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Multifunctional and lightweight load-bearing composite structures for satellites

Martin Schubert[1,*], *Sara* Perfetto[2] , *Anthanasios* Dafnis[1] , *Heiko* Atzrodt[2] , and *Dirk* Mayer[2]

[1]Institute of Structural Mechanics and Lightweight Design, RWTH Aachen University, 52062 Aachen, Germany
[2]Fraunhofer Institute for Structural Durability and System Reliability LBF, Division of Smart Structures, 64289 Darmstadt, Germany

Abstract. Within the framework of the German national project *multiSat* multifunctional composite structures for satellite applications are developed. The objective is the integration of passive and active functions into the load-bearing spacecraft structure by using suitable materials, components and mechanisms. The passive functions include heat transfer, radiation shielding and protection against space debris impacts, whereas the active functions comprise electric energy and data transfer and vibration reduction. Due to their multi-layer build-up composite materials are suitable for functional integration since each layer can be defined and designed to provide one or more specific functions. The concept of a multifunctional structure allows for the reduction of the overall satellite mass and of installation space required for subsystems. It also opens up new opportunities for highly integrative and standardized production processes and lower total costs and time for manufacturing, qualification and launch. This paper describes the development and design of a concept for a multifunctional sandwich panel and the results of the analyses, numerical simulations and experiments conducted at coupon level.

1 Introduction

Conventional satellite design usually separates between structural-mechanical and non-structural functions of a structure. The primary structure mainly supports mechanical loads and provides attachment points to the subsystems. These are normally developed, tested and qualified independently and their integration into the satellite bus is often carried out at the final stage of the assembly process. Such distinct separation between the functional subsystems typically not only increases mass and installation volume but also times and costs for the production and launch of the spacecraft.

Highly integrated multifunctional structures promise to eliminate these drawbacks. By functional integration non-structural functions that are usually provided by stand-alone subsystems are integrated directly into the primary structure during production. This offers high potential for mass savings and minimized installation space required for the subsystems. Furthermore, this concept also opens up new opportunities for highly

* Corresponding author: martin.schubert@sla.rwth-aachen.de

integrative and standardized production processes which lower total costs and times for manufacturing, qualification and launch of the entire satellite. Composite materials such as carbon fiber reinforced plastics (CFRP) offer high lightweight potential and due to their multi-layer character they are suitable for functional integration because each layer can be defined and designed to provide one or more specific functions, as visualized in Fig. 1.

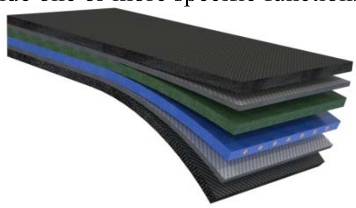


Fig. 1. Idea of a multifunctional structure combining different material layers with specific functions.

The project multiSat, promoted by the Federal Ministry of Economic Affairs and Energy, aims at developing multifunctional load-bearing lightweight structures for satellite applications. In the framework of a comprehensive technological concept several functions are integrated into two typical structural elements of a typical satellite structure: a sandwich panel and a tube. The multifunctional concept adds six functions to the primary structure. They are divided into three passive functions, these are heat transfer, radiation shielding and impact protection, and three active functions, namely vibration reduction, energy transfer and data transfer. Different materials and composite lay-ups are compared in order to realize the passive functions and to enable the integration of tertiary components for the active functions. As additive manufacturing increasingly gains importance and offers a design freedom which can be exploited to create light core structures which are not only optimized from a structural-mechanical point of view, but also enable the realization of passive and active functions. Based on a conceptual analysis a design of a multifunctional composite sandwich panel is developed and pursued towards demonstrator level.

The technological concepts of the multifunctional structures with integrated functions already described in [1] are elaborated in this paper. Further, manufacturing and integration issues are addressed. Numerical simulations and experimental tests at coupon level have been conducted with sandwich panels to verify the integration and the performance of the active functions. The results of the experiments are also described in this paper.

2 Passive functions

Passive functions improve the inherent properties of a sandwich structure and following functions are integrated: heat transfer, radiation shielding and impact protection.

2.1 Heat transfer

Thermal design is a crucial aspect in space structures as they are subject to extreme temperatures and significant temperature gradients. Due to the vacuum in space the only heat transfer mechanisms are heat radiation and heat conduction. Lightweight composite and sandwich structures often have a modest capability of conducting heat, especially through-thickness, and can be improved by appropriate choice of materials. By use of pitch-based carbon fibers instead of conventional PAN carbon fibers, the in-plane thermal conductivity of a CFRP laminate is improved substantially without weight penalty. The very low thermal conductivity of the polymeric matrix can be increased by addition of nanoparticles such as carbon nanotubes (CNT), but this has little effect on the total conductivity. In a sandwich conventional core materials such as honeycomb or polymeric foam act as thermal barrier due to their low density and porosity. Aluminum open-cell foams provide higher thermal conductivities, but also at the expense of higher areal density.

An alternative solution for transferring heat between specific regions is to use an additively manufactured lightweight aluminum core with defined thermal paths created by locally increased material density. On the one hand, heat can be transferred through the thickness from one to the other face sheet without the need to integrate a thermally conductive potting or thermal strap. On the other hand, a dense cross section running as thermal path in-plane within the core can be designed instead of integrating a heat pipe.

Static thermal finite element simulations performed with ANSYS® show the effectiveness of thermal paths added within the additively manufactured lightweight core, as visualized in Fig. 2. A CFRP sandwich panel of dimensions 400x250x21.2 mm with 0.6 mm thick CFRP face sheets is heated by an electronic component to 80°C locally on the inner face sheet and the outer face sheet acts as radiator. The reference panel with PAN fibers and honeycomb core radiates 32.8 W of heat towards outer space. A panel with pitch fibers, CNT-enriched epoxy matrix and a truss grid core with a solid aluminum block acting as thermal link between the face sheets, dissipates 46.8 W (+43%). In this case the solid aluminum block adds 133 g to the panel. By variation of geometry and core density the AM core can be optimized in terms of thermal performance and mass. Concerning production and integration such type of sandwich panel is favourable in applications where the superior heat transfer capabilities of heat pipes are not necessary.

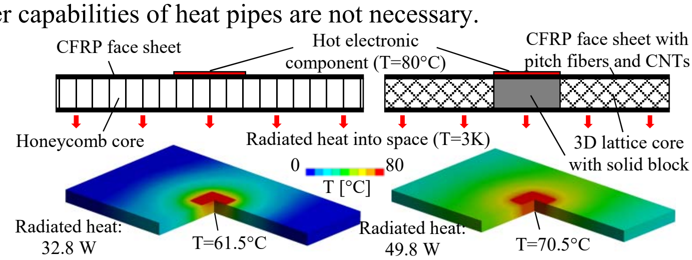


Fig. 2. Static thermal simulation of conventional sandwich (left) and multifunctional sandwich (right).

2.2 Radiation shielding

Space structures are permanently exposed to highly energetic particle radiation. To minimize the disturbance and damage of electronic devices due to charged particles adequate radiation shielding by the surrounding primary structure is aspired. Due to their thin-walled character the shielding capability of primary structures is very limited and highly energetic particle radiation can only be shielded with help of thick walls, which is not acceptable. But long term dose due to permanent low and mid energy particles can be reduced by appropriate choice of structural materials. A weight efficient approach is the concept of the graded-Z shielding with alternating material layers of low (e.g. polyethylene, epoxy) and high atomic number (e.g. tungsten) [2]. This multi-layer shield provides relatively high energy absorption and reduction of secondary radiation. It can be realized as low-Z/high-Z/low-Z configuration with CFRP face sheets and an intermediate layer of thin tungsten foil within the laminate or sandwich.

To investigate the shielding capability of multi-layers representing a sandwich structure, simulations have been conducted. Using SPENVIS [3] the long term fluxes for trapped particles were calculated for two orbits in the radiation belts for a 15 year mission. At 25000 km/0° electrons with up to few MeV and at 4000 km/0° protons with energies of more than 100 MeV are present. The energy spectrum has been used as input for a radiation transport simulation in MULASSIS [4]. The Total Ionizing Dose (TID) in a 2 mm thick silicon target layer representing a computer chip was calculated for different multi-layers.

Fig. 3 shows the TID for sandwich panels with constantly 0.6 mm thick CFRP face sheets and varying thicknesses of intermediate layers. Already thin layers of tungsten are sufficient to shield against electrons, whereas high-energy protons require notably higher wall thicknesses for both high-Z and low-Z materials.

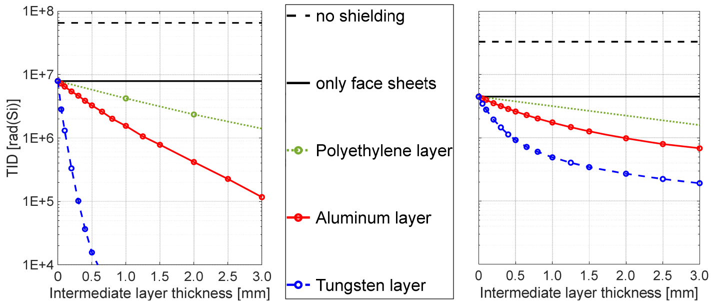


Fig. 3. TID deposited by trapped electrons (25000 km, left) and trapped protons (4000 km, right) behind a CFRP honeycomb sandwich without and with intermediate layers during 15 years.

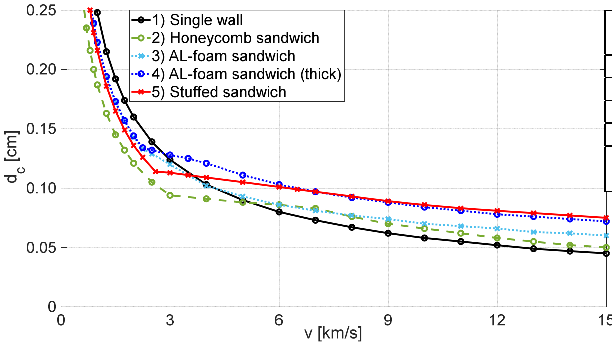
Global shielding by introduction of additional intermediate layers into the structure is only weight efficient if much of the volume inside the satellite needs shielding. Otherwise conventional local or spot shielding is favourable. Often aluminum is used as shielding material and from a design point of view an additively manufactured aluminum lightweight core is attractive. It can include regions with higher material densities or integrate solid aluminum, tungsten or polyethylene inserts to locally shield radiation sensitive components mounted on the sandwich panel.

2.3 Protection against space debris

With ongoing space activities space debris is becoming a steadily increasing issue, especially in near earth orbits where impact velocities can reach up to 15 km/s and even small particles can cause detrimental damage to payloads and subsystems. To protect against debris impact shield concepts are being used mainly in manned spaceflight. Effective and weight efficient shielding is provided by multi-wall shields with at least two thin walls which are separated by a certain distance, called stand-off, from each other.

A sandwich inherently represents a double-wall shield. The outer layer called bumper is relatively thin and causes fragmentation of the impacting particle. A debris cloud is generated and it expands between the two layers before impacting the rear wall, distributing the residual kinetic energy onto a bigger surface. In contrast to a Whipple shield, a honeycomb sandwich provides less protection because the honeycomb cells walls impede the expansion of the debris cloud due to channelling. By replacing the honeycomb with usually heavier open-cell aluminum foam with high energy absorption capability, the protection can be increased [5]. Here, advanced shielding concepts with more than two layers shall be applied to a sandwich. Following the Stuffed Whipple shield concept, impregnated layers of Nextel and Kevlar are added to the sandwich. Nextel ceramic fabric supports effective projectile break-up whereas Kevlar as aramid high-strength fabric has high energy absorption capability to slow down remaining particles.

Ballistic limit equations have been applied according to [6] to different shield types to roughly estimate the performance of a modified sandwich. The curves in Fig. 4 show the critical particle diameter size for perforation of the shield as a function of impact velocity for a sandwich with aluminum face sheets, 20 mm core height and equal areal densities of 0.65 g/cm^2. Compared to honeycomb panels the Stuffed Whipple shield concept and the aluminum foam indicate to offer superior impact protection in the hyper velocity regime.



	t_{face} [mm]	h_{core} [mm]	ρ_{core} [g/cm^2]
1	2.4	-	-
2	1.0	20	0.05
3	0.8	20	0.11
4	0.8	30	0.07
5	0.5	20	0.05
	$AD_{Nextel/Kevlar} = 0.28$ g/cm^2		

Fig. 4. Ballistic limit curves for structures representing a sandwich of 0.65 g/cm^2 areal density (AD).

Thin-walled structures can only provide moderate impact protection. The stand-off between the layers should be maximized, but it is only effective if no channelling by the honeycomb occurs. For increased protection intermediate layers according to the Stuffed Whipple shield are favourable, but they inevitably increase the mass of the panel though. As alternative to a foam structure a 3D grid structure is supposed to provide a comparable performance to foam [5]. Through design, its cell density can be varied through the thickness or higher densities can be created locally in case only local shielding is sufficient, making it weight efficient.

3 Active functions

Active functions extend the operational performance of a sandwich structure. The functions added are vibration reduction, electric energy transfer and data transmission.

3.1 Vibration reduction

Vibration reduction is relevant for any kind of structure subject to dynamic loads. Despite high levels of vibration occur during the launch phase, important vibrations can also occur in orbit. These, usually referred to as micro-vibrations, are induced by on-board devices with moving or rotating parts. Nowadays the sensitivity of the on-board equipment has increased steadily and it requires insulation from such micro-vibrations.

Passive methods are conventionally used to insulate sensitive payloads from disturbances. However, they often involve the use of damping materials that can be unable to maintain their properties in the harsh space environment due to their temperature dependence and susceptibility to radiation and off-gassing. To overcome these disadvantages, active solutions have been widely studied in the last two decades. However, much work is still necessary in this field to ensure the necessary reliability for space applications. The most common isolators used for active vibration reduction involve either piezoelectric (PZT) actuators or voice coil actuators. Unlike electrodynamic systems, piezoelectric actuators are characterized by a very compact design since they can be produced in the shape of flat actuators. In the context of vibration reduction of satellite structures in composite materials, the use of shunt damping by integrating piezoelectric actuators into the vibrating structures is a promising approach. When a hosting structure vibrates, the integrated actuators produce electricity. By connecting the terminals of the actuators to an electrical impedance provided by a shunt circuit, mechanical energy is dissipated reducing the vibration of the structure. Simulation models of sandwich panels with integrated piezoelectric actuators have been implemented to investigate the effectiveness of the vibration reduction [1], showing promising results.

In order to validate the simulations, experiments at coupon level have been performed. A sandwich coupon with dimensions 360x90 mm and thickness 22 mm (20 mm aluminum honeycomb core and 1 mm CFRP face sheets) with two integrated PZT actuators has been produced. Conventional DuraAct actuators [9] are flexible thanks to an epoxy casing, but the electric and magnetic isolation of the electrodes is not provided. Thus, piezoelectric actuators with integrated flat cables have been customized for this application [9,10]. Each actuator has dimensions 60x35x0.5 mm including isolation (50x30x0.2 mm active PZT material). The actuators are integrated between the core and the face sheets. To maximize the electromechanical coupling factor, the actuators are first bonded to the CFRP face sheets and after that the sandwich is cured by bonding the core, face sheets and actuators with help of an adhesive film. The coupon is tested in the configuration of a cantilever beam with a tip mass of 100 g. The tip is selected as location for applying a horizontal excitation force, in order to excite the first bending mode.

First, a modal analysis of the coupon is performed in ANSYS® in the range from 0 Hz to 500 Hz. To preliminary investigate in simulation the performances of the coupon with shunt damping the FE model is imported in MATLAB/Simulink® and analysed first in full scale, and then reduced only to the first bending mode via model order reduction (MOR) [1,7,8]. To estimate the level of vibration reduction, a RL shunt circuit optimized to absorb the first resonance frequency is connected to the actuators in simulation. The reduction of the amplitude of acceleration at the tip is calculated as 14 dB for the first bending mode. To validate the vibration reduction experimentally, a shaker is used to excite the coupon at the tip and the response in the same location is measured using an accelerometer. The flat PZT actuator, the sandwich coupon with actuators and the test setup are shown in Fig. 5.

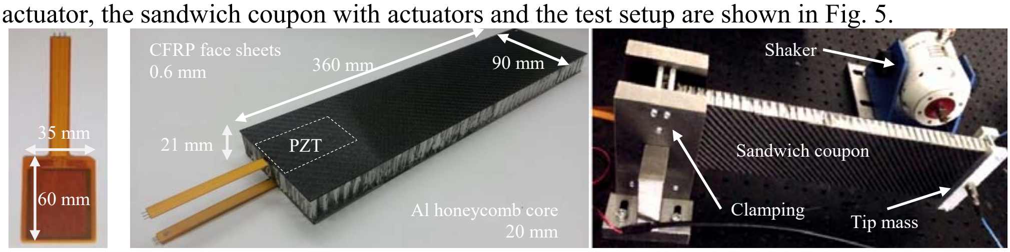


Fig. 5. Customized DuraAct patch transducer (left), sandwich coupon with integrated PZT actuators (middle) and experimental set-up for vibration reduction (right).

When the actuators are connected to the RL shunt circuit a vibration reduction of 17 dB is measured at the resonance frequency of 65.5 Hz, demonstrating the effectiveness of the concept. Fig. 6 shows the measurements of the acceleration amplitudes over the excitation force when the actuators are in open circuit conditions, short circuit conditions and connected to the RL shunt circuit. By measuring the resonance frequencies in open and short circuit conditions, an electromechanical coupling factor of 12% is measured, demonstrating the good coupling between the actuators and the hosting sandwich structure.

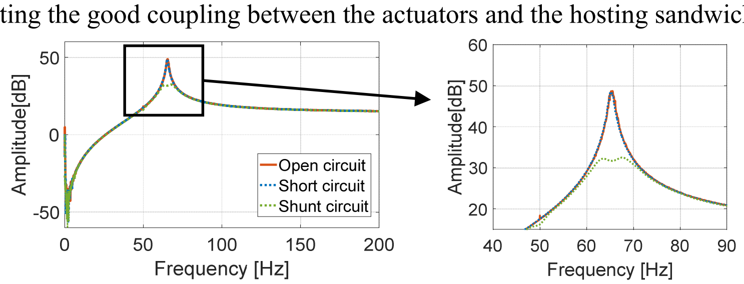


Fig. 6. Measurement of vibration reduction by shunt damping (green line) for the 1st eigenfrequency.

3.2 Energy and data transfer

Active payloads and subsystems need electric energy and the satellite harvests data that need to be transmitted first to the memory on-board and then to the ground. Commonly, cables and power lines are used to transfer electric energy and data and the entire harness and mounting structures considerably add mass to the structure. Hence, embedding lines for energy and data transfer into the load-carrying structure offers potential for weight and volume savings. Here flat cables (14 poling lines, 1 A, 60 V, thickness 0.25 mm) are integrated into a sandwich panel for energy and data transfer while the integration of optical fibres (cable diameter 0.9 mm, with SC connectors) is investigated for data transfer only. These components are integrated near the neutral axis of the panel and in correspondence to an intermediate layer which serves a passive function (e.g. impact protection). To verify the correct operation of the cables after integration and manufacturing of the sandwich panels, the transmission of data and electrical energy has been measured by using a test setup including transmitters, receivers and electric boards. No defects have been detected. A coupon equipped with PZT actuators, flat cable and optical fibres is shown in Fig. 7.

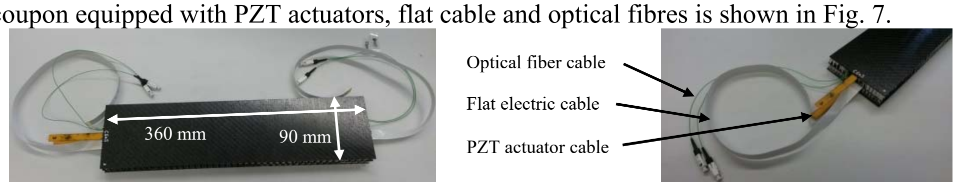


Fig. 7. Sandwich coupon with PZT actuators and embedded cables.

4 Multifunctional concept

The solutions for the passive and active functions presented are combined in order to develop two concepts of a multifunctional sandwich panel for satellite structures. The first concept follows a conservative approach exploiting potential performance reserves in conventional honeycomb sandwich panels. In contrast to this, the second concept aims at taking advantage of innovative additive manufacturing processes for multifunctional cores. Nowadays these technologies still face restrictions and challenges with regard to manufacturing, but they promise high potential for the development of future structures.

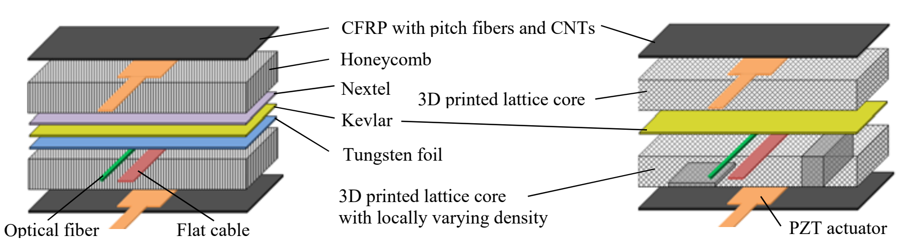


Fig. 8. Multifunctional sandwich concepts with honeycomb (left) and 3D printed lattice core (right).

Both approaches are presented in Fig. 8. The sandwich panel is made of CFRP face sheets and an aluminum honeycomb or printed lattice core. The face sheets have pitch-based carbon fibers to increase the in-plane thermal conductivity and the matrix is filled with CNTs to improve the thermal conductivity, radiation resistance and impact toughness of the epoxy. The double-wall character of the sandwich is exploited to adopt the Stuffed Whipple shield concept by integrating Nextel and Kevlar fabric as intermediate layers. Additionally, a thin tungsten foil is placed within the intermediate layer for shielding against particle radiation. Additionally, the concept with an additively manufactured core has varying cell densities to provide locally increased thermal and protective properties.

With regard to the active functions, the flat cables for energy transfer and the optical fiber cables for data transmission are embedded in the core next to the intermediate layer of the sandwich. The customized piezoelectric DuraAct actuators are adhesively bonded to the inner side of the face sheets and connected to a shunt circuit for vibration reduction.

5 Conclusion and outlook

The development and design concept of a load-bearing multifunctional composite sandwich panel has been presented in this paper. The multifunctional concept integrates both passive functions (heat transfer, radiation shielding and impact protection) and active functions (vibration reduction, energy and data transfer) into the primary structure by using suitable materials, components and mechanisms. After analysis of different materials and design considerations concerning the passive functions, the integration and testing of the components for the active functions have been described. The feasibility of the vibration reduction by shunt damping with piezoelectric actuators has been verified on coupon level.

Coupon tests for verification of the discussed concepts for improved passive functions are currently in progress and include thermal, radiation and impact testing. Concerning the active functions, further tests in a thermal vacuum chamber are conducted to examine the behaviour and performance of the piezoelectric actuators under space environment conditions. To show the feasibility of combining the presented solutions, a multifunctional demonstrator sandwich panel is being produced according to the presented concepts.

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