Design Science

Optimization of load introduction points in sandwich structures with additively manufactured cores

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Abstract

This paper presents how numerical optimization methods, like topology optimization, and new design possibilities through additive manufacturing (AM) can be used for structural improvements of the load introduction points in sandwich structures. A new design approach is presented, which allows a direct load-path optimized integration of the load introduction point into the sandwich core. The corresponding methodical procedure is shown and the application is demonstrated exemplarily for a sandwich structure with a honeycomb core. The advantages for design science are that the new design possibilities of AM can be considered and used when designing the load introduction points. Thus, the additional reinforcements of the sandwich structures to absorb locally introduced forces in the lightweight structure can be minimized. This enables a meaningful technical comparison and it can be decided in the future whether such a design can be used for sandwich structures under economic aspects. In addition, the influence of the initial and boundary conditions on the design is presented and discussed in this paper. The challenges of optimizing multiple load introduction points simultaneously as well as the special aspects to be considered when transferring the design approach to larger sandwich structures are also highlighted.

Key words: sandwich structure, insert, topology optimization, additive manufacturing, load introduction point

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1. Introduction

This paper aims to show how numerical optimization, especially topology optimization, and new design possibilities through additive manufacturing (AM), can be used to improve the structural integration of load introduction points into sandwich structures. In the beginning, an overview of the current state of the art of sandwich structures, inserts and AM of inserts as well as of sandwich cores is given. The performance of load introduction points can be improved by new design concepts, which reduce the stiffness discontinuity at the interface between the insert and the core. Due to the high number of inserts in sandwich structures, especially in the aircraft cabin, there is a high potential for targeted weight reduction. Therefore, a new design approach is presented, which allows a direct load-path optimized integration of the load introduction point into the core. After the presentation of the methodical procedure, a simple demonstration example is shown. A load introduction point oriented perpendicular to the face sheets of a sandwich structure is topologically optimized. A new design is derived from the optimization results, additively manufactured and tested in a pull-out test. The stiffness and maximum pull-out force determined in the test are compared with a reference design. The evaluation of the results is followed by a discussion about the influence of the initial and boundary conditions on the optimization and the design. In particular, the differences between standardized tests and real-life applications such as the applied load case and the clamping are considered more closely. Finally, it is shown exemplarily how the new design approach can be extended from a single load introduction point to multiple load introduction points. In conclusion, the content is summarized and a brief outlook is given.

2. State of the art

The term sandwich structure refers to a composite material that consists of two thin and stiff face sheets with a thicker, lightweight core in-between. Because of their excellent weight-specific material properties, especially stiffness and strength, sandwich structures are often used for aircraft cabin interiors, such as galleys, lavatories, partitions or crew rest compartments. For these applications, honeycomb cores, which consist of hexagonal cells, out of aramid fiber and phenolic resin are used. Weak spots of sandwich structures are the load introduction points since the core cannot absorb the local loads or rather introduce them properly into the thin face sheets. Load introduction points are the mechanical interfaces of the sandwich panels. Aircraft cabin monuments consist of numerous sandwich panels with a high number of internal and external interfaces. External interfaces are the lower and upper attachments, which are required to connect the monument to the fuselage of the aircraft. Internal interfaces are all the other joints between two individual sandwich panels or a sandwich panel and a mounting part. Local reinforcements, so-called inserts, are used for these interfaces, which are usually glued with a potting compound into cutouts in the sandwich structure (Bitzer 1997; Zenkert 1997).

There are a wide variety of different insert elements due to different and changing requirements and the absence of a uniform design approach. To give an example, in the manufacturing process, a distinction is made whether the insert is bonded during the production of the sandwich panel (hot bonded) or is installed after the production of the sandwich panel (cold bonded) (Bianchi *et al.* 2010; Lim & Lee 2011). Other distinguishing criteria are the orientation of the connection, the decisive load case and the installation depth. The orientation of the inserts varies so that a distinction is made between inserts perpendicular and parallel to the face sheets. For inserts oriented perpendicular to the face sheets, the decisive load cases are pull-out (out-of-plane) and shear (in-plane) as shown in Figure 1.

For inserts oriented parallel to the face sheets, the load cases pull-out (in-plane) and shear (in- and out-of-plane) need to be investigated as shown in Figure 2.

The quasi-standard test methods for inserts in sandwich structures are pull-out tests and shear tests as described in the Insert Design Handbook (ESA 2011). The installation depth of the inserts perpendicular to the face sheets can be divided into three different variants. In the variant 'Through-the-Thickness' the entire core height is filled by the insert. In the variant 'Partially Potted' a part of the core remains under the insert. This space is filled with a potting compound in the variant 'Fully Potted' (Thomsen 1998).

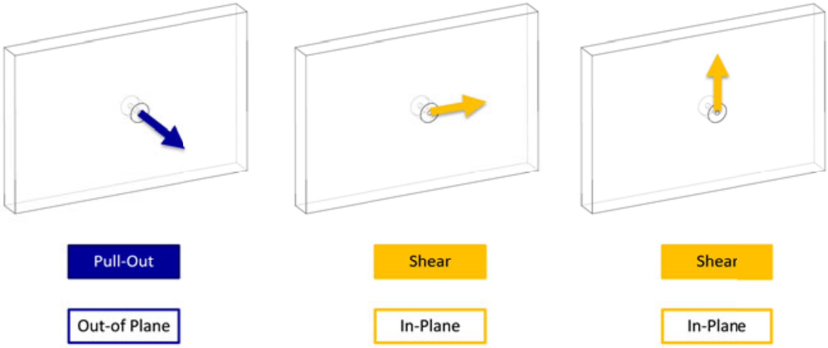

Figure 1. Inserts oriented perpendicular to the face sheets.

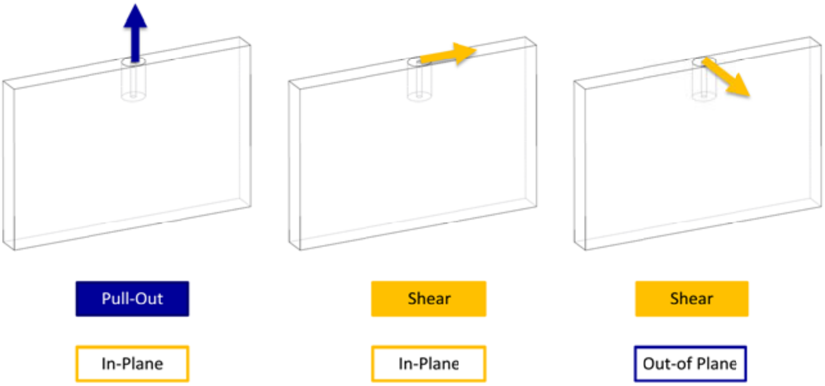

Figure 2. Inserts parallel to the face sheets.

In the development and optimization of inserts, the diameters of the cylindrical insert or the surrounding potting compound are varied to increase the pull-out strength (Raghui *et al.* 2009). If higher strengths are required, the core is replaced locally by solid material blocks out of fiber-reinforced plastics or metal. This leads to high stiffness discontinuities between the insert and the core and increases the mass of the structure.

2.1. Additive manufacturing of inserts

In the production of inserts, AM offers enormous potential for weight reduction. One way to reduce the structural mass while maintaining the same functionality is to optimize the topology of the inserts starting from the original design space and to manufacture them additively. Cavities in the inner structure instead of full material make it possible to reduce the mass of the insert. Türk *et al.* (2016) show an example where the mass of the insert is reduced by 60% through an optimization . Other options are to change the shape or increase the size of the insert without increasing the mass of the insert. For example, using a star shape instead of the common cylindrical shape can improve the mechanical properties (Schwenke *et al.* 2019).

2.2. Additive manufacturing of sandwich cores

Besides the possibility to optimize the inserts, AM also enables the optimization and manufacturing of the core structure. There are plenty of examples in the literature, which are described by the term hierarchical honeycombs, where additively manufactured core structures are derived and tested instead of the classic honeycomb core design to improve the mechanical properties of the entire core. Ajdari *et al.* (2012) and Oftadeh *et al.* (2014) use a concept with smaller hexagons at the intersections of honeycombs. Mousanezhad *et al.* (2015) investigate structures in which a smaller honeycomb is added in the middle of each honeycomb and connected to the corners like a spider's web. Sun *et al.* (2015) use a triangular pattern as well as a pattern of triangles and hexagons to construct the cell walls of the honeycombs with a substructure. Taylor *et al.* (2012) investigate the use of a hexagon pattern as a substructure for the cell walls. The results of the new hierarchical cores are compared with conventional honeycomb cores manufactured with the same AM process and not with sandwich cores out of aramid paper or aluminum, which are currently used in real-life applications. The reason for this is that the currently typical wall thickness of AM cores (1.0–0.5 mm) is one order of magnitude greater than the wall thickness of honeycomb cores made out of aramid paper (0.1–0.05 mm). As a consequence, a larger cell size must currently also be used for AM cores. Smaller wall thickness and smaller cell size lead to a more uniform material distribution of the core, a lower mass and better support of the face sheets.

2.3. Additive manufacturing of sandwich cores and inserts

A combination of both concepts offers a greater potential for improving load transfer and weight reduction. By integrating the load introduction point directly into the core structure, the additional interface for connecting the two components is eliminated. Additive manufacturing ensures that they can be manufactured as a single component. Türk *et al.* (2016) show a concept in which pockets or snap connections are already integrated into the core. This simplifies the integration of the inserts and reduces the effort required to complete the sandwich structures. Another concept deals with the targeted stiffening of the core. In areas with higher stresses, the honeycomb walls are thickened or the cells are even filled (Türk *et al.* 2016). Riss *et al.* (2014) and Teufelhart *et al.* (2016) pursue a similar concept of direct implementation of functional elements in the core. Again, by increasing the wall thickness in the direction of the load application point, the areas with higher stress are reinforced. Oltmann *et al.* (2016) show that adaptive cores, in which the size of the honeycomb cells is reduced in the direction of the load introduction point, increase the weight-specific stiffness and strength.

2.4. Conclusion from the state of the art

All previous concepts, which integrate the insert into the sandwich core, do not use the full possibilities of AM and numerical optimization to generate an improved load-path optimized design. Therefore, a new design approach along with a methodical procedure is presented to exploit the potential of AM in terms of function integration, the complexity of design geometry and individualization for the load-path optimization of the load introduction points in sandwich cores.

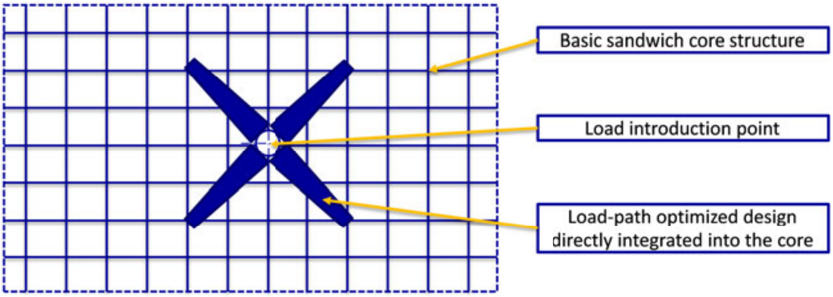

Figure 3. Basic principle of the new design approach.

3. New design approach

The new design approach is presented in this section. First, the basic principle of the approach is explained, then the methodical procedure is introduced and finally, the procedure is applied to a demonstration example.

3.1. Basic principle of the approach

The basic idea of the approach is to use numerical optimization methods and the new design possibilities through AM. The numerical optimization is used for the structural improvement of the load introduction into the sandwich structure and enables better integration of the load introduction point into the core structure. The aim is to improve the load introduction by reducing the stiffness discontinuity at the interface. In this way, it is possible to improve the mechanical properties of the sandwich panel joints or reduce the mass. Because of the integrated load-path optimized load introduction point, the sandwich core has a more complicated geometry. Additive manufacturing ensures that the sandwich core can be produced. In Figure 3, the basic principle of the new design approach is visualized.

The aim of the approach is to derive an additively manufactured sandwich structure in which a load-path optimized design of a load introduction point is directly integrated into the basic core structure. In addition to the basic core structure, a design space is defined in a certain area around the load introduction point and a numerical optimization is performed. For the derivation of the final design the two independent components, the basic core and the additional load-path optimized design, are combined. The approach works independently of the geometric design of the basic core structure. For example, it is possible to use honeycomb cores, hierarchical honeycomb cores, cores with other geometrical patterns or even cores with lattice structures.

For the production of the derived design, where the optimized load introduction point is directly integrated into the core structure, additively manufacturing is recommended. Only AM ensures that the more complicated geometry of the design can be produced. The state of the art shows that currently additively manufactured sandwich cores, especially for entire sandwich panels, cannot be produced economically with the required low wall thicknesses and cell sizes of real-life applications. For current applications, the approach could be used to design a load-path optimized insert. In particular, such inserts could replace

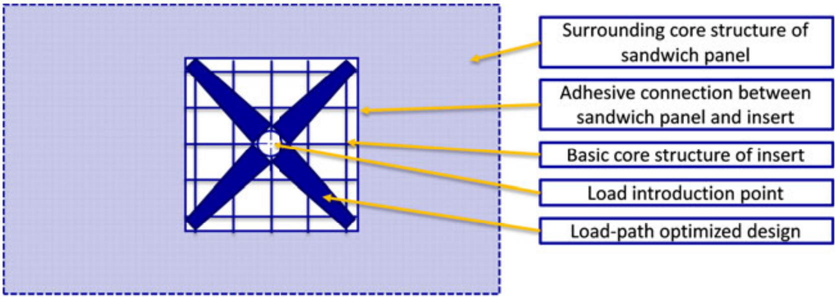

Figure 4. Basic principle for inserts.

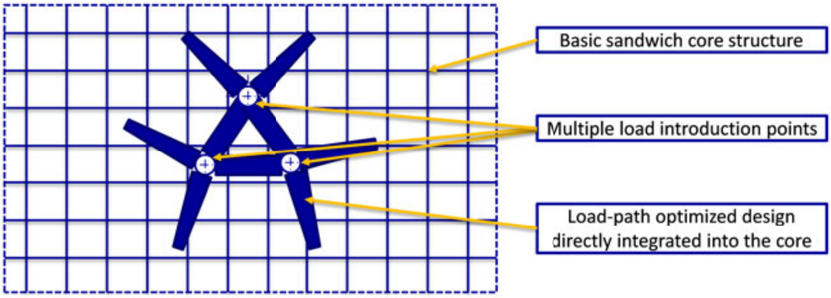

Figure 5. Basic principle for multiple load introduction points.

solid material blocks used for highly loaded load introduction points. Figure 4 shows the basic principle of this alternative to designing an insert that is glued into the surrounding core structure.

The approach presented is not limited to a single load introduction point. It is also possible to combine the local optimization of multiple load introduction points. The long-term goal is to include optimization of the basic core structure across the entire panel and not just the local load introduction point. The basic principle of this variant with multiple load introduction points is shown in Figure 5.

This variant also has the alternative of optimizing multiple load introduction points close to each other and combining them to form a larger insert, which is inserted into the surrounding core structure of a sandwich panel.

3.2. Methodical procedure

The methodical procedure of the approach for load-path optimization of the load introduction points is shown in Figure 6. It consists of three main steps, each of which can be divided into two substeps. The main steps of the procedure are based on the common optimization process. In Step 1 all necessary boundary conditions are defined, in Step 2 the design is derived from the optimization results and in Step 3 the analysis of the design is carried out.

The substeps take into account the particularities of the optimization of load introduction points. The definition of the boundary conditions in Step 1 determines what is optimized and how it is optimized. Substep 1.1 contains a

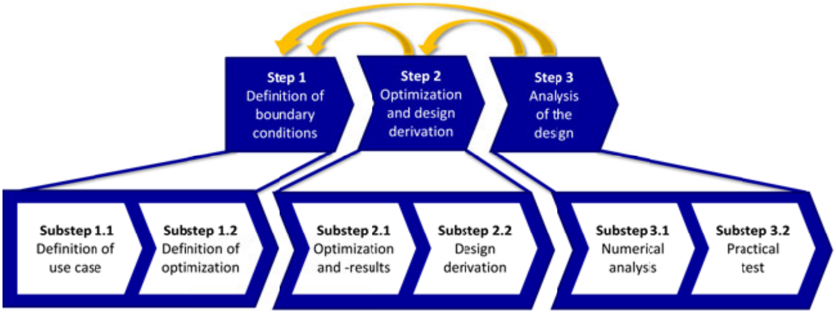

Figure 6. Methodical procedure for the optimization of the load introduction points.

detailed definition of the use case to consider all relevant requirements. These are in particular the orientation (alignment and position of load introduction points), the test setup consisting of load case and clamping (height, direction and position of loads, position and restricted degrees of freedom of clamping) and the sandwich structure (geometry, material of core and face sheets and manufacturing process).

In Substep 1.2 the boundary conditions for the optimization are considered. An optimization model is created with the selected software and the selected optimization method. In this model, the sandwich structure is implemented with all boundary conditions from Substep 1.1 and the design space for the optimization of the load introduction point is defined. Furthermore, all other boundary conditions of the optimization are defined.

Step 2 includes optimization and design derivation. In Substep 2.1 the optimization is performed to obtain the optimization results. In Substep 2.2 the design is derived from the optimization results. Since a basic core structure is used, a complete redesign is usually not necessary. The result of the load-path optimization is regarded as a direct addition to the basic core structure. For the derivation of the design, the basic core and the additional load-path optimized design, which are two different components in the optimization, are combined to a common component.

Step 3 is the analysis of the design. Substep 3.1 contains the numerical analysis of the derived structure. Critical deformations or stresses can be analyzed and different designs can be compared in advance without the effort of manufacturing specimens for the design and performing practical tests. In Substep 3.2 a practical test is performed and evaluated, therefore test specimens have to be manufactured according to the boundary conditions of Step 1. The procedure is linearly run through, but the possibility to go through iteration loops is included. The influences on the design due to changes in the boundary conditions are the drivers for the iterations. Generally, a single optimization run is insufficient to derive the best optimal result for a design. A detailed analysis of the boundary conditions and their impact on design and performance is required.

3.3. Application of the methodical procedure

To demonstrate the potential of the approach and to clarify the methodical procedure, it is applied to a demonstration example. In the demonstration example, the area around the load introduction point in a synthetic resin

Figure 7. Basic test setup of a pull-out test.

honeycomb core of a sandwich sample with aluminum face sheets is topologically optimized. A design for the core is derived from the optimization result and additively manufactured. Core and face sheets are glued to a sandwich specimen and tested in a pull-out test. A reference design is also manufactured and tested. The results of both designs are analyzed and compared. In the following, the individual substeps, as well as the materials used and methods applied, are described in more detail. No iteration loop of the procedure is displayed for the demonstration example. The influence of the initial and boundary conditions is described and discussed in the next section.

Step 1: Definition of Boundary Conditions

Substep 1.1: Definition of use case

The test setup, the load case and the orientation are defined in this substep. The orientation of the load introduction point is determined as perpendicular to the face sheets. A pull-out test is selected as the basic test setup, as shown in Figure 7.

Only a small sandwich specimen with a size of approx. 100 × 100 mm is required. During the test, a single central load introduction point is loaded perpendicular to the sandwich structure. For simplification, no thread is used in the demonstration example. Instead, the load is applied over the contact surface of a washer positioned between the sandwich specimen and the screw head on the bottom of the sandwich specimen. The circular opening of the clamping device has a diameter of 70 mm.

Furthermore, the sandwich structure, the materials and the manufacturing process are defined. The basic core structure of the sandwich specimen is a conventional honeycomb structure with constant cell size and wall thickness. It consists of regular hexagons with a cell size of 9.5 mm. This size corresponds to a large but available cell size used for honeycomb cores. The core height of 12 mm is also approximately one of the standard heights of sandwich cores. A stereolithography process is used for AM of the core out of a photopolymer

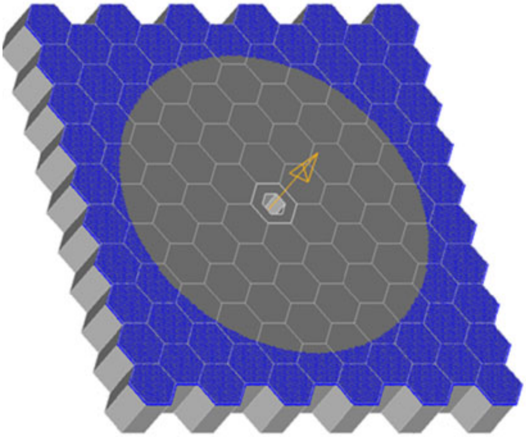

Figure 8. Optimization model.

synthetic resin. The wall thickness is set to 0.5 mm to ensure the manufacturability of the core. Aluminum sheets with a thickness of 0.5 mm are used for the face sheets. The materials and the manufacturing process are described in more detail in Substep 3.2, which includes the manufacturing of the sandwich specimens.

Substep 1.2: Definition of optimization

The CAE software package HyperWorks 14.0 from Altair Engineering (Troy, Michigan, USA) is used for numerical investigation of the problem. HyperMesh is used as the preprocessor for modeling, OptiStruct as the solver for optimization and calculation, and HyperView as the postprocessor for evaluation of the optimization results. Topology optimization is used as the optimization method. Figure 8 shows the optimization model. The blue area displays the clamping and the orange arrow the applied force.

The geometric dimensions are determined from the defined use case in substep 1.1. Shell elements with a side length of approx. 0.5 mm are used to model the cell walls of the basic core structure (quads) and the two face sheets (trias). Volume elements (pentas) are used to fill the honeycombs evenly in the design space. The design space for the optimization is defined by all honeycombs cells that are completely located inside the circular opening of the clamping. By using these element types and sizes, the components can be connected directly via the nodes of the elements without additional contact definitions. In this way, the connection between the face sheets and the two different core components can be neglected and the direct integration of the design space to the basic core structure can be ensured. To model the clamping, all degrees of freedom of the corresponding elements of the upper face sheets are fixed. The load is a single force of 10 kN applied to the bottom of the sandwich structure via an RBE3 element. Only elastic material behavior is taken into account during the optimization. A modulus of elasticity of 69 GPa and a Poisson's ratio of 0.34 are used for the aluminum face sheets and a modulus of elasticity of 2.8 GPa and a Poisson's ratio of 0.35 are used for the synthetic resin core. The objective of the conducted optimization is to minimize the compliance of the structure, which is equivalent to maximizing the stiffness. In this example, only a volume constraint and no stress

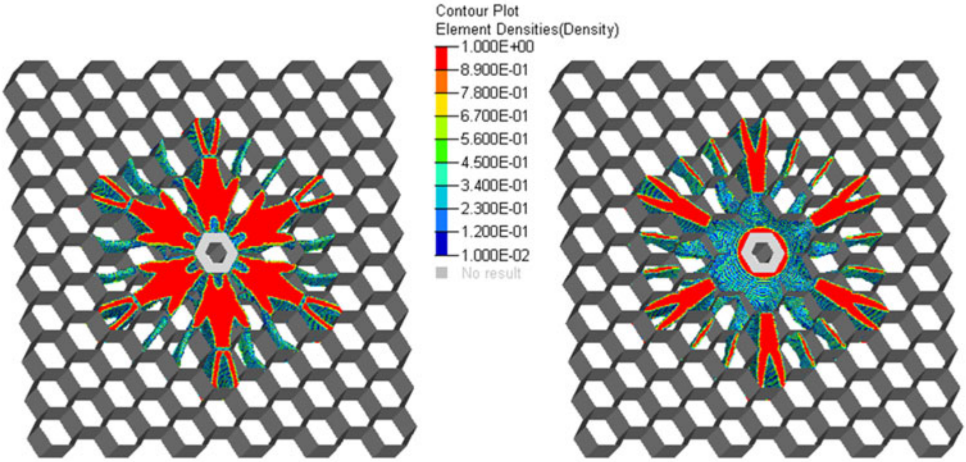

Figure 9. Optimization result from the top (l.) and bottom (r.).

constraint is defined. The volume constraint is set to 33.3% of the volume of the design space.

Step 2: Optimization and design derivation

Substep 2.1: Optimization and optimization result

After the optimization run, the optimization results are analyzed. In Figure 9 the visualized optimization result is shown. The calculated element densities of the elements in the design space are displayed in false color. The threshold value for the element density for the visibility of the elements in the design space is set to 33%. The basic core structure is shown in gray and the face sheets are hidden.

Substep 2.2: Design derivation

The load-path optimized design is directly derived from the optimization result. All elements of the optimization result with an element density greater than 37.35% are used for the design, while all other volume elements of the design space are deleted. To evaluate the test results, a reference design is defined, which is also manufactured and tested. As a reference design, a full cylinder with a diameter of 36.8 mm is integrated directly into the basic core structure. Therefore, the comparison of the two designs shows the potential for improvement in the load-path optimization of a directly integrated load introduction point. By selecting the specified values for the threshold value and the diameter, both designs have the same mass and the test results can be directly compared with each other. Figure 10 shows the reference and the load-path optimized design.

Step 3: Analysis of the design

Substep 3.1: Numerical analysis

The substep of the numerical analysis, in this case for the optimized design and the reference design, is not shown in this demonstration example. This substep of the methodical procedure serves to determine the influence of the boundary conditions on the derived design and to reduce the test effort of the practical test

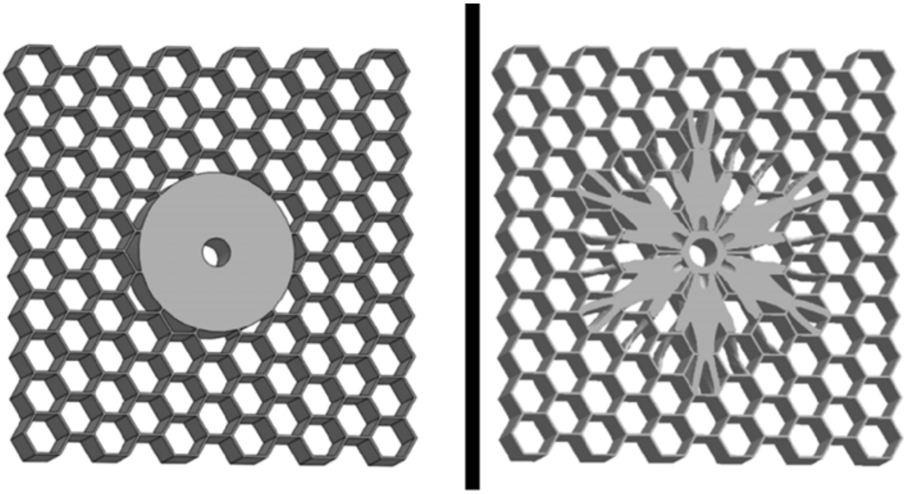

Figure 10. Reference design (l.) and load-path optimized design (r.).

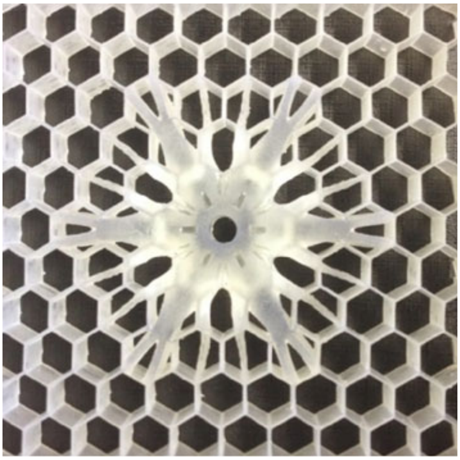

Figure 11. AM sandwich core with a load-path optimized design of the load introduction point.

when determining an optimal design. Both designs are compared in a practical test in the following substep.

Substep 3.2: Practical test

The two core designs are additively manufactured with a commercial stereolithography printer (Form 2; Formlabs; Somerville, Massachusetts, USA) from a photopolymer synthetic resin (Clear Resin FLGPCL02). After completion of the printing process, the support material is removed, the core structure is cleaned of liquid material residues in two ethanol baths for 10 minutes each and cured at approx. 30 °C for at least 24 hours in a UV chamber. In Figure 11 the 3D-printed core with the load-path optimized design for the load introduction point directly integrated into the core structure is shown.

Figure 12. Test setup of the pull-out test.

To produce the test specimens, the additively manufactured cores are then bonded to the aluminum face sheets by using the solvent-free two-component adhesive (UHU PLUS ENDFEST 300). The adhesive bond is cured at 100 °C for 10 minutes in an oven. To apply the load via a screw, a thru-hole (M6) is drilled into the specimen. The analysis of the mass of the individual specimens, which is approx. 53 g, shows no significant differences between the individual sandwich cores or the bonded sandwich specimen.

The used test setup for the pull-out test to test the specimens is shown in Figure 12.

The pull-out test is carried out with a universal testing machine (GALDABINI QUASAR 100). For the test, the sandwich specimen is mounted with an M6 screw, washer and nut. During the tests, the traverse of the universal testing machine is moved at a quasi-static speed of 1 mm/minute. The internal load cell of the testing machine is used to determine the occurring force and the displacement of the traverse is used to measure the displacement.

The test is performed with three sandwich specimens for each design. Figure 13 shows the test results for both designs in a force–displacement diagram. The different starting behavior at the beginning of the test, which occurs during the first contact phase, is filtered and linearized in the force–displacement diagram.

Although the three identical specimens of each design show qualitatively similar graphical progressions, the individual specimens still differ from each other. The specimen Reference_2 shows a deviation in stiffness and a different failure behavior compared to the other specimens in the reference design. These two specimens have similar stiffness but fail at different forces. Of the three specimens of the reference design, specimen Reference_3 fails at the highest force of about 3700 N at a displacement of about 1.5 mm. The three load-path optimized specimens are all stiffer, although the specimen Optimized_3 has a

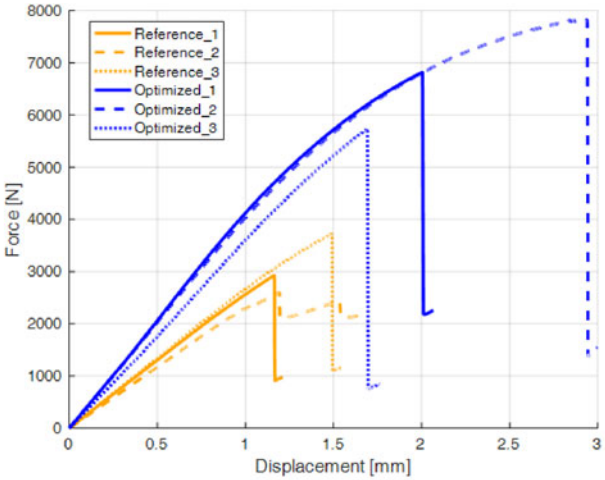

Figure 13. Force-displacement diagram.

Table 1. Test results for stiffness and maximum force

Specimen	Stiffness (N/mm)	Mean and standard deviation of stiffness (N/mm)	Max. force (N)	Mean and standard deviation of max. force (N)
Reference_1	2610	2545±177	2928	3084±578
Reference_2	2344		2600	
Reference_3	2680		3724	
Optimized_1	4059	3855±322	6822	6797±1041
Optimized_2	4022		7825	
Optimized_3	3483		5743	

deviation in stiffness from the other optimized specimens. The three optimized specimens fail at different forces. For the specimen Optimized_2, the failure occurs at a displacement of about 3 mm at a force of about 7800 N. The specimen Optimized_3 fails at a force of about 5700 N at a displacement of about 1.7 mm. For comparison and analysis of the stiffness and maximum force values achieved for the six specimens, these are shown in Table 1. The stiffness of the specimens is determined by linear interpolation in the force range between 1000 N and 1500 N.

The evaluation shows that the optimized integration into the core increases the stiffness of the specimen on average by more than 50%. Furthermore, the maximum achievable force is increased by more than 120% on average. Due to the small sample size ($n = 3$) and the relatively large variance, no significance test is performed at this point. The demonstration example is the first exemplary application of the approach. In a very conservative estimate, where the best reference specimen (Reference_1) is directly compared with the worst optimized specimen (Optimized_3), the improvement is still 30% in stiffness and over 50% in maximum force. The results show the potential of the new design approach,

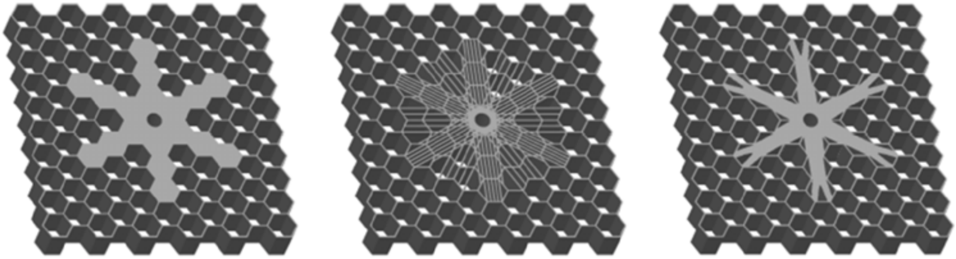

Figure 14. Different optimization methods: Filled cells (l.), additional walls (m.) and topology optimization (r.).

but further applications and testing are required. These could be performed on real-life application examples with other materials.

4. Influence of the initial and boundary conditions

An important aspect of the new design approach is the consideration of the initial and boundary conditions. Therefore, the methodical procedure includes iteration loops. The reason for this is that many different initial and boundary conditions influence the optimization, design and performance. In most cases, it is not sufficient to perform a single optimization run, because to derive the optimal result for an integrated load introduction point a detailed analysis is necessary. In the optimization model, a lot of different boundary conditions are required, for example, element types and sizes, degrees of freedom, loads, constraints and contact definitions. It is obvious, for example, that the modeling of the pull-out test influences the optimization result. Since this applies to all numerical optimizations, this is not the main consideration in this paper. The focus in this section is on the special features of optimizing the load introduction points and to integrate them directly into the basic core structure. By superimposing the optimization of the load introduction point with the basic core structure, the influence of the selected optimization method must be considered. In Figure 14 the derived designs for the sandwich core from the results of a parameter optimization with filled cells, additional walls and a topology optimization are shown.

It is recognizable that the optimization method has a strong influence on the optimization results and in consequence on the design. Theoretically, a topology optimization with a very small element size results in the best results, because it has, considered geometrically, the greatest degree of freedom. One occurring problem is, that such a topology optimization becomes very computationally intensive because of the high number of volume elements and that the individual load paths become smaller than the achievable resolution of the AM process. Therefore, it could be sufficient to use an optimization method with reduced expenditure like the parameter optimization with additional walls. Instead of volume elements, only shell elements are required to model the additional walls. The derived design of a parameter optimization is load-path optimized within the geometric possibilities. Through the thin and to AM adjusted wall thickness, it is possible to achieve mechanical properties in the same order of magnitude compared to the topology-optimized design (Schwenke *et al.* 2017). A design

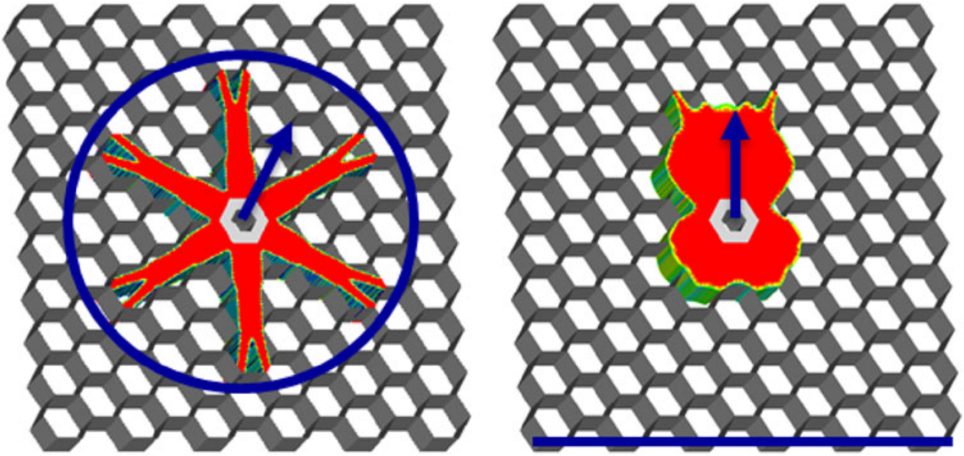

Figure 15. Load cases: Pull-out (out-of-plane) (l.) and Shear (in-plane) (r.).

from the parameter optimization with filled cells does not achieve the same performance. However, since the structure has a simpler geometry, it could be possible to use other manufacturing processes. For example, is the subsequent filling of the cells of a conventional honeycomb core with a potting compound in a load-path optimized design conceivable. Therefore, the presented design approach could be adapted to the materials, manufacturing constraints and the fact that no direct integration of the load-path optimized design into the core is achieved. Depending on the planned application, it must be decided which optimization method and which manufacturing process are used.

Besides the chosen optimization method the optimization result depends on the geometry, as the geometry of the basic core structure, the size and form of the design space and symmetry or extrusion constraints. In this paper, the focus is on the described geometry with a honeycomb core as the basic core structure. In addition, the boundary conditions of the test, in particular, the direction of the applied load and the clamping, influence the result.

4.1. Load case

As mentioned before, the two decisive load cases for inserts in sandwich structures perpendicular to the face sheets are out-of-plane load and in-plane load, which can be tested via a pull-out test and a shear test. In Figure 15 the optimization results for a pull-out test and a shear test are shown. In the schematic representation, the face sheets are hidden and only the core of the sandwich structure is displayed. The direction of the forces is indicated by blue arrows and the position of the clamping by blue lines. Apart from these differences, the identical initial and boundary conditions are used in the optimization for both load cases.

As expected, the results of the two different load cases vary. The optimization result of the pull-out test shows a symmetrical star shape. The optimization result of the shear test resembles an hourglass, whose orientation depends on the load direction in the plane of the sandwich core. For the load cases considered, it can be shown that it is more important to optimize the structure in a pull-out test than

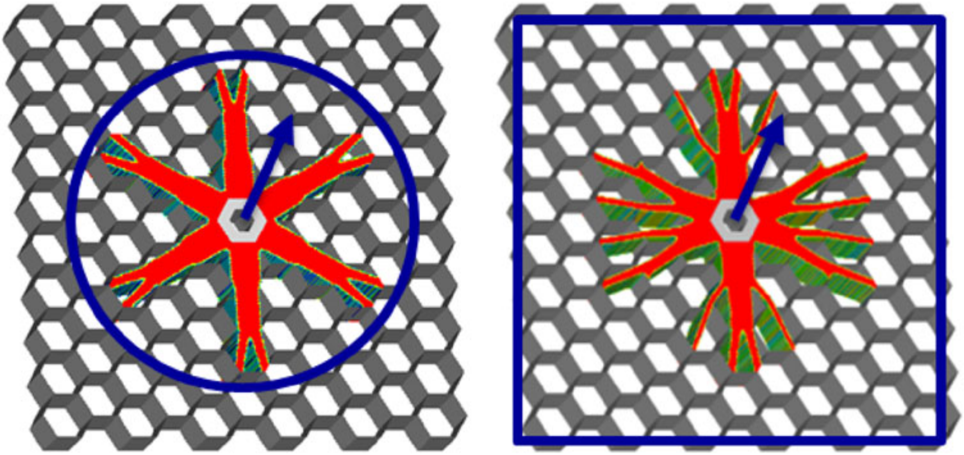

Figure 16. Opening of the clamping circular (l.) and square-shaped (r.).

in the shear test. By an in-plane case, the load can be introduced more directly into the face sheets, which are in this case parallel to the direction of the load. Therefore, less material in the core is required to transfer the load. Even more important is that the design optimized for pull-out performs better under shear load than vice versa. Because the structure optimized for pull-out has six in-plane symmetry axes the design performs well regardless of the direction of the applied shear load. When six in-plane symmetry axes are forced by a symmetry constraint, there are only minimal differences between the design from a combined load and the design from a pull-out load. In the case of inserts aligned parallel to the face sheets, the out-of-plane load case, in which the force acts perpendicular to the face sheets (in this case shear) is also decisive.

In real-life applications, the load direction is most time a combination of both load cases and also bending and torsion can occur. There is some additional potential if the exact direction of the force is considered during the optimization and through AM. One occurring challenge is to validate such a design with the simple standard tests. Another challenge is to ensure the exact orientation of the insert during the manufacturing process. Virtual test models and a digitalized design and manufacturing process are possible solutions to these challenges.

4.2. Clamping

Additionally, the shape of the opening of the clamping of the pull-out test has also an impact on the optimization result. In Figure 16 the results of a topology optimization for a pull-out test with a circular and square-shaped opening of the clamping are shown. Again, only the core of the sandwich structure is displayed in the schematic representation and the blue arrows indicate the direction of the forces and the blue lines the position of the clamping. Apart from these differences, the identical initial and boundary conditions are used in the optimization for both shapes of the clamping.

The optimization results vary between the standard circular opening and the square-shaped one. Instead of a six in-plane symmetry axes for the result optimized with a circular opening of the clamping, the result optimized for the square-shaped opening has only two in-plane symmetry axes. The differences are caused by the different shapes and symmetry of both openings. Instead of the same distance from the clamping to the load introduction point for the circular opening, the distance varies for the square-shaped one. The midpoints of the edges are closer to the load introduction point than the corners. The load paths point in the direction of these areas, because in an optimization they tend toward the shortest way.

The size of the design space is limited by the clamping since a design space for optimization larger than the opening of the clamping allows a structure that is supported directly by the clamping in the pull-out test. The original purpose of the pull-out test is to determine and compare the mechanical properties of inserts glued into the sandwich core in a simple standard test. One requirement is that the insert is smaller than the opening of the clamping so that the entire insert can be pulled out of the sandwich structure. Therefore, it is sufficient to test the common inserts in a small section of a sandwich panel with a standard clamping. In real-life applications, there is no such clamping around the load introduction point. In the aircraft cabin, the monuments made out of sandwich panels are only attached at few attachment points. And the individual sandwich panels are only connected at some few points to other panels or parts. For every individual load introduction point, the distances and arrangement to the other load introduction points vary. An optimization with more realistic test conditions would lead to an increased effort, but it is necessary to derive an optimal load-path optimized design with the load introduction point directly integrated into the core. This aspect needs to be examined more closely, especially to optimize multiple load introduction points simultaneously.

4.3. Multiple load introduction points

Another advantage of the presented design approach is the possibility to extend it from a single load introduction point to multiple load introduction points. In particular, if these points are nearby it becomes advantageous to optimize them simultaneously. In Figure 17 a load-path optimized design with three load introduction points is shown in a schematic representation.

The design is based on the same honeycomb structure and optimized in a combined pull-out test. Again, only the core of the sandwich structure is displayed and the blue arrows indicate the direction of the forces and the blue lines the position of the clamping. To design the form of the clamping the three individual circles are combined. The core cells in this area define the design space. Apart from that, the same initial and boundary conditions as for the single load introduction point were used. The example shows that the new design approach allows also a combined optimization of multiple load introduction points. A pronounced reinforcement between the three load introduction points in the structure is recognizable. Despite the asymmetrical arrangement, a star-shaped structure similar to the one that occurred for a single load introduction point can be recognized.

An emerging challenge is to test these kinds of designs. The required design space for the multiple load introduction points becomes much larger than the design space for a single pull-out test. Therefore, it is unsuitable to test the load introduction point successively in a single pull-out test, because the opening of the clamping interferes with the load-path optimized design. At the moment there

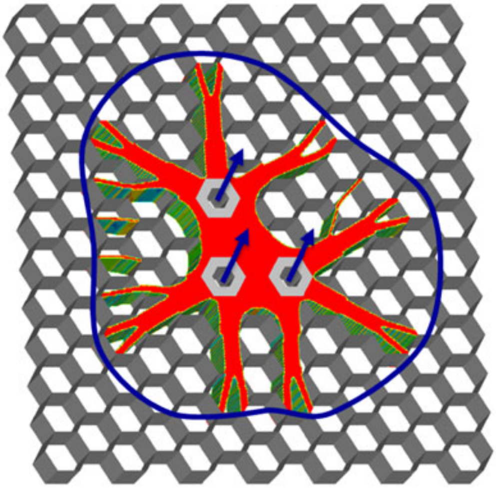

Figure 17. Example with multiple load introduction points.

is no suitable test method for testing multiple load introduction points defined. Therefore, such test methods need to be developed. Thereby is to keep in mind that, the positions of the load introduction points could be changed due to the application and a superposition of different load cases with a different amount of load would be necessary. Nevertheless, with the presented design approach, it is possible to derive a load-path optimized design for all the individual load introduction points of a sandwich panel.

5. Conclusion

The presented design approach uses the potential of AM for a load-path optimized integration of load introduction points into the sandwich structure. Starting from a basic core structure, a numerical optimization is performed for a single load introduction point or multiple load introduction points. A new design is derived from the optimization results by integrating the load-path optimized addition for the load introduction points into the core structure.

The demonstration example shows that the development of individual, load-path optimized core structures is possible with the new design approach. The load-path optimized design from the topology optimization is compared to a reference design with the same mass. The results of the practical pull-out test show that an improvement in stiffness of over 50% can be achieved and that the maximum pull-out force is increased by 120%. It is shown why a detailed analysis of the influence of the initial and boundary conditions is necessary to reach an optimal design. The example of a core structure with three load introduction points shows that multiple load introduction points can be load-path optimized simultaneously. With the approach, an extension to other basic core structures and load introduction points, which are oriented parallel to the face sheets, is also possible. Even the optimization of an entire sandwich panel or structure is conceivable. If the manufacturing boundary conditions are taken into account in the numerical optimization of the geometry, it is also possible to use alternative or conventional manufacturing processes. In order to further expand the design approach, the optimization of the basic core structure could be included. It is conceivable to adapt the basic core structure in the area of the local load introduction as well as in the entire core, for example, by an additional optimization of the thickness of the cell walls.

A major challenge is that there are no standardized tests for such load-path optimized designs and the common tests do not exactly consider the installation situation of real-life applications. Alternative test methods, especially for multiple load introduction points, must be developed. A pull-out test, in which the entire sandwich panel is only clamped at all the other load introduction points or at the corners of the panel, seems advantageous but would require a high effort for testing. The basic requirements for such test methods are that they can be carried out with a manageable amount of effort and that the installation situation like load directions, symmetry conditions and multiple load introduction points must be taken into account more precisely. This ensures that the application is optimized not only for practical testing but also for practical use. For the numerical optimization, it is possible to automatically create a new model with different boundary conditions with relatively little effort. For the practical test, the change of the boundary conditions of the test means a substantially higher effort. One possible solution is the development of a virtual test model, as is already being done for tests of conventional inserts in sandwich structures (Seemann & Krause 2018; Seemann 2019). The basic virtual test model has to be validated with practical tests. With such a virtual test model, a new design for a load introduction point with slightly different boundary conditions could be derived and verified.

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