Spider web inspired composite structures - a new concept for load introduction in fiber-reinforced-plastics sandwich structures

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Abstract

Sandwich structures represent a lightweight design method which leads to very light and at the same time stiff components through the combination of stiff outer skins and light core material. A major challenge in the design of sandwich structures is load introduction. In order to realize improved load introduction in sandwich structures and to leverage further possible lightweight design potential, the following paper presents a new concept using spider web inspired structures made of fiber reinforced plastic materials. In order to investigate the potential of the spider web concept, simulative comparative studies between the spider web structures and conventional load introductions are carried out.

Keywords

Composite structures, load introduction, spider web inspired

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1. Motivation

Sandwich structures represent a very effective lightweight design method. The combination of stiff outer skins, often consisting of fiber-reinforced-plastic (FRP) composite materials, and lightweight core materials, e.g. Nomex® honeycomb cores, leads to very light but at the same time rigid components [1]. The core material, which has a significantly lower density than the outer skins, increases the distance of the outer skins to the neutral fiber of the sandwich structure and thus the second moment of area with a comparatively small increase in weight.

Due to their good lightweight properties, sandwich structures are widely used in weight-sensitive industries such as aerospace: in the interior, but also in secondary structures such as aerodynamic fairings, covers or flaps. [2, 3] Challenges in the design of sandwich structures include the design of new load introduction and reinforcement concepts [3].

2. State of research on load introduction in sandwich structures

Inserts bonded in the sandwich structure usually implement point load introductions in sandwich structures. These can be placed into the sandwich structure during the manufacturing process (hot-bonded) or subsequently (cold-bonded). In addition, the load inserts are categorized based on their bonding in the sandwich. Figure 1 shows the different variants: "Through Thickness", "Fully Potted" and "Partially Potted". They differ based on the bonding depth. [4]

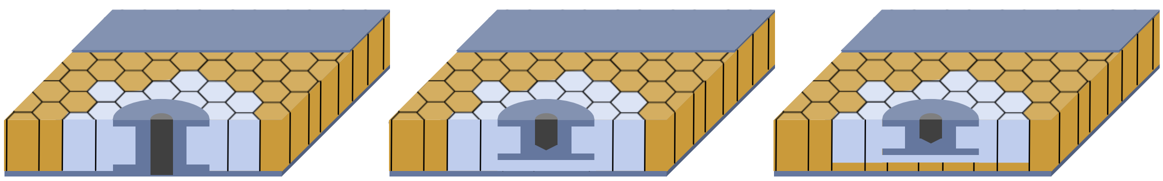


Figure 1: Different variants for bonding inserts in sandwich structures

Potted inserts usually consist of an insert, a metallic part with a thread or through hole for fastening attachments such as crew seats. A large number of norms and standards describe the different insert variants. Examples include the National Aerospace Standard NAS 1833 and the German Institute for Standardization DIN 65190. Most standardized inserts consist of an upper and a lower flange, as shown in Figure 2, a screw locking mechanism and an anti-rotation mechanism. In the upper flange, there are two holes, which are used for bonding and venting. The two flanges create a form closure after bonding, so that the shear loads can be transferred better. The recess for screw locking allows the thread to deform under compressive load. A serration or two flat, opposing surfaces in the central area prevent the insert from twisting. [4]

Manufacturing the load introduction elements is usually performed by drilling holes in prefabricated sandwich panels. The insert is placed into the hole and bonded, for example using an epoxy resin. Another possibility is to fill the areas of the inserts with a potting compound before applying the top layer. The potting compound usually consists of a filled epoxy resin to reduce its density. Finally, a hole is drilled in the potting compound and the insert is bonded into place. This allows larger filled and stiffened areas as well as a better load transfer.

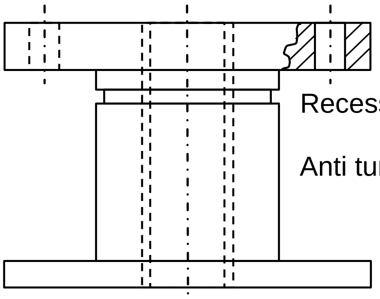


Figure 2: Schematic design of a metallic insert according to [4, 5]

The structural design of potted inserts is usually based on empirical knowledge or requires detailed simulation models to predict the load capacity. Particularly important design parameters are the potting radius and the potting depth [4]. Current research is therefore investigating simulative modeling of load introduction elements and improvement of their design.

For the usually critical load perpendicular to the sandwich plane, studies on the predominant failure mode have been carried out [6]. The analysis revealed failure of the honeycomb core material due to shear buckling. The shear loads, which result from the application of force to the insert, must be transferred through the honeycomb core between the face sheets. The true potting radius, which depends on the positioning and geometry of the honeycomb core, is mentioned as an influential parameter affecting the failure behavior. Additionally, attention has been drawn to problems caused by irregular filling of the honeycomb core. However, failure of the FRP face sheets beyond this has not been investigated. [6]

Numerical modeling allows an accurate representation of the failure modes and thus the possibility to perform tests on the virtual product, for which a virtual testing approach has been presented in [7, 8]. However, this also leads to an increased computational effort. Less detailed homogenized models are therefore considered sufficient for the design of sandwich structures.

The improved modeling methods contribute to a better understanding of load introduction and failure. Furthermore, new approaches explore the optimization of load introduction elements. Topology optimization methods allow components to be optimally designed for the applied loads and to be precisely adapted to the intended application. SEEMANN built a linear elastic optimization model, subject to a pull-out load case and a shear load in the sandwich plane and used it to perform topology optimization. He verified the results using the virtual testing approach as well as experimentally. He was able to show an improvement in mechanical properties related to weight. [8] New manufacturing processes such as additive manufacturing also lead to new concepts that exploit the design freedoms of the process. In [9] SCHWENKE and KRAUSE combined topology optimization of load introduction elements with additive manufacturing (AM). For this purpose, sections of the honeycomb core were used, which also represent the design space of the topology optimization. The topology optimization result was overlaid with the honeycomb core geometry, then manufactured with AM and tested. Further work on the use of AM and its design freedoms in the context of sandwich structures considered the use of lightweight potential through functional integration and thus part reduction in additively manufactured core elements [10], as well as the use of different design principles, for example the integration of positioning elements in additively manufactured inserts [11].

Bio-inspired approaches or even the transfer of biological principles, referred to as biomimetics, can be chosen to solve technical problems. Successful examples of biomimetics are the structural optimization algorithms *Computer Aided Internal Design* or *Soft Kill Option* [12]. Previous approaches improving load introduction into sandwich structures mainly consider the load application element rather than an areal transfer of the applied loads into the outer skins. Spider webs, in turn, represent a typical example for the transfer of high loads into large areas in nature. For this purpose, the structure of the spider web consists of stiff, radial silk threads and less stiff, spiral threads. [13] While the spiral threads are mainly used to catch the prey, the radial strands dissipate the loads into the environment. [14] The structure of spider webs also emerged from topology optimization of structures that can only carry tensile loads. While the result without design constraints consisted only of radial threads, which corresponds to the mathematically optimal topology, the formation of spiral threads occurred when the cross-sectional areas of the threads, and thus the stiffness, have been constrained. [15]

3. Research question

Previous research has investigated approaches to validate and improve the simulation of load introduction in sandwich structures. Based on this, the focus so far is mainly on the improvement and development of new concepts for the load introduction elements and the core. This is due to one of the most relevant failure modes, the buckling of the core under shear loading resulting from pull-out. The consideration of the surface layers or locally reinforcing layers and their combination with optimized load introduction elements is still pending.

In order to realize an improved load transfer in sandwich structures and to increase further possible lightweight potentials, the following paper will investigate **whether an improvement of the load transfer can be realized by spider web inspired structures made of FRP materials and an optimized load transfer element.**

4. Spider web inspired composite structures - a new concept for load introduction in fiber-reinforced-plastics sandwich structures

The new concept of spider web inspired composite structures is depicted in Figure 3. The concept is based on the analysis of the load state in the sandwich structure for the most critical pull-out load case. In addition to the outer skins made of glass fiber reinforced plastic (GFRP) and the core material of the sandwich structure, they have an insert, which serves as a connection point for a screw connection or as a through hole. The so-called hardpoint, an injection-molded thermoset component, transfers the applied loads from the insert into the spider web being subject to shear stresses. The spider webs made of unidirectional, carbon fiber reinforced plastic (CFRP) tapes transfer the loads over a large area into the face sheets of the sandwich structure and reinforce them by increasing the bending stiffness and their radial alignment along the largest principal stress directions.

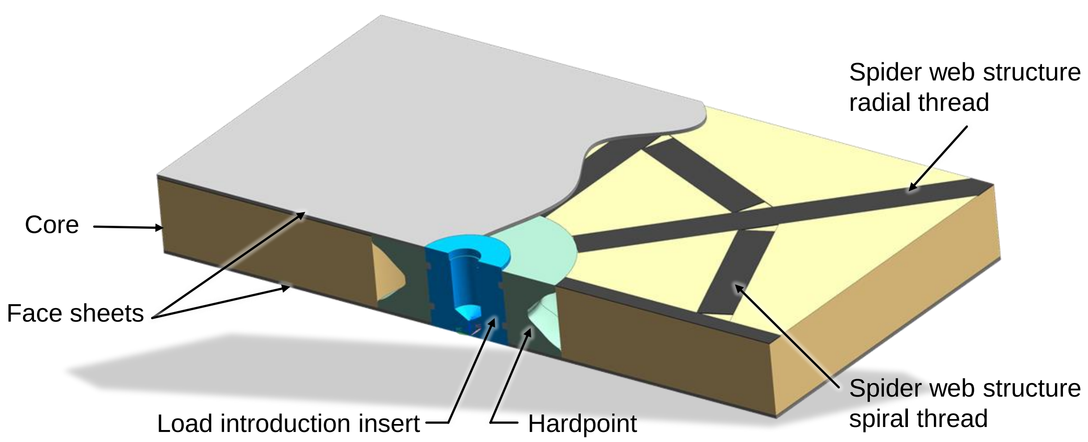


Figure 3: Novel load transfer in sandwich structures by a spider web reinforced structure and an optimized hardpoint

In the following, GFRP prepreg fabrics are used as face sheets. A typical application of GFRP fabrics is aircraft interior, as glass fibers are less expensive than carbon fibers and still have sufficient stiffness and strength. The fabrics are modelled by dividing them into unidirectional (UD) layers with the material properties listed in Figure 5 b).

The concept of spider web structures does not limit the core material used. Both foamed cores and structured cores (e.g. honeycomb) can be used. However, in order to ensure a high surface quality of the sandwich structure, appropriate grooves must be machined in the core for the tapes of the spider webs. Further investigations have to answer which core type is more suitable from a manufacturing point of view. In addition, the influence of the core type on the manufacturing quality of the spider webs has to be investigated. In the following, a honeycomb core is used, as this allows a good comparison with conventional sandwich structures.

The spider web structures are used for local reinforcement of the face sheets. Their stiffening effect is intended to reduce the bending component of the deformation. Based on natural spider webs, the spider web structures are also divided into radial and spiral parts. The radial parts take over the main reinforcing effect, as they transfer the loads along the principal stress trajectories over a large area, towards the edges. As described in the state of the art, the spiral tapes suggest a smaller reinforcing effect. The design of the spider web structures is based on the local load condition. For this purpose, measures for determining optimal structures, such as the strain energy density or the principal stress trajectories, are to be used in future research. In accordance with widely used structural or topology optimization methods the measures are used to obtain a parametric design of the spider web structure. [12, 16, 17] Compared to topology optimization, the optimization problem is more constrained, which means that the degree of optimality of the designs is reduced. However, the parameterized designs can directly ensure their manufacturability and feasibility. Parameters for the definition of the spider web structures are the angles between the radial tapes, the width of the tapes, as well as the number and pitch of the radial paths. The circumferential web structures are also defined by the distances and the number of rings. The spider web structures are produced by depositing CFRP-UD prepreg tapes. These are applied to the face sheets using an automated tape laying (ATL) process. Subsequently they are bonded to the core material and the hardpoints.

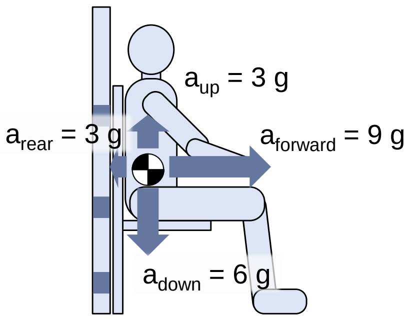
The hardpoint is used for force transmission from the insert into the sandwich and the spider web structure. For the pull-out load case, which is mostly critical in the aerospace sector, shear stresses occur in the the hardpoint, analogous to the shear stress of the core material. For loads in the sandwich plane, mainly tension and compression loads are present, partly superimposed with a bending moment (depending on the distance of the load to the sandwich plane). The hardpoint is designed to be rotationally symmetrical to the greatest possible extent, so that it can be used independently of the spider web geometry. This should enable cost-efficient production by means of thermoset injection molding. In order to still be able to adapt to the respective spider web, the hardpoint is designed including grooves, analogous to the core, which accommodate the spider web tape and thus create the bond between the hardpoint and the spider web. The insert is connected to the hardpoint by integrating it into the injection molding process, but can also be connected to the hardpoint via an additional bonding process step. The aim of the hardpoints is to achieve improved mechanical performance through optimized geometry, but at the same time to avoid increasing the mass through the hardpoint as much as possible. For this purpose, it may be useful to use filled thermosets to reduce the weight.

The used inserts are standardized metallic inserts as described in section 2 described. For the current studies, a high-load insert from a project partner is used. However, the concept of spider web structures and hardpoints is transferable to other insert geometries, for example according to NAS 1833.

5. Lightweight potential of spider web inspired composite structures and optimized hardpoints

In order to investigate the potential of the spider web inspired composite structures concept, a simulative comparative study between the spider web structures and a load application by "potted inserts" is carried out.

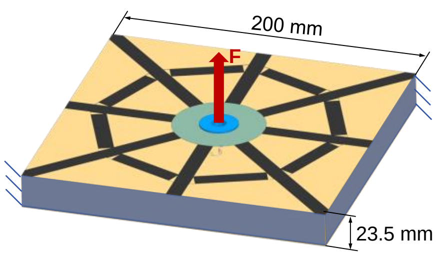
The dimensioning loads are calculated on the basis of the design specifications for aircraft according to EASA CS-25 [18] and are shown in Figure 4 shown. A maximum load of 20 kg is assumed for a single insert. The forward load case has the largest forces and is therefore used as load case in the following for the simulation of the pull-out test.



Load case	Force
Upward (3 g)	783 N
Forward (9 g)	2349 N
Sideward (3 g)	783 N
Sideward seat (4 g)	1044 N
Downward (6 g)	1566 N
Rearward (1.5 g)	391 N

Figure 4: Load cases according to EASA CS-25 and the resulting forces for an acting weight of 20 kg per insert with a safety factor S=1.33

The comparative study comprises three variants with the same boundary conditions. A square sandwich cutout with an edge length of 200 mm is considered. The thickness of the sandwich results from the height of the insert, so that a "through thickness" insert with a height of 23.5 mm is present. The cover layers have a total thickness of 1 mm for all variants and are each stacked from 4 layers with a thickness of 0.25 mm and an orientation of (0°/90°/45°/-45°). The values of the material properties are listed in the table in Figure 5 b) for a UD prepreg layer made of glass fiber reinforced plastic (GFRP). The spider web structure consists of 8 radial tapes with 45° spacing. The circumferential tapes have a distance of 74 mm of the center axis to the center of the insert. All tapes are 10 mm wide and have a thickness of 0.2 mm. The corresponding material properties are shown in the table in Figure 5 b) for a CFRP UD prepreg. The hardpoint diameter is 60 mm with an inner diameter of 25 mm, which is also the insert diameter.



a)

Material-property	UD-Prepreg CFRP	UD-Prepreg GFRP	Honey-comb	Epoxy resin (isotropic)
E_x in MPa	121000	45000	1	3780
E_y in MPa	8600	10000	1	
E_z in MPa	8600	10000	255	
G_{xy} in MPa	4700	5000	1e-6	1400
G_{yz} in MPa	3100	3846	37	
G_{xz} in MPa	4700	5000	70	
ν_{xy}	0.27	0.3	0.49	0.35
ν_{yz}	0.4	0.4	0.001	
ν_{xz}	0.27	0.3	0.001	

b)

Material-property	UD-Prepreg CFRP	UD-Prepreg GFRP
R_{xt} in MPa	2231	1100
R_{yt} in MPa	29	35
R_{zt} in MPa	29	35
R_{xc} in MPa	-1082	-675
R_{yc} in MPa	-100	-120
R_{zc} in MPa	-100	-120
R_{xy} in MPa	60	80
R_{yz} in MPa	32	46
R_{xz} in MPa	60	80

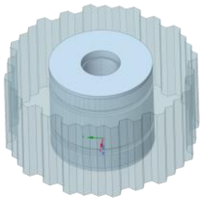
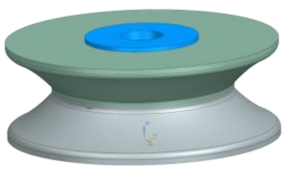
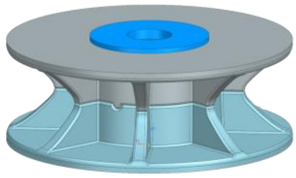
c)

Figure 5: a) Pull-out load case of the sandwich structure with fixed edges (blue) and a force applied at the insert (red), as well as the hidden top face sheet; b) material properties used in FEA; c) stress limits of the FRP materials needed for the Puck strength criterion

The model is fixed at the edges of the structure. Preliminary studies showed no significant influence of the spider web structures on the structural performance for the pull-out test according to the Insert Design Handbook of the ESA [4]. The comparatively small diameter of the hold-down clamp in comparison to the spider web structure and the hardpoint diameter reduces the positive stiffening effect. The load case is shown in Figure 5 a) for the spider web structure.

The three variants considered are shown in Table 1. The variant of potted inserts corresponds to the usual implementation of load introductions in sandwich structures.

Table 1: Results of the simulative study for the three different variants

	Variant 1: **Potted Insert**	**Variant 2:** **Spider web** **Opti-Hardpoint**	**Variant 3:** **Spider web** **Rib-Hardpoint**
Geometry			
Mass	38 g (1.3 g/cm^3) 18 g (0.7 g/cm^3)	42 g (ohne SpiFa, 1.3 g/cm^3) + 4.3 g SpiFa	22 g (ohne SpiFa, 1.3 g/cm^3) + 4.3 g SpiFa
Max. Deformation	0.53 mm	0.49 mm	0.63 mm
Max. Strength criterion (PUCK)	1.91 (pmA)	0.69 (pmA)	0.66 (pmA)
Max. Stress (von Mises) Hardpoint	75.00 MPa	17.36 MPa	52.01 MPa

Variant 2 includes a spider web as well as a split two-part hardpoint. The hardpoint was shape optimized based on the pull-out load case and then reconstructed before being used for the present study. Through the shape optimization integrated in ANSYS MECHANICAL, the tapered surfaces were optimized in terms of stiffness. In order to ensure the best possible contact with the face sheets, the top and bottom surfaces of the hardpoint were excluded from the optimization.

Variant 3 includes further material savings, as well as the consideration of further manufacturing restrictions, which result from the intended injection molding process. It is also designed as a two-part hardpoint. Further weight savings were achieved through the design of the ribs. At the same time, material accumulations could be reduced. The tapered surfaces of the ribs still correspond to the optimized geometry.

The simulation study is implemented as a linear-elastic structural simulation in ANSYS WORKBENCH 2022 R1. The modelling of the FRP components is carried out in ANSYS COMPOSITE PRE AND POST using solid elements, preferably hexahedral elements.

The results of the study are listed in Table 1. The masses of the three variants differ significantly. While variants 1 and 2 have very similar masses with the same density, variant 3 has a significantly reduced mass of 22 g due to the ribbed design. Since thermosets filled with hollow glass spheres are usually used as potting compound for variant 1, the mass for the density of a common potting material (Cytec BR 623P4) is also given in addition to the density of the epoxy resin material model used for the simulation. With this, the potted insert achieves the lowest mass. In addition to the mass of the hardpoint, the mass of the spider web structure has to be considered for variants 2 and 3. At 4.3 g the spider web structure is relatively light.

The criteria evaluated for structural performance were the maximum deformation of the sandwich structure, the maximum value of the PUCK strength criterion in the FRP layers, and the maximum VON MISES stress in the hardpoint.

There are only minor differences of the maximum deformation of the demonstrator between the variants. Variant 2 has the lowest deformation, but also the greatest mass. Variant 1 has a 0.04 mm lower deformation with a slightly lower weight and therefore has a slightly better performance. Variant 3 has the greatest deformation of 0.63 mm, but with a significantly reduced weight.

The strength of the FRP components of the sandwich structure are evaluated using the PUCK strength criterion [19]. The criterion differentiates into two failure modes: fiber failure and inter-fiber failure. Inter-fiber failure is further subdivided into modes A, B and C based on the load condition [19]. Values of the strength criterion greater than or equal to one indicate a failure of the component or the corresponding layer. Variant 1, with a maximum value of 1.91, has the highest value of the three variants. Inter-fiber failure occurs in mode A (pmA) in the innermost of the top face sheets layers. Variants 2 and 3 show maximum values smaller than one. Both are in a similar range with 0.69 and 0.66. Consequently, the spider web structure and the hardpoints lead to a reduction or improvement in the stress on the FRP components, enabling a higher performance of the sandwich structure at the same or even lower weight.

The evaluation of the maximum VON MISES stress in the hardpoint shows similar results. The optimized geometries of variants 2 and 3 result in a more uniform stress distribution in the hardpoint as well as a smoother stiffness transition to the core material. As a result, the stresses are significantly reduced, whereby variant 2 has an advantage over variant 3 due to the larger amount of material employed.

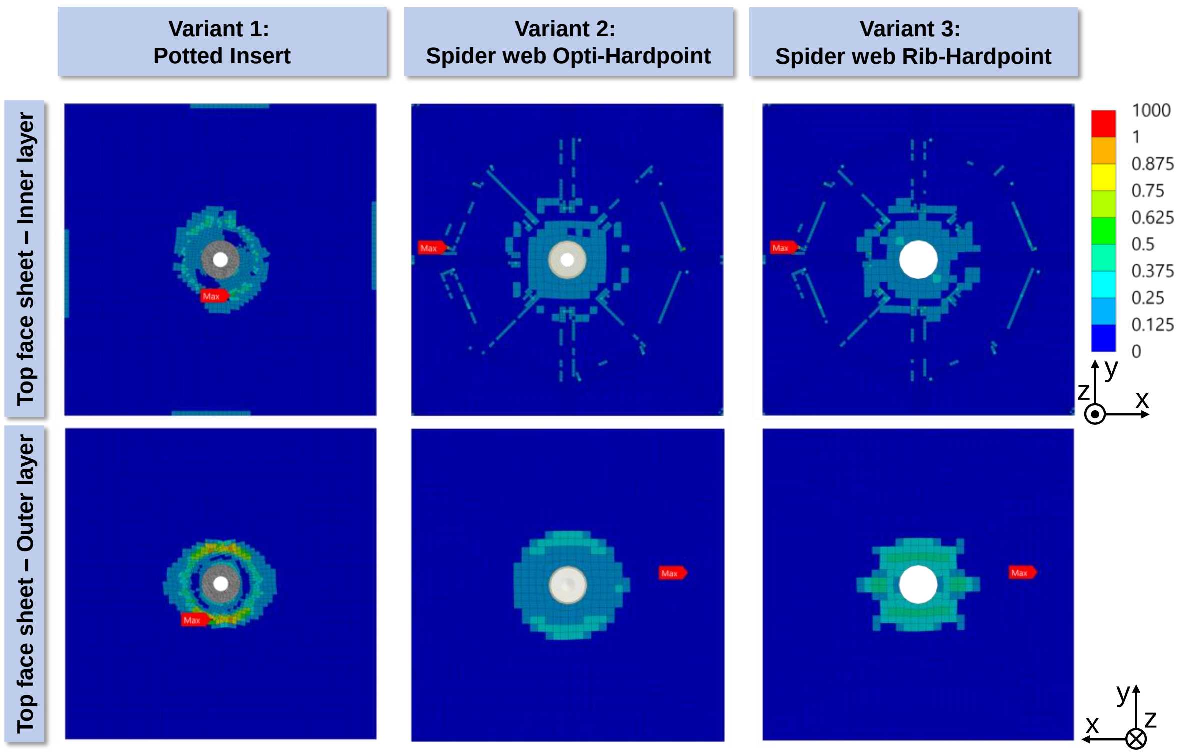


Figure 6: Illustration of the strength criterion according to Puck for the three different variants, evaluated for the outermost and innermost layer of the upper surface layer.

The last evaluation considers the local influence of the spider web structure and the hardpoint on the strength criterion. For this purpose, the outer and inner layers (including the spider web structure) of the top face sheet are shown in Figure 6. Variant 1 has a local concentration of high PUCK criterion values, which corresponds to high local loads. These are concentrated in particular on the edge of the potted honeycomb. In contrast, variants 2 and 3 show a lower overall level and a more uniform distribution. For both variants, increased values of the strength criterion can be seen on the inner side at the edges of the spider web structure. Due to the restriction to the edges, there is the possibility that these are edge effects, which can be caused by stiffness jumps resulting from the different materials. Therefore, they do not necessarily indicate a better distribution of the load through the spider web. This should be considered in more detail in further investigations. The PUCK criterion values of variant 3 on the outer layer show higher values in the hardpoint area than for variant 2. Since the only difference lies in the different hardpoints, this can be explained by the lower stiffness of the ribbed and lighter variant.

6. Conclusion and outlook

Since a long time, engineers have made use of principles from nature and transferred them to technical applications. In this paper, a novel concept for load introduction into sandwich structures by means of spider web inspired composite structures is presented and investigated. The hardpoint, which transfers the applied loads from the location of the load introduction into the spider web structures and face sheets, was optimized and a simulative comparative study of the new concept with conventional "potted inserts" was carried out. The study indicates a first promising exploitation of lightweight potentials. However, some open questions remain, which have to be investigated in future research work: Beside the additional investigation of design decisions, e. g., the improvement by an overlap between hardpoint and spider web structure, further design and optimization of the spider web structure is necessary.

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