



In-situ automated fiber placement gap defects filled by fused granular fabrication



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ABSTRACT

This paper presents an investigation into the effect of Fused Granular Fabrication gap filling on the composition and mechanical performance of in-situ consolidation Automated Fiber Placement-manufactured laminates. Two laminates with staggered triangular gap defects were manufactured using in-situ consolidation Automated Fiber Placement. In the first laminate, the defects remained unmodified whereas in the second laminate Fused Granular Fabrication was used to fill the gap defects to mitigate out-of-plane waviness in subsequent plies and large pores which can initiate cracks. The process was successfully demonstrated. Fused Granular Fabrication layer thickness was however hard to adjust to match consolidated ply thickness of the AFP process due to the slightly uneven surface of the AFP substrate resulting in out-of-plane undulations. Compressive strength remained at the same level for both, reference and gap specimens. Tensile strength decreased 11 % and 23 % for gap defects and filled gap defects, respectively. Further work is required to utilize the full potential of the process combination.

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1. Introduction

In-situ consolidation Automated Fiber Placement (in-situ AFP) has great potential to significantly reduce manufacturing time and cost of large-scale aerospace components by eliminating the need for subsequent consolidation in an autoclave. The recent development of AFP-grade prepreg tape material enables mechanical performance close to autoclave level [1,2]. Complex geometries, however, still present a challenge for in-situ AFP since geometry-induced defects such as gaps or overlaps cannot be mitigated by subsequent post-consolidation and remain unchanged as weak points in the laminate. Previous work by the authors showed significant compressive strength knockdown in the order of 50 % due to co-located rectangular gap defects in quasiisotropic in-situ AFP laminates [3]. Groundbreaking work by Sawicki et al. first investigated gap and overlap defects in thermoset AFP laminates in 1998. Gap defect widths between 0.76 mm and 2.5 mm resulted in 0° ply out of waviness and 5 % to 27 % compressive strength reduction [4].

Most of the research was conducted with simplified rectangular defect geometries. Gap- and overlap defects in real double-curved parts are however triangular in shape. Falcó et al. investigated realistic triangular gap defects in thermoset laminates with ¼ inch

tape width and 12° opening angle and found tensile strength decrease of up to 22 % for gap defects without staggering. [5,6].

Zenker et al. investigated hot-press and autoclave post consolidated thermoplastic AFP gap defect specimens and found ultimate compressive strength knockdown of over 60 % compared to reference, due to misalignment and out-of-plane waviness of all plies in the laminate [7]. Previous work by the authors investigated rectangular co-located gap defects in in-situ AFP laminates and found no impact on tensile strength but severe decrease in compressive strength of up to 54 % for 13.2-mm gap defects [3].

A possible solution to overcome the limitation of gap defects in thermoplastic AFP-manufactured laminates was presented by Rakhshabahr et al. who presented a combination of AFP with continuous-fiber-reinforced 3D printing (Fused Filament Fabrication FFF and Continuous Filament Fabrication CFF) to fill gap defects. In the study, 3D printed gap filling elements were printed separately and manually inserted into AFP gap defects. The laminates were subsequently hot pressed for consolidation. Almost no strength knockdown for tensile strength, interlaminar shear strength and flexural strength was found compared to laminates without gap defects [8].

The present work aims to adopt the principle of combining 3D-printing and AFP for gap mitigation of in-situ consolidated laminates. There are several technologies available for joining thermoplastic structures onto thermoplastic laminates. Overmolding uses

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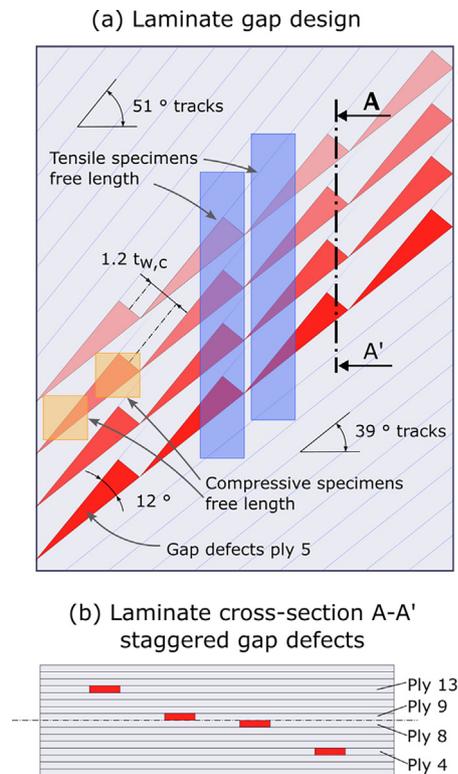


Fig. 1. Laminate gap defect design: (a) Angle difference of defect plies and resulting triangular gap defect geometries; (b) Cross-section with ply stacking sequence and gap staggering.

the injection-molding process to in-situ bond structures directly onto a laminate [9]. This process requires a mold to partially or completely enclose the laminate. In order to eliminate the need for a mold, and thus reducing cost and allowing for a wide range of complex geometries to be manufactured, the over-printing process was developed. This process is based on extrusion-based additive manufacturing technology such as fused granular fabrication (FGF). Using overprinting, structures can be 3D-printed directly onto a laminate where the bond is achieved in-situ through the introduction of energy by the heated extrudate. Previous work on the overprinting of CF/LM-PAEK laminates with short-fiber-reinforced PEEK showed that a shear strength of the bond of up to 40 MPa can be achieved [10].

This work presents an investigation into the combination of in-situ AFP and FGF to mitigate gap defects. To this end laminates with triangular staggered defects with- and without FGF-filled gaps were manufactured and compared in terms of microstructure of defect areas and mechanical properties. A viable and scalable process chain is presented to manufacture complex laminates using the combination of the aforementioned processes.

2. Materials and methods

2.1. Laminate manufacture

While in an industrialized application of the process combination of in-situ AFP and FGF, manufacturing of the laminates can take place in a single production facility, using cooperating robots or a single robot with interchangeable end-effectors, the laminates in this work were manufactured in two robotic cells using a portable flat tooling. A robotic AFP facility with a 6 kW near-infrared-laser and a Multi Tape Laying Head end-effector (AFPT GmbH, Dörth) was used for the AFP process. A closed-loop temperature

control system automatically adjusts the laser power to keep the temperature in the consolidation zone (nip-point) within the optimum process window. AS7/LM-PAEK unidirectional ½-inch prepreg tape with 55 % fiber-volume-fraction was used for the AFP portion of the laminates. The optimum process parameters for the facility and material were established in previous work [11,12] and are summarized in Table 1. These process parameters result in a consolidated tape width of 14.2 mm.

The ply stacking sequence of the manufactured laminates was based on a 16-ply balanced and symmetric (quasiisotropic) stacking sequence. The 45° plies were replaced with 39° and 51° tracks, resulting in 12°-opening angle triangular gaps at the meeting points of the tracks with different fiber orientation, similar to the defect design by Falcó et al. [5]. The four plies with gap defects were staggered using a staggering factor of 1.2 times the consolidated tape width $t_{w,c}$. While for a standard quasiisotropic ply stacking sequence a staggering factor of 0.2 would be used to avoid collocation of track boundaries, here a staggering factor of 1.2 is used, to avoid collocation of gap defects in the laminate (Fig. 1). The resulting ply stacking sequence can be described as $[0^\circ/-45^\circ/90^\circ/(51^\circ/39^\circ)]_{2S}$. Tensile and compressive specimens were positioned in vertical orientation on the laminate. The length of the triangular defects resulting from consolidated tape width and opening angle exceeds the width of the tensile and compressive specimens. One column of triangular gap defects therefore covers two samples and thus every second sample has the same gap pattern. From each laminate eight tensile and compressive specimens were extracted, respectively.

For the second process step of filling the gaps with short-fiber-reinforced polymer, a robotic FGF facility with a single screw extruder end-effector (Hans Weber Maschinenfabrik GmbH, Kronach) was used. The screw has a diameter of 16 mm and can be heated in three different zones to up to 450 °C. The extruder uses granulate as its feedstock. The nozzle diameter was set to 1 mm for this study.

Gaps were filled with TECACOMP PEEK 450 CF30 black granulate (Ensinger GmbH). The PEEK granulate contained 30 % short carbon fibers (by mass) [13].

The geometry and location of the gaps were measured using the robotic system of the FGF facility. A measuring tip was installed on the end-effector and the measured coordinates of defined geometric features of the gap defects were extracted from the control unit of the robot. A digital model of the defects was generated and used for generating the toolpath of the extruder. The software AISync (AIBuild, London) was used to create the desired toolpath.

The print speed was set to $20 \text{ mm} \cdot \text{s}^{-1}$. The layer height was set to the measured thickness of the last ply of the laminate. The extruder temperature was set to 400 °C.

2.2. Microanalysis

Computed tomography scans were acquired using a V|tome|x L (Baker Hughes, Wunstorf) Computed Tomography system. Scan-

Table 1
Process parameters for CF/LM-PAEK [11,12].

Parameter	Value	Unit
Tool temperature	20	°C
Nip-point-temperature ¹	470	°C
Consolidation pressure ²	6	bar
Layup speed	125	mm/s

¹ Nip-point-temperature as measured by the thermocamera, emissivity coefficient $\varepsilon=1$

² Consolidation pressure is the system internal pneumatic pressure, which is applied to the extendable part of the end-effector including the consolidation roller

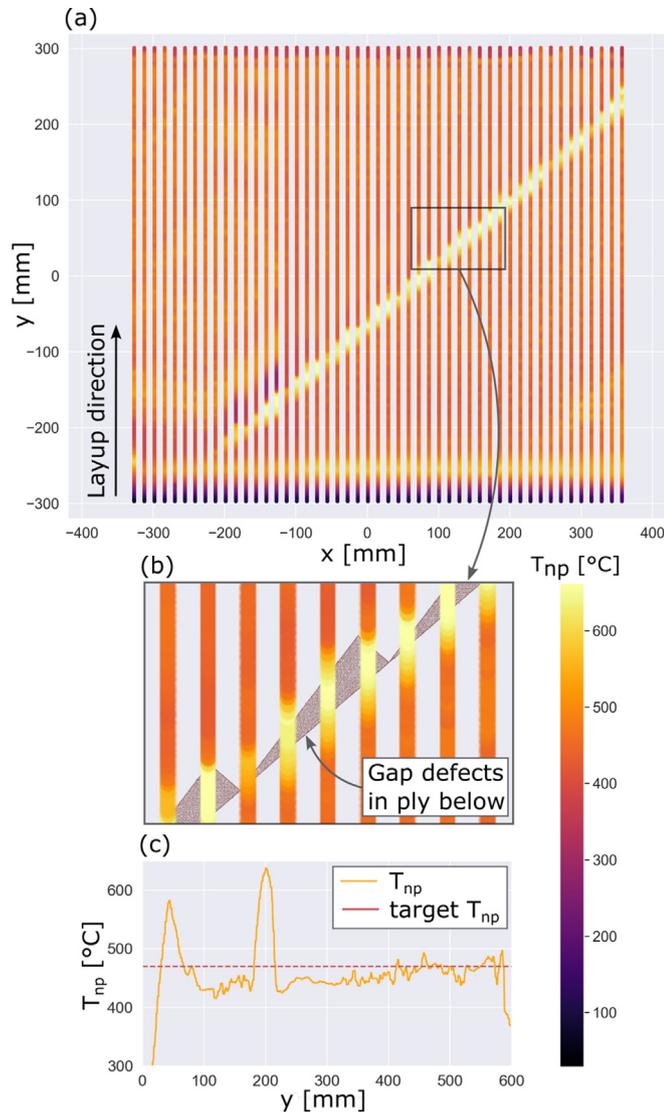


Fig. 2. Temperature profiles of ply 5 of laminate with 3D printed gap defects: (a) heatmap of entire ply; (b) detail section of heatmap and superimposed gap defects in ply below, (c) temperature profile track 20 of ply 5.

ning voltage of 180 kV, current of 250 mA and exposure time of 333 ms were used.

2.3. Mechanical testing

Tensile strength was determined according to AITM 1–0007 A2 test standard [14]. Specimen dimensions were 250 mm in length and 22 mm in width. 50 mm end tabs were attached to the specimens. The specimens were tensile tested to ultimate failure using a test speed of 2 mm/min. Compressive strength was determined according to AITM 1–0008-A2 test standard [15]. Specimen dimensions were 152 mm in length and 22 mm in width with 65 mm end tabs. The specimens were tested to ultimate failure using a test speed of 0.5 mm/min.

3. Results and discussion

Fig. 2 shows a temperature plot that was generated using the AFP temperature control system as tapes were placed on top of a defect ply with FGF-filled gap defects. An increase in process temperature at the location of FGF-filled gaps can be noticed. The temperature was measured by the thermal camera using an emissivity coefficient of $\epsilon = 1$. Different emissivity properties and local surface angle changes of the FGF-filled areas likely affect the measurements. Further investigation using thermocouples is required to analyze the local process temperature.

Porosity plots derived from computed tomography scans of the tensile specimens with gap defects (Fig. 3a) and FGF-filled gaps (Fig. 3b) show significant porosity in the defect areas. Pure triangular gap defects result in porosity primarily at the edges of the gap defects and at the narrow side of the triangle. This can be explained by fiber bridging effects. Due to the bending stiffness of the fibers, the tape cannot be molded closer to the ply drops. FGF-filled defects in some places exhibit extensive porosity over the entire defect area. This suggests that consolidation was not successful in some cases. Furthermore, the characteristic FGF-specific extrusion pattern can be observed in the porosity scans. The width of the extruded course strongly depends on the z-distance between the nozzle and the substrate. The local surface unevenness caused by the in-situ AFP signature makes it difficult to optimize the planned path which can result in over- or under-extrusion and layer thickness, which does not correspond to the in-situ AFP consolidated ply thickness.

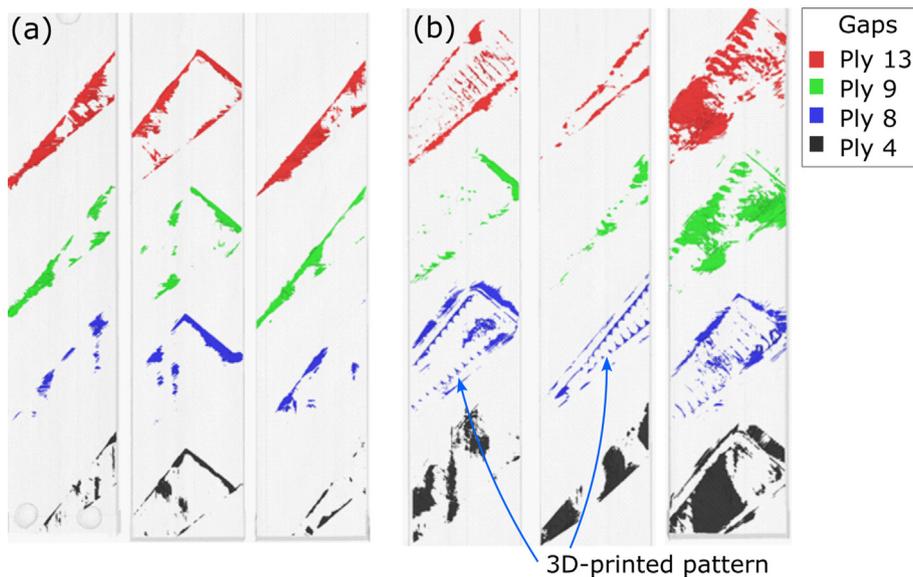


Fig. 3. Compute tomography porosity analysis of tensile test specimens: (a) in-situ AFP gap specimens, (b) in-situ AFP specimens with 3D printed gaps.

Table 2
Mechanical test results.

Configuration	Mean strength [MPa]	Standard deviation [MPa]
Tensile strength		
Reference laminate	761.1	21.3
Gap defects	680.4	45.2
Gap defects + FGF filled gaps	588.8	44.7
Compressive strength		
Reference laminate	325.1	27.3
Gap defects	339.2	13.2
Gap defects + FGF filled gaps	339.6	35.8

Mechanical tests (Table 2) showed similar compressive strength for reference specimens, gap defects and FGF-filled gaps, respectively. The limited free length of 22 mm of the samples only allows for one partial defect in the relevant test area which is likely not sufficient to induce significant impact on the laminate properties.

Tensile strength however decreased 11 % and 23 % for gap defects and FGF-filled gaps compared to reference tensile strength, respectively. The longer free length allows for all four gap defects to be positioned in the relevant sample area. Falcó et al. found a similar result of 9 % tensile strength knockdown for staggered triangular defects. The higher knockdown for FGF-filled defects can be explained by the suboptimal consolidation and layer thickness of the FGF-filled areas. Contrary to the objective of levelling the gap defects the out-of-plane waviness increased due the local change in layer thickness.

4. Conclusion

The process combination of in-situ AFP and FGF was successfully demonstrated to fill geometry-induced triangular gap defects of in-situ AFP laminates. Further work is however required to optimize consolidation of FGF layers and the AFP laminate. In order to utilize the full potential of the process combination, FGF layer thickness needs to be adjusted to match the consolidated AFP ply thickness. Both the use of a heated tooling and different FGF materials will be subject to future investigation.

CRedit authorship contribution statement

Lukas Raps: Conceptualization, Data curation, Writing – original draft, Visualization, Investigation, Methodology. **Fynn Atzler:** Investigation, Methodology, Formal analysis. **Ashley R. Chadwick:** Writing – review & editing, Validation, Supervision. **Heinz Voggenreiter:** Supervision, Validation, Resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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