

Application of additively manufactured shape-optimized core fillers in composite aircraft landing gear structures

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ABSTRACT

This paper presents the application of additively manufactured (3D-printed), shape-optimized core fillers in a full-scale composite aircraft landing gear structure. Preliminary investigations included a comparison of conventional PVC foam cores and 3D-printed honeycomb cores using three-point bending tests. The main part of the study focused on the design and integration of geometrically complex 3D-printed fillers into a composite landing gear leg. The fillers enabled accurate reproduction of the variable, curved and twisted internal geometry, integration of brake-line channels, and manufacture of the closed-section component in a single lamination and curing cycle. The manufactured landing gear was subsequently subjected to airframe-level strength tests and a separate component-level destructive test. The landing gear successfully sustained the required structural verification loads, while the maximum load recorded during the destructive test reached approximately 219% of the calculated maximum allowed load. No failure initiation or structural instability associated with the additively manufactured fillers was observed. The proposed solution was implemented in the production process of a light aircraft, demonstrating its practical applicability as a process-enabling element in the manufacture of complex composite structures.

Keywords: additive manufacturing, composite structures, sandwich structures, 3D-printed core fillers, aircraft landing gear, structural testing

INTRODUCTION

Composite sandwich structures are widely used in aerospace engineering due to their high stiffness-to-weight and strength-to-weight ratios. In a typical sandwich structure, thin, high-strength face sheets carry the tensile and compressive stresses resulting from bending, whereas the lightweight core maintains the separation between the face sheets, transfers transverse shear loads and provides local support against buckling [1,2]. Conventional core materials include polymer foams and honeycomb structures, typically manufactured from aluminium, aramid paper or polymeric materials [2].

Despite their widespread use, conventional core materials may present manufacturing limitations when applied to components with complex three-dimensional geometries. Foam cores can be shaped by machining, thermoforming or moulding; however, these processes may require dedicated tooling, additional manufacturing operations or substantial manual finishing. Conventional honeycomb cores are particularly difficult to adapt to components with strongly varying cross-sections, spatial curvature or internal functional features. In such applications, the core may need to be divided into multiple segments and subsequently fitted and bonded during assembly, increasing manufacturing time and introducing additional interfaces.

Additive manufacturing provides new possibilities for the production of lightweight cores with customized geometry and internal architecture. Recent studies have investigated additively manufactured honeycomb, lattice and other cellular core topologies with regard to their stiffness, strength, energy absorption and failure [3–11]. The geometric freedom offered by additive manufacturing enables the modification of cell topology, dimensions, wall thickness, relative density and material distribution, potentially allowing the internal structure to be adapted to local geometric and mechanical requirements. Furthermore, functional features can be incorporated directly into additively manufactured core structures, reducing the need for separate inserts, additional components or subsequent manufacturing [12].

Additive manufacturing may also enable greater integration between the individual elements of a sandwich structure. Sugiyama et al. demonstrated the manufacture of composite sandwich structures with different core geometries as integrated components using continuous carbon-fibre additive manufacturing [13]. Although the manufacturing method investigated in that study differs from the combination of conventional composite lamination and polymer FFF printing considered in the present work, it illustrates the potential of additive manufacturing to reduce assembly operations and overcome some of the geometric limitations associated with conventional core materials.

The mechanical performance of sandwich structures with additively manufactured cores depends not only on the properties and topology of the printed material, but also on the interaction between the core and the composite face sheets. Cao et al. demonstrated that resin uptake in the skin–core interphase region can significantly affect the bending and shear performance of sandwich composites with 3D-printed cores [14]. Insufficient bonding or limited mechanical interlocking at the interface may lead to premature skin–core delamination even when the printed core itself retains sufficient load-carrying capacity. Consequently, both the mechanical properties of the core and the conditions governing its integration with the surrounding laminate must be considered.

Most published studies concerning additively manufactured sandwich cores focus on flat specimens with regular cellular geometries tested under controlled laboratory conditions [3,4,13,14]. These investigations are essential for characterizing mechanical behaviour; however,

comparatively less attention has been devoted to the implementation of additively manufactured core elements in full-scale composite aircraft components. In practical applications, the function of a core or internal filler may extend beyond its direct contribution to structural load transfer. Shape-adapted internal elements may support uncured laminate layers, maintain the required geometry during mould closure and curing, simplify the manufacturing sequence and enable the integration of additional functional features.

The present study investigates the use of additively manufactured, shape-optimized core fillers in a full-scale composite main landing gear leg developed for a light aircraft. Preliminary three-point bending tests were conducted on sandwich specimens with conventional PVC foam cores and 3D-printed PLA honeycomb cores to compare their mass, load-carrying behaviour and failure modes. The main part of the study concerns the application of geometrically complex 3D-printed fillers in the leading- and trailing-edge regions of the landing gear leg. The fillers were designed primarily as process-enabling elements intended to maintain the required cross-sectional geometry, support the composite shell during manufacturing and incorporate internal channels for brake-line routing. The resulting landing gear structure was manufactured in a single lamination and curing cycle and subsequently subjected to airframe-level strength tests and a separate component-level destructive test.

MATERIALS AND METHODS

Reference sandwich specimens

To provide a baseline for comparison, a series of flat sandwich specimens were manufactured and tested. The specimens had nominal dimensions of 200 × 36 mm with 6 mm core thickness and consisted of glass fiber-reinforced epoxy face sheets with two different types of core materials.

The specimens were designed as non-standard specimens in accordance with [15]. A support span of 150 mm was selected based on the standard test configuration. The length of a non-standard specimen should exceed the support span by 50 mm; therefore, a specimen length of 200 mm was adopted. The same section specifies that the specimen width should be between two and six times the total sandwich thickness. The adopted specimen width of 36 mm satisfied this requirement.

The reference specimens were produced using a conventional extruded PVC foam core. In the alternative configuration, the foam core was replaced with a 3D-printed honeycomb structure manufactured from PLA using fused filament fabrication (FFF). The honeycomb geometry was designed such that, considering the achievable wall thickness and material density, the total mass of the specimens remained comparable to the foam-based counterparts.

As a result, both configurations exhibited similar mass, approximately 12.5 ± 1.0 g per specimen. Both types of specimens were manufactured using the same layup procedure for the composite face sheets in order to ensure comparability of results. The core thickness and overall geometry of the specimens were kept consistent across all configurations. A visual comparison of the specimens is presented in Figure 1.

The specimens were first compared in terms of mass. Subsequently, three-point bending tests illustrated in Figure 2 were performed using a universal testing machine in accordance with [15]. Each specimen was simply supported at two points over a span of 150 mm and loaded at the midpoint of the support span. The tests were conducted under displacement control at a crosshead displacement rate of 6 mm/min. The load was increased continuously until structural failure occurred. The applied force and the corresponding crosshead displacement were recorded throughout the test. This loading arrangement generated combined bending and transverse shear in the sandwich specimens and

enabled a direct comparison of the load-carrying behaviour and failure modes of the two core configurations. The results of the comparison are summarized in Table 1.

The first letter of the specimen designation identifies the core configuration. Specimens designated with the letter C were reference specimens manufactured with a conventional PVC foam core, whereas specimens designated with the letter D incorporated a 3D-printed PLA honeycomb core. The two-digit number identifies the individual specimen within each series. Two distinct failure modes were observed for the specimens with 3D-printed cores. In a subset of samples, the failure was characterized by local crushing and progressive collapse of the honeycomb structure, resulting in load-carrying capacity comparable to, or in some cases exceeding that of the foam-core specimens (see Figure 2).

However, in some cases, failure occurred through delamination between the composite face sheets and the printed core (see Figure 3). These specimens exhibited a reduction in maximum load of approximately 30–50% compared to the reference foam-core specimens.

This observation indicates that the limiting factor in the performance of the 3D-printed core specimens was not the intrinsic strength of the core itself, but rather the quality of the bond between the core and the composite skins, which is a well-known limitation in sandwich structures with additively manufactured cores [14].

The purpose of these tests was not to provide a comprehensive characterization of

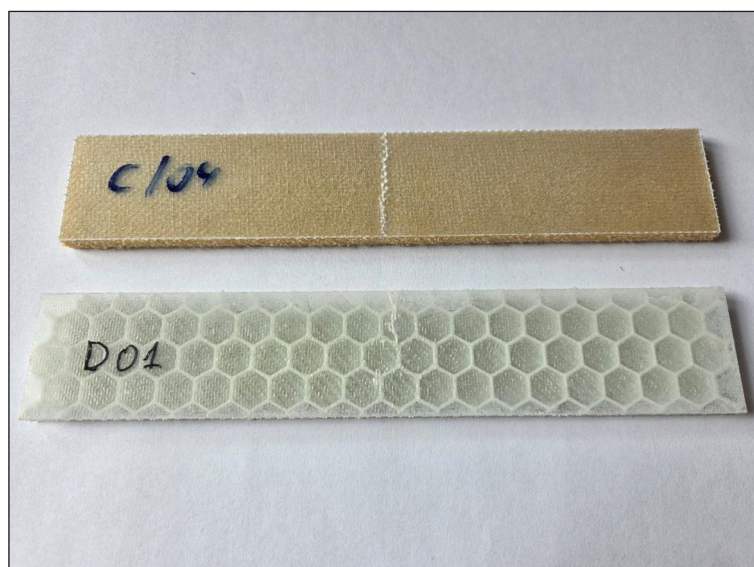


Figure 1. Expanded PVC vs 3D printed honeycomb core specimen comparison

Table 1. Specimen mass and ultimate strength comparison

Specimen type	Specimen series and number	Ultimate load	Crosshead displacement	mass
		[N]	[mm]	[g]
PVC foam core	C01	143	3.34	11.6
	C02	132	3.41	11.3
	C03	141	3.29	11.4
	C04	142	3.47	11.3
	C05	145	3.63	11.5
PLA 3D printed honeycomb core	D01	196	5.48	12.8
	D02	165	5.73	13.7
	D03	90	2.50	13.2
	D04	172	4.34	12.7
	D05	60	1.80	12.8
	D06	156	7.15	13.7
	D07	186	7.87	13.2
	D08	113	5.11	13

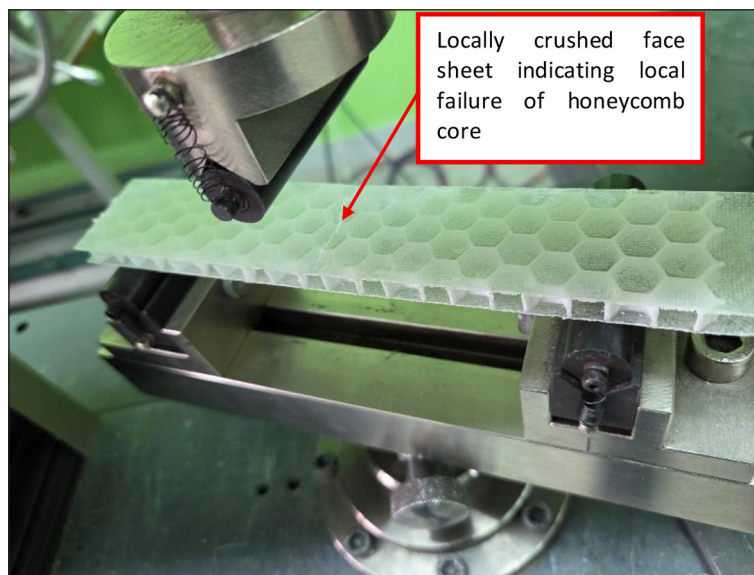


Figure 2. Core-collapse failure mode

sandwich behaviour, but to identify key performance aspects of additively manufactured cores relevant to their practical application in composite structures.

LANDING GEAR DESCRIPTION

The investigated component is a composite main landing gear leg designed for a light aircraft, as shown in Figure 4. The landing gear is a primary structural element responsible for transmitting landing loads from the wheels to

the airframe, including vertical, longitudinal and lateral load components associated with various landing conditions. Due to geometric constraints and integration with the aircraft structure, the component exhibits a complex three-dimensional shape, combining curvature and twist along its length. This results in significant challenges in both structural design and manufacturing.

Structural configuration of the landing gear

The primary load-carrying mechanism is based on a classic beam analogy. Bending loads

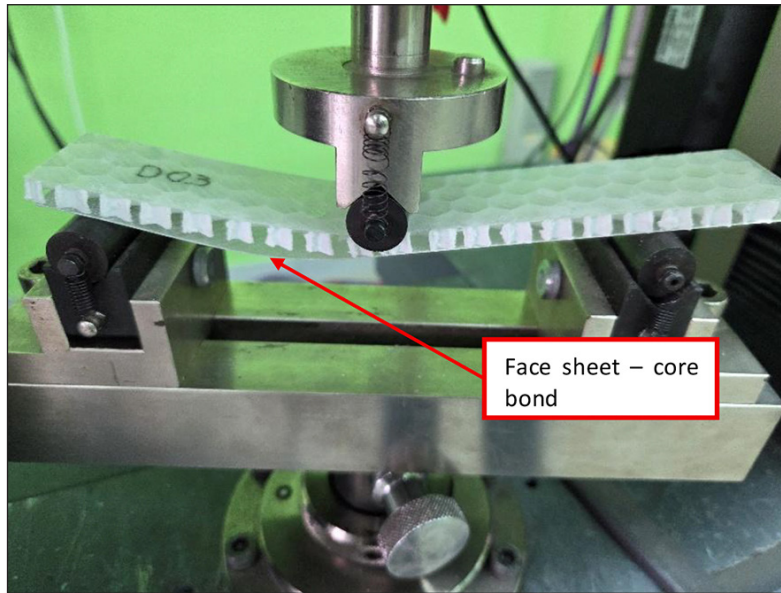


Figure 3. Delamination failure mode

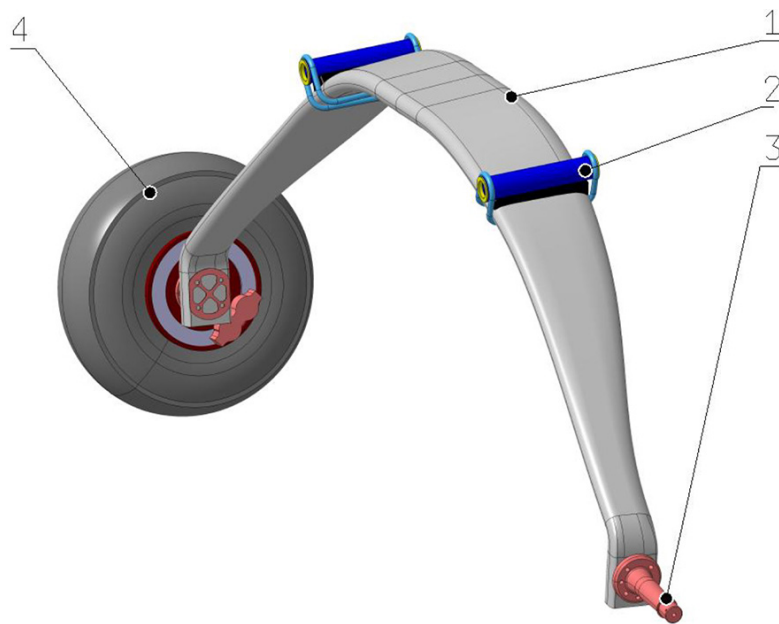


Figure 4. General view of the composite main landing gear assembly: 1 – landing gear leg, 2 – attachment fittings, 3 – axle, 4 – wheel

are predominantly resisted by longitudinal carbon fibre reinforcements located in the upper and lower skins of the structure, forming the equivalent of tension and compression flanges. The internal shear forces are transferred by vertical webs connecting the skins. These webs are manufactured as flat sandwich structures with carbon/epoxy face sheets and a core made of extruded PVC foam. To enhance shear performance, the face sheets of the webs are reinforced with diagonally oriented fibres. In

addition to the structural elements, the geometry of the cross-section includes leading and trailing edge regions with complex curvature. These regions do not significantly contribute to the global load-carrying capacity but are essential for maintaining the shape of the structure and ensuring proper load distribution in the skins. The structural arrangement of the landing gear cross-section, including the load-carrying flanges, shear webs and additively manufactured fillers, is illustrated in Figure 5.

Manufacturing approaches

Traditionally, components of this type are manufactured as two separate shell halves, as illustrated in Figure 6. Each half is laminated independently in a dedicated mould and includes an overlap region (bonding flange) along the joining edge. After curing, the two halves are bonded together in a secondary operation to form the final closed-section structure.

This approach, commonly used in composite wing and tail structures, introduces additional manufacturing complexity [2]. In

particular, it requires a technological pause for curing of the individual halves, followed by a separate bonding process. As a result, the total production time is extended, typically by at least one working day. Furthermore, the bonding is performed between fully cured (“dry”) composite surfaces, which may introduce variability in joint quality and requires careful surface preparation. In addition, the conventional approach results in the presence of internal laminate layers located near the mid-thickness of the structure, originating from the folded plies used to close each shell half. These layers contribute little to the global

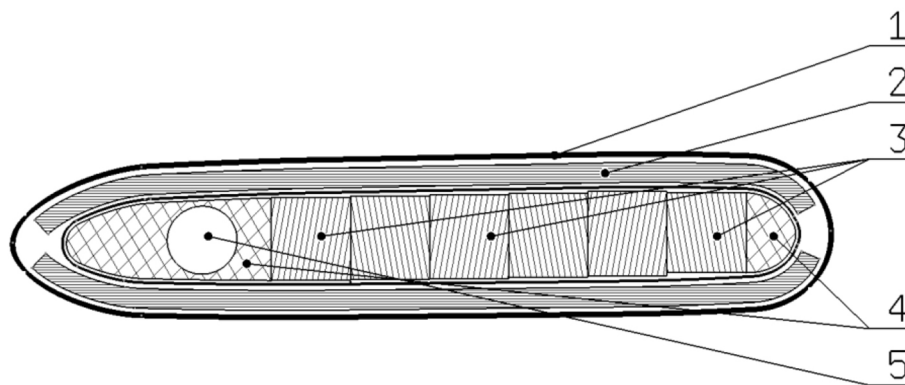


Figure 5. Cross-sectional configuration of the composite landing gear structure: 1 – composite skin
2 – carbon fibre flanges, 3 – sandwich shear webs (carbon/epoxy with PVC foam core),
4 – additively manufactured fillers, 5 – internal channel for brake line routing

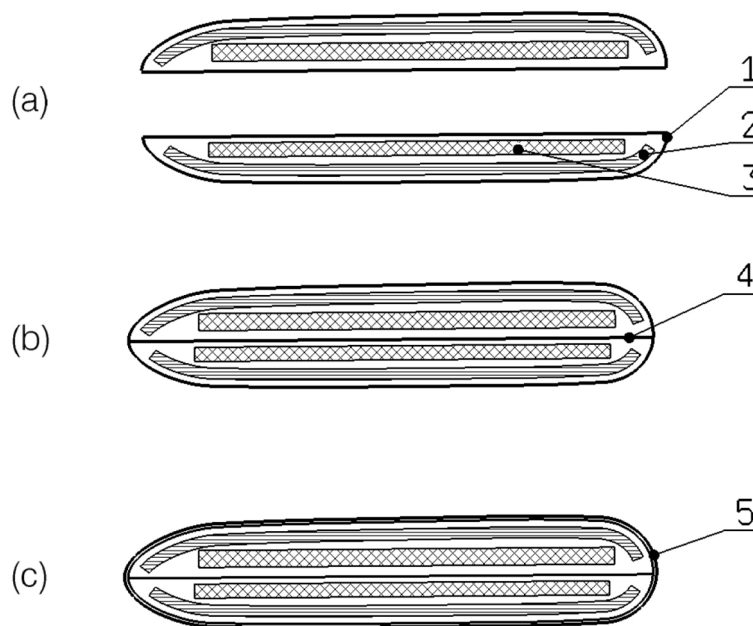


Figure 6. Conventional manufacturing process of the landing gear structure: [a] independent lamination of upper and lower shell halves with folded inner plies, [b] assembly and bonding of cured halves, [c] application of external reinforcement layer; 1 – composite skin, 2 – carbon fibre flange, 3 – PVC foam core, 4 – adhesive bond line, 5 – external reinforcement layer

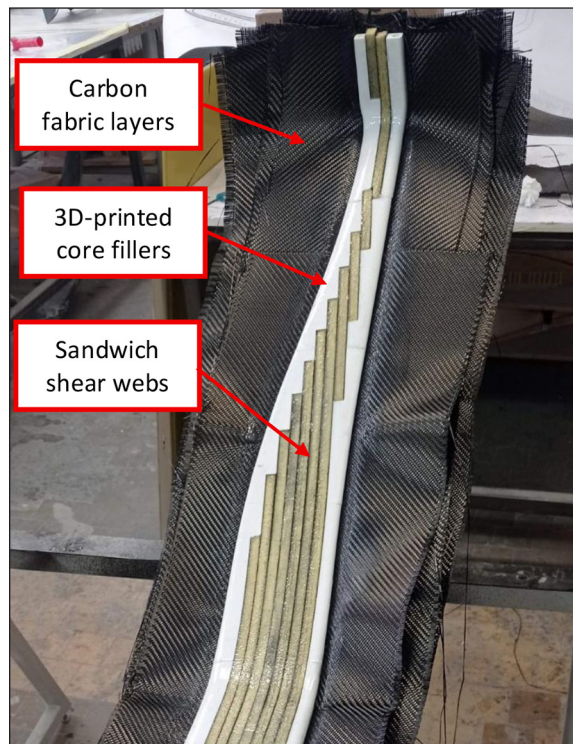


Figure 7. Core structure positioned in the mould during the layup process, showing integration with the composite skins in the initial stage of manufacturing

bending stiffness, as they are located close to the neutral axis, while increasing the overall mass of the component.

In the present work, an alternative manufacturing approach is proposed, enabled by the use of additively manufactured core fillers (Figure 7).

The entire landing gear structure is produced in a single lamination and curing cycle, eliminating the need for secondary bonding operations. The geometric freedom offered by additive manufacturing has previously been used to integrate complex core geometries and additional functions into sandwich structures [12,13].

The process can be described using a simplified cross-sectional sequence, as illustrated in Figure 8. The component is manufactured in an inverted position. First, the outer skin layup is placed in the mould, with sufficient material overlap to form a continuous closed perimeter of the cross-section, as illustrated in Figure 8, where the core structure is shown positioned within the layup. Next, the upper carbon reinforcement [corresponding to the compression flange in service] is positioned, followed by the placement of the core fillers and the lower carbon reinforcement. Finally, the initially placed

skin layers are wrapped around the internal structure, forming a fully closed external contour. The mould is then closed and the structure is cured as a single integrated component.

Without the presence of the 3D-printed fillers in the leading and trailing edge regions, such a process would not be feasible. The unsupported skin layers would not maintain their intended geometry and would collapse inward under their own weight during layup and curing. The additively manufactured fillers therefore play a critical role in stabilizing the geometry during manufacturing, rather than acting as primary load-bearing elements.

EXPERIMENTAL TESTING

The structural performance of the proposed landing gear was evaluated as part of full-scale strength tests of the aircraft. The testing program included both system-level tests performed on the airframe and a subsequent component-level destructive test of the landing gear.

Airframe-level tests

The landing gear was installed in a representative aircraft fuselage structure and subjected to a series of load cases corresponding to different landing conditions. The applied loads included combinations of vertical, longitudinal and lateral forces acting at the wheel, representing both typical and critical landing scenarios.

Three primary load cases were considered, each corresponding to a different loading condition defined for structural verification. The loads were applied incrementally using a dedicated test rig until the required test levels were reached. For the load case presented in Figure 9, the calculated maximum allowed [limit] load components were $F_z = 8.794$ kN in the vertical direction and $F_x = 2.03$ kN in the longitudinal direction. The corresponding ultimate-load components, defined as 150% of the limit loads, were $F_z = 13.192$ kN and $F_x = 3.046$ kN. The force components were applied simultaneously while maintaining the prescribed load ratio.

Quantitative displacement measurements of the landing gear tip points were not included in the original test procedure. Although deformation of the landing gear was observed during loading, the available displacement data were not considered sufficiently reliable for quantitative analysis

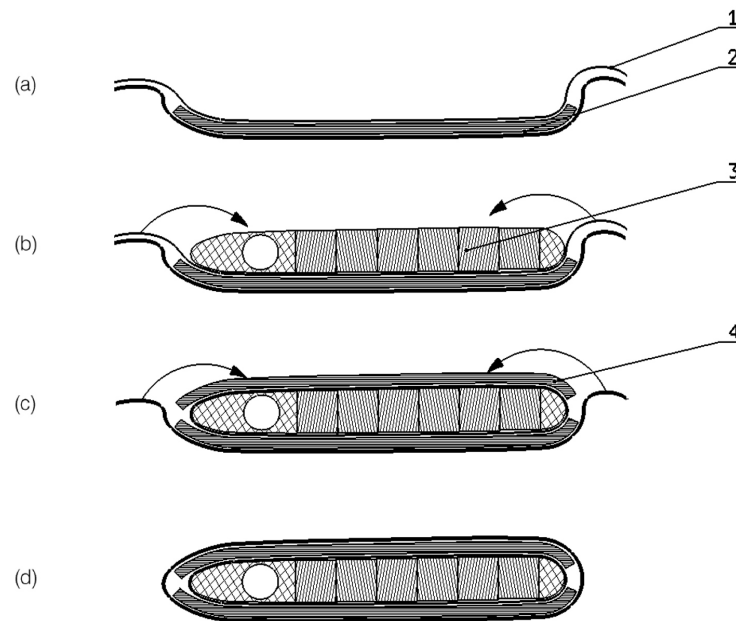


Figure 8. Single-stage manufacturing process enabled by additively manufactured fillers: [a] placement of composite skin layup, [b] positioning of internal structural elements, including carbon flanges, sandwich webs and printed fillers, [c] closure of the structure by wrapping the skin layers, [d] final integrated cross-section after curing; 1 – composite skin, 2 – carbon fibre flanges, 3 – sandwich shear webs and additively manufactured fillers, 4 – closing direction of the skin layers.

and are therefore not reported. The assessment was consequently based on the applied load levels, visual inspection of the tested structure and identification of the location and sequence of structural damage.

During these tests, the landing gear remained structurally intact. Failure occurred in elements of the supporting fuselage structure after exceeding the assumed ultimate load level. This indicates that the landing gear possessed sufficient strength within the tested loading range and did not represent the critical structural component in the system.

A photograph of the test rig, together with a schematic representation of the applied forces, is shown in Figure 9.

Component-level destructive test

Following the successful completion of the airframe-level tests, the landing gear was removed and subjected to a separate destructive test to determine its ultimate load-carrying capacity.

The component was mounted in a dedicated test fixture providing boundary conditions representative of the fuselage attachment shown in Figure 10 (before) and Figure 11 (after failure). The close-up view of the landing gear fracture zone after the component-level destructive test is

shown in Figure 12. Loads were applied at the wheel location in directions corresponding to the most critical load case, i.e. simultaneously upward and backward. The load was increased progressively until structural failure occurred.

The maximum recorded load was approximately 19.26 kN upwards, representing 219% of the calculated maximum allowed load, and 4.47 kN forward, corresponding to 220% of maximum allowed longitudinal load.

Failure was characterized by compressive rupture of the upper carbon flanges, followed by failure of the core and subsequent rupture of the lower flange. This indicates that the primary load-carrying elements of the structure governed the failure mechanism.

Importantly, no critical damage or instability associated with the additively manufactured fillers was observed. The fillers maintained their geometric integrity throughout the loading process and did not initiate failure.

Observations

The test results demonstrate that the proposed manufacturing approach enabled the production of a landing gear structure capable of sustaining the required structural verification loads. No



Figure 9. Landing gear installed in the representative aircraft fuselage structure during the airframe-level strength test. The fuselage was attached to the steel test frame through the wing attachment fittings, with an additional restraint connected to the tail boom to limit the pitching moment transferred through the wing attachment points. The arrows indicate the longitudinal [F_x] and vertical [F_z] force components applied simultaneously at the wheel.



Figure 10. Landing gear leg mounted in a dedicated test fixture and connected to the loading system during component-level testing before failure

failure initiation, local instability or other adverse structural behaviour associated with the additively manufactured fillers was observed during either the airframe-level tests or the component-level destructive test.

Although the additively manufactured fillers were not designed as primary load-carrying elements, they provided sufficient support for the surrounding composite shell during manufacturing and maintained their intended

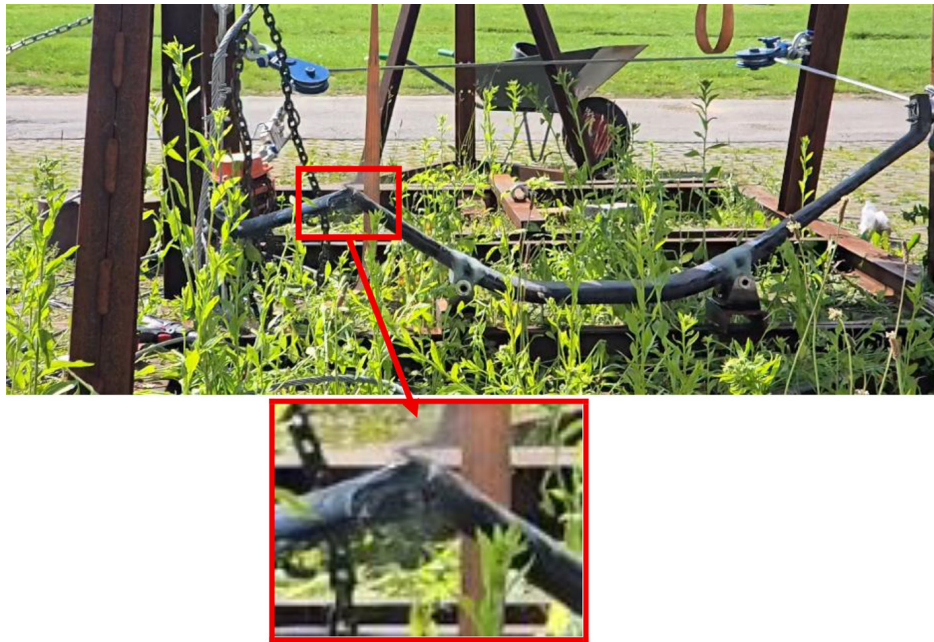


Figure 11. Landing gear leg mounted in a dedicated test fixture and connected to the loading system during component-level testing after failure



Figure 12. Close-up view of the landing gear fracture zone after the component-level destructive test

function throughout the structural tests. Their possible contribution to load transfer was not evaluated separately; however, no evidence was found that their incorporation adversely affected the load-carrying behaviour of the complete component.

The failure mode observed during the destructive test was consistent with the expected behaviour of a beam-like composite structure. Failure occurred within the primary load-carrying elements, with the carbon fibre flanges governing the ultimate load-carrying capacity, rather than through premature failure associated with the additively manufactured fillers.

RESULTS AND DISCUSSION

The conducted experimental program demonstrates that the proposed manufacturing approach based on additively manufactured core fillers can be successfully applied in a full-scale composite aircraft structure without compromising its structural performance. The manufactured landing gear sustained the required structural verification loads, and no failure initiation or local instability associated with the additively manufactured fillers was observed.

The results of the reference sandwich specimen tests indicate that the mechanical

performance of 3D-printed honeycomb cores is highly dependent on the quality of the bond between the core and the composite skins. While some specimens exhibited load-carrying capacity comparable to, or exceeding, that of conventional PVC foam cores, others failed prematurely due to core–skin delamination. The observed variation indicates that the skin–core interface may govern the load-carrying capacity even when the printed core itself retains sufficient compressive strength. This observation is consistent with the findings of Cao et al. [14] who demonstrated that resin uptake and bonding conditions in the skin–core interphase region significantly affect the bending and shear performance of sandwich composites with 3D-printed cores.

In the landing gear application, the additively manufactured fillers were not designed as primary load-carrying elements but as geometrically tailored, process-enabling elements supporting the formation of the closed-section structure during manufacturing. Their possible contribution to load transfer was not evaluated separately. The global structural response was governed primarily by the carbon fibre flanges and internal shear webs, as indicated by the failure mode observed during the destructive test. No premature failure associated with the additively manufactured fillers or their interfaces with the surrounding composite structure was observed.

The airframe-level tests demonstrated that the landing gear sustained the required ultimate load components without structural failure. During the subsequent component-level destructive test, the applied load was increased until failure occurred at a vertical force component of $F_z = 19.26$ kN and a longitudinal force component of $F_x = 4.47$ kN. These values corresponded to approximately 219% of the calculated maximum allowed load for the investigated loading condition of $F_z = 8.794$ kN and $F_x = 2.03$ kN. The failure mechanism was consistent with the expected behaviour of a beam-like composite structure: compressive failure of the upper carbon fibre flange was followed by progressive failure of the internal structure and eventual rupture of the lower flange. Importantly, no failure initiation associated with the additively manufactured fillers was observed.

From a manufacturing perspective, the introduction of 3D-printed fillers enables a transition from a multi-stage process involving secondary bonding to a single-stage lamination and curing

approach. This eliminates the need for bonding of cured composite surfaces and reduces process time and variability. In addition, the proposed solution avoids the presence of internal laminate layers located near the neutral axis, which contribute to mass without significantly improving structural performance.

Another important advantage of the additively manufactured fillers is the ability to integrate functional features directly into the structure. In the presented case, internal channels for brake line routing were incorporated without the need for additional manufacturing operations. Furthermore, the use of additive manufacturing allows for accurate reproduction of complex, spatially curved and twisted geometries, which would be difficult to achieve using conventional foam-based solutions.

Overall, the results confirm that additively manufactured core fillers can serve as effective process-enabling elements in composite structures, particularly in components with complex geometry and integrated functionality. Their use allows for simplification of manufacturing processes while maintaining the required structural performance. The proposed solution has been successfully implemented in the production of the aircraft, confirming its practical applicability under real operating conditions.

CONCLUSIONS

The conducted study demonstrated the practical applicability of additively manufactured, shape-optimized core fillers as process-enabling elements in the manufacture of complex composite aircraft structures. In the investigated landing gear, the fillers enabled the required internal geometry to be maintained during layup and curing, allowing the closed-section component to be manufactured in a single lamination and curing cycle. This approach eliminated the need for secondary bonding of separately cured shell halves and enabled the integration of additional functional features, including internal channels for brake-line routing.

The reference specimen tests indicated that the performance of sandwich structures with 3D-printed cores is strongly influenced by the quality of the core–skin interface, with premature delamination limiting the load-carrying capacity of some specimens. However, the

possible use of additively manufactured cores as primary load-bearing core materials was beyond the scope of the present study. In the full-scale landing gear application, no failure initiation or adverse structural behaviour associated with the printed fillers was observed. The landing gear sustained the required structural verification loads and reached 219% of the calculated maximum allowed load during the destructive test. This result characterizes the performance of the complete structural design and should not be attributed directly to the use of the additively manufactured fillers.

The relatively high failure load reflects the iterative development history of the landing gear structure and indicates that the final design retained a conservative structural margin. During three preceding development tests, earlier configurations employing only conventional PVC foam fillers failed before reaching the required strength level. The load-carrying structure was progressively reinforced after each test. Following the third unsuccessful configuration, the internal structure was redesigned and additively manufactured fillers were introduced to improve its geometric definition and internal arrangement. The resulting increase in load-carrying capacity should not be attributed solely to the printed fillers, as the primary structural reinforcements had also been progressively modified during the preceding development iterations. Once the required strength level had been achieved, no further reduction of the primary load-carrying structure was undertaken, as the resulting mass and strength characteristics were considered satisfactory. Further mass optimization would have required additional design iterations, manufacturing of new test components and repeated destructive testing, involving additional cost and development time. Therefore, the reported failure load should be interpreted as the result of a conservative, experimentally developed structural configuration rather than as a direct effect of the additively manufactured fillers.

The results indicate that additive manufacturing can provide significant technological benefits in low-volume production of composite aircraft components with complex, spatially varying geometries. The proposed solution was successfully implemented in the aircraft production process, demonstrating its applicability beyond laboratory-scale specimens. Further research

may investigate the mechanical contribution of printed fillers and their potential use as load-carrying sandwich core materials, with particular emphasis on improving and characterizing the core–skin interface.

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