Compression testing of additively manufactured continuous carbon fiber-reinforced sandwich structures

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Article Information

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The novel, additive manufacturing technique, continuous lattice fabrication, combines the advantages of continuous fiber-reinforcement with those of additive manufacturing. This enables the generation of fiber-reinforcement within a single layer and especially along an out-of-plane load path inside all spatial dimensions. This study is a test-related evaluation of sandwich panels with lattice core structures modifying a compression test. The specimens were manufactured differentially via plug and bond and automatically using continuous lattice fabrication. Additionally, the spatial arrangement of the rods within the lattice core structure varied in terms of base area. The ultra-lightweight sandwich panels have lattice core structures with core densities < 10 mg × cm^{-3}. The material testing was performed by a modified compression test at room temperature. The damage analysis of the single rods shows current deficits and future potentials for optimization of lattice core structures. It could be shown that sandwich panels exhibit a compression strength of up to 0.30 MPa at a core density of 6.57 mg × cm^{-3}. Using a dimensionless lightweight index demonstrates a mechanical performance on a level comparable with that of selected core materials.

Due to the high frequency of innovations within additive manufacturing, more sophisticated technologies come onto the market. This leads to a change of application from prototypes to serial components. This switch is challenging in areas such as material choice, surface quality, dimensional stability and mechanical properties [1]. Torrado and Roberson [2], as well as Forster [3], determined that there is currently no standardized material testing for additively manufactured components, in particular with regard to manufacturing orientation and specimen geometry. To determine the mechanical properties of such components, research is needed for application-oriented material testing in areas such as modifying experimental setups and specimen geometries.

In this study, the focus is on sandwich panels. The core structure within a sandwich panel creates a defined top layer distance and absorbs the shear forces. The top layers at the surface increase the load-bearing capacity of the sandwich panel [4]. In this way, the sandwich panel achieves high stiffness at low weight. However, to achieve high stiffness, foams with high density are necessary. For ultra-lightweight with core densities of < 10 mg × cm^{-3} the weight of core structures has to be reduced. In this context, lattice core structures show advantages with respect to adjusting the lattice core structure to loading conditions and designing a force-flow-optimized core structure [5, 6].

In general, additive manufacturing techniques are beneficial for producing bionic-weight-optimized structures. Additionally, a faster and thus more efficient product development is feasible. Nowadays, the manufacturing of additive, continuous fiber-reinforced, and load-path-optimized components is a great challenge. One way of generating lattice core structures is the novel additive manufacturing technique of continuous lattice fabrication (CLF). CLF combines a serial pultrusion and extrusion system to extrude carbon fiber-reinforced polymer (CFRP)-rods and enables in situ manufacturing within three-dimensional space, including the out-of-plane direction by means of free form spatial extrusion [6, 7]. In previous studies, CLF and first demonstrators were introduced. In focus is the lattice core structure of sandwich panels that ensure a defined distance between the top layers. This lattice core structure consists of single CFRP-rods which act in total as a framework [6-8].

In this study, sandwich panels with lattice core structures are evaluated by modifying a compression test. The specimens were manufactured in two ways: differentially by plug and bond (DIF) and automatically by CLF. Additionally, the base areas of lattice core structures are varied, either triangular, quadratic or hexagonal, resulting in six different sandwich panels. To realize and verify the systematic approach, the compression test must be modified.

Manufacturing process and materials

Manufacturing process. The specimens are manufactured in three steps. The first step encompasses the production of the individual top layers via the additive manufacturing method fused filament fabrication (FFF). The second process step, manufacturing a lattice core structure, is accomplished according to two techniques DIF or CLF. During the last step, the two top layers including CFRP-rods are joined together manually via adhesive bonding. A schematic visualization of the three process steps is shown in Figure 1 (DIF) and Figure 2 (CLF).

DIF uses plug-in-connectors to place and bond the CFRP-rods. The plug-in-connectors are relevant for force transmission between the rods and the top layers. For load-path-optimized force transmission, notches should be reduced because of the resulting stress concentrations [9]. In order to counteract these stress concentrations, the connection between top layer and plug-in-connector is equipped with radii. The bionic-optimized plug-in-connector is shown in Figure 3a.

Within the production cell, the CLF-application head is combined with a six-axis robotic arm (KRC5 sixx, KUKA, Germany). The in situ manufactured CFRP-rod is solidified within a few seconds after leaving the CLF-application head. The high viscosity of the fiber filled material enables an extrusion of CFRP-rods out-of-plane without further support structures for forming the CFRP-rod. The force transmission between the top layer and the CFRP-rod is realized by a CLF-interface as displayed in Figure 3b. In Figure 4, the motion cycle for the manufacturing of one CFRP-rod as well as the corresponding production cell is shown.

Materials and joining. The top layers made of thermoplastic polymer polylactic acid (PLA) (EasyFill™, Formfutura BV, Netherlands). These substrates include process specific connectors depending on the lattice core structure and the manufacturing process. Because of the high individuality of the process specific connectors, the substrates are built with a commercial FFF-3D printer (Ultimaker 2+ Extended, Ultimaker BV, Netherlands). All specimens regardless of the manufacturing technique use single CFRP-rods manufactured by the CLF-application head (52 vol.-% stretch broken carbon fibers (STS 40, Toho Tenax, Japan), 48 vol.-% melt spun polyamide 12 (PA12) (PA12, EMS Chemie, Switzerland [5]). The manual adhesive bonding in the last process step is performed using a two-component epoxy resin (ScotchWeld DP490, 3M, USA). The DIF-plug-in-connector is joined by means of the same two-component epoxy resin. Hence, DIF-panels consist entirely out of

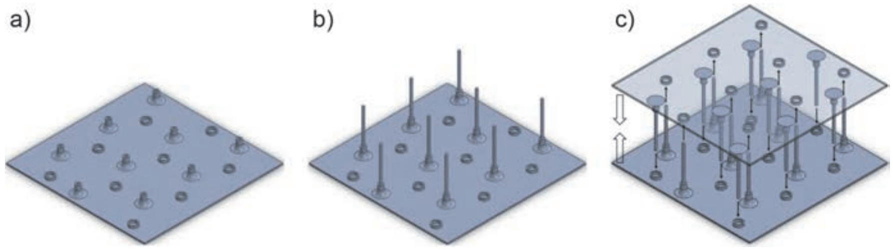


Figure 1: Scheme for differential manufacturing (DIF) process steps, a) individual top layers (FFF), b) manufacturing of lattice core structure, c) manual assembly

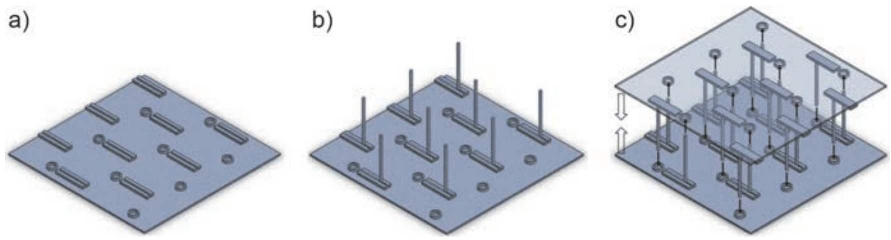


Figure 2: Scheme for continuous lattice fabrication (CLF) process steps, a) individual top layers (FFF), b) manufacturing of lattice core structure, c) manual assembly

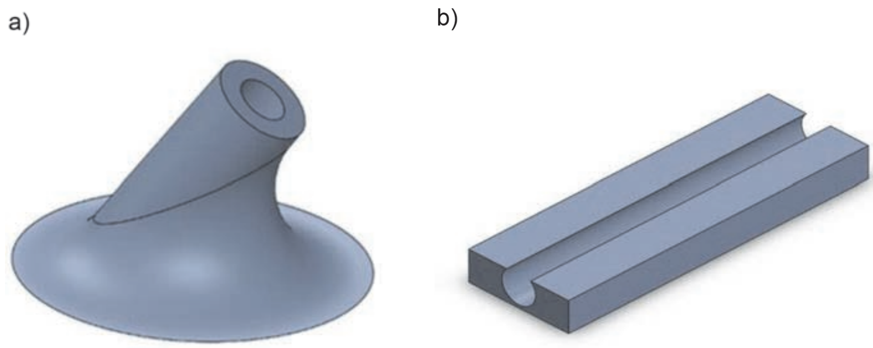


Figure 3: Force transmission, a) plug-in-connector (DIF), b) interface (CLF)

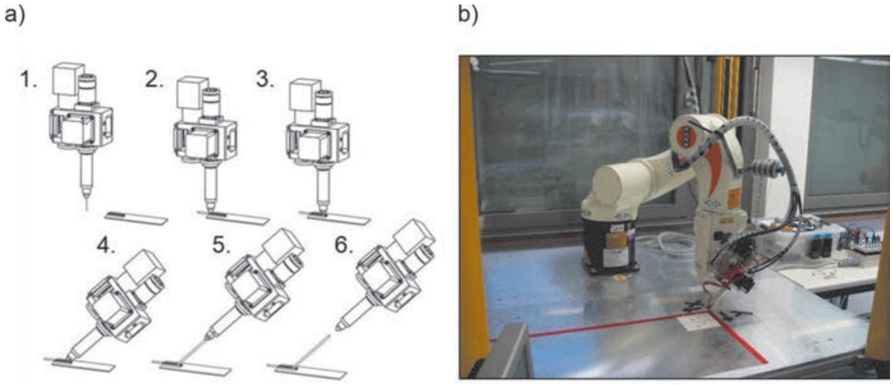


Figure 4: Manufacturing of CFRP-rod (CLF), a) motion cycle of CLF-application head, b) production cell with six-axis robot und CLF-application head

adhesive bonding (second and third process step). Within the CLF-interface two different thermoplastic polymers, PLA and PA12 are joined together via melt adhesive bonding. In contrast, CLF-panels consist out of melt adhesive bonding (second process step) and adhesive bonding (third process step).

Base area and unit cell. On the basis of the first demonstrators developed by Eichenhofer et al. [6], additional base areas for lattice core structures have been introduced, see Figure 5. The edge lengths of the base areas are given by geometrical coordinates like the height of the lattice core structure h_{core} (30 mm) and varying rod angles (90°, 60° or 55°). The 55° angle is an average based on previous studies by Fan et al. (54.7°) [10] and Schneider et al. (56°) [11]. The edges of the base areas are used as the source for CFRP-rods. Models of DIF-panels and CLF-panels with a quadratic lattice core structure are presented in Figure 6. CLF-process constraints require an adaptation of the base area. Specific information for the different variations is listed in Table 1. The core densities of lattice core structure ρ_{core} are entirely out of CFRP-rods and the adhesive in the third manufacturing step. CLF-panels have greater densities compared to DIF-panels because of the interface.

Manufacturing parameters. For manufacturing a CFRP-rod with a CLF-application head, process parameters based on Eichenhofer et al. [6] are used. In two heat phases at 230 °C and an extrusion velocity of 100 mm × min^{-1} seven commingled yarns are consolidated to a CFRP-rod 1.5 mm in diameter. The resulting CFRP-rods have a tensile strength of 560 MPa, Young's modulus of 83 GPa in reinforcement direction and 4 % void content [6].

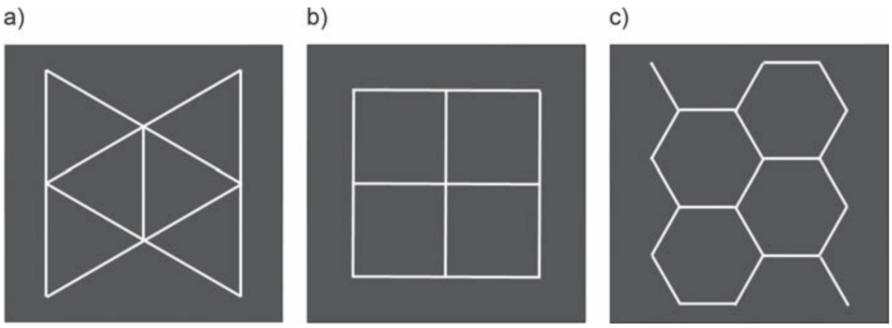


Figure 5: Base areas of unit cells, a) triangular, b) quadratic, c) hexagonal

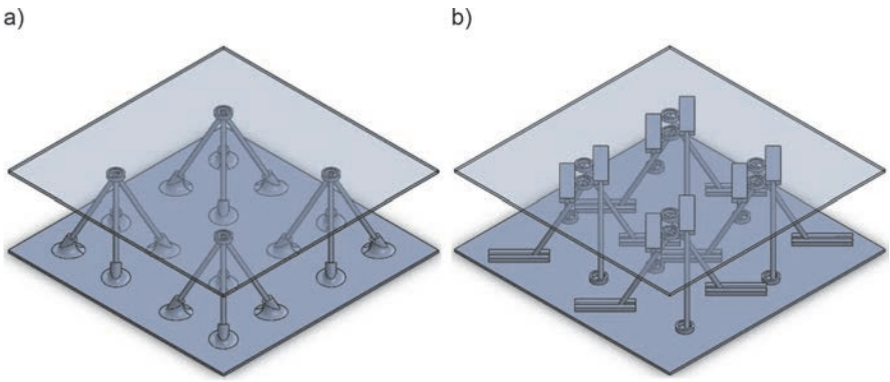


Figure 6: Sandwich panels with a quadratic lattice core structure, a) DIF, b) CLF

Manufacturing process	Variation base area	Number of rods	Angle of rods (°)	ρ_{core} (mg × cm^{-3})
DIF	△	18	55	7.23
	□	16	60	5.47
	⬡	18	90	6.57
CLF	△	18	55	8.70
	□	16	60	7.93
	⬡	18	90	8.30

Table 1: Specific information regarding different variations for DIF and CLF

Experimental setup

Quasi-static investigations. The compression tests of sandwich panels are perpendicular to the top layer plane. According to ASTM C365 C365/M, the tests were performed on a universal testing machine (Instron 5567, F_{max} = 30 kN). The displacement was measured by traverse-position. After preloading with +45 N the tests were carried out with a displacement speed of 0.5 mm × min^{-1}. The tests were stopped at a 20 % drop in force or a displacement of 3 %. The value of percentage refers to the initial specimen thickness $h_{specimen}$. For force introduction, two compression plates are used, see experimental setup in Figure 7. Figure 8 displays the geometry of the specimen with respect to ASTM C365 C365/M. Dimensions of the top layers are 100 × 100 mm with a thickness of 1.5 mm. The design of the specimen and the adjustment of the process settings are set up to yield a height of lattice core structure h_{core} = 30 mm. Because of inaccuracies within the manufacturing processes, the exact thickness varies about ±1 mm and was measured before each test.

Results

Quasi-static investigations. The compression tests are performed in six different variations. For each variation, three specimens were tested. Consequently, the re-

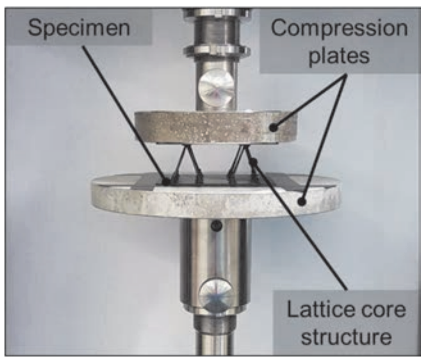


Figure 7: Experimental setup of compression test according to ASTM C365 C365/M

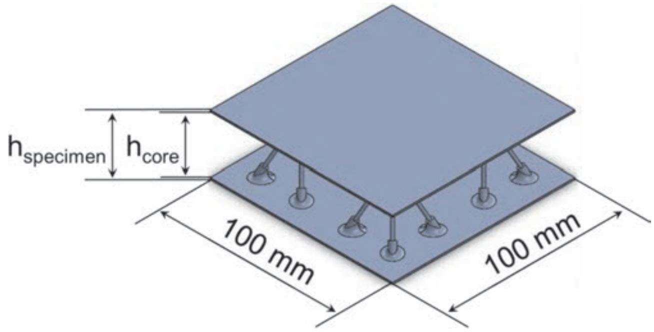
sults displayed are the mean and the corresponding standard deviation within a test series. In Figure 9 the results of the hexagonal lattice core structure are given. The axis of abscissas shows the displacement in the z-direction in percent points. The axis of ordinate shows the applied nominal force F_n. The examples illustrate the main differences between both manufacturing processes and represent characteristic curves for the respective manufacturing process.

In Figure 9a, the results of the DIF-panels with a hexagonal lattice core structure are plotted. At the beginning, all curves show a continuous and great increase of force. During the tests, single CFRP-rods of the lattice core structure break, resulting in abrupt reductions of force without a significant change in displacement. The first failures of CFRP-rods vary within the different specimens in a range of about 1,600 N and 2,600 N. Specimens 1 and 3 represent a further increase in force until approximately 2,700 N and 3,200 N, respectively, followed by an abrupt failure of the entire structure. In contrast, specimen 2 absorbs a high number of failed CFRP-rods, leading to a significantly increased displacement until failure. All specimens within the test series fail through the stop criterion of a 20 % drop in force. The maximum force F_{max} of the DIF-panels with a hexagonal lattice core structure is in average 2,960 ± 300 N (compression strength σ_c of 0.30 ± 0.03 MPa). The mean of compression modulus K is 37.71 ± 9.31 MPa.

Figure 9b presents the graphs of CLF-panels with a hexagonal lattice core structure. All curves increase nearly similarly to a quasi-linear slope. The curves of CLF-panels show no explicit peak. After a decreasing of stiffness at a displacement of about 2 %, an area with increasing displacement under constant force follows until failure. Neither during the tests nor on the basis of the resulting curves is an abrupt failure recognizable. The tests of the CLF-panels were stopped by reaching the stop criterion of 3 % displacement. Further investigations have shown that a test to a maximum displacement of 15 % has no influence on the constant force until failure. The CLF-panels reach in average a maximum force F_{max} of 1,130 ± 139 N (compression strength σ_c of 0.11 ± 0.01 MPa) and a compression modulus K of 8.40 ± 0.95 MPa.

The bar chart in Figure 10 presents all average results of compression strength σ_c and compression modulus K along with the corresponding standard deviations. It can be seen that the DIF-panels have higher compression strengths and compression modulus compared to CLF-panels. Separating the base areas clarify that the hexagonal lattice core structure has the highest compression strength σ_c and compression modulus K within the respective manufacturing process (CLF: compression strength σ_c 0.11 MPa, compression modulus K 8.40 MPa; DIF: compression strength σ_c 0.30 MPa, compression

Figure 8: Specimen geometry and dimensions



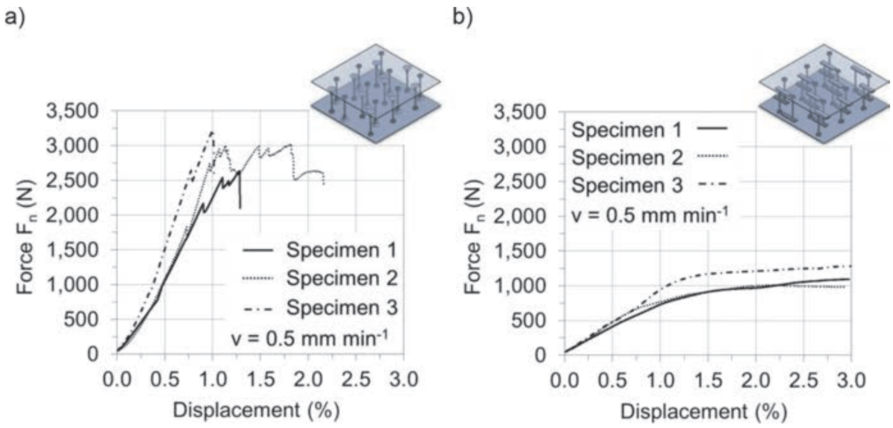


Figure 9: Compression tests with a hexagonal lattice core structure nominal force vs. displacement diagram, a) DIF, b) CLF

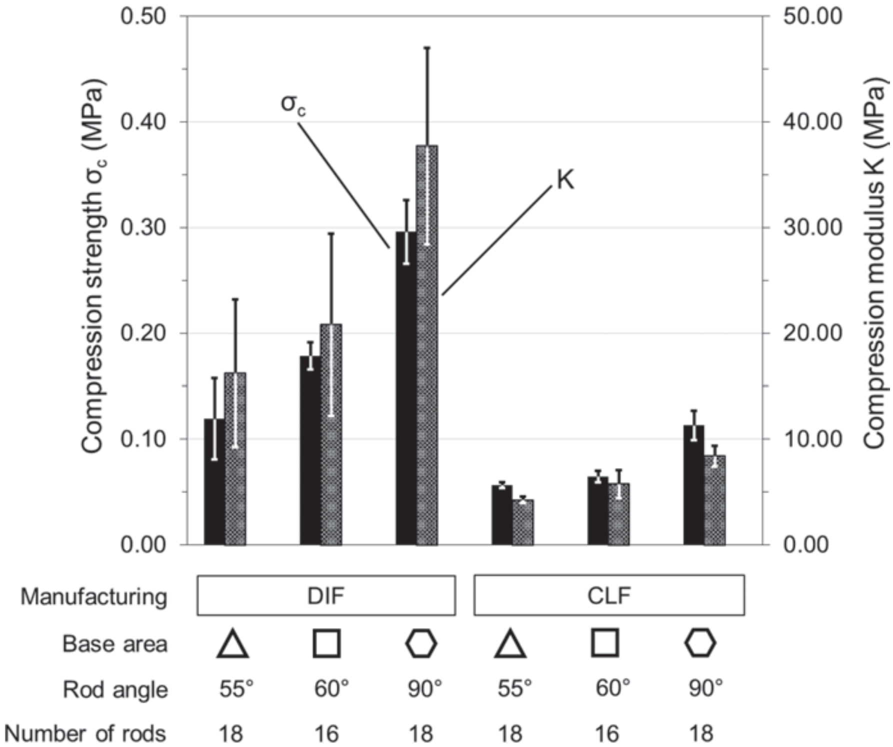


Figure 10: Compression strength σ_c and compression modulus K depending on variation for DIF and CLF

modulus K 37.71 MPa). Furthermore, the bars visualize that the triangular lattice core structure has the lowest values within the respective manufacturing process (CLF: compression strength σ_c 0.06 MPa, compression modulus K 4.26 MPa; DIF: compression strength σ_c 0.12 MPa, compression modulus K 16.21 MPa). In addition, the bar chart shows that for DIF-panels the corresponding standard deviation is higher as compared to CLF-panels. On the average, standard deviation of DIF-panels is about factor 3.5 higher in terms of compression strength and even about factor 9.6 higher in terms of compression modulus. One explanation for this high standard deviation for DIF-panels is inaccuracy during manufacturing. In particular, inaccuracies in feed-rate-unit and cutting process result in CFRP-rods with tolerances in length of ±0.5 mm. Hence, a similar distribution of forces cannot be ensured. The longer CFRP-rods have to withstand higher loads and fail before the loadbearing of the entire lattice core structure is reached. The inaccuracies in the influence of CFRP-rods described, in particular, with respect to the DIF-panels and the CLF-panels manufactured in an automated production cell do not show these inaccuracies.

To explore these inaccuracies and high standard deviations more closely, a failure analysis was done using a scanning electron microscope (SEM) (Philips, XL 20, Netherlands) as well as preparing cross-sections. The DIF-panels fail independently of the lattice core structure either at the fixing points or in the middle of the CFRP-rods. Figure 11a shows a fracture of a DIF-panel in the middle of the CFRP-rods, representing a kink band [12, 13]. The detailed view in Figure 11b illustrates the local elongated matrix which surrounds broken fibers. The broken fibers have perpendicular fractured surfaces and support the approach of an abrupt high impact failure. Figure 12a displays a cross-section of the plug-in-connector which is used for the DIF-panels. Between the outer top layer and the plug-in-connector, radii are visible that prohibit an abrupt change of stiffness. The transition between plug-in-connector and CFRP-rod, in particular between epoxy and CFRP-rod, turns out rather sharply. This sharp notch, located at the two fixing points of CFRP-rod, results in stress concentrations and affects the mechanical properties negatively [9, 14].

Figure 12b shows a cross section of the CLF-interface. A good connection within the melt adhesive bonding as well as the turning point of the fibers can be seen. In Figure 13, the CLF-force transmission is shown before and after the compression test. As mentioned regarding the curves in Figure 9b, there is no abrupt failure of the CLF-panels. The tests stopped by reaching 3 % maximum displacement. One approach for the slow increase at the beginning is the lack of stiffness in the area of fibers turning. Hence, there is no abrupt failure of the CFRP-rods, but the CFRP-rods return to the interface-direction under constant force. This failure behavior can be described as noncritical with a high energy absorption capacity.

Lightweight index. For a comparison with other core materials, the measured values refer to the core density ρ_{core}. One possibility to receive a comparable, dimensionless value is the lightweight index (LWI). The LWI is defined as the quotient of total load F_t and dead load F_d as shown in Equation (1) [15].

$$LWI = F_t \times F_d^{-1} \tag{1}$$

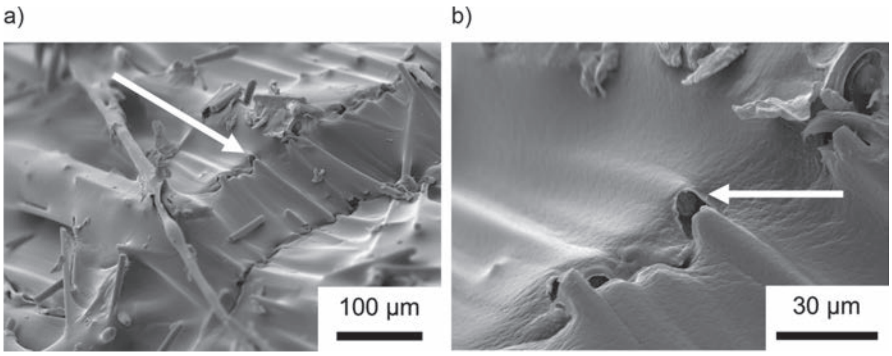


Figure 11: SEM recording of failure in the middle of the CFRP-rod, a) kink band, b) detail of kink band with perpendicular carbon fiber failure surface within PA12 matrix

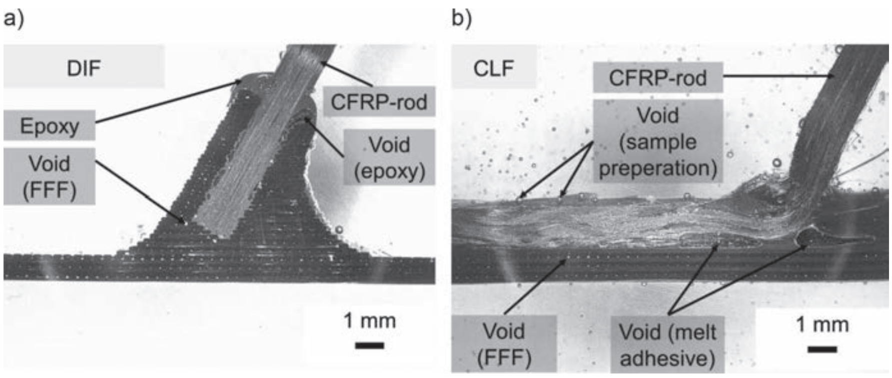


Figure 12: Optical microscope of cross sections, a) plug-in connector (DIF), b) interface (CLF)

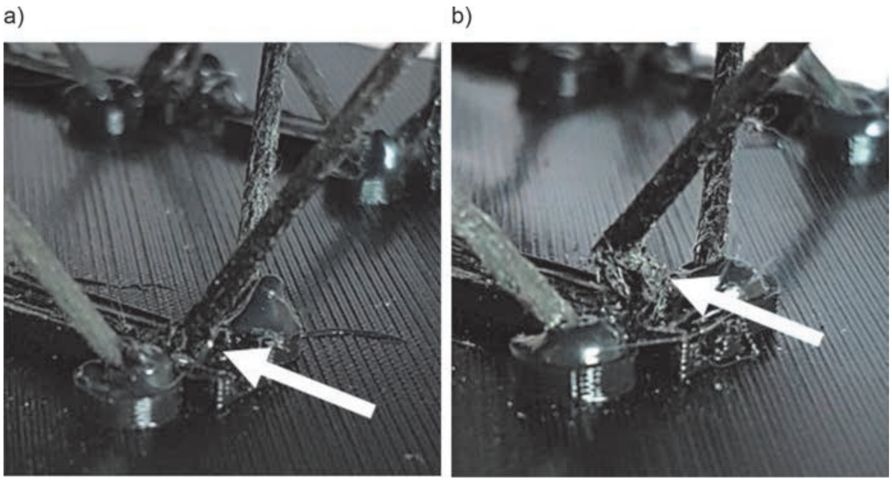


Figure 13: CLF-force transmission, a) before testing, b) after testing

The total load F_t is defined as the product of multiplying compression strength σ_c and base area $base_{core}$ (2). The dead load F_d is defined as the product of multiplying the volume of core $h_{core} \times base_{core}$, the density of core ρ_{core} and force of gravity g (3). Modifying Equation (1) with Equation (2) and (3) the Equation (4) for calculating LWI under compression load result. [15]

$$F_t = \sigma_c \times base_{core} \quad (2)$$

$$F_d = h_{core} \times base_{core} \times \rho_{core} \times g \quad (3)$$

$$LWI = \sigma_c \times (h_{core} \times \rho_{core} \times g)^{-1} \quad (4)$$

In Table 2, all tested variations with their core density ρ_{core}, their compression strength σ_c, and the resulting LWI for a core height h_{core} = 30 mm are listed. The higher the LWI, the better the ratio between compression strength σ_c and core density ρ_{core}. The highest LWI in the respective manufacturing process has the hexagonal lattice core structure (DIF: 154,450; CLF: 44,870). In Table 3, a selection of other core materials with the corresponding data from the manufacturer for core density ρ_{core} and compression strength σ_c are listed. It can be seen that the mechanical properties of DIF-panels with a hexagonal lattice core structure are comparable with the technically applicable balsa wood Baltek®. The CLF-panels with a hexagonal lattice core structure are comparable with foams like ROHACELL® 31 A and AIREX® R82.60.

Conclusions and outlook

With the aid of the novel additive manufacturing technique, continuous lattice fabrication (CLF), ultra-lightweight sandwich panels were produced. The material testing was performed by a compression test perpendicular to the top layer plane. The lattice core structure within the sandwich panel consists of continuous carbon fiber-reinforced polymer (CFRP)-rods. The lattice core structures have densities < 10 mg × cm^{-3} and selective pivots for force transmission. In this context, the test-related evaluation of sandwich panels with lattice core structures is in focus. The methodical procedure, as well as the results, can be summarized in a systematic approach for failure analysis of sandwich panels with lattice core structures. The systematic approach includes the modified compression test, the determination of standard deviation and failure analysis by means of a scanning electron microscope. Furthermore, it could be shown that lattice core structures, in spite of obvious potential for improvement, have lightweight indices on a level comparable to performance materials such as balsa wood.

Manufacturing process. Using lattice core structures as a sandwich core material shows high potential for reducing the weight of core structures and achieving core densities < 10 mg × cm^{-3}. Two different manufacturing processes were realized. Differential manufacturing (DIF) shows high potential but inaccuracies within the manufacturing process. The feed-rate-unit and the cutting process within a manual operation mode of the CLF-application head lead to higher tolerances and therefore to an unequal force transmission of a lattice core structure. Using the CLF-application head in the production cell, results in a more precise lattice core structure and consequently in more accurate force transmission. Hence, the standard deviation of the CLF-panels is much smaller as compared to the DIF-panels.

Quasi-static investigations. The DIF-panels achieve higher values for compression strength and compression modulus as compared to CLF-panels. The failure was abrupt and localized at the fixing points or in the middle of the CFRP-rod. The failure behavior of CLF-panels could be described as noncritical and was primarily localized in the force transmission between the CFRP-rod and top layer. Within a manufacturing series, the hexagonal lattice core structure has the highest amount of compression strength and compression modulus. Hence, for a uniaxial compression load, the hexagonal lattice core structure with perpendicular CFRP-rods are to be preferred.

In further studies, the manufacturing process will be optimized to improve the force transmission of both processes and decrease the void content of CFRP-rod. In addition, the load capacity of DIF-panels will be improved through a reduction of stress concentrations in plug-in-connectors. The mechanical properties of CLF-panels in terms of compression strength and compression modulus can be adjusted by different approaches to the level of DIF-panels. In further investigations, the high residual load capacity will be considered to optimize the stop criterion for lattice core structures. In addition, the systematic approach developed will be expanded with shear loads as well as an overlap of compression and shear loads. Thus, existing experimental setups will be modified to determine the shear strength of lattice core structures and will be included in the systematic approach. Based on the quasi-static results, the systematic approach will be extended in cyclic investigations in order to characterize the fatigue behavior of lattice core structures. Compression after im-

Manufacturing process	Variation base area	ρ_{core} (mg × cm^{-3})	Compression strength σ_c (MPa)	LWI
DIF	△	7.23	0.12	56,027
	□	5.47	0.18	111,814
	⬡	6.57	0.30	154,450
CLF	△	8.70	0.06	23,434
	□	7.93	0.06	25,709
	⬡	8.30	0.11	44,870

Table 2: Lightweight index of different variations for DIF and CLF

Material	ρ_{core} (mg × cm^{-3})	Compression strength σ_c (MPa)	LWI
Plascore Honeycomb PN2-1/4-2.0	24	0.48	67,958
ROHACELL® 31 A	32	0.40	42,474
AIREX® R82.60	60	0.70	39,642
AIREX® C70.75	80	1.45	61,587
BALTEK® SB.50	109	5.50	171,453
ROHACELL® 110 S	110	2.80	86,492

Table 3: Lightweight index of comparative core materials [16-21]

pact tests will be performed to determine future applications.

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References

1 A. Bellini, S. Güceri: Mechanical characterization of parts fabricated using fused deposition modeling, Rapid Prototyping Journal 9 (2003), No. 4, pp. 252-264 DOI:10.1108/13552540310489631
2 A. R. Torrado, D. A. Roberson: Failure analysis and anisotropy evaluation of 3D-printed tensile test specimens of different geometries and print raster patterns, Journal of Failure Analysis and Prevention 16 (2016), No. 1, pp. 154-164 DOI:10.1007/s11668-016-0067-4
3 A. M. Forster: Materials testing standards for additive manufacturing of polymer materials: State of the art and standards applicability, National Institute of Standards and Technology, Gaithersburg, USA (2015), pp. 1-45 DOI:10.6028/NIST.IR.8059
4 O. Huber, H. Klaus: Cellular composites in lightweight sandwich applications, Materials Letter 63 (2009), No. 13-14, pp. 1117-1120 DOI:10.1016/j.matlet.2008.11.059
5 X. Zheng, H. Lee, T. H. Weisgraber, M. Shusteff, J. DeOtte, E. B. Duoss, J. D. Kuntz, M. M. Biener, Q. Ge, J. A. Jackson, S. O. Kucheyev, N. X. Fang, C. M. Spadaccini: Ultralight, ultrastiff mechanical metamaterials, Science 344 (2014), No. 6190, pp. 1373-1377 DOI:10.1126/science.1252291
6 M. Eichenhofer, J. C. H. Wong, P. Ermanni: Continuous lattice fabrication of ultra-lightweight composite structures, Elsevier Additive Manufacturing 18 (2017), pp. 48-57 DOI:10.1016/j.addma.2017.08.013
7 F. Eichenhofer, M. Eichenhofer: Method for producing a framework, Germany (2015), Patent number: WO2015169414A1, pp. 1-39
8 M. Eichenhofer, J. I. Maldonado, F. Klunker, P. Ermanni: Analysis of processing conditions for a novel 3D-composite production technique, Proc. 20th International Conference on Composite Materials ICCM20, Copenhagen (2015), pp. 1-12
9 D. L. DuQuesnay, T. H. Topper, M. T. Yu: The effect of notch radius on the fatigue notch factor and the propagation of short cracks, Mechanical Engineering (1986), pp. 323-335
10 H. Fan, W. Yang, B. Wang, Y. Yan, Q. Fu, D. Fang, Z. Zhuang: Design and manufacturing of a composite lattice structure reinforced by continuous carbon fibers, Elsevier Tsinghua Science & Technology 11 (2005), No. 5, pp. 515-522 DOI:10.1016/S1007-0214(06)70228-0
11 C. Schneider, M. N. Velea, S. Kazemahvazi, D. Zenkert: Compression properties of novel thermoplastic carbon fibre and poly-ethylene terephthalate fibre composite lattice structures, Elsevier Materials & Design 65 (2015), pp. 1110-1120 DOI:10.1016/j.matdes.2014.08.032
12 C. R. Schultheisz, A. M. Waas: Compressive failure of composites, Part I: Testing and micromechanical theories, Elsevier Aerospace Science 32 (1996), No. 1, pp. 1-42 DOI:10.1016/0376-0421(94)00002-3
13 N. A. Fleck, D. Liu: Microbuckle initiation from a patch of large amplitude fibre waviness in a composite under compression and bending, Elsevier European Journal of Mechanics – A/Solids 20 (2001), No. 1, pp. 23-37 DOI:10.1016/S0997-7538(00)01124-4
14 Y. Verreman, N. Limodin: Fatigue notch factor and short crack propagation, Elsevier Engineering Fracture Mechanics 75 (2008), No. 6, pp. 1320-1335 DOI:10.1016/j.engfracmech.2007.07.005
15 B. Klein: Leichtbau-Konstruktion, 10th Ed., Springer Vieweg, Wiesbaden, Germany (2013), pp. 23-37 DOI 10.1007/978-3-658-02272-3
16 Plascore Inc: PN2 Aerospace Grade Aramid Fiber Honeycomb, Zeeland, USA (2017)
17 Evonik Resource Efficiency GmbH: Technical information: ROHACELL® A, Darmstadt, Germany (2017)
18 Airex AG: Data Sheet AIREX® R82, Sins, Switzerland (2011)
19 Airex AG: Data Sheet AIREX® C70, Sins, Switzerland (2011)
20 Airex AG: Data Sheet BALTEK® SB, Sins; Switzerland (2016)
21 Evonik Resource Efficiency GmbH: Technical information ROHACELL® S, Darmstadt, Germany (2017)

Bibliography

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Abstract

Druckversuch von additiv gefertigten und kontinuierlich kohlenstofffaserverstärkten Sandwichstrukturen. Das neuartige Verfahren Continuous Lattice Fabrication kombiniert die Vorteile einer kontinuierlichen Faserverstärkung und der additiven Fertigung. Dabei kann die Faserverstärkung nicht nur innerhalb einzelner Schichten, sondern auch kraftflussgerecht (out-of-plane) im dreidimensionalen Raum generiert werden. Ziel dieses Beitrags ist eine testbasierte Bewertung von Sandwichstrukturen mit fachwerkähnlichen Kernstrukturen durch die Modifikation eines Druckversuchs. Dafür wurden Proben differentiell mit Steck- und Klebeverbindungen sowie automatisch mittels continuous lattice fabrication gefertigt. Zusätzlich wurde die räumliche Anordnung der Fachwerkstäbe, durch verschiedene Grundflächen und Stabwinkel, variiert. Ultraleichtbau-Strukturen mit fachwerkähnlichen Kernstrukturen haben Kerndichten kleiner 10 mg × cm^{-3}. Die grundlegende werkstoffmechanische Untersuchung wurde mit Hilfe eines modifizierten einachsigen Druckversuchs bei Raumtemperatur durchgeführt. Die erarbeitete Systematik zur Schadensanalyse legt zukünftiges Optimierungspotential des noch jungen Verfahrens offen. Es konnte gezeigt werden, dass die Sandwichelemente mit einer Kernstrukturdichte von 6.57 mg × cm^{-3} eine Druckfestigkeit von bis zu 0.30 MPa aufweisen. Durch Auswertung einer dimensionslosen Leichtbaukennzahl konnte gezeigt werden, dass die Kennwerte der entwickelten Strukturen auf einem ähnlichen Niveau mit ausgewählten technischen Kernmaterialien liegen.

Martin Eichenhofer, born in 1988, obtained his Bachelor's degree in Mechanical Engineering at the University of Applied Sciences Ravensburg-Weingarten, Germany followed by a Master's degree in Mechanical Engineering at ETH Zurich, Switzerland and a post-graduate Master's degree in Economics at the Collège des Ingénieurs, Paris, France. He specializes in functional design, processing and mechanics of composite materials. While working on his Master's thesis, he developed a new processing route for the continuous fabrication of composite materials (CLF). He is particularly interested in the symbiosis of digital fabrication and load tailored design.

Daniel Schupp, born in 1991, studied Mechanical Engineering with an emphasis on designing and developing at the University of Applied Sciences (UAS) Ravensburg-Weingarten, Germany. He received his Bachelor's degree in 2015, focusing on the development of new products for Bosch Power Tools. After that, he studied Technical Management at the UAS Ravensburg-Weingarten and received his Master's degree in 2017. Since 2015, he has been working for the Laboratory of Material Testing at UAS Ravensburg-Weingarten. His research mainly focuses on quasi-static testing of fiber-reinforced materials and the development and manufacturing of ultra-lightweight parts for aircrafts.

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Daniel Huelsbusch, born in 1986, studied Mechanical Engineering with an emphasis on technical management and materials science at the TU Dortmund University, Germany, where he received his diploma degree in February 2013 after focusing on joining techniques for fiber-reinforced polymers at BMW group. Since then he has been working as a scientific assistant and group leader for "Composites" at the Department of Materials Test Engineering (WPT) at the TU Dortmund University, Germany, and was appointed general Senior Engineer in 2015. His research is mainly focused on the fatigue properties of fiber-reinforced polymers, including the determination of deformation behavior, by advanced hysteresis measurements, and the corresponding damage propagation by in situ computed tomography.

Prof. Dr.-Ing. Frank Walther, born in 1970, studied Mechanical Engineering majoring in Materials Science and Engineering at the TU Kaiserslautern University, Germany. There, he finished his PhD on the fatigue assessment of railway wheel steels in 2002 and his habilitation on physical measurement techniques for microstructural-based fatigue assessment and lifetime calculation of metals in 2007. At Schaeffler AG in Herzogenaurach, Germany, he headed the Public Private Partnership within Corporate Development from 2008 to 2010. Since 2010 he has been Professor for Materials Test Engineering (WPT) at the TU Dortmund University, Germany. His research portfolio includes the determination of structure-property relationships of metal- and polymer-based materials and components under fatigue loading from LCF to the VHCF range, taking the influence of manufacturing and joining processes as well as service loading and corrosion deterioration into account. Prof. Walther has published more than 200 research papers and conference proceedings and maintains close scientific contact with institutions and industries in materials science and engineering field worldwide.