Applied Research

Development of a single subfloor plate for a light cargo vehicle in sandwich construction

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1 Abstract

The Institute for Vehicle Concepts of the German Aerospace Center (DLR) is developing new concepts for very light vehicles. One of these concepts is a light freight vehicle for urban logistics. The complete chassis is designed as a sandwich structure. Challenges in using these sandwich structures are the introduction of loads and joining technology. Additionally, the structure should be easy and efficient to produce. This leads to the question, if it is possible to use a single sandwich subfloor plate as the load-bearing structure of this vehicle. As a solution, the implementation of through-the-thickness inserts, which are mounted in the production process of the sandwich structure are proposed. Validation with simulations will be presented and the production process of such structures will be illustrated.

2 Introduction: Sandwich structures for vehicles

Sandwich structures are compound parts, they consist of two different materials. Two thin and strong top layers are separated by a lightweight core with low density. The top layers are bonded to the core with adhesives. The core keeps the top layers at a distance, so the compound has similar properties like an I-beam, for example high bending-stiffness [1].

Materials for the top layers can be plates of metal, wood, fibre composites, cardboard, etc. The core can be a homogenous foam, balsa wood, honeycombs or corrugated material, for example. From the experiences of former projects, it is known, that 3d-parts respectively curved sandwich parts are very complex. The foam core already has to be manufactured in the desired shape or has to be foamed in situ with liquid chemicals like epoxy. Therefore, the focus of this work is on aluminum top layers and a PET-foam core (Polyethylene terephthalate) as 2d-panels, which are easy to manufacture and to handle.

One of the main challenges in the design of sandwich structures is to introduce the loads without damage. The sandwich can resist a wide spreaded, perpendicular introduction of load, but will easily be destroyed by local forces. Furthermore, the core is not able to support threads for a screw by itself. Therefore, through-the-thickness inserts are used to support the sandwich and provide mounting points for attaching any components. As these inserts have to be mounted during the production process, a concept for a new, fully automated process was developed and patented [2].This process is suitable for the continuous production of sandwich panels.

3 Vehicle concepts incorporating sandwich structures at the Institute for Vehicle Concepts

3.1 The Safe Light Regional Vehicle

To fulfill the global goals against the climate change, it is important to reduce greenhouse-gas emissions also in the transport sector. New concepts involving new technologies for alternative drivetrains, energy concepts, advanced materials and lightweight design can increase the efficiency of vehicles and make them more ecofriendly [3].The Institute for Vehicle Concepts of the German Aerospace Center (DLR) is developing new concepts for very light vehicles using these fields of technology. In the research project Next Generation Car (NGC), three different vehicles were developed. One of them is the Safe Light Regional Vehicle (SLRV) [4]. Powered by a fuel cell hybrid powertrain, it is designed for medium distances up to 400km. The SLRV concept has a mass of 450kg and is placed in the European L7e class. The chassis as the load-bearing structure is entirely made of a sandwich structure. The front and rear end consist of sandwich plates with a 20mm PET foam core and two 0.5mm top layers of aluminum. The middle part is a monocoque design. Here, the three-dimensional sandwich structure consists of two aluminum shells with an epoxy-foam as core. With this new design approach, a very light structure was obtained, which also demonstrated the safety performance in a crash test. In a next step, this promising architecture was further evaluated and led to a concept for a light cargo vehicle. The vehicle was designed for the last-mile-delivery in urban areas [5]. It is already common for such vehicles, that the body panels of the cargo area are made of sandwich parts. Just like the SLRV, now the load-bearing structure should also be made of a sandwich structure.

Figure 1: Safe Light Regional Vehicle (SLRV)

3.2 Concept of the cargo vehicle

The transporter is a 4-wheeled battery-electric vehicle concept intended for the L7e-class with a payload of 1000kg. It is 3700mm long and 1500mm wide. The construction of the cargo vehicle is based on 2d-sandwich-panels. It is one of the main goals of the construction to build the load-bearing structure as one single subfloor plate. On this subfloor, the undercarriage, suspension and other components will be attached. This will make it easy to produce most of the vehicles structure from very few parts [5].

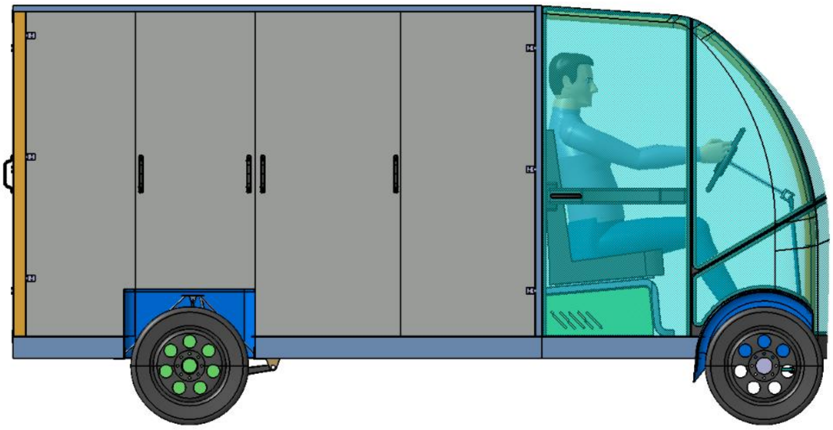

Figure 2: Light transport vehicle concept with extensive use of sandwich parts [5]

The subfloor plate is the base of the vehicle. All other components are mounted on top or below this plate. At the front is the driver cabin for one driver. The cabin consists of a tubular frame with glass-panels. Batteries are located under the seats. The cargo area has a rectangular shape and provides space for two palettes or multiple packages. Doors are at the rear and on the right-hand side, as this will be the side facing the sidewalk. For the undercarriage and suspension, there are some cutouts in the subfloor plate. The axle at the rear is a trailing arm, the suspension is mounted at the subfloor plate with a 3-point socket. The front axle has a MacPherson strut with a leaf spring suspension.

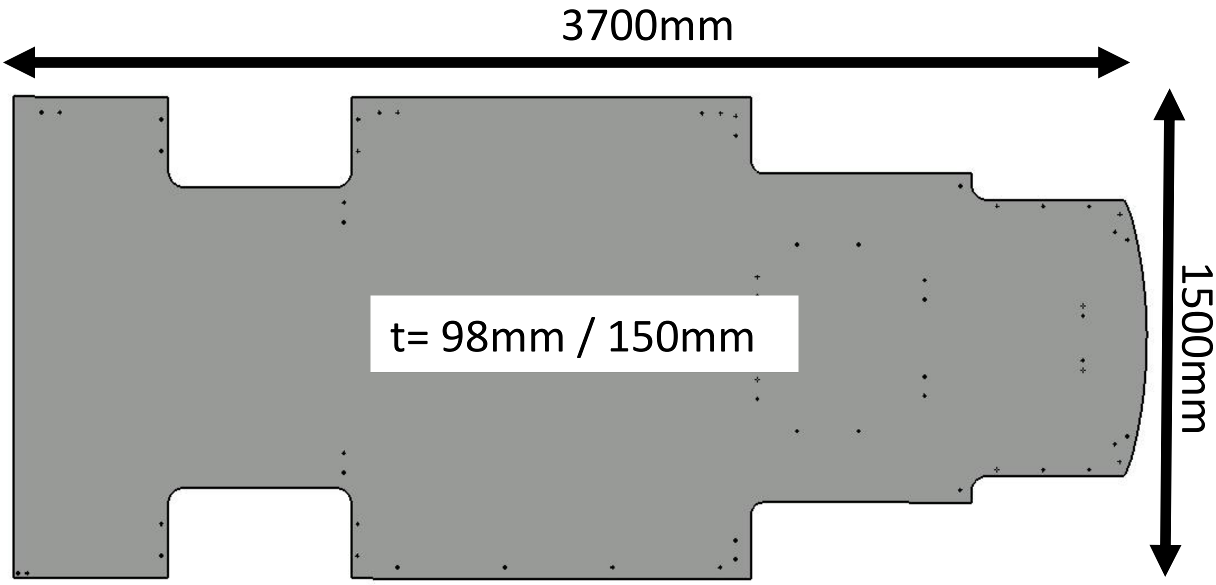

Figure 3: Dimensions of the subfloor plate [5]

Table 1: Properties of used materials [6,7]

Material properties	Material	Density $[kg/m^3]$	Tensile strength [MPa]	Yield strength [MPa]
Top-layers	Aluminum, 6082-T6	2700	310	260
Core	PET-Foam	60	1,5	-
Wooden insert	Wood	≈600	≈100	-
Bushing insert	Steel	7850	300	-
3d-printed inserts	PLA (polylactic acid)	1300	≈50	-

4 Methodology: Development of the single subfloor plate

4.1 Inserts for sandwich panels

For every mounting point in the sandwich panel, there has to be an insert. The inserts support the sandwich locally and provide a thread for screws. The best support is obtained by through-the-thickness inserts. They have the same length like the thickness of the core, so the sandwich can not be compressed. A disadvantage of this type of inserts is that they have to be mounted during the production process. Most other already commercially available inserts have to be mounted afterwards by drilling a hole in the sandwich plate and are glued in in. The here presented inserts, have only a small hole for the screws, the inserts are not visible from the outside (Figure 4)

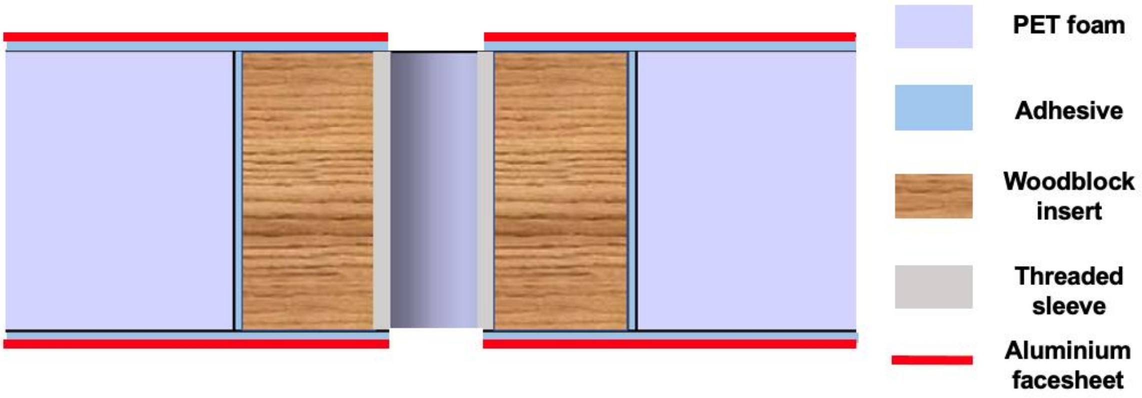

Figure 4: Wooden insert between two top layers (adapted after [6])

Through-the-thickness inserts can have many shapes and materials. The focus was on wooden inserts and metal bushing inserts. In a later project, 3d-printed inserts made of PLA (polylactic acid) were also investigated.

The wooden insert are simple blocks (Figure 5) with an additional metal threaded insert. The metal bushing inserts are composed of two washers which are glued on a threaded bushing. Both are self-developed, as they are not available as standard parts on the market.

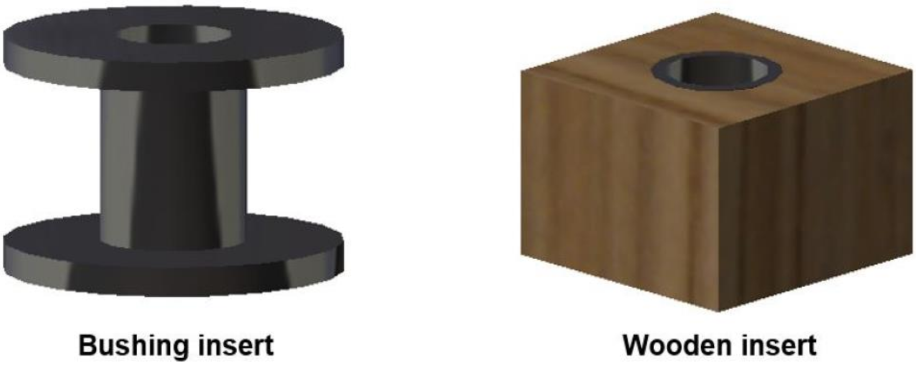

Figure 5: Bushing insert and wooden insert [6]

The 3d-printed inserts have a cylinder-shape with a hole in the middle. Like the wooden inserts, there is a metal threaded insert in this hole. The holes around serve as reservoir for the adhesive. The inserts are not solid, they have a squared support structure inside (Figure 6).

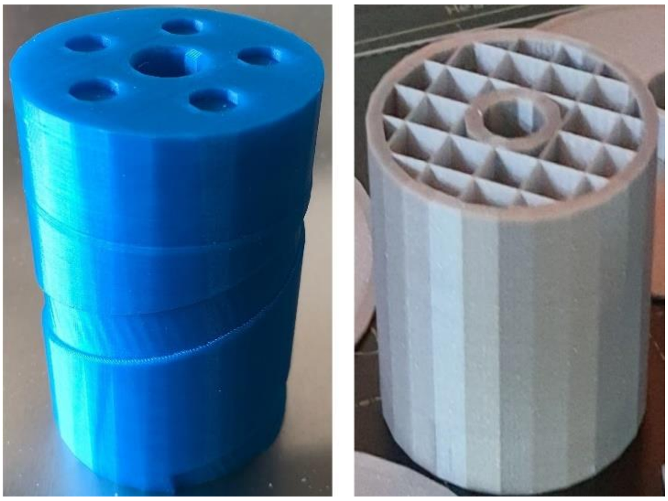

Figure 6: 3d-printed PLA inserts

4.2 Production process

So far, the production of a sandwich panel with integrated inserts like the subfloor plate has to be done mainly made by hand. In the first step, the top layers, the core and the inserts are cut in the right shape and the necessary holes are drilled. This step can also be done with the help of machines. In the next step, one of the top layers will be bonded to the core. Now, the inserts can be bonded in the recesses of the core. The last step is to bond the second top layer on the panel.

For the further development of this sandwich technology, an improved production process is important. For industrialization, every production step should be done automatically. Concepts for a continuous production process for sandwich panels with inserts, both with solid cores (Figure 7) as well as liquid foams [2] were developed. There were already first steps performed to validate the automated process [7].

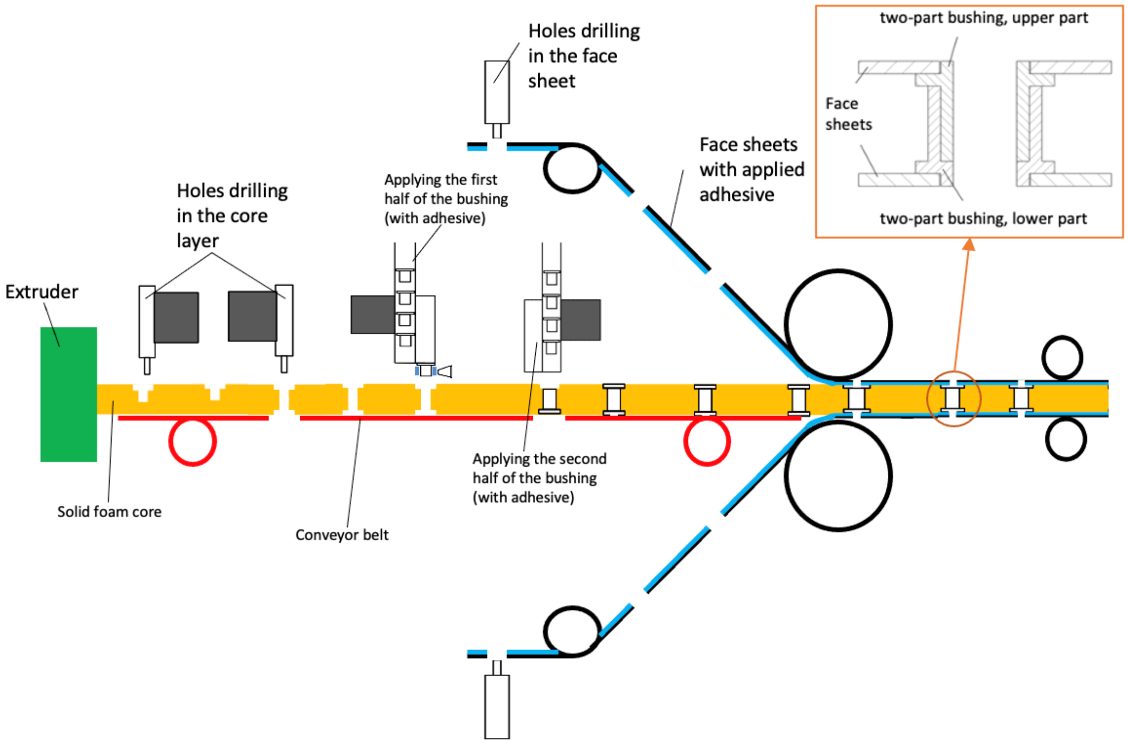

Figure 7: Concept for a continuous production line of flat solid-cored sandwich panel with integrated inserts [2]

5 Results: Validation of the single subfloor plate

5.1 FEM-Simulation of the subfloor plate

To validate the suitability of form, mounting and strength of inserts and sandwich panel, the subfloor plate is simulated with FE-methods. As the CAD construction was done with CATIA V5, the CATIA V5 FEM-workbench was subsequently used for these simulations. It is easy to use and produces acceptable results. The CATIA V5 FEM-workbench works with the ELFINI-solver with an overall linear-elastic material behavior. This means that CATIA does not recognize the exceeding of the yield limit or consider the yield range. So CATIA can not be used for simulations above breaking or for crashs. But it shows good results for estimating how much force the subfloor can withstand [10]. For the top-layers, the von-Mises stress is considered, as the used aluminum 6082 is a ductile material. The used PET-foam is more a brittle non-elastic material, so the principal stress is used for simulation.

The core is discretized with parabolic tetrahedron elements with ten degrees of fredom (T10), the top-layers with parabolic triangular shell elements with six nodes (TR6).

Three load-cases are investigated: Driving through a 3g-depression (3-fold load in -Z-direction), extreme cornering while driving through a 3g-depression (3-fold load in -Z-direction and 2-fold load in Y-direction) and braking while driving through a 3g-depression (3-fold load in -Z-direction and 2-fold load in X-direction). As these are extreme conditions, it can be ensured that the subfloor plate will withstand the forces of all normal driving situations. The maximum permissible weight of the transporter is 1600kg, 600kg vehicle mass and a payload of 1000kg. This leads to the following forces (Table 2):

Table 2: Forces on the vehicle, as load cases for the FE-Simulation

	Load case	**Load and direction**	**Value**
1.	Driving straight ahead through a 3g-depression	3-fold maximum weight in -Z direction	(3 * 9,81m/s2 * 1600kg = -47088 N)
2.	Extreme cornering while driving through a 3g-depression	3-fold maximum weight in -Z direction	(3 * 9,81m/s2 * 1600kg = -47088 N)
		2-fold maximum weight in ±Y direction	(2 * 9,81m/s2 * 1600kg= ±31392 N)
3.	Braking while driving through a 3g-depression	3-fold maximum weight in -Z direction	(3 * 9,81m/s2 * 1600kg = -47088 N)
		2-fold maximum weight in +X direction	(2 * 9,81m/s2 * 1600kg = +31392 N)

All loads are applied in the center of gravity (COG) and distributed to the mounting points (Figure 8).

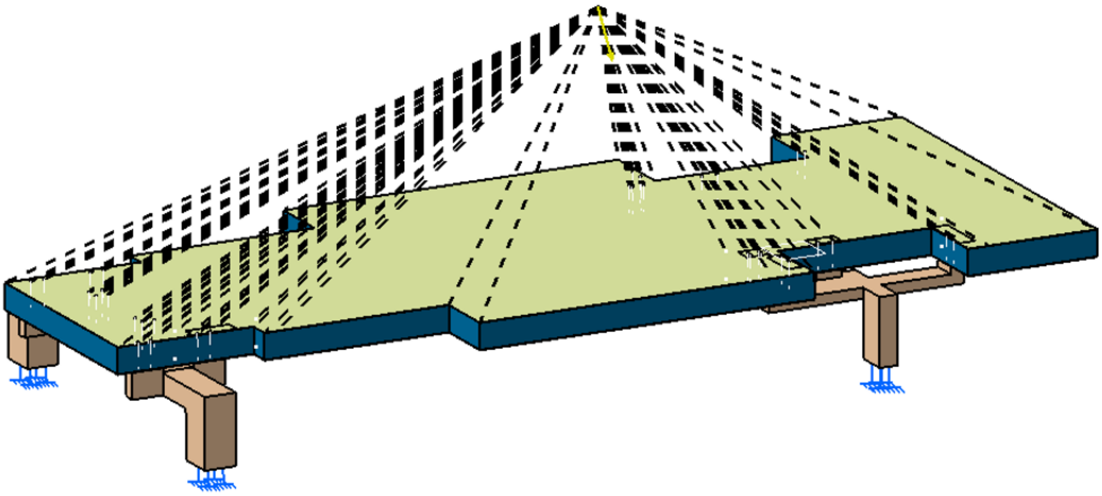

Figure 8: Subfloor plate with simplified undercarriage and applied forces, adapted after[6]

5.2 First results of the FEM-Simulation

The initial parameters of the Simulation were as follows: The core material is a PET-foam with a tensile strength of 1,5MPa and a compressive strength of -0,8 MPa at a density of 60kg/m^3 [8]. The top layers are Aluminum EN AW-6082 with a yield strength of 260MPa and a tensile strength of 310 MPa [9]. For the permissible stresses, a safety factor of 1,5 is applied. The core thickness was chosen with 98mm.

In the first approach, the plate is simulated without inserts. This simulation serves as a reference and can be used to determine the effects of the inserts. The results showed that the highest stresses occur in the load case of extreme cornering while driving through a 3g-depression. Therefore, only this load case is regarded in the following. It can be assumed that the plate will also be able to withstand the other load cases. Figure 9 illustrates the stresses in the top layers, Figure 10 the stresses in the core. The scales are already limited to maximum allowable stresses, including the safety factor of 1,5.

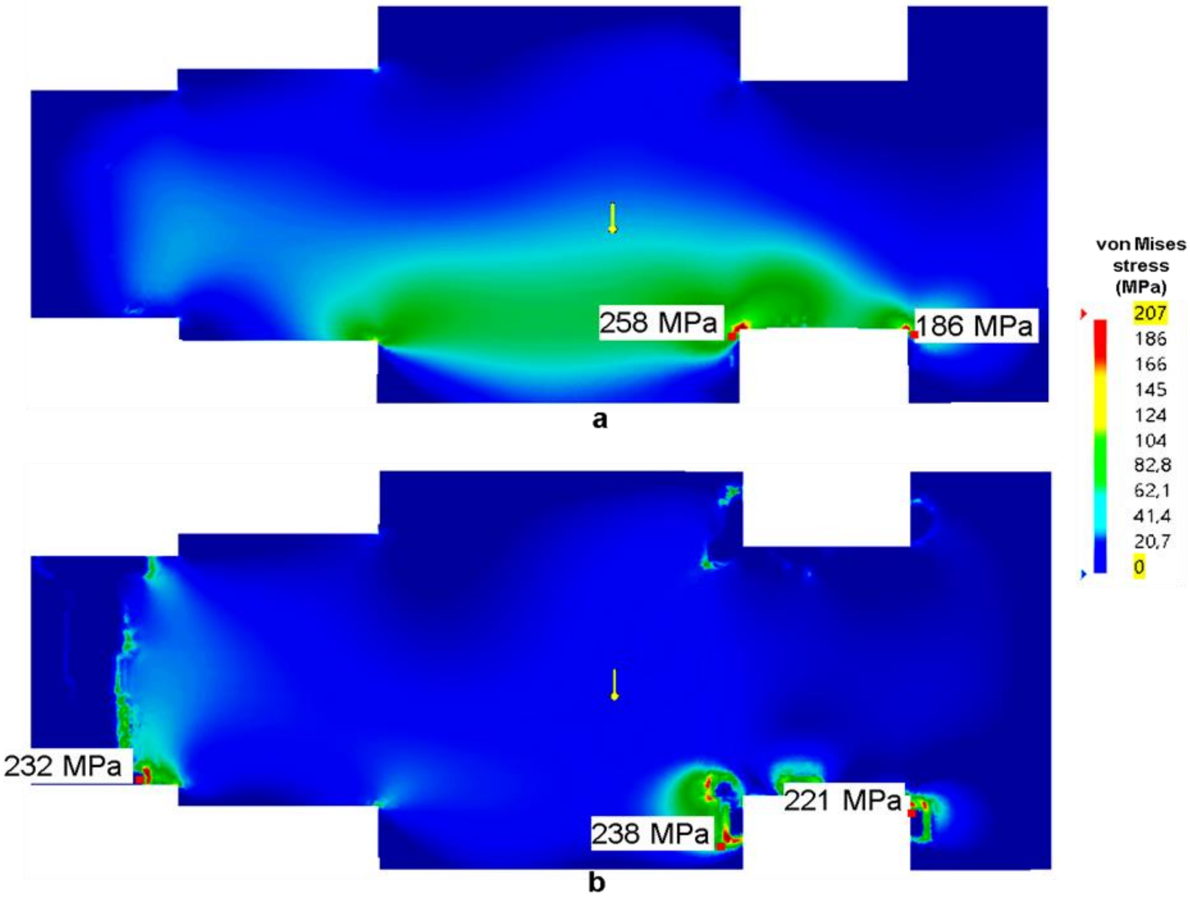

Figure 9: von Mises stress of top (a) and bottom (b) cover layer (Simulation without inserts, extreme cornering maneuver) [6]

The highest stresses are located in the corners near the mounting points for the undercarriage at the front and rear axle. The highest stress in the top layers is 258 MPa, which is about 24% higher than the allowed stress of the aluminum.

The highest stresses in the core are directly located around the mounting points. Here, the highest stress of 4,7 MPa is 370% higher than allowed.

As expected, the results show that the critical stresses occur at the mounting points [6].

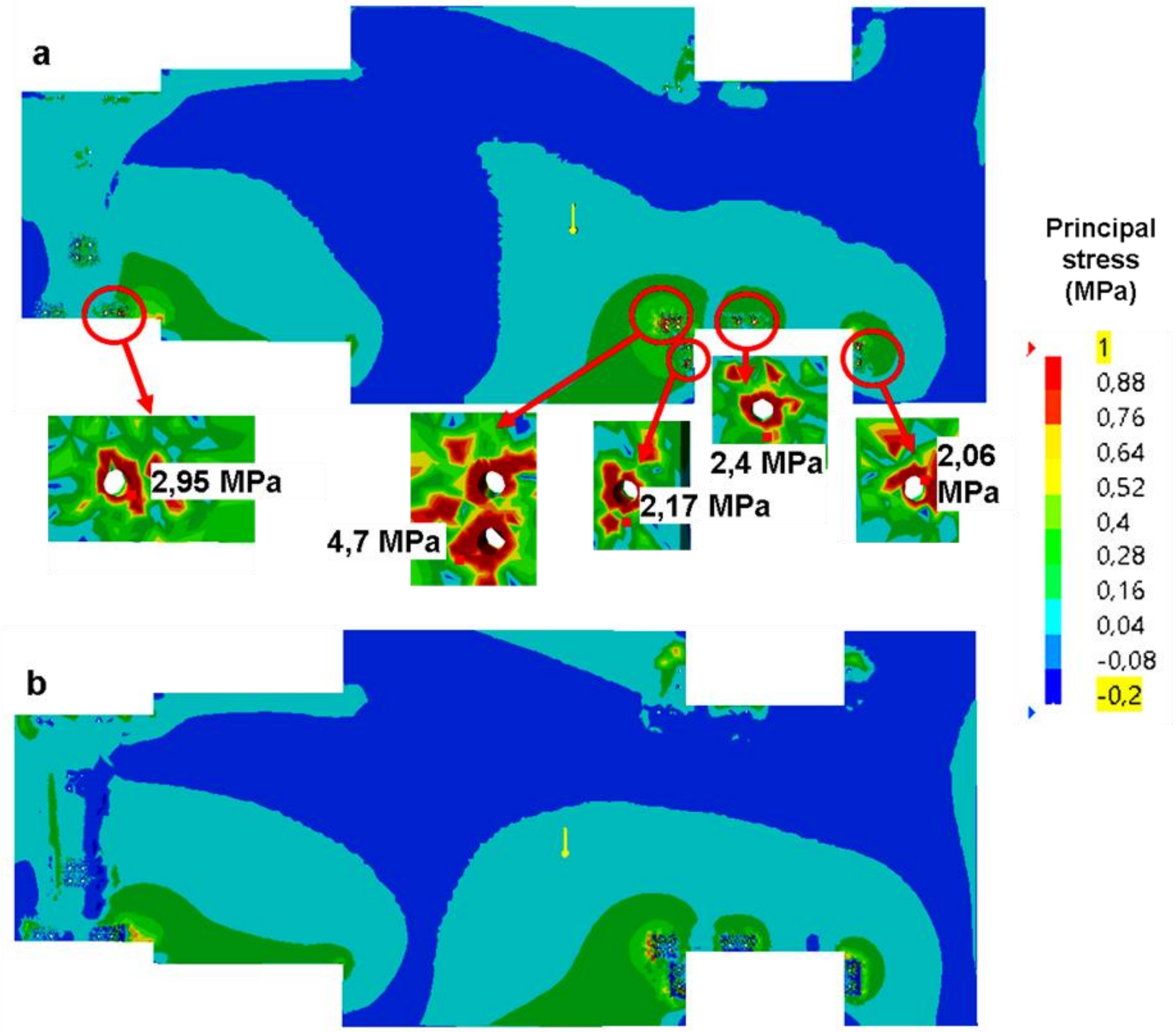

Figure 10: Principal stress in the core, directly under the top (a) and bottom (b) cover layer (Simulation without inserts, extreme cornering maneuver) [6]

5.3 Iteration and effects of parameter changes

For improving the performance of the subfloor plate, inserts are applied in the mounting points. Simulations are conducted with wooden inserts and bushing inserts. The wooden inserts were also simulated with slightly changed shape and size. Additionally, the influences of the core thickness and density were investigated.

First try are the simple rectangular wooden inserts (Figure 5, right). Close mounting points are composed in one insert. With the wooden inserts, the stress in the top layers could be reduced to about 186 MPa. This 10% below the defined tensile strength limit of 207 MPa. Figure 11 shows the stresses in the core of the sections with the mounting points for the undercarriage, which were identified as critical before. There are still some stresses above the limit. The highest with1,71MPa is 71% above.

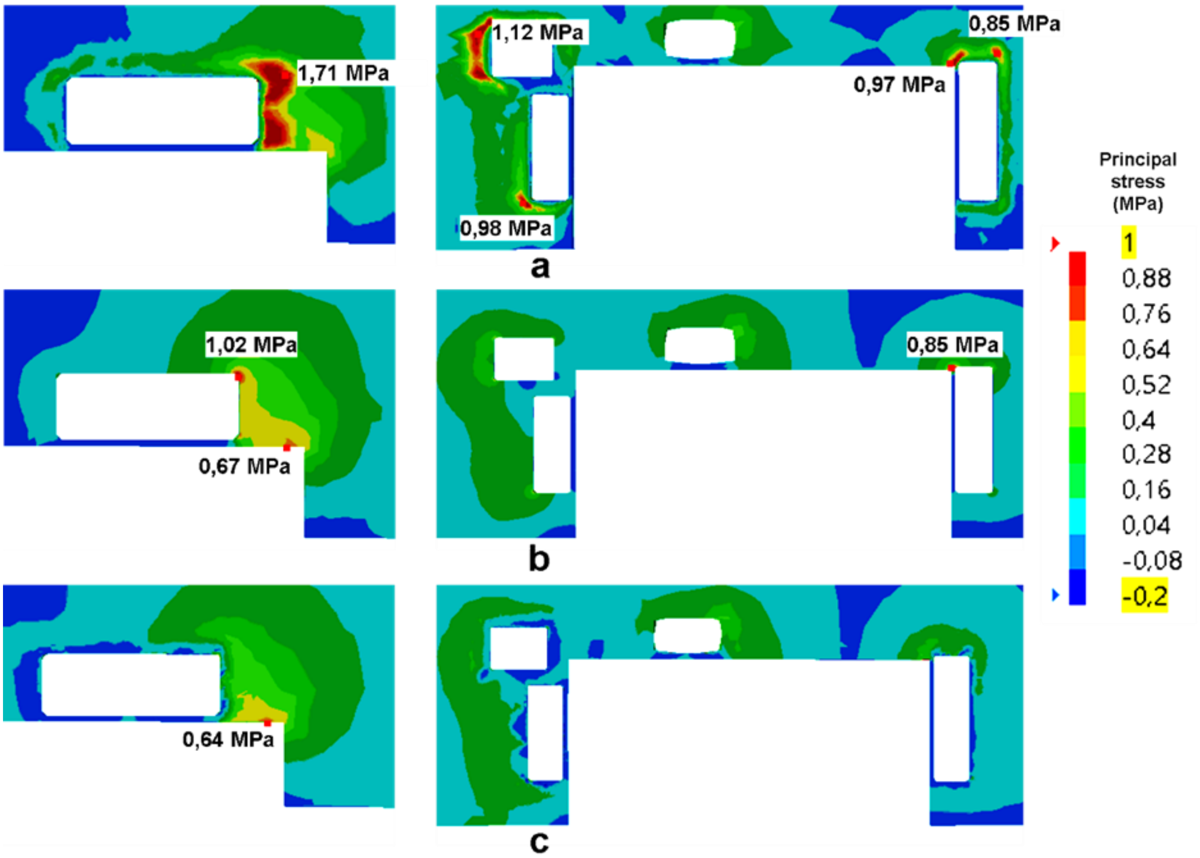

Figure 11: Principal stress on upper (a), middle section (b), and lower (b) side of core layer (Simulation with wooden inserts) [6]

The variation of the density showed no visible improvements. The stresses will remain almost the same, while the tensile strength of the core material only increases from 1,5 MPa (at 60 kg/m^3) to 2,7 MPa (at 150 kg/m^3). The higher density will also increase the mass rapidly by about 120%. In contrast, increasing the core thickness will reduce the stresses effectively (Figure 12).

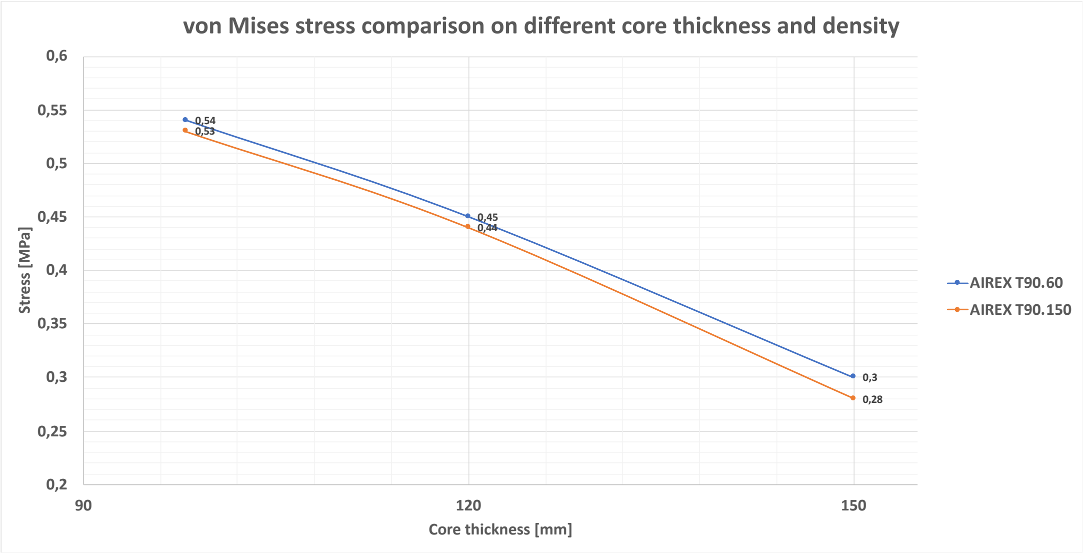

Figure 12: von Mises stress comparison on different core density and thickness [6]

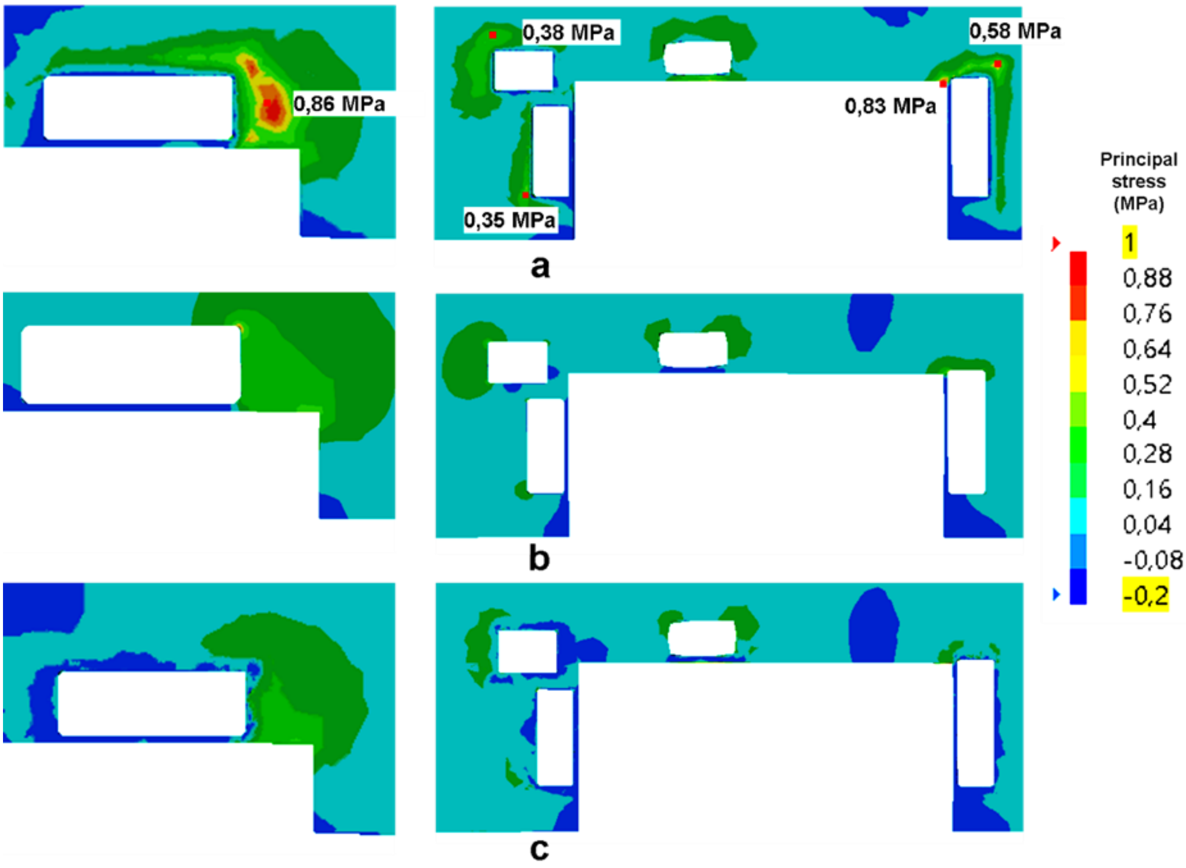

Figure 13: Principal stress on upper (a), middle (b) and lower (c) side of core layer (joined wooden insert, 150mm core thickness) [6]

The core with a thickness of 150 mm showed good results and is chosen for the next steps. It increases the mass only by 50%. The stress is reduced to 0,86 MPa at the maximum, this is 14% below the allowed limit of 1 MPa.

The shape of the wooden inserts can be easily varied in many ways. The size can be increased and the insert can comprise a couple of close mounting points. Simulations of this bigger variants showed only little reduction of the stresses [6].

The metal bushing inserts (Figure 5, left) were also simulated at a core thickness of 150 mm. Compared to the plate without inserts, they showed a good performance in reducing the stresses in the top layers and the core. But in relation to the wooden inserts, they showed no improvement. The top layer stresses were about 237 MPa at maximum, which is 15% more than the allowed limit of 207 MPa. Stresses in the core were up to 1,42 MPa, 42% above the limit of 1 MPa [6]. Reason for this worse performance could be the smaller contact area of the inserts to the top layer. Further, the wooden inserts have a support structure for the whole contact area, while the bushing inserts are only supported in the middle of the washer.

5.4 Final Design

The results of the simulations were used for a final design for the subfloor plate. Thickness of the PET-foam core should be 150 mm, the density 60 kg/m^3. The wooden inserts are well-suited to fulfill the requirements.

For easier manufacturing, the wooden inserts will slightly change. Some Mounting points are combined in one big round insert or in a rectangular shape with round edges. Round shapes can be easily drilled in the core. Figure 14 shows the final design, which will also be used for the scale test-demonstrator.

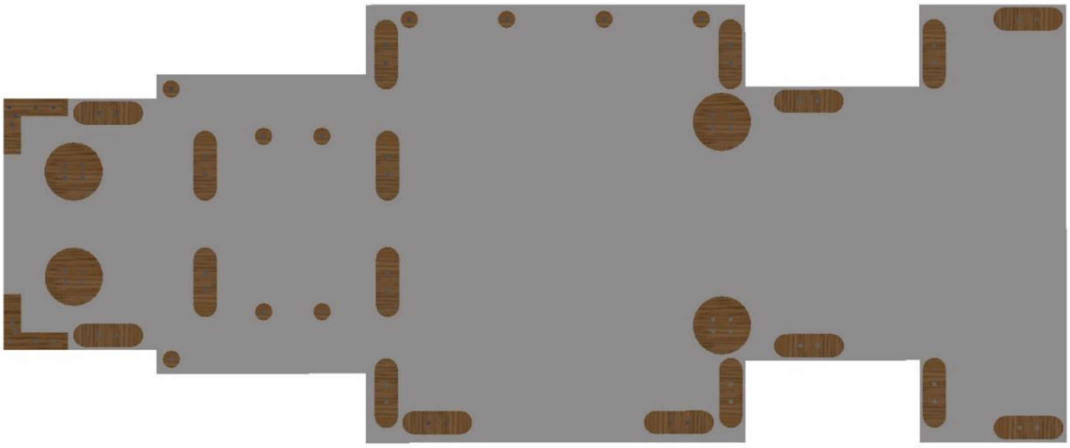

Figure 14: Scale test-demonstrator 1:2

6 Conclusion and Outlook

With the SLRV, it could already be demonstrated that is it possible to build the complete load-bearing structure of a car with sandwich materials. The simulation results of the subfloor plate suggest that this is also possible for the cargo transporter. The next step is to test a scale-demonstrator, in order to evaluate the results of the simulations. If the tests are successful, it would be very interesting to build a full functional demonstrator of the cargo transporter.

For the load-bearing of the sandwich, the inserts are essential. They are needed to support the structure locally and provide mounting points at the same time. Wooden inserts are well-suited and can be produced in almost every shape as needed for the application. The next step will be to investigate some other materials. 3d-printed plastic-inserts are promising and further research just begun.

Sandwich structures are very promising because of their lightweight construction. To produce them in an economic way, the presented continuous manufacturing process has to be further investigated and improved. A possible next step here should be the involvement of the industrial partners. With a positive outcome, a lightweight transporter or any other car can be produced cheaply and efficiently with sandwich structures.

7 References

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