face sheets varied.
Constant: PUR „A“, open cell core.

(b) Core structure varied.
Constant: PUR „A“, 2 layers woven fibers.

(c) Amount of applied PUR varied.
Constant: 2 layers woven fibers, open cell core.

(d) Comparison of upper and lower mold side.
PUR „C“(least amount) vs. „B“(highest amount).

Figure 3. Influence of parameter variations on PUR penetration depth

4.2. Influence of process parameters on peel forces

The set of tested specimens could be distinguished by the predominant position of the crack propagation in the climbing drum peel test. Four types of crack propagation could be observed: The crack could propagate through the PUR, either directly underneath the face sheet fibers (see fig. 4, „1“) or alternating between face sheet fibers and the core structure (see fig. 4, „2“). The third observed failure mechanism was crack propagation partially through the aluminum cells of the core, with parts of the core structure remaining on the face sheet (see fig. 4, „3“). In the fourth failure mechanism, the crack propagated partially through the face sheet, with some of the fibers remaining on the core structure (see fig. 4, „4“).

The observed failure mechanisms were assumed to correlate to the resulting amount of peel torque per mm of crack propagation, and partially also to the PUR penetration depth. All of the tested specimens in the climbing drum peel test are shown in fig. 5(a), with details highlighted in fig. 5(b) and (c). It can be observed that each of the four failure mechanisms correlates to a distinct range of peel torque. Type „1“, with the crack propagating along the face sheet fibers, occurred with the lowest recorded values of peel torque, and is the predominant failure mechanism for specimens with a high PUR penetration depth. Fig. 5(c) shows that almost all of the specimens with the peeled face sheet located at the top half of the mold during manufacturing show this type of failure, all of them with low peel torque values.

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Slightly higher values of peel torque are achieved by specimens of the second failure mechanism, with the crack alternating between face sheet fibers and core. This failure mechanism also occurs with some of the specimens with high PUR penetration depth. The third failure mechanism, with the crack partially propagating through the core, correlates to higher values of peel torque. Type „4“crack propagation coexists with the highest recorded values of peel torque. Most of the specimens with NCF fabric show this failure mechanism (see fig. 5(b)), and none of specimens with woven fabric. Type „3“and „4“do not occur with specimens with high PUR penetration depths.

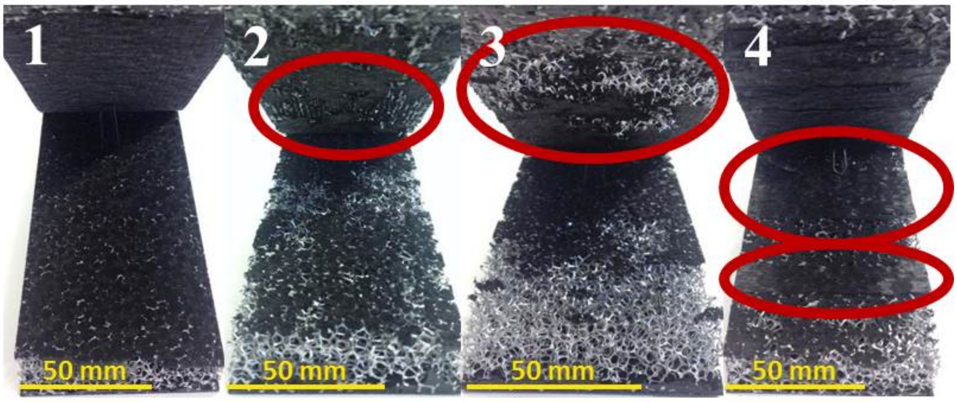
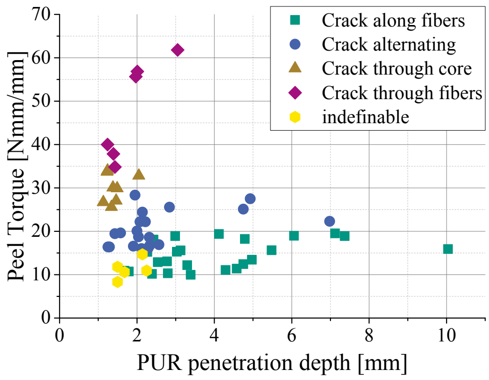
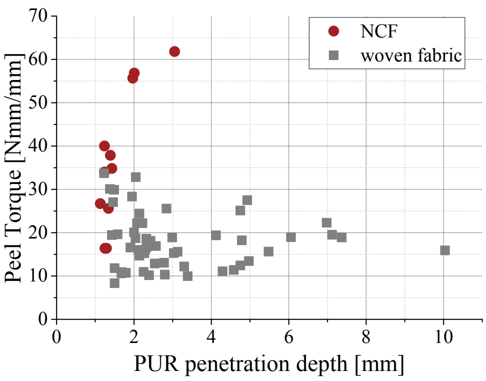


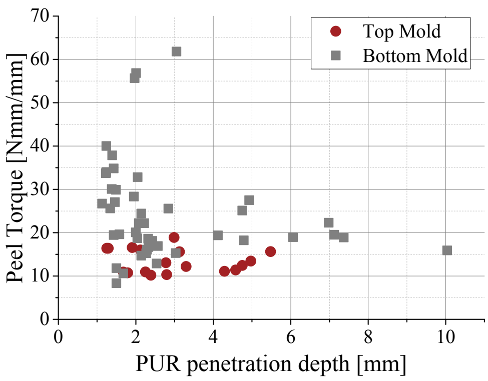
Figure 4. Four types of crack propagation, characteristics highlighted



(a) Observed types of crack propagation routes



(b) Influence of face sheet fiber architecture



(c) Influence of face sheet position in mold

Figure 5. Influence of parameter variations on face sheet peel torque vs. average PUR penetration depth

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5. Discussion

The average PUR penetration depth is largely influenced by the amount of applied PUR resin (see fig. 3(c)), which can be associated almost proportionally. With a linear dependency, the quotient of applied PUR and PUR depth should be constant. For PUR „C“, the quotient is 42.0 g/m·mm, for PUR „A “40.6 g/m·mm, and for PUR „B“45.9 g/m·mm. The PUR penetration depth can therefore be approximated linearly to the amount of applied PUR. Similar results are achieved in [9], where an exponential dependency was found. NCF fabric face sheets seem to be a higher barrier for PUR penetration than woven fabric, when more than one layer is applied. This assumption is supported by the strong decrease of PUR penetration depth from one layer of NCF to two layers, see fig. 3(a). In the woven fabric, the PUR resin can penetrate through the gaps around the junctions of the 0°/90°-fibers, which appears to be the predominant penetration procedure, as there was no noticeable difference between one- and two-layered face sheets (see fig. 3(a)). The influence of the core structure seems to be only limited by cell size, which is supported by the slightly lower average of the closed cell core (see fig. 3(b)).

The correlation of the position of the face sheet inside the mold and the PUR penetration depth has a tendency, but no significant influence is visible. The PUR penetration depth also seems to depend on the amount of applied PUR, as the effect inverted from PUR „C“to PUR „B“. However, there is a larger impact on the results of the climbing drum peel test, where the face sheets located at the top part of the mold did not achieve high values of peel torque (see fig. 5(c)) with a crack propagation almost exclusively along the face sheet fibers (see fig. 5(a)). Lower values of peel force for the face sheet located at the top part of the mold were also observed in [9], where they were explained by gravitational influences. This statement is supported by the fact that the manufacturing process for this work mainly differs from [9] in the application of the PUR, but not in the curing process.

A high PUR penetration depth appears to facilitate crack propagation along the fibers or alternating between core and fibers, as only failure types „1“and „2“occurred with high PUR depths (see fig. 5(a)). This supports the assumption of a higher interlocking volume, as described in section 3.2, with PUR supporting the core structure and thus reducing tension peaks, which could otherwise cause crack propagation through the core. Different failure mechanisms with a correlation to the peel forces are also obtained in [9]. However, the routes of crack propagation differ from this work, as chopped fiber GFRP face sheets are investigated in [9].

Almost all of the specimens with NCF face sheets showed crack propagation through the fiber layers, with patches of fibers orthogonal to the peel direction torn out of the face sheet and remaining on the core. This effect produced high values of peel torque, which were possibly caused by fiber bridging and small intervals between the orthogonal fibers as crack obstructions. As each layer of woven fibers cannot be split without destroying the fibers, the crack in those specimens was forced to either propagate along the fiber package or proceed transversely across the PUR foam and potentially through the core.

6. Conclusion

Within this work, a PUR spraying process has been successfully adapted for manufacturing sandwich panels with bi-axial CFRP face sheets and aluminum foam cores. A series of sandwich panels, including some with open cell core structures, was produced. Investigating the influence of process parameters on the interface of face sheets and foam core, the penetration depth of the PUR resin through the face sheet into the core was optically measured and identified as a suitable benchmark. The climbing drum peel test was performed to mechanically characterize the interface, with the recorded peel torque values compared to the PUR penetration depth of the corresponding specimen. Different types of failure, defined by the route of crack propagation, were observed and correlated to the PUR penetration depth.

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