Effects of defects on laminate quality and mechanical performance in thermoplastic Automated Fiber Placement-based process chains

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ABSTRACT
Automated Fiber Placement of thermoplastic unidirectional tape materials offers several advantages over conventional organsheets, such as enhanced part performance through tailored fiber architecture, and economic and ecological benefits due to scrap reduction. Because material is cut perpendicular to the feeding direction in state-of-the-art machine technology, triangular gaps and overlaps occur when geometrically complex layups are fabricated. Their effect on part properties is unknown for thermoplastic materials. This study investigates the influence of various defect configurations on laminate quality and mechanical performance for different consolidation processes. Analysis of microsections prepared from post-consolidation specimens shows out-of-plane undulations in defect areas. The undulation extent is quantified by angle and deflection. Tensile and compressive testing is performed. Gaps reduce ultimate tensile and compressive strength significantly for variothermal press and autoclave consolidation. Digital-image-correlation-based strain measurement during tensile testing shows strain concentration in the defect area for these specimens. Specimens consolidated in an isothermal stamp forming process show no comparable stress concentration, as well as no reduced ultimate strength. Specimens containing overlaps generally show a better performance in terms of ultimate strength compared to those containing gaps. Even though no full factorial design of experiments was used, the results obtained from this study can be used as a baseline for sector-boundary design strategies. The definition of defect-specific knock-down factors would be a next step towards the solid engineering of thermoplastic Automated Fiber Placement parts.

1. Introduction
The market share of thermoplastic composites has been constantly increasing over the past years [1]. While most automotive applications are based on short and long fiber reinforcements, processing technologies like injection molding, SMC and LFT-
D, or on the forming and overmolding of woven organosheets, structural aerospace applications require the layup of continuous unidirectional tape material to meet design requirements. This can be achieved by state-of-the-art machine technology like Automated Fiber Placement (AFP) machines. Since perfectly consolidated laminates are hard to achieve in the AFP process, in-situ layup capabilities are limited. Di Francesco et al. in [2] show that obtained bond strength decreases at high layup speeds. They conclude that the maximum layup speed for in-situ layup is limited for the machine technology currently available – even for simple straight layup. In their consideration of the layup of curved paths, which is referred to as fiber steering, Clancy et al. in [3] show that the steering radius and layup speed limit the achievable layup quality in terms of geometrical deviation and laminate consolidation. In [4] the authors show that a steered layup leads to an inhomogeneous temperature distribution over the roller width, which is why the in-situ processing window is hard to meet entirely in a complex laminate. Consistently, in-situ consolidation was so far successfully shown only for rather simple geometries, such as for example a booster casing [5] and a wing box demonstrator [6]. Also, in-situ layup requires the use of an expensive, high-quality tape material [7, 8]. Therefore, producing a partially consolidated preform by rapid AFP layup, which is then fully consolidated in a subsequent process step such as stamp forming or autoclave consolidation, is an promising alternative. The degrees of freedom of the robot-based layup system, as well as the individual cut and feed of the tows, enable the net-shape layup of double-curved parts, as well as optimized preforms in this context. The stamp forming process chain based on AFP was investigated by Slange et al. in [9] and [10] and successfully demonstrated for the rapid manufacturing of a tailored spar [11].

One restriction of most commercially available AFP machines is that material can only be cut perpendicular to the feeding direction. As a consequence, full part coverage cannot be achieved when allowable angular deviation is limited in double-curved areas or, more generally, areas with curved neutral fibers. The same applies when variable stiffness panels are considered, as in [12–14]. The commonly used tow drop on course boundaries leads to the formation of triangular defect areas, as depicted in Figure 1 for a 45° ply of a part with a curved neutral fiber. These defects can be executed as gaps or overlaps, and need to be clearly distinguished from unwanted defects related to randomized effects such as machine tolerances or inappropriate layup quality, as their existence is planned. Therefore, the position of these defects can be controlled during part design; it is thus important to understand their effects on part performance. When we are able to quantify their impact, specific allowables and requirements in combination with knock-down factors for stress engineering can be defined, and the design can be adjusted to account for the defect influence in an appropriate way.

Many studies have considered the influence of defects on part performance in thermoset material [14–22]. There is a consensus among these publications that ply discontinuities can lead to local fiber misalignments, which then eventually have impact on the mechanical behavior of the laminate. As fiber misalignments are expected to have the most severe influence on fiber dominated material properties, many of the studies focus on two of the basic loading modes for continuous fiber reinforced composites, tension and compression. Furthermore, the geometry of these specimens, according to the corresponding test standards, allows a systematic integration and variation of ply discontinuities in the specimen’s design. Also, the uniform loading of the specimen during the test facilitates the identification of physical mechanisms.

Generally, the failure mode in tensile testing of multiaxial laminates, made from unidirectional material, depends on the material’s matrix system and its properties. It usually involves a sequence of matrix cracking in off-axis plies and sometimes delamination, until the final failure of the 0° fibers [23]. Thickness effects might influence failure modes and damage progression [24, 25]. Considering laminates with embedded defects, Croft et al. reported in [19] that their tensile specimens fail in a catastrophic manner over the entire test section. The toughened epoxy matrix system of their specimens creates a uniform stress distribution. However, for specimen that contain a defect, the failure occurred next to the defect position and then propagates along the defect. Falcó et al. in [26] reported fiber pull-out and delamination as the two main failure modes for their material based on a non-toughened matrix of a part with curved neutral fiber.

Figure 1. Triangular defects due to angular adjustments for a 45° ply of a part with curved neutral fiber.
epoxy matrix. Woigk et al. in [21] studied various defect configurations regarding their impact on tensile and compressive performance. They manufactured a quasi-isotropic stacking sequence of 24 plies by hand layup and embedded their defects in the +45°, 90° and −45° plies. They used a high-speed camera system to monitor failure propagation. All specimens showed a delamination-based failure initiation in tensile load mode, which was reported to be characteristic for quasi-isotropic layups. None of the considered studies, in which tensile testing of specimens that contain fiber waviness or misalignments is carried out, reported a change of failure mode compared to pristine specimens [16, 19, 21, 26, 27].

For compression testing, Woigk et al. report further that their non-defective specimens showed local buckling of several surface plies. This behavior is accompanied by a load drop, which was described by Hwang et al. [28] as buckling delamination under uniaxial compression. After another load increase, the complete fiber failure occurred below the maximum load level of the first phase. Specimens with gaps and overlaps did not show a similar behavior, but failed due to simultaneous fiber breakage and delamination. Specimens with mixed defects (gaps and overlaps) failed predominantly due to delamination. Sawicki and Minguet in [17] investigated un-notched compression of multiaxial laminates with mixtures of gap and overlap in 90° plies. By FEM analysis and tensile follow-up experiments, they found the compression failure to be most likely caused by interaction of in-plane compression and intralaminar shear stresses in the out-of-plane undulated 0° plies. Based on their model, intralaminar shear stress was found to peak at areas of maximum peak slope and to be linearly proportional to this peak slope value. Wisnom and Atkinson reported shear instability in areas of maximum deflection, causing kink-banding and subsequently compressive failure in laminates containing ply waviness [29]. Mukhopadhyay et al. in [20] also reported the correlation of out-of-plane fiber misalignment and local delamination for quasi-isotropic laminates made from thermoset UD prepreg. They added stripes of material in 90° direction, in order to create laminates with out-of-plane undulations. By varying the thickness and width of the stripe, they produced laminates with varying wrinkle severity. The severity was quantified by the maximum angle of the undulations, which was determined via microsections. They developed an adequate FEM model and found a good consistency, <10% deviation with experimental results in terms of failure load levels. A decrease in ultimate compressive strength with increasing wrinkle severity was detected. Moreover, the failure mode changed from fiber-compression to delamination failure for wrinkle severities >8°, which was confirmed experimentally by failure propagation analysis with a high-speed camera. Delamination was also identified, along with fiber kinking, as a source of failure initiation for OHC specimens with out-of-plane waviness by Elhajjar et al. [30].

For multiaxial laminates built from unidirectional tape material with thermoplastic matrix, no relevant publications addressing the failure modes for laminates that contain defects are available. The authors expect that the actual polymer type as well as the state of the polymer, in terms of crystallinity and moisture could have a significant effect on the failure mode of the composite, as it is affecting the polymer’s brittleness and fracture toughness.

Regarding the shape of fiber misalignments, deflections of the plies in the laminate thickness direction often are referred to as ‘out-of-plane undulations’. In [31], Lightfoot et al. perform forming experiments with thermoset UD-prepreg material in order to understand the mechanism for out-of-plane deformation and in-plane fiber misalignment. They use microscopy to locate instability sites and determine the wrinkle heights as multiples of the cured ply thickness of their material and the angular in-plane deviation of the 0° plies. The latter was done by measuring the aspect ratio of the elliptical shaped fibers, a principle that was originally introduced by Yurgartis [32] and applied and refined since then [15, 33–35]. Belnoue et al. studied the formation of out-of-plane wrinkles during prepreg de-bulking and curing due to AFP gaps and overlap in [15]. They used micrographs to compare the out-of-plane deflection of their experiments to the results of their manufacturing process simulations of the autoclave curing cycle for various curing pressures. In [16], Lan et al. studied the influence of gaps and overlaps on in-plane shear, as well as on compressive stress and strain. They also investigated the influence of curing with and without a caul plate on microstructure, which they analyzed by scanning electron microscopy. For laminates with a [(−45°/45°)3s − 45°] stacking sequence, they found resin-rich zones for gaps and fiber-rich zones for overlaps. This was less observed for a [90°/0°/90°] stacking sequence, where gaps were partially closed by adjacent plies of the same orientation. In both cases, using a caul plate for curing improved gap healing.

To the authors’ knowledge, no studies on the effects of characteristic AFP defects are available for thermoplastic material. Since thermoset curing and thermoplastic consolidation processes are likely to induce different homogenization processes for the laminate subsequent to the AFP layup, the results
available for thermoset materials cannot be directly applied to thermoplastic laminates. Since, as mentioned above, thermoplastic AFP technology is becoming more and more relevant for structural applications, this study is meant to make a first attempt to fill this gap. We manufactured coupon laminates, which contained characteristic defects. For these laminates, parameters like stacking sequence, defect type and size were varied. We used different processes to consolidate the laminates. Microsections were prepared at different process steps. Tensile and compression tests were performed to quantify the impact on part performance. We investigated whether the consolidation process does have an impact on the mechanical performance of benchmark laminates (Null-Hypothesis 1; \( H_{0,1} \)), whether the defect type \( (H_{0,2}) \) or size \( (H_{0,3}) \) has an effect on mechanical performance, and whether the stacking sequence \( (H_{0,4}) \) or consolidation process \( (H_{0,5}) \) changes these effects.

## 2. Materials and methods

### 2.1. Material

A slit tape material with a polyphenylene sulphide (PPS) matrix and unspecified carbon fibers (CF) was supplied by Celanese for the purpose of this study. The material contains 60% wt. unidirectional, continuous fibers. The tradename of the material is Celstran CFR-T3 CF60-01. Table 1 presents relevant material data, that was taken from the manufacturer’s data sheet [36]. The supplier provided the material as a slit-tape with a width of 1/4". Since the moisture absorption of PPS is considered to be relatively low, the tape material and the preforms were not dried before layup and consolidation, respectively.

### 2.2. Specimen design

The baseline for all specimens was a quasi-isotropic, symmetrical 16-ply layup with 45° relative angle of adjacent plies. Besides defect-free reference laminates (R), laminates that contained Gaps (G) and Overlaps (O) were considered. The defect-containing plies (0°, 90°) and the distribution strategies of these plies among the laminate were varied. Table 2 shows the resulting different Stacking Sequences (SS). The defects in 0° plies are in fiber direction, while for defects in 90° plies, a perpendicular shift of fibers is considered, as illustrated by Figure 2. Defect sizes were chosen based on aerospace requirements to lie at 7.35 mm and 2.5 mm for gaps and 7.35 mm and 1 mm for overlaps.

### 2.3. Specimen manufacturing and preparation

For preform layup, we used a state-of-the-art Coriolis AFP machine. A diode laser system (Laserline LDF 6000-100) heated the material. The laser was working at a near-infrared wavelength range (980 – 1040 nm). The nip-point temperature was monitored using a FLIR A325sc infrared camera and was kept constant at 350 °C for all specimens. The laser spot of the used optics/homogenizer configuration is rectangular with dimensions of approximately 6.5 mm × 53.3 mm, derived from the calibration records for an intensity level of 80%. We configured the angle of incidence under the premise that the fed material and the substrate show the same temperature when reaching the nip-point. Layup was performed on a polyimide film with a thickness of 50 μm (Kapton HN 200). The film was attached by a vacuum technique to a heated aluminum plate, which was mounted on the vertical positioner system of the AFP workcell. The plate temperature was set to 100 °C. We used a constant placement speed of 0.2 m/s and a compaction force of 1000 N, which corresponds to an average pressure of around 7.2 bar with the used compaction roller system.

We investigated three different consolidation processes subsequent to layup. The first process was a variothermal process (PV) conducted with a closed mold inside a hydraulic press. To limit squeeze flow due to tool tolerances during the process, the specimens were wrapped with polyimide film. Shuler and Advani used a comparable sealing technique in [37] for specimen manufacturing in a hot press. Autoclave (A) consolidation with a caul plate is considered as the second process. The third process is an isothermal press-based stamp forming process (PI) with external pre-heating in an infrared oven. Figure 3 shows the corresponding processing parameters as well as pictures of the resulting blanks and sketches of the processing chains. We used a 130-ton hydraulic heating press for all press-
based consolidation experiments. The infrared oven used for stamp forming consists of twelve elements of Krelus’s Mini emitters that work at a mid-infrared wavelength. The process was calibrated by the production of test specimens with integrated thermocouples (TC) to monitor the temperature distribution over the laminate and its development throughout the consolidation process. No further laminate replicates were manufactured due to the large number of configurations and the limited capacities. Laminates with all four stacking sequences were examined in the PV process. In the PI and the A process, only laminates with 90°/C14 defects were considered.

2.4. Nomenclature

Specimens are referred to by a generic nomenclature: consolidation process – defect type-defect ply-stacking sequence-defect size. Defect size is denoted as L for large defects of 7.35 mm, and S for small defects with 2.5 mm and 1 mm for gaps and overlaps, respectively. Table 3 summarizes the parameters.

2.5. Characterization

All specimens were cut on an ATM Brilliant 265 disk cutter with a 1.67 mm corundum disk. We used wet-chemical analysis following DIN-EN 2564 to determine porosity and fiber mass fraction. Here, three samples from one specimen were taken on laminate level for each consolidation process. A total of nine samples from three specimens were taken on preform and neat-tape level. To determine the average degree of crystallinity, differential scanning calorimetry measurements (DSC) were performed on all levels using a Netzsch 214 Polyma. We used a heating rate of 10 K/min to heat the sample up to 320°C. The degree of crystallinity \(X_c\) was calculated according to Equation (1), as taken from [38]:

\[
X_c(\%) = \frac{\Delta H_f + \Delta H_c}{\Delta H_m(1 - x)} \times 100\%
\]

\(\Delta H_f\) is the measured fusion enthalpy, \(\Delta H_c\) the measured cold crystallization enthalpy, \(\Delta H_m\) is the fusion enthalpy of a 100% crystalline PPS and \(x\) the fiber mass fraction, obtained through wet-chemical analysis.
Literature [38] reports values for $\Delta H^o_m$ of between 50 J/g and 150.4 J/g. Here, the latter was used to simplify the absolute comparison with the findings of Sacchetti et al. [39].

To investigate laminate quality, one microsection per configuration was prepared. Mounted samples were micrographically analyzed using a Leica DM4000 M LED microscope.

All mechanical tests were conducted on a Hegewald Peschke Inspekt universal testing machine with a 250 kN load-cell. Five valid specimens per laminate and loading mode were tested in $0^\circ$ direction. Tensile testing and corresponding specimen preparation was carried out according to DIN ISO 527. Gripping areas were supported with 50 mm-long, 2 mm-thick tabs made from glass-fiber-reinforced material in $a+45^\circ/−45^\circ$ fiber orientation. We used a GOM Aramis system as a digital extensometer to record the strain based on digital image correlation. An 8 mm-long area in the midsection of the specimen over the entire specimen width was chosen as region of interest for quantitative strain analysis. Values were obtained within this area at a spacing of 0.5 mm, as depicted in Figure 4. To visualize strain concentration development over the test, the average of ten maximum and minimum strain values as well as the average strain over the entire visible specimen area were plotted over the stress, comparable to the analysis described by Sause [40].

Compressive testing was conducted in reference to ASTM-6484, a test standard for the open-hole-compression (OHC) test. However, no hole was applied to the specimens, to avoid possible interactions with the present defects. The OHC standard was chosen over other standards for compressive testing because of the high gauge length, which allows testing with multiple or staggered defects. The specimens’ total length of 300 mm was taken from the test standard; the width was adjusted to 25 mm instead of 36 mm. An OHC clamping fixture was used as an anti-buckling guide for the test. For this reason, digital image correlation could not be used to measure the strain in compressive testing. Table 4 summarizes the specimens’ dimensions. For both tensile and compressive test specimens, the specimen thickness was approximately 2.4 mm, which matches with the tensile testing standard, but is below the range defined in the OHC test standard, which is 3 – 5 mm.

2.5. Hypotheses and statistical methods applied

For the statistical analysis of results, Levene tests were conducted to assess whether homogeneity of variance could be assumed for statistical analysis of the samples within one consolidation process and stacking sequence. Groups that did show variance homogeneity were tested with analysis of variance (ANOVA). Welch tests were selected for groups that showed inhomogeneity of variance, as the test was reported superior to comparable ones, such as Brown-Forsythe or Kruskal-Wallis, in literature [41–43]. Tukey HSD and Games-Howell post-hoc tests were selected for groups with homogenous and inhomogeneous variances respectively, according to [44] and [45]. An $\alpha$ level of .05 was used for all analyses. The following five null-hypotheses have been tested:

- $H_{0,1}$: The consolidation process does not have an effect on the mechanical performance of the benchmark laminates for a certain SS – referred to in the text as ‘effect of consolidation process on benchmark laminates’
- $H_{0,2}$: The defect type (gap, overlap) does not change the mechanical performance in terms of ultimate strength (tensile, compressive) for a certain SS, defect size and consolidation process – referred to as ‘effect of defect type’
- $H_{0,3}$: The defect size does not change the mechanical performance in terms of ultimate strength (tensile, compressive) for a certain SS, defect type and consolidation process – referred to as ‘effect of defect size’
- $H_{0,4}$: The stacking sequence does not change the mechanical performance in terms of ultimate strength (tensile, compressive) for a certain ply on the mechanical performance in terms of ultimate strength (tensile, compressive) for a certain consolidation process – referred to as ‘effect of stacking sequence’

| Table 4. Specimen dimensions mechanical testing (*: adjusted; test standard is 36 mm). |
|---|---|---|
| Length [mm] | 250 | 300 |
| Width [mm] | 25 | 25* |
| Thickness [mm] | 2.4 | 2.4 |

Figure 4. Local strain analysis (PV-G-90°-D-L).

Table 4. Specimen dimensions mechanical testing (*: adjusted; test standard is 36 mm).
- **$H_{0.5}$**: The consolidation process does not change the effect of the defect on the relative mechanical performance in terms of ultimate strength (tensile, compressive) for G-90°-D-L configuration – referred to as ‘effect of consolidation process on distributed, large 90° gaps’

For testing the influence of the defect type in $H_{0.2}$, the defect size is split binary in small and large. For small defects, this means that a 2.5 mm gap compares to a 1 mm overlap, as these sizes are considered the threshold for aerospace defect investigations. In both cases, the size of the large defect is 7.35 mm.

### 3. Results and discussion

#### 3.1. Microscopy

**3.1.1. Overall laminate structure and porosity**

Figure 5 shows a micrograph prepared from the tape material. Fibers are distributed homogenously over the tape cross-section. Unsaturated fiber bundles can be found embedded in the tape. A comparable poor impregnation was observed in micrographs of polyamide tapes from the same supplier in [46].

Figure 6 shows preforms with agglomerated defects. All laminates contain some micro-porosity in defect-free areas. The AFP process is not able to re-impregnate the tapes entirely, as reported in [8] and [9] for PEEK-CF material. All defects align well, which proves the high layup accuracy of the AFP machine. In the preform with agglomerated, large 90° gaps (G-90°-A-L), the remaining plies fill the defect area macroscopically as a result of plastic flow deformation during layup. However, the plies contain a higher amount of porosity in these areas compared to the defect free areas. Only the last ply perpendicular to the defect (ply 15) shows bridging over the defect edge. Local porosity can likely be accounted for by the enhanced laser energy absorption during layup on non-plane substrates. In addition, free tow edges are prone to take up more energy. These phenomena create hotspots on the substrate during layup, which could lead to local deconsolidation and could therefore be the reason for high porosity in these areas. Another possible reason for porosity is the locally reduced compaction pressure due to insufficient roller deformation in the defect area. For the preform with small, agglomerated 90° gaps (G-90°-A-S), subsequent plies do not entirely fill the gaps, which consequently lead to the formation of large pores. Again, porosity of the remaining plies also seems to be locally higher in the defect area. The preform with agglomerated, large 90° overlaps (O-90°-A-L) likewise displays porosity on the ramps resulting from the embedded overlaps, as well as some fiber bridging of ply 15.

Figure 7 presents images of the reference laminates with distributed stacking sequence after consolidation.
The images of A-R-90°-D and PV-R-90°-D show no porosity. Consolidation processes were able to improve material impregnation, as no micro-porosity could be detected. This does not apply for isothermal press consolidation. PI-R-90°-D shows a significant amount of micro-porosity, which is evenly distributed over the laminate thickness. This difference can be explained by the short dwell time of the material in molten state when subjected to the consolidation pressure, due to the high cooling rates of the stamp forming process. Furthermore, Slange et al. identified the deconsolidation of AFP based blanks during IR heating as one reason for porosity after stamp forming in [9]. For PV configurations, some matrix cracks were found, which could occur because of the thermal stresses induced by the closed mold during cooling inside the press and the brittle behavior of the PPS matrix [47].

Figure 8 shows micrographs of specimens with distributed, large defect configuration of both types for all three consolidation processes. The porosity tendencies found for the corresponding reference plates also apply here. Even the defect zones, which locally showed a very high amount of pores on preform level, are void-free after PV and A consolidation. This indicates that squeeze flow did take place during consolidation, which is common during the deformation of unidirectional material under temperature and pressure [48–50].

3.1.2. Flow processes, remaining defect sizes, undulation severity

Figure 9 schematically depicts the flow processes observed.

3.1.2.1. Effect of the defect orientation. In laminates with gaps in 90° plies, these plies partially close the gap by transverse squeeze flow during consolidation. The adjacent plies also contribute to the gap closing, which results in out-of-plane deflections. For PV laminates, these two closing mechanisms vary over the laminate cross section, which results in an irregular laminate with variations in local ply thickness, out-of-plane deflection and remaining gap size and location. The variations could be related to local temperature differences inside the press mold during the heating phase. A further reason might be the varying contact conditions of the press mold and the laminate due to the non-planar surface on one side. Finally the embedded porosities may have caused inhomogeneous temperature distribution inside the preform. The resulting non-uniform viscosity and pressure distribution could have caused such random flow phenomena. The image of PV-G-90°-D-L in Figure 8 confirms the disorder of plies. All four initial gaps remain, but are no longer aligned. The same applies, in a less strong way since there are no defects, to
the PV reference. In laminates with gaps in 0° plies, these 0° plies hardly contribute to gap closing. Instead, the gaps get filled mostly by the adjacent plies, which results in large out-of-plane deflections and local ply thickness variations. PV-G-0°-D-L does even show surface defects in the defect area,
which indicated the lack of material due to limited flow.

These observations correlate with the general anisotropic flow behavior of unidirectional thermoplastic material. Due to the high ratio of extensional viscosity of the composite material in the fiber direction to its shear viscosity transverse to the fiber direction, flow is only assumed to occur in the direction transverse to the fibers for unidirectional laminates [49, 50]. Schäfer confirmed this behavior as one result of his squeeze flow experiments with PA6-CF UD tape [51]. Comparable observations were also made for thermoset AFP laminates by Croft et al. in [19] based on micrograph analysis. Gaps were filled by subsequent layer application, and therefore no resin rich areas were found. Li et al. report similar flow mechanisms for gap filling in [22]. Concerning multiaxial laminates, Shuler and Advani further found instable squeeze-flow to occur for cross-ply laminates with thermoplastic matrix [37]. They assumed a non-slip criterion at ply interfaces. Therefore, the inextensibility of the two adjacent plies limits each other’s flow, which causes instable macroscopic flow deformation. The extent is found to depend on the ratio of ply surface to ply volume. In this study, the relative orientation of plies is 45°. Therefore, adjacent plies have different effective viscosities in the defect direction, which might enhance irregular flow phenomena during gap closing.

3.1.2.2. Effect of the consolidation process. In the PI laminate with distributed, large gaps (PI-G-90°-D-L), the gaps in the plies near the surface remain larger than the ones closer to the mid-plane of the laminate. This can be well explained by the cooling of the laminate from the outside to the inside, as
soon as it is in contact to the press mold. Therefore, the inner plies of the laminate remain in molten state, which permits more flow. The out-of-plane deflections are less strong, compared to PV, which might be due to the tensile stress state of the laminate during consolidation created by the clamping frame. The $0^\circ$ plies in the middle of the laminate in fact remain very straight. An additional reason for this might be the external preheating, which ensures that the entire laminate is in molten state when press pressure is applied, in combination with the short time that the laminate is under pressure in molten state, due to the high cooling rates. Therefore, the flow processes happen very systematically and symmetrically. This is in contrast to the heating characteristics described for the variothermal process.

The corresponding autoclave laminate (A-G-90°-G-L) generally is comparable to the PV sample. The gaps are closed only partially by transverse flow of the ply that contains the defect, which results in out-of-plane undulations of the adjacent plies. The underlying mechanisms are comparable, however the general appearance of A-G-90°-G-L is slightly more homogeneous compared to PV-G-90°-G-L. This might be due to the fact that an open mold was used in autoclave consolidation, which causes less variations in viscosity and pressure distribution compared to the closed mold of PV process. Also, the heating and cooling rates were reduced by 50% compared to PV, which enhances normalization processes.

3.1.2.3. Effect of the defect type. Concerning PV overlap configurations, all specimens shown in Figure 8 have plane surfaces. This means that the consolidation process redistributed the local excess of material. For overlaps in 90° plies consolidated in the variothermal press process, an increased thickness of these plies can only be found locally and of much smaller extent compared to the preform. This shows that, as for gaps, the transversal squeeze flow is dominating during consolidation. For PV-O-90°-D-L, local differences were observed. These lead to an inhomogeneous laminate structure. The interpretation discussed for PV-G-90°-D-L applies here, too. The corresponding laminate that was consolidated in the isothermal press process (PI-O-90°-D-L) showed an increased thickness of the 90° plies close to the laminate surfaces, while a regular thickness of the 90° plies close to the mid-plane of the laminate could be detected. This indicates that the inner plies thinned down more by transversal flow compared to the outer plies, which matches with the processing characteristics described for PI-G-90°-D-L. All overlaps in 0° plies of PV-O-0°-D-L configuration were still present after consolidation. However, they were no longer aligned. These longitudinal moves appeared to be of random direction and extent. They seemed to be connected to the flow of the adjacent plies, which showed large local variations in individual ply thickness. The thickness variations were larger for 90° plies than for $+45^\circ$ and $-45^\circ$ plies. The ply thickness variations lead to thickness normalization of the entire laminate, but a very inhomogeneous laminate appearance. At the tip of the ending 0° plies, some small pure matrix regions could be found.

Small resin-rich pockets at the tips of the plies that contain the defect were also found for thermoset material by Li et al. [22]. In this study, such areas were found only occasionally for some ply tips in variothermally consolidated laminates. In most zones affected by flow processes, the fibers were still distributed homogenously among matrix material. Generally, squeeze flow can either be matrix flowing through the fiber bed, or matrix and fibers flowing together. Shuler and Advani in [37] assumed that high matrix viscosities and dense fiber packing limit flow through the fiber bed. Therefore, they considered the squeeze flow of matrix and fibers together as being dominant for thermoplastic material, which matches with our observations. The rare matrix rich zones at the tips of defect plies can be explained by the limited ability of the adjacent $45^\circ$ plies to deform locally into these zones, which are most likely former voids caused by fiber bridging. Therefore, they were filled by matrix flow through the fiber bed.

3.1.2.4. Effect of the defect distribution. In the PV laminate with agglomerated, large gaps (PV-G-90°-A-L), plies between the defect zones and the skins remain comparably straight, while the plies in between the defect zones show large undulations, as they appear to fill the remaining gaps. Similar tendencies can be found when considering the laminates containing agglomerated overlaps. So generally, for PV specimens, laminates with defects distributed over the stacking sequence deform in a more homogenous way, while for the laminates with agglomerated defects, plies between defect layers are more affected than plies between defect layers and skins. Besides out-of-plane undulations, in-plane fiber misalignment can be found when considering the appearance of the $0^\circ$ fibers in the images of Figure 8. It appears to be concentrated in the out-of-plane deflection areas and next to the same, which corresponds well with the findings of Lightfoot et al. [31]. Belhoue et al. reported the maximum extent of the in-plane misalignment to be in the areas with maximum deflection amplitude.
[15]. E.g. Ply 13 of PV-G-90°-D-S seems to confirm this behavior. This indicates that squeeze flow is connected to inter-ply shear mechanisms, which were considered likely by Picher-Martel [50].

In case of isothermal press consolidation, the agglomerated stacking sequence has a different influence. In contrast to the distributed configuration, both double gaps of PI-G-90°-A-L have the same distance to the skin and therefore display comparable closing. As they are not entirely closed by transverse flow, the adjacent -45° plies on both sides of the gaps deflect out of their plane in these areas. The gap between plies 12 and 13 is slightly less closed than that between ply 4 and ply 5, which can be explained by the fact that the top skin comes into contact with the mold first, when the upper mold moves down, and therefore is subjected to faster cooling and solidification. This also results in a local surface defect in this area on this side of the laminate. However, the plies in the middle of the laminate remain unaffected.

3.2. Wet-chemical and DSC

Table 5 includes the results for the porosity and the degree of crystallinity. Neat-tape showed a porosity of over 3%vol., which corresponds with the insufficient impregnation of the material observed in microsection analysis. After AFP, the porosity level increased to 4.5%vol. The layup process is not able to improve micro impregnation, which matches with the findings described in [52] for imperfectly impregnated tape material with polyamide 6 matrix from the same supplier. All subsequent consolidation processes reduced porosity. However, only A and PV specimens yielded a very low porosity of under 0.5%vol. PI process re-impregnated the unsaturated preforms only up to a certain level, similar to the findings of [52] and [9] for stamp forming of AFP blanks made from tape with PA6 and PEEK matrices, respectively.

Concerning the degree of crystallinity, PV and A specimens displayed no significant differences, with both values being just under 30%. These absolute values lie in the range of these findings of Sacchetti et al. [39]. They manufactured their press consolidated PPS-CF laminate with 20 bar consolidation pressure and 5 K/min heat rate. DSC measurements of these specimens yielded a crystallinity of over 33%. However, their PPS-CF UD tape was sourced from a different supplier and had a higher fiber weight content of 66%. The crystallinity of PI specimens in this study was 26.5%. When comparing the value to PV, the decrease in crystallinity can be related to the higher cooling rates of the PI process, as cooling rate is expected to influence the crystallinity growth in PPS [53, 54]. Cooling rates were measured with embedded TC in the center layers of a test specimen. During PI process at 320°C, a cooling rate of 2950 K/min was found, for a mold temperature of 150°C. In [39], Sacchetti et al. noted even higher cooling rates of 4200 K/min and 7600 K/min for mold temperatures of 200°C and 100°C, respectively. However, their laminates were only 12 plies thick, and unidirectional. This, and the higher fiber mass content of their material, may improve the thermal conductivity in laminate thickness direction and therefore increase the cooling rate in the center of the laminate. The absolute value for crystallinity obtained for PI lied between their results for mold temperatures of 200°C and 100°C, which are 28.1% and 22.4%, respectively. Possible reasons for the fact that the crystallinity values of both studies fit better than the corresponding cooling rates are that the entire laminate thickness was considered for DSC, and cooling conditions in outer layers tend to be more alike. Another possible reason is that data for determining the cooling rate was only sampled at 2 Hz in this study, which might be a reason for the distortion of the obtained cooling rate values. Also, the dwell time in the press before demolding must be considered, as all dwell temperatures were above glass transition temperature. Sacchetti et al. used 60 s dwell time, in contrast to 120 s applied in this study.

3.3. Tensile testing

3.3.1. Ultimate stress

Figure 10 shows the average ultimate tensile strengths (UTS) of the five specimens tested for each configuration, as well as the corresponding standard deviations as error bars. When comparing the UTS values of the benchmark configurations, Levene’s F test revealed that the homogeneity of variance assumption was not met ($p = .026$). According to Welch’s F test results ($F(7, 12.982) = 118.264, p < .001$), significant differences were found between the samples consolidated in different processes. Therefore, $H_{0,1}$ (effect of consolidation process on benchmark laminates) had to be rejected for ultimate tensile stress. For stacking sequences, A and PI configurations showed an increased UTS compared to the similar PV configuration, which was found to be significant according to Games-Howell post-hoc tests ($p < .05$). A similar comparison of A and PI configurations yielded no significant differences. Regarding the influence of the stacking sequence within the configurations of one consolidation process, only PV-R-0-A showed a significantly higher UTS than the other SS for PV. No significant influence of the SS was found for A or PI. Generally, the low UTS of PV
configurations, as well as the high standard deviation of PV-R-90°-A, could be related to the severe undulation found in the benchmark laminate. Also, the matrix cracks could initiate delamination failure, as such interactions were reported for multiaxial thermoset laminates [55–57]. These findings suggest that the applied process is not ideal for this type of material (Table 5).

Table 6 summarizes the results of the corresponding post-hoc tests, the appendix contains the corresponding data. Within each combination of consolidation process and stacking sequence, significant effects of the embedded defects were found in all cases, except the two PI configurations. To compare effect strengths among configurations with large gaps, Figure 11 shows a bar chart of the relevant UTSs relative to the corresponding references. The highest values of over 70% reduction were found for the laminates with defects in 0° plies. PV-
Table 6. Summary effects of defects on ultimate strength.

| Defect Type-Defect Size | G-L | G-S | O-L | O-S |
|-------------------------|-----|-----|-----|-----|
| Consolidation-defect ply-SS | PV-90°-D | - | +/– | +/– |
| PV-90°-A | - | +/– | - | +/– |
| PV-0°-D | - | - | +/– | +/– |
| PV-0°-A | - | - | - | - |
| A-90°-D | - | - | - | - |
| A-90°-A | - | - | - | - |
| PI-90°-D | +/– | +/– | +/– | +/– |
| PI-90°-A | +/– | +/– | +/– | +/– |

> 25% decrease.

Significant decrease < 25%.

+/– no significant effect.

Significant increase.

Table 7. Significance p for UTS post-hoc tests of hypotheses H0,2 - H0,5.

| Defect Type-Defect Size | PV-90°-D | PV-90°-A | PV-0°-D | PV-0°-A | PI-90°-D |
|-------------------------|---------|---------|---------|---------|---------|
| Consolidation-defect ply-SS | - | 0.084 | 0.527 | 0.000 | 0.977 |
| PV-90°-A | 0.000 | 0.004 | 0.000 | 0.000 | 0.000 |
| PV-0°-D | 0.793 | 0.000 | 0.000 | 0.000 | 0.000 |
| PV-0°-A | 0.972 | 0.000 | 0.000 | 0.000 | 0.000 |

Concerning the defect size, H0,3 (effect of defect size) had to be rejected for 90° gaps and 0° overlaps. Again, the behavior of the laminates with 90° defects can be correlated to the measured undulation severity. For PV laminates with distributed defects, small gaps on average showed less strong undulations then large gaps, which could explain the stronger decrease in UTS. The size of a 0° overlap is important for both SS considered, as reducing the initial overlap length from 7.35 mm to 1 mm lead to a > 40% reduction in UTS for both cases. This indicates that a certain overlapping length is required for a suitable load transmission between the ending fibers by the matrix. For laminates with gaps in 0° plies, H0,3 could not be rejected, which shows that even a gap as small as 2.5 mm caused a large drop in UTS.

H0,4 (effect of stacking sequence) could only be rejected for autoclave consolidation. Here, the differences of both SS regarding the undulations of the individual 0° plies, which are described in Chapter...
could be a reason. The outer two 0° plies of PV-G-90°-A-L, which remain almost straight, were able to transfer the tensile stress and therefore lead to less UTS reduction compared to each reference. For the other two consolidation processes considered, this irregular undulation distribution was not found, and consequently the variation of SS did not significantly influence UTS. Post-hoc tests revealed that $H_{0.5}$ (effect of consolidation process on distributed, large 90° gaps) had to be rejected for all pairwise comparisons. This seems evident, as major differences between the corresponding laminates were found throughout the analysis performed.

The relevant literature benchmarks available regarding the effects of defects in non-open-hole tensile testing are the publications by Woigk et al. [21] and Croft et al. [19], as most other publications focus on compressive and shear behavior. Since the actual strength reduction found in the considered studies strongly depends on the material used and the exact defect geometry, an absolute comparison can generally not be recommended. However, the values might help to get a feeling for the magnitude. Woigk et al. in [21] tested basic gap and overlap configurations contained defects in 1/4 of these plies, staggered gaps configuration in 1/2. For the mixed gap/overlap configuration, all non 0° plies contained defects. They reported no significant effect of their agglomerated tow-wide gaps perpendicular to the loading direction on the UTS, which was found in this study for PI consolidation for a comparable stacking sequence and gap size (PI-G-90°-A-L).

The micrographs they presented for their gap laminate showed resin pockets and undulations of the adjacent 0° plies; the other 0° ply seemed to be unaffected. They further found a significant increase in ultimate tensile strength by 3% for the overlap configuration, and a significant reduction of 7.4% for the mixed configuration. In [19], tow-wide defects were oriented in the fiber direction in their unidirectional stacking. This has to be seen as the main reason why they did not find a significant effect on the UTS for both gaps and overlaps more than the fact that they did use material with a thermoset matrix.

### 3.3.2. Strain concentrations

Figure 12 shows examples of strain/stress plots for PV and PI laminates with distributed, large gaps and overlaps, as well as the corresponding reference.
All reference specimens showed a linear increase of the measured maximum strain concentration that is slightly higher than the average strain, which is also increasing linearly. The strain of PV-R-90°-D remained linear until sudden failure at ~380 MPa. For PV-G-90°-D-L, maximum strain increased in a non-linear manner almost from the beginning of the experiment. As can be seen from the corresponding color-coded strain distribution maps at a 14 kN load depicted in Figure 13, this strain concentration zone spreads over the entire specimen width. PV-O-90°-D-L showed a lower than average strain in the defect area, which caused a drop in the minimum strain curve compared to the average strain measured. The same tendencies applied for PV-G-0°-D-L and -O-L, and were found to be even stronger compared to the laminates with 90° defects. This could be explained by the fact that defects are embedded in the 0° layers, which contribute more to the stiffness of the multiaxial laminate than the 90° plies. PI-G-90°-D-L and PI-O-90°-D-L did not show any non-linearities, and accordingly no clear strain concentration could be found in the defect region. This matches with differences found in the consolidation processes regarding the influence on the UTS, as well as with the small extent of local undulations that was found in the micrographs of the different configurations in these areas. The non-linear behavior found in the plots of PI-R-90°-D after ~500 MPa was caused by deformations of the top 45° layer, as can be seen in Figure 14. Similar effects were observed for defect configurations as well; however, these were not located in the analysis area.

3.4. Compressive testing

Figure 15 shows the average ultimate compressive strengths (UCS) of five specimens, which were tested for each configuration, including the
standard deviations as error bars. For UCS values of reference specimens, Levene’s F test yielded homogeneity of variance (p = .271). ANOVA showed that there were significant differences among all configurations, F (7, 31) = 16.32, p < .001, so H₀₁ (effect of consolidation process on benchmark laminates) had to be rejected for UCS as well. According to the Tukey HSD post-hoc tests among PV configurations, 90° agglomerated stacking showed a significantly lower UCS than 90° distributed stacking (p = .002). No other differences were found to be significant. Also for autoclave specimens, the UCS of distributed configuration was found to be 87 MPa higher than for agglomerated configuration. For PI specimens, PI-R-90°-D showed 29 MPa higher UCS than PI-R-90°-A, which was non-significant according to the post-hoc tests. These UCS reductions by agglomerated stacking of transverse plies could be possibly related to the in-situ effect [59, 60].

Regarding the influence of the consolidation process, A-R-90°-D showed that the UCS increased by 35 MPa and 22 MPa compared to PV-R-90°-D and PI-R-90°-D, respectively. Only the first case is significant. Possible reasons can be seen in the undulations (PV) and porosities (PI). According to Berbinau et al. [61], both porosity and undulation can initiate elastic kinking, the first stage of compressive failure in their model.

Table 6 summarizes the post-hoc tests conducted on defect configurations and the corresponding reference, the statistical data can be found in the appendix. For PV laminates with distributed defects, the tests found significant negative effects on the UCS for large defect sizes, PV-G-90°-D-L (p < .001) and PV-O-90°-D-L (p = .033). All other three stacking sequences showed a significant decrease in the UCS for all defects, except for the large-overlap configurations. The configurations with defects in 0° plies showed the largest decrease in the UCS of over 60%. The 7.35 mm gap did also lead to a significant decrease for both autoclave configurations. Concerning the isothermal press processed samples, no significant effect was found for PI-G-90°-D-L (p = .200) and PI-G-90°-A-L (p = .797). Figure 16 summarizes the influence of the large gap defect relative to the corresponding reference for all laminates under consideration.

Table 8 presents the results of the hypothesis tests. H₀₂ (effect of defect type) had to be rejected for all large defects, as well as for small, distributed 0° defects in a PV laminate. For all these laminates, overlaps show a higher UCS than gaps. H₀₃ (effect of defect size) had to be kept only for distributed 90° overlaps and agglomerated 0° gaps in variothermally consolidated laminates. Large 90° gaps lead to a reduced UCS compared to small 90° gaps for both SS. This can be explained in terms of the more severe undulations, which were found for large defects. The correlation between undulation severity, strain concentrations and compressive strength has been previously reported for laminates with thermoset matrices [17, 20, 62, 63]. It is likely that this applies for brittle thermoplastic matrices as well. For 0° gaps, a significant effect of size was found only for distributed defects, also because the variance of PV-G-90°-A-S was very high. Again, smaller gaps showed slightly higher UCS than large gaps, which is still only around 50% the reference’s UCS. Large overlaps in 0° plies did not cause a significant drop of UCS for PV3 (p = .0875) and PV4 (p = .999). Small overlaps of 0° defects, however, lead to a considerably high strength reduction of 32% and 35% for distributed and agglomerated stacking. H₀₄ (effect of stacking sequence) had to be kept for PV and PI consolidation. As for tensile testing, an influence of the SS on the effect of a large gap was only found for autoclave consolidation. Here, UCS was reduced by 33% and 23% for distributed and agglomerated gaps, respectively. The observations made for tensile testing regarding the fiber undulation distribution seem to apply here also. The described differences regarding the gap closing mechanism and the remaining gap lengths between PI-G-90°-D-L and PI-G-90°-A-L did not cause an effect on either UTS or UCS. H₀₅ (effect of consolidation process on distributed, large 90° gaps) had to be kept for the comparison of A and PV consolidation, as distributed, large gaps in both cases caused a reduction of UCS by a little over 30%. H₀₅ had to be rejected for PI compared to PV and A. As reported above, the small decreases for PI specimens of 1% and 5% were identified to be non-significant according to post-hoc tests.
Croft et al. in [19] did not find any significant effects of their defects on the UCS. The increase of the overlap configuration by 7% according to their discussion can mostly be accounted to the error of the area estimation during stress calculation. The defects investigated by Sawicki and Minguet in [17] for un-notched compression of multiaxial laminates were mixtures of gap and overlap in 90° plies with a defect size of 0.03" and 0.10". Therefore, a comparison with the small defect size of this study seems most appropriate. Sawicki and Minguet found a decrease of the ultimate strength between 8 and 13% at ambient conditions, which is higher than the values obtained for the distributed stacking (8% for PV-G-90°-D-S and 2% for PV-O-90°-D-S), but lower than for agglomerated stacking (16% and 17%). In addition, the ratio of defect plies was lower than in this study. Mukhopadhyay et al. in [20] quantified the out-of-plane wrinkle severity by the ramp angle $\alpha$, and found the failure mode to change for $\alpha > 8°$. Regarding UCS, they found a 33% decrease for a ramp angle of ~10°. These values correspond quite well to the ones obtained for A-G-90°-D-L, where 8° ramp angle and 33% UCS decrease were found. Woigk et al. in [21] also found delamination failure for their mixed-gap overlap specimens, along with a UCS decrease of 14.7%. 

Figure 15. Ultimate compressive strength.
However, their isolated gap and overlap specimens showed an increased UCS. In this study, the laminates with the highest undulation extent, G-1 configurations, also showed the greatest decrease of UCS. This matches with the findings that performance is unaffected for PI specimens, since the measured deflections here were small, in general. Marouene et al. in [18] manufactured AFP laminates with gaps and overlaps and carried out open-hole compression (OHC) tests. Defects vary in layer (0°, 90°), position and shape (straight, triangular). They also built a 2D FEM model in ABAQUS, which showed good consistency with experimental results. Gaps in the 90° layer, that were positioned in the center of the specimens and therefore at the position of the hole, and gaps in the 0° layer, that were shifted 10 mm from the hole center, were found to decrease the OHC strength by 7% and 5%, respectively. Both defects combined lead to a strength decrease of over 12%. However, centered gaps and overlaps increased the OHC strength.

4. Conclusion and outlook

The results of this study give a first reference point towards the influence of characteristic AFP defects in thermoplastic laminates. Table 6 briefly summarizes these results. It is difficult at this stage to make a direct absolute comparison with thermoset laminates because of the many parameters involved and the few studies available. However, gaps in particular were found to have a comparably large negative effect on both UTS and UCS for variothermal press and autoclave processes. This is not surprising, as gaps in 90° plies disrupt fiber alignment over the entire laminate thickness according to microscopic analysis of corresponding samples, and gaps in 0° plies create a weak spot due to the absence of fibers in load direction as the initial gap gets filled by the adjacent plies during consolidation. Consequently, digital-image-correlation-based strain measurements showed strain concentrations in the affected areas. In isothermally stamp formed specimens, fiber misalignments were found to occur more locally and of smaller extent, which corresponds to the fact that no negative effects on mechanical performance and no strain concentrations were found. Large overlaps in variothermally consolidated specimens generally showed no significant reduction of ultimate strength either, even for the stacking sequences with interrupted 0° layers. Here, the overlaps locally reduced the strain. Therefore, the mechanical performance as well as the laminate appearance in micrographs strongly depended on the defect configuration and the applied consolidation processes. This means that for a future definition of knock-down factors, data need to be interpreted very case-specifically for each thermoplastic process route. As a more general guideline based on the current results, 7.35 mm overlaps seem to be preferable to create a laminate that is robust in non-uniform load cases. However, additional effort will be necessary to verify the performance of laminates that contain overlaps for all consolidation processes. Especially for autoclave consolidation, it is interesting whether a comparable performance gain compared to gaps can be reached as it was found for variothermal consolidation. For isothermal consolidation, it must be examined whether the compression performance is also not affected for this defect type.

The use of digital image correlation enabled the monitoring of strain behavior during tensile testing, and the analysis of defect-specific deviations. For
compressive testing, a corresponding analysis would be interesting, but is hard to realize with currently available equipment. In addition, a failure mode analysis would be important to investigate the underlying mechanisms inducing the performance reduction in more detail, as was done by Woigk et al. in [21] with the help of a high-speed camera system. In 'tensile' and 'compression', only the two most basic loading types were considered. It would make sense to expand the considered load cases to include 'shear', for example. Open-hole experiments are a next step towards understanding the interactions of boreholes with the considered defects, as examined for thermoset materials in [18, 19, 30]. Also, fatigue experiments are important because of the general differences between thermoset and thermoplastic materials in terms of their fatigue behavior [64].

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No potential conflict of interest was reported by the authors.

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**Data availability statement**

The data that support the findings of this study are openly available in Mendeley at DOI: 10.17632/29b5dzk6f.2.

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Appendix

Table A1. Significance p for UTS post-hoc tests of defect configurations to reference.

| defect type-defect size | G-L | G-S | O-L | O-S |
|--------------------------|-----|-----|-----|-----|
| Consolidation-defect ply-SS | PV-90°-D | 0.002 | 0.258 | 0.445 | 0.984 |
| PV-90°-A | 0.000 | 0.898 | 0.035 | 0.594 |
| PV-0°-D | 0.000 | 0.000 | 0.273 | 0.001 |
| PV-0°-A | 0.000 | 0.000 | 0.095 | 0.000 |
| A-90°-D | 0.000 |
| A-90°-A | 0.000 |
| PI-90°-D | 0.069 | 0.063 |
| PI-90°-A | 0.667 |

Table A2. Significance p for UCS post-hoc tests of defect configurations to reference.

| defect type-defect size | G-L | G-S | O-L | O-S |
|--------------------------|-----|-----|-----|-----|
| Consolidation-defect ply-SS | PV-90°-D | 0.000 | 0.460 | 0.033 | 0.996 |
| PV-90°-A | 0.000 | 0.015 | 0.373 | 0.007 |
| PV-0°-D | 0.000 | 0.000 | 0.875 | 0.000 |
| PV-0°-A | 0.000 | 0.016 | 0.999 | 0.006 |
| A-90°-D | 0.002 |
| A-90°-A | 0.000 |
| PI-90°-D | 0.200 |
| PI-90°-A | 0.797 |