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Optimization of the potting design using an approach for load path optimized designs of sandwich structures

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Abstract

In sandwich structures, mass can be reduced or mechanical properties increased if the challenging local load distribution can be improved. Through numerical optimizations, novel designs can be determined and investigated in physical and virtual tests. This paper presents an approach for load path-optimized design of sandwich structures and novel design concepts. The approach is applied to the design concept of honeycombs filled with potting compound. Due to the shown transferability to higher structural levels, it can be used as a basis for the design optimization of any sandwich structure.

Keywords: sandwich design, design optimisation, inserts, virtual testing, lightweight design

1. Introduction

The mass of a product is a decisive factor in the field of mobility, as it has a direct influence on fuel consumption and resulting emissions (Krause et al., 2018). Sandwich structures are used in aircraft cabins because they have excellent weight-specific material properties that make it possible to design the secondary structure of an aircraft to be lightweight (Zenkert, 1997; Bitzer 1997; ESA 2011). In order to save additional weight, it is necessary to optimize the sandwich structure with its load introduction elements for the specific application. A distinction can be made between the optimization of the local structural behavior at the load introduction points and the global structural behavior of the whole sandwich structure. The large number of constituents, their geometric characteristics and the materials used result in a high combinatorial variety, which must be taken into account in the design. In addition to numerical models for optimization and virtual tests, appropriate test setups are also required for the design optimization of sandwich structures. In order to avoid excessively high safety factors, the boundary conditions should be abstracted from the real application. In addition, suitable design concepts must be found which, through optimization, will improve the performance of the sandwich structures.

This paper presents an approach for load path optimized design of load introduction elements in sandwich structures. For this purpose, Chapter 2 first provides an overview of the state of the art. Subsequently, the approach is presented in Chapter 3 and applied at the component level in Chapter 4 to a new design concept. In the application of the approach to the substructure level in Chapter 5, it is examined how numerical optimization for load-path-compatible design concepts should be developed in order to identify a design with improved mechanical properties, especially for the selected example of optimizing the geometry of the potting compound. This is followed by a description of the further planned application of the approach in Chapter 6 as well as a summary and an outlook in Chapter 7.

2. State of the art

Sandwich structures consist of several constituents, including face sheets, core and bonded inserts, whereby different materials are used depending on the application (Zenkert, 1997). In aircraft cabins, glass fiber prepregs are commonly used for the face sheets. Among other reasons, they are more cost-effective and meet the special fire protection requirements in aviation (Zenkert, 1997). The face sheets are held at a distance by a lightweight core. There are different structures for the core such as rod, honeycomb, folded or continuous cores, and different materials that can be used including aramid, foam, 3D printing filament or resin (Zenkert, 1997). Aramid honeycomb cores are often used in aircraft cabin applications. Due to their structure and anisotropic material behavior, these have a more complex structural behavior than other core types. Inserts are bonded with a potting compound into the sandwich structure for local load introduction (ESA, 2011).

The large number of different constituents, materials used and geometric variations, such as the height of the core, the height of the potting mass or the number of cover layers, leads to a considerable variety of possible combinations in the design of sandwich structures. Failure mode maps, such as those described by Rodríguez-Ramírez et al. (2020), can assist in predicting the initial failing constituent when varying different design parameters. The Insert Design Handbook (ESA, 2011) presents an approach to designing inserts in the form of a flow chart, where only the radius and the number of inserts are varied. In contrast, there are also approaches in the literature that focus on optimizing the design of individual constituents, especially the inserts (Seemann, 2020; Qi et al., 2020; Lim et al., 2020). In addition, Schwenke and Krause (2020) show a procedure and corresponding results for the direct integration of the load introduction elements into the core to introduce the local loads into the structure in a load path-optimized manner. A topology optimization is carried out on the 3D-printed core and it is shown that the boundary conditions have a significant influence on the optimization results. Consequently, these must be taken into account in the design and dimensioning of sandwich structures and their constituents. The boundary conditions are either based on the actual conditions of the real application or are determined based on a corresponding physical test. In addition to certification requirements, physical tests are necessary to verify new design concepts. In aviation, entire cabin monuments are tested for aircraft cabin applications in extensive full-size tests in accordance with the CS-25 regulations (EASA, 2023). The load introduction elements are also tested in corresponding component tests. There are no standardized tests, but the tests are often carried out in accordance with the recommendations from the Insert Design Handbook (ESA, 2011). The shear and pull-out tests are particularly relevant for the design, although the boundary conditions in these tests are highly idealized and do not correspond to the actual conditions of the real application (Heyden et al., 2019, Schwan et al., 2021). Initial approaches for test setups with realistic boundary conditions exist, which can serve as a basis for carrying out corresponding optimizations. This enables the consideration of global structural behavior and thus efficient load transfer (Hartwich et al., 2022, Schwan et al., 2022).

Due to the enormous effort involved in physical tests to verify design concepts, virtual tests based on the finite element method (FEM) are increasingly being used. These enable a numerical simulation of the physical tests and thus can lead to savings in development times and costs (Seemann, 2020). The development of the virtual models takes place hierarchically from the constituents to the final structure (Seemann, 2020; Heyden et al., 2019, Schwan et al., 2021). This is illustrated in Figure 1, for instance.

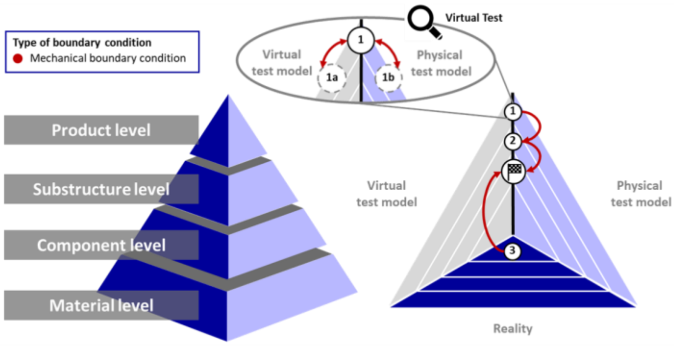

Figure 1. Product component test pyramid for virtual tests (Schwan et al., 2021)

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Corresponding virtual models are described in the literature, which make it possible to represent the progressive damage behavior of sandwich structures up to the component level (Heimbs and Pein, 2009; Roy et al., 2016; Seemann and Krause, 2018; Schwan et al., 2022). However, there is no detailed description in the literature of an extension of these virtual models to higher structural complexity levels considering global structural behavior. Nevertheless, Hanna et al. (2018) show a first suggestion to include these detailed models as well as tests with application-oriented boundary conditions in the optimization of sandwich structures.
The state of the art shows that initial approaches and results for the optimization and design of sandwich structures exist. However, previous approaches and design concepts usually focus on the optimization of individual components without taking into account the application-specific boundary conditions and the different failure mechanisms that can occur depending on the configuration of the panel. This procedure can lead to the optimization not achieving the desired effects. If the initial failure of the critical constituent remains unaffected by the design changes, a failure cannot be prevented or postponed by the optimization.

3. Approach for load path optimized designs of sandwich structures

3.1. Presentation of the approach

In this section, the approach for load path optimized design of load introduction elements in sandwich structures is described. This is based on the publication "Approach for load path optimized design of sandwich structures using virtual tests and realistic test setups " by Schwenke et al. (2022) in German language. It combines several concepts for various sandwich designs and extends them to create a general approach applicable to sandwich structures. A further development of the approach is presented here and shown in Figure 2. In particular, the focus is on the transfer to higher levels with larger structures and higher structural complexity.

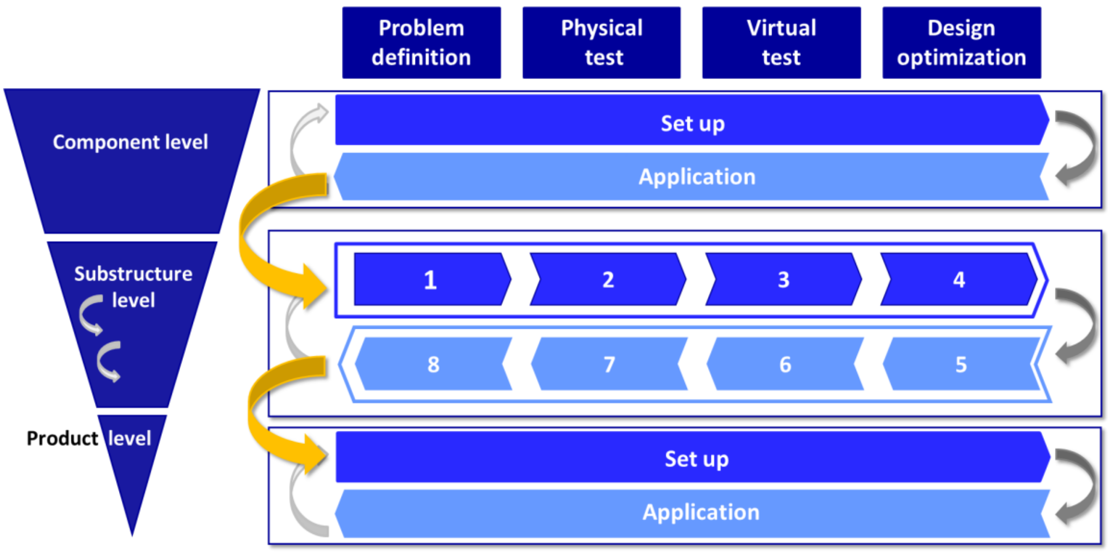

Figure 2. Approach for load path optimized design of sandwich structures

The approach is divided into cycles that are run through for the individual levels. Each cycle consists of the two phases *set up* and *application*. Each phase is subdivided into four steps, which relate to the four areas of *problem definition*, *physical test*, *virtual test* and *design optimization*. The steps for the setup in the first phase are numbered 1-4, while the steps in the application phase, which go through the areas in reverse order, are numbered 5-8. These steps are run through iteratively at one level until it is possible to jump to the next level. The phases and steps are then repeated at this level in the next cycle. The approach's ideal scenario is therefore that a suitable physical test model is first selected or developed based on the definition of the problem. A virtual test model is set up for the chosen test setup, which ideally can reproduce all design-relevant failure mechanisms. In addition, an optimization model is set

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up for the selected design concept, which is used to determine design alternatives for the load introduction elements. These are then compared with each other in the virtual test model, after which the best alternative is selected and physically tested. A suitable reference sample must be selected for comparison. A reference with the same mass and/or the same design space is recommended. An exact dimensioning for the same stiffness or strength at this point in the development process represents an additional challenge that makes direct comparison more difficult.
If necessary, the steps of the cycle are run through iteratively in loops so that physical tests, virtual tests and optimization models can be adjusted. After completion of the cycle at the component level, the jump to the substructure level takes place. At the substructure level, several cycles at different sublevels may be necessary. This is the only way to continuously build up the models and ensure that the results can be transferred to the corresponding size of the sandwich structure and the number of load introduction elements. Finally, the last jump is made to the product level at which the last run of the cycle takes place.

3.2. Selection of a design concept

Depending on the type and location of the failure, different constituents and different possibilities for design optimization of sandwich structures can be considered, which go beyond simple material adjustments or parameter optimization of the global sandwich structure. Figure 3 shows examples of different concepts for a sandwich structure with a honeycomb core and a load introduction point.

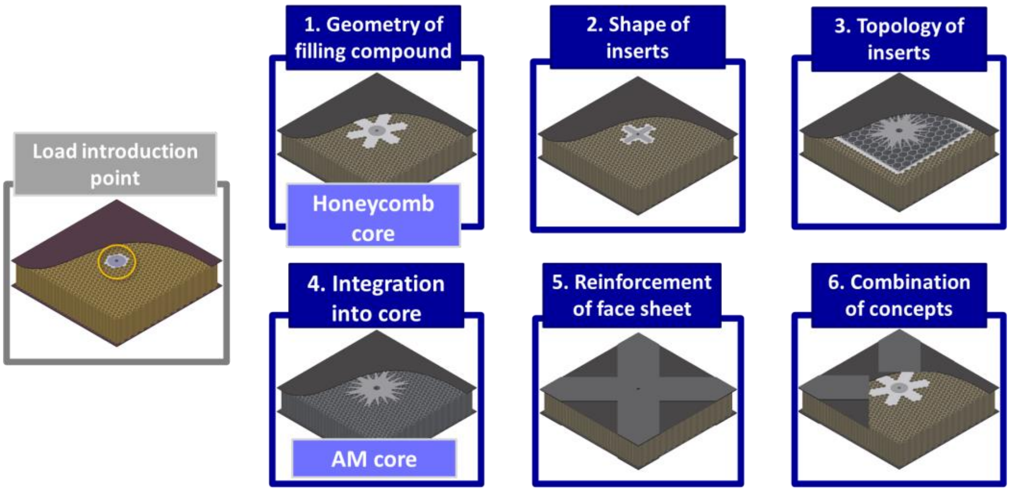

Figure 3. Design concepts for load path optimization of sandwich structures

1. Geometry of filling compound: A distinction is made here between the core filling compound applied before the panel is pressed and the potting compound for subsequent bonding.
2. Shape of inserts: This concept optimizes the three-dimensional shape of larger inserts, blocks and bushings. It is applicable to different types of cores. Schwenke et al. (2020) have shown it exemplary for an insert with a constant cross-section in a foam core.
3. Topology of inserts: The inner topology of the inserts is optimized to save mass without changing the shape (Schwenke and Krause, 2020).
4. Integration into core: Direct and load-path-optimized integration into the core can be implemented with the help of additively manufactured sandwich structures (Schwenke and Krause, 2020).
5. Reinforcement of face sheet: The face sheet is reinforced on the outside or inside by local patches or by doubling up the layers.
6. Combination of concepts: Either design concepts are combined or transferred to an additional reinforcing constituent. For example, by introducing an additional reinforcing element in the sandwich structure to strengthen core and face sheets and to transfer locally applied loads over a larger area.

4. Application of the approach at the component level

In this section, the approach is applied at the component level, with the subsections numbered according to the eight steps in each cycle of the approach.

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4.1. Problem definition

In the application example, the design of the load introduction elements in a panel for the aircraft cabin will be optimized as an example, whereby the tensile load is critical in terms of dimensioning. The sandwich panel with a height of 12 mm consists of a Nomex® honeycomb core (ABS5035-A4) with two glass fiber prepregs per cover layer (ABS5047-07) and a standard insert (SL607-3-6S), which is fully-potted in the structure with potting compound (Scotch-Weld EC 9323). The aim of the design optimization is to increase the mechanical properties of the insert system while maintaining the same mass. For the reference design at the component level with sample dimensions of 100x100 mm, 127 honeycombs are filled in the shape of a hexagon, as shown in Figure 4. The typical circular shape is approximated by a hexagon.

4.2. Set up of physical test

A pull-out test is selected as the test setup, whereby the inserts are pulled out perpendicular to the face sheets (ESA, 2011). The diameter of the clamping is 70 mm (see Figure 5). The initial failure that occurs for inserts with a small potting diameter and the same materials is the shear buckling of the single walls in the core adjacent to the potting.

4.3. Set up of virtual test

As a virtual test model a model based on the material models and modeling procedures according to Seemann (2020) and Schwan et al. (2022) is used. This model reliably reproduces the failure that occurs at the small potting diameters tested, in particular the shear buckling of the core (Schwan et al., 2023). Accordingly, suitable design concepts can be identified to delay this failure.

4.4. Set up of design optimization

This contribution examines the design approach of optimizing the geometry of the filling compound. In this way, the effective potting radius can be increased so that the shear load is distributed over more individual walls of the core. In this case, the shape of the subsequently inserted potting compound is considered. Since the design approach has not yet been investigated, an optimization model will not be developed initially, but the potential will be investigated using a derived design in comparison to a reference sample.

4.5. Application of design optimization

The new star-shaped design is derived from existing results for the design concepts of the shape of the inserts and integration into the core (Schwenke and Krause, 2020; Schwenke et al., 2020). It has six prongs, which can be manufactured with a milling head diameter of 6 mm (see Figure 4). Due to the theoretically equal number of filled honeycombs of 127, an almost identical mass of the two sample designs is achieved.

4.6. Application of virtual test

To perform the virtual test, the designs are implemented in the virtual test model. For this purpose, the potting is enlarged in order to model both the reference design and the optimized design. The virtual test is then carried out using Abaqus 6.14-1 (Dassault Systems) as an explicit solver. The results are shown in Figure 4. Figure 4 shows that for the optimized design an increase in stiffness and maximum achievable force is predicted. However, the analysis of the virtual test also shows that edge effects are to be expected due to the small distance between the filled honeycombs and the clamping and the large increase of the potting area. Also could the forces be overestimated due to the ideal symmetrical arrangement of the cell walls with regard to the clamping. Therefore, a comparison with the data from the physical test is necessary, in which effects due to inhomogeneities in the material and geometric imperfections are to be expected.

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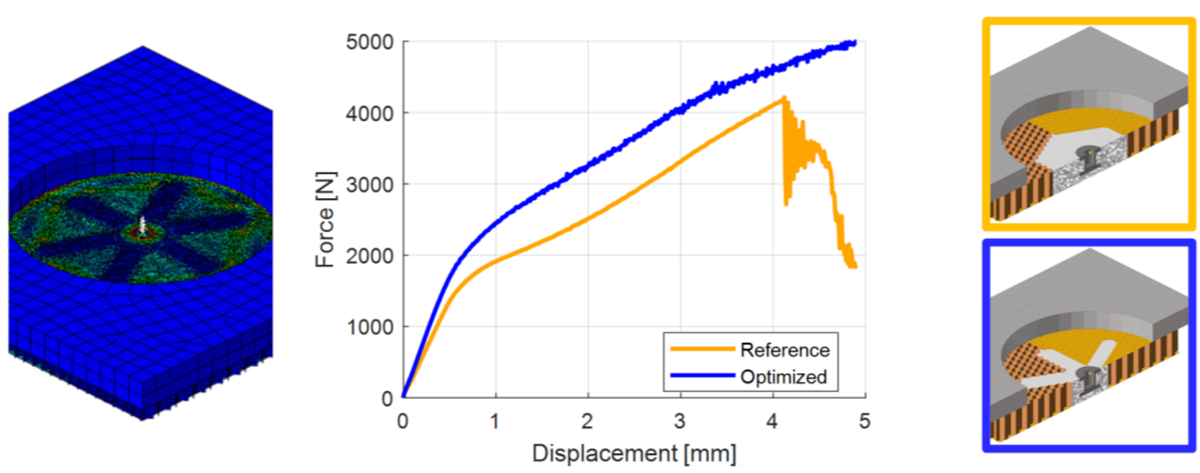

Figure 4. Virtual Test on component level

4.7. Application of physical test

To manufacture the two designs shown in Figure 4, corresponding cut-outs were milled into the sandwich samples and the insert was bonded in the middle of these. Figure 5 shows both the samples and the results of the physical test.

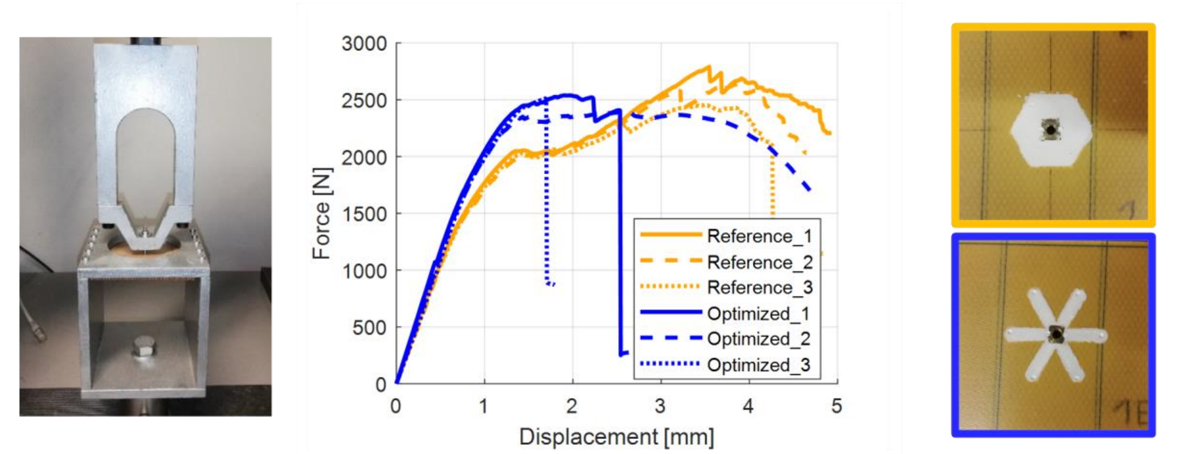

Figure 5. Physical test on component level

As can be recognized in Figure 5, all samples have a very similar stiffness at the beginning. A later flattening of the curve for the optimized specimens shows increased strength. The initial failure in both sample designs is the shear buckling of the cell walls adjacent to the potting, but in two out of three of the optimized samples, a complete failure of the potting in the form of a shear fracture occurs shortly afterward. The maximum forces achieved by the reference samples are therefore higher but are only of limited relevance because they are only reached well after the initial failure and the stagnation of the measured forces. At a deflection of 1.5 mm (in the range in which the measured force stagnates for all samples), the optimized samples achieve an average force that is 20 % higher than the reference samples.

4.8. Analysis of the problem definition

The results of the pull-out test show a high potential for the design concept, as the star-shaped design can improve the mechanical properties without increasing the mass. Compared to the physical test, however, there are clear deviations in the virtual test model. On the one hand, no criteria for failure of the potting was implemented, which is necessary given the larger surface area of the potting and the delay in shear buckling of the walls. Also, deviation due to random scattering in combination with edge effects can occur due to the small distance from the design to the fixture and the ideally symmetrical

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arrangement. This could be investigated in an iteration of the whole cycle. At this point, however, the jump is made to the substructure level. A relatively small jump is initially made by enlarging the sample, as the sandwich structure is then large enough to be mounted directly via load introduction elements at a higher substructure level in the next cycle.

5. Application of the approach at the substructure level

This section provides an initial application of the approach to substructure levels, with the subsections again numbered according to the eight steps of the approach.

5.1. Problem definition

In the second cycle, the same material is used as described in section 4.1. The dimensions of the sandwich sample are increased to 200 x 200 mm and the height is increased to 20 mm. A design with 217 filled honeycombs is defined as a reference, as shown in Figure 7.

5.2. Set up of physical test

As the test setup, a larger pull-out test is used, in which the circular cut-out has a diameter of 140 mm (Hartwich et al., 2022 and Schwan et al., 2023).

5.3. Set up of virtual test

A virtual test model is not used in this stage, as the potting failure has not been implemented yet in the previous cycle. The failure of the potting could be implemented in a further iteration loop. The initial focus is on a procedure for optimizing the shape of the filled honeycomb cells, that did not exist before.

5.4. Set up of design optimization

To optimize the potting geometry a modified topology optimization is applied. HyperWorks 2021.2 from Altair Engineering with the pre-processor HyperMesh, the solver Optistruct and the post-processor HyperView is used for this purpose. From a 2D drawing with the corresponding honeycombs and design space etc., a script-based optimization model is created in HyperWorks. The cell walls of the honeycombs are modeled in detail, divided into single and double walls. Using the two symmetry axes of the sample in relation to the central honeycomb, all honeycombs with the same symmetry are combined into a group and all volume elements of this group are combined into one component. The element types and uniform meshing are selected so that tied contacts can be used directly at the nodes. For this purpose, the honeycomb walls are meshed with quadratic shell-, the face sheets with triangular shell- and the potting with triangular prism volume-elements. In addition, an extrusion constraint transverse to the face sheet and a minimum member size of 2 mm are set. The optimization objective is to minimize compliance under the constraint that the potting should reach the same volume as in the reference. The optimization model and the selected design space are shown in Figure 6.

5.5. Application of design optimization

After the optimization run, the average element density is determined for each honeycomb group. These are then sorted based on the average density. In the next step, the honeycomb groups with the highest average density are integrated into the design. Theoretically, however, it is also possible to remove the honeycombs with the lowest element density from the design. This procedure can be repeated several times by gradually adapting the design space and performing the topology optimization again. The number of repetitions can thus be varied, either by successively reducing the size of the design space or by gradually integrating more filled honeycombs into the design. The topology optimization is then performed again for the newly defined design space. In this case, the final run is carried out taking into account the manufacturing boundary conditions. In order to take into account, the milling head diameter of 6 mm, the average density is determined for seven honeycombs arranged in the hexagon and integrated into the design accordingly until the same amount of cells as in the reference design is reached. The results of the optimization are summarized in Figure 6.

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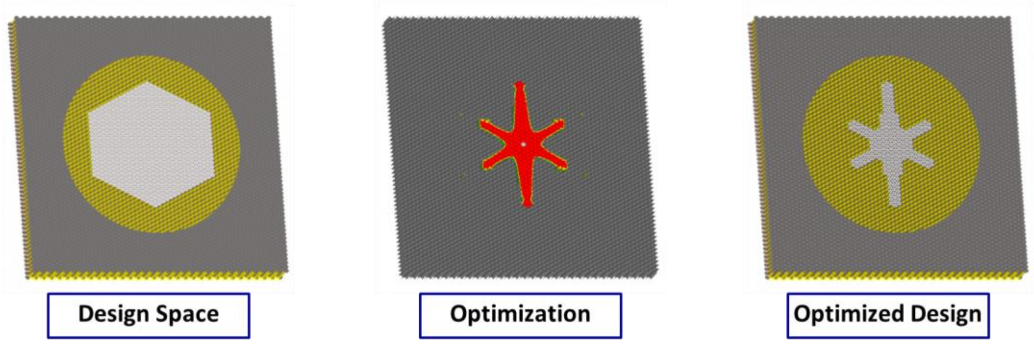

Figure 6. Optimization model, result and design

5.6. Application of virtual test

No virtual test model is used in this step, as already described. Nevertheless, it is possible to determine several design alternatives by adjusting the boundary conditions and number of iterations in the optimization. For these alternatives, a reanalysis with the optimization model was carried out to ensure a high stiffness. However, no direct statement can be made about possible failure. Taking into account the manufacturing restrictions, the results from one iteration are better than the results from two iterations. The alternatives determined could then be tested virtually in a detailed failure model. This enables the selection of the best design for the shape of the potting compound, for future application.

5.7. Application of physical test

The production of the samples again involves cutting the samples to size, milling the cut-outs and inserting the insert with potting. The insert is again fixed to an aluminum sheet with double-sided adhesive tape and sealed at the edge with additional adhesive tape, with holes provided for the inlet of the potting compound and outlet of the air. After the potting compound has completely hardened, the tests are carried out. The results and the two designs of the samples are shown in Figure 7. The results show that the graphs of the optimized samples are completely above the graphs of the reference samples until the final failure. The reference samples show a similar curve to samples with very small potting diameters.

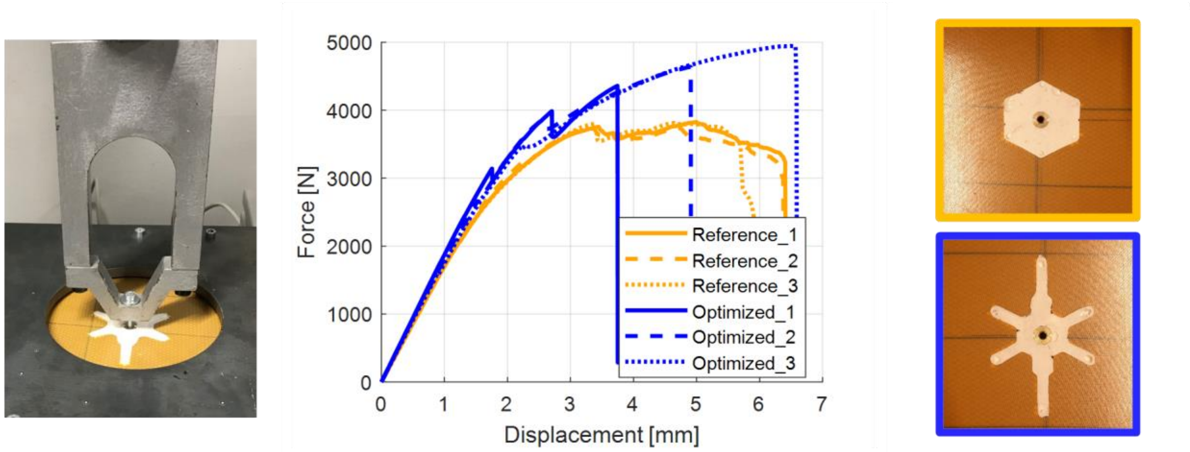

Figure 7. Physical test on substructure level

In the optimized samples, the first small cracks in the potting were detected acoustically early on, some of which occurred before or together with the first shear buckling of the honeycomb walls adjacent to the potting. This can be attributed to various factors, including air inclusions in the potting that occurred during the manual manufacturing process. The maximum force can be added at this point as a criterion for assessing the improvements, with the optimized samples showing an average improvement of 23% compared to the reference samples.

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5.8. Analysis of the problem definition

The results of the large pull-out test once again show the high potential of the design optimization, as the mechanical properties could be improved by the optimized design without increasing the mass. Air inclusions that occur during production should be minimized by improving the manufacturing as they are known to negatively influence the mechanical properties. Since the potting failure would still have to be implemented in the virtual model, it is recommended to change the design concept to optimize the shape of the insert. This is particularly suitable for highly loaded load application points. The potting is then only used for bonding, while most of the volume is filled with a metal or hard fabric insert, which is much less likely to fail. The optimization procedure shown can also be used to find an optimized shape for the honeycombs, which are filled by the insert and the surrounding potting compound. The effective potting radius can thus be increased, also by utilizing the double walls. The shear load in the core is distributed over a higher number of individual walls, thus delaying their shear buckling.

6. Further planned application of the approach

As a further leap at the substructure level, it is planned to change the type of clamping for the same specimen dimensions in order to support them via load introduction elements in the next cycle. For this purpose, the test setup presented by Hartwich et al. (2022) can be used, in which the sandwich structure is mounted via additional load introduction elements. This is also used by Schwan et al. (2023). In the test, the shear buckling of the core is the initial damage mechanism, but the evaluation of the virtual model revealed differences in the shear stress distribution in the cell walls compared to the simple pull-out test. As a further leap to achieve the product level of a sandwich panel, an enlargement of the sample to dimensions of 400 mm x 1200 mm is planned. This will result in an increase in the distance between the load introduction elements and a change from a square to a rectangular sample**.**

7. Summary and outlook

In this contribution, the further developed approach for optimizing the design of sandwich structures was presented. This approach consists of cycles that are carried out at different structural levels. Each cycle consists of the two phases of set up and application, whereby the steps of problem definition, physical test, virtual test and design optimization are run through. In the selected example, the approach was applied to a new design concept that optimizes the geometry of the potting compound. Virtual models were created at the component level and physical tests were carried out. Subsequently, a procedure for the numerical optimization of the filled honeycombs was implemented at the substructure level. The investigations have provided new findings at the substructure level and illustrate the possibilities of design optimization and its transferability to higher structural levels. The results of the physical tests clearly show the potential for mass reduction through this approach. The future adaptation of the models and the modification of the design concept are intended to ensure that the results can be transferred to actual applications. The approach can thus be used as a foundation for the design optimization of any sandwich structure.

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