CFRP and aluminum foam hybrid composites

R. Hartmann[1], *M. Koch*[1]

[1]Technische Universität Ilmenau, Germany

ABSTRACT

This paper deals with the RTM manufacturing process and FEM simulation of a hybrid material. By using the sandwich design method two tensile-stiff carbon fiber reinforced plastic (CFRP) layers are connected to a low-density aluminum foam (AF) core in order to produce components with high weight-specific bending stiffness. On the basis of the beam theory, an analytical calculation method is developed, which allows a first estimation of the mechanical properties of the composite beam. These findings are incorporated into the development of a numerical FEM calculation method, which allows the simulation of various load cases with selectable composite beam structure. Preliminary tests are carried out to determine the usable range of the RTM process parameters like injection pressure, mold temperature and compression pressure of the press. In the course of this first specimens are produced, which show a smooth surface, no displacement of the fibers and almost no air inclusions in the laminate.

Index Terms – RTM, FEM, CFRP, aluminum foam, hybrid material

1. INTRODUCTION

One way to minimize the energy consumption of production processes is to reduce moving masses in machinery. This reduction of mass can be carried out through the exchange of solid material, like steel or aluminum, with hybrid materials. They allow the application-oriented combination of different type of materials and their properties. The aim of this paper is to examine, describe, simulate and manufacture a lightweight and bending-resistant hybrid material made of CFRP and AF. At the beginning of this paper the theory of flexurally rigid sandwich structures are explained, followed by their mathematical description as a bending beam and the extended description with the sandwich theory. Subsequently the material selection based on findings from theoretical considerations takes place. Then the manufacturing process of these composites by means of the RTM process is illustrated. Finally the developed calculation models, the preliminary tests as well as their results and the derived conclusions are presented.

2. BASICS

2.1 Sandwich design

Components developed by using the sandwich design method are comparatively lightweight and can withstand great mechanical stress. Fig. 1 demonstrates the effect of a bending load on a sandwich composite.

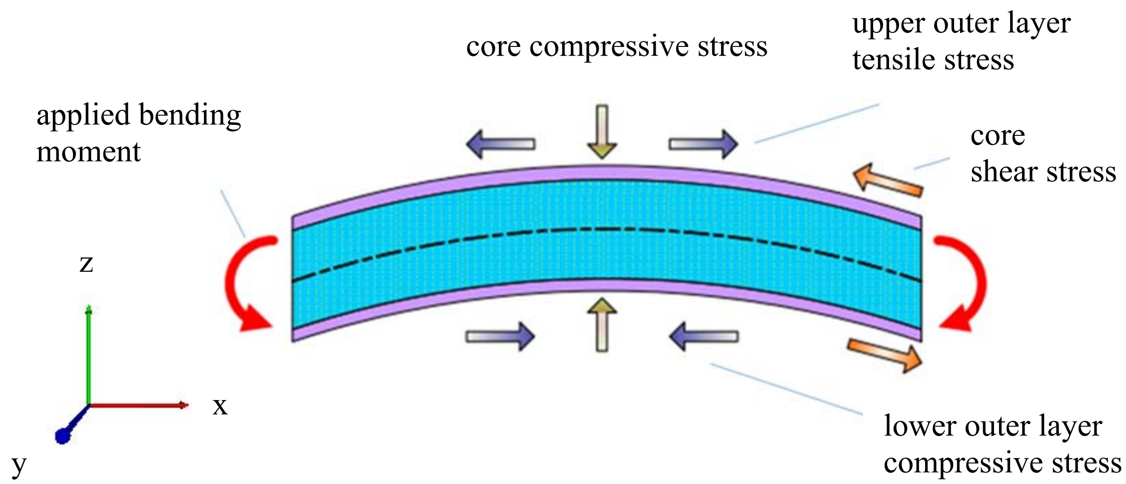

Figure 1: Sandwich composite beam with bending load [1]

In the bending case illustrated in Fig. 1, the upper outer layer is strained by tensile stress and the lower by compressive stress. These two oppositely directed stresses cause a shearing stress and a compressive stress in the sandwich core.
The requirements for the sandwich materials can be derived from these resulting strains: the core layer and the connecting layer have to be compressive- and shear stable; and the outer layers must have high tensile and compressive stiffness.

2.2 From the beam theory to the sandwich theory

The sandwich theory is based on the classical beam theory, which describes the behavior of long, slender and monolithic beams, which are purely subjected to bending strain.

2.2.1 Classical beam theory

The classical beam theory states, that the bending stiffness can be estimated through the determination of the elastic bending modulus and the moment of inertia (Fig. 2, Eqn. 1).

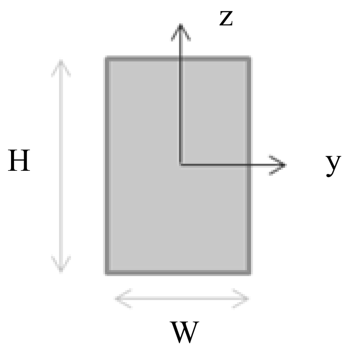

Figure 2: Cross-section of a monolithic beam

Fig. 2 shows the cross-section of a monolithic beam, in which H is the beam height and W is the beam width.

$$B = E \cdot I \tag{1}$$

The bending stiffness B can be calculated using Eqn. 1. E is the elastic modulus and I the moment of inertia.

$$A = W \cdot H \tag{2}$$

The cross-sectional area A can be calculated using Eqn. 2.

The moment of inertia can be determined using Eqn. 3.

$$I_{y,0} = \int_A z^2 \cdot dA = \int_{-\frac{W}{2}}^{\frac{W}{2}} \int_{-\frac{H}{2}}^{\frac{H}{2}} z^2 \cdot dz \cdot dy = \frac{H^3}{12} \cdot W \tag{3}$$

The bending stiffness can be determined by turning Eqn. 1 into Eqn. 4.

$$B = E \cdot I = E \cdot \frac{H^3}{12} \cdot W \tag{4}$$

2.2.2 Sandwich theory

If the beam consists of two outer layers and a core layer, the sandwich theory can be applied.

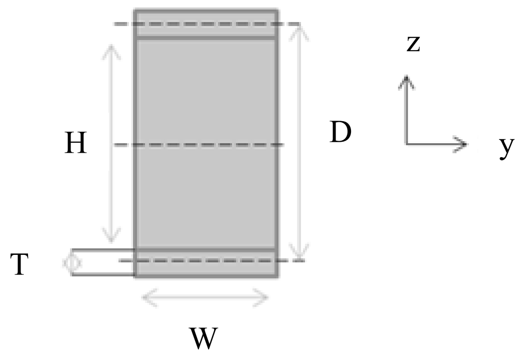

Figure 3: Cross-section of a sandwich beam

Fig. 3 shows the cross-section of a composite beam, in which H is the core height, W is the beam width, T is the outer layer height and D is the distance of the outer layer centrodial axes.

The moment of inertia of the outer layers can be calculated by a normal ($I_{y,1,n}$) and a Huygens–Steiner share ($I_{y,1,HS}$) (Eqn. 5, Eqn. 6).

$$I_{y,1,n} = \frac{T^3}{12} \cdot W \tag{5}$$

$$I_{y,1,HS} = \left(\frac{D}{2}\right)^2 \cdot T \cdot W \tag{6}$$

The total bending stiffness of a sandwich composite is the sum of the core bending stiffness B_{core} and the outer layer bending stiffness B_{layer} (Eqn. 7).

$$
\begin{aligned}
B_{total} &= B_{core} + B_{layer} \\
&= E_{core} \cdot I_{y,0} + E_{layer} \cdot 2 \cdot I_{y,1,n} + E_{layer} \cdot 2 \cdot I_{y,1,st} \\
&= E_{core} \cdot \frac{H^3}{12} \cdot W + E_{layer} \cdot W \cdot T \cdot \left(\frac{T^2}{6} + \frac{D^2}{2}\right)
\end{aligned}
\tag{7}
$$

If $E_{core} << E_{layer}$ is true, which is mostly the case, Eqn. 7 can be simplified as follows:

$$B_{total} \sim E_{layer} \cdot W \cdot T \cdot \left(\frac{T^2}{6} + \frac{D^2}{2}\right) \tag{8}$$

The total bending stiffness B_{total} of a composite beam is mainly determined by the elastic modulus of the outer layer E_{layer} and the outer layer centroidal axis distance D (Eqn. 8).

$$D = H + T \tag{9}$$

The outer layer centroidal axis distance D is the sum of core layer height H and outer layer height T (Eqn. 9).

Eqn. 10 results, when Eqns. 8 and 9 are combined.

$$B_{total} \sim E_{layer} \cdot W \cdot T \cdot \left(\frac{T^2}{6} + \frac{(H+T)^2}{2}\right) \tag{10}$$

According to Eqn. 10 to effectively increase the total bending stiffness of a composite beam the outer layer modulus and/ or the outer layer centroidal axis distance have to be enlarged.

3. SELECTED SANDWICH MATERIALS

3.1 Overview

Fig. 4 shows the composition of a symmetrical sandwich composite. It consists of a core (b) and two outer layers (a). Core layer and outer layers are connected by a connecting layer (c).

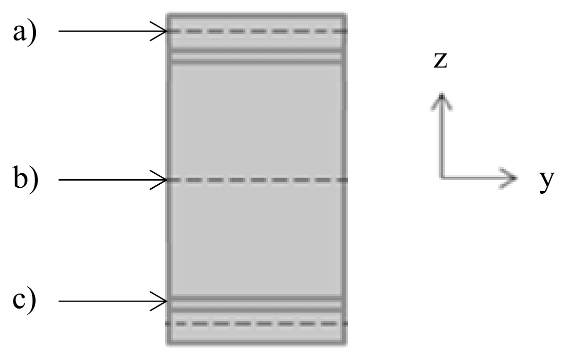

Figure 4: Composition of a symmetrical sandwich composite

3.2 Outer layer - CFRP

CFRP is chosen to maximize the outer layer modulus. It has excellent weight-specific mechanical properties. For example the elongation length $\left(\frac{E}{\rho \cdot g}\right)$ of unidirectional CFK-HM is over 17000 km [2]. The elongation length of thermoplastics is about 1000 km and of metals under 3000 km. The modulus of CFRP with unidirectional fiber reinforcement parallel to the direction of force can be estimated using Eqn. 11 [2].

$$E_{CFRP,||} = v_f \cdot E_{CF} + (1 - v_f) \cdot E_{ER} \tag{11}$$

In which $E_{CFRP,||}$ is the elastic modulus of CFRP with unidirectional fibers parallel to direction of force, v_f is the fiber volume content, E_{CF} is the elastic modulus of unidirectional carbon fibers and E_{ER} is the elastic modulus of the epoxy resin. The modulus of CFRP is mainly determined by the fiber volume content and the elastic modulus of the used carbon fibers.

3.3 Core layer - AF

A core made of AF is used to enlarge the outer layer centroidal axis distance. AF has a low density, typically in the range from 0.5 to 2 $\frac{g}{cm^3}$ [4], caused by pores and cavities. For production reasons the homogeneity of the foam structure cannot be ensured. The pores vary in diameter. This is the reason why the density and hence the substantial mechanical properties of the foam are not constant. There are two basic types of foam: closed-cell; and open-cell foam. The modulus of elasticity of metal foams can be estimated using Eqn. 12 [3]:

$$E_F = C_0 \cdot E_S \cdot \left[C_2 \cdot \left(\phi \cdot \frac{\rho_F}{\rho_S} \right)^2 + C_1 \cdot \frac{\rho_F}{\rho_S} \right] \tag{12}$$

In which E_F is the elastic modulus of the foam, ρ_F is the density of the foam, E_S is the elastic modulus of the solid material, ρ_S is the density of the solid material, ϕ is the coefficient of mass distribution and C_0, C_1, C_2 are foam structure parameters. The coefficient of mass distribution ϕ indicates the ratio of cell web thickness to cell wall thickness and can be calculated according to [3] as follows:

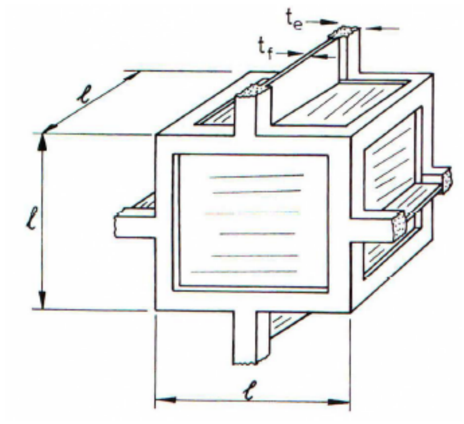

Figure 5: Simplified cube model of a closed cell AF [3]

Fig. 5 shows the simplified cube model of a closed cell AF, in which t_e is the cell web thickness, t_f is the cell wall thickness and l is the cell length. The coefficient of mass distribution ϕ can be calculated using Eqn. 13.

$$\phi = \frac{{t_e}^2}{({t_e}^2 + t_f \cdot l)} \tag{13}$$

Table 1 lists the needed parameters for solving Eqn. 12.

Table 1: Parameters for the calculation of the elastic modulus of metal foams [4]

parameter	closed-cell foam	open-cell foam
C_0	0.5 to 1	0.5 to 1
C_1	0.3	0
C_2	0.5	1
ϕ	< 1	1

3.4 Connection layer - ER

Epoxy resin (ER) is chosen as connection layer material, because it has a remarkable adhesion to almost all substrates, high mechanical strength (elastic modulus about 3000 MPa) and a low shrinkage during curing. It is the standard resin for the RTM process.

3.5 Resin transfer molding process (RTM) for CFRP/ AF hybrid composites

Fig. 6 shows the principle of the RTM process. The AF and the CF preforms are placed into the mold (a), the mold is closed and evacuated. Subsequently the reaction resin mixture is injected (b). After the resin mixture is cured (c), the mold is opened and the CFRP/ AF hybrid component can be removed (d).

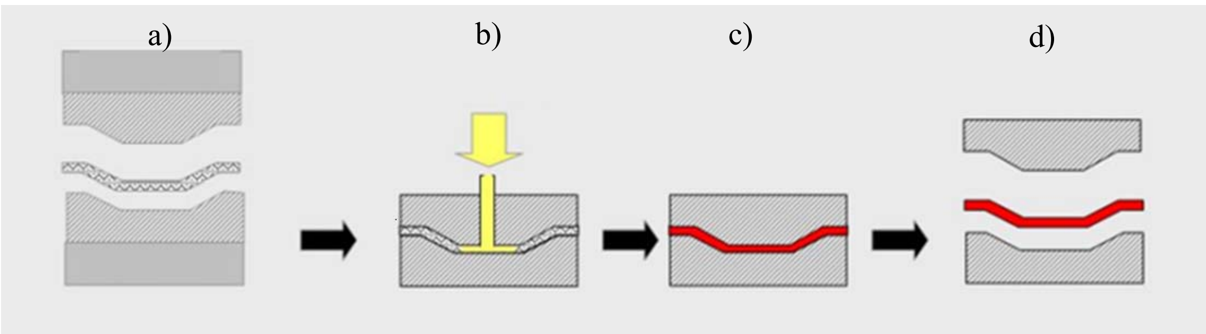

Figure 6: Principle of the RTM process [2]

The control parameters of the RTM process are the injection pressure, the vacuum level, the compression pressure of the press and the resin temperature. Initial tests are conducted to detect the usable range of these control parameters (Chap. 5).

4. CALCULATION MODELS

4.1 Analytical

One approach of this paper is to carry out the analytical calculation of the total bending stiffness of a CFRP/ AF sandwich composite. This is achieved by the merging of the known Eqns. 7, 9, 11 and 12.

$$B_{total} = C_0 \cdot E_S \cdot \left[C_2 \cdot \left(\phi \cdot \frac{\rho_F}{\rho_S} \right)^2 + C_1 \cdot \frac{\rho_F}{\rho_S} \right] \cdot \frac{H^3}{12} \cdot W$$
$$+ \left[v_f \cdot E_{CF} + \left(1 - v_f \right) \cdot E_{ER} \right] \cdot W \cdot T \cdot \left(\frac{T^2}{6} + \frac{(H+T)^2}{2} \right) \quad (14)$$

Eqn. 14 illustrates, that the total bending stiffness depends on geometrical and material-related variables.

4.2 Numerical

Another approach of this paper is to develop an FEM model, which allows the estimation of the mechanical properties of the composite at various geometrical dimensions of core and outer layers. The challenge in developing this numerical calculation model is the implementation of the material-specific peculiarities. These include the anisotropy of the mechanical properties of the CFRP layers and the core structure of the AF.

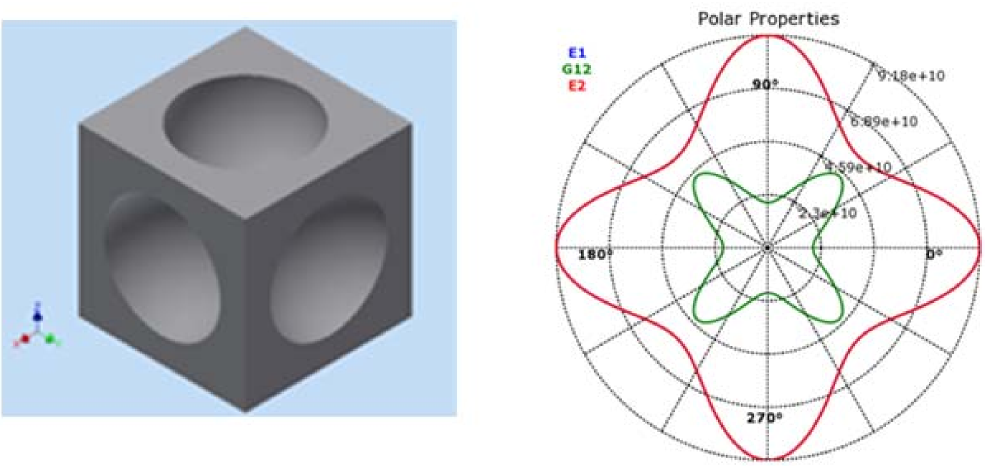

Figure 7: FEM cube model of the AF core structure (left) and polar properties of the CFRP layers (right)

The polar properties of the CFRP layers are calculated with the help of the ANSYS® fiber-reinforced plastic additional software ACP (Fig. 7, right). The AF core structure is modeled by a cube with spherical material removal on all exterior surfaces (Fig. 7, left). That causes the number of cube grid points to rise from 8, for a monolithic material, to over 20, which leads to greater computational workload.

5. INITIAL TESTS

By using the fractional factorial design of experiments method (DoE) an experimental plan is developed. It allows the determination of the RTM process parameters, which will lead to components with the highest weight-specific bending stiffness. On this account preliminary tests are carried out to identify the usable range of injection pressure, mold temperature and compression pressure of the press (Tab. 2, Fig. 8, left).

Table 2: RTM process parameters for preliminary tests

process parameter	unit	test 1	test 2	test 3
injection pressure	bar	2	3	5
vacuum	bar	0.9	0.9	0.9
mold temperature	°C	60	80	100
curing time	h	4	4	4
curing temperature	°C	60	80	100
mass of the AF plate	g	336	347	377
mass of the CF mat	g	110	102	113

A 10 mm closed-cell AF with open surface and a density of 0.8 $\frac{g}{cm^3}$ is chosen for the core layer. The outer layers are prepared from five layers 0.2 mm CF twill fabric with an area weight of 200 $\frac{g}{cm^2}$. The optical properties of the hereby manufactured CFRP/ AF plates are promising. They show a smooth surface and the ER link layer covers the entire plate. Almost no air inclusions are visible, which is indicative for a low volumetric void content of the CFRP laminate (Fig. 8, right).

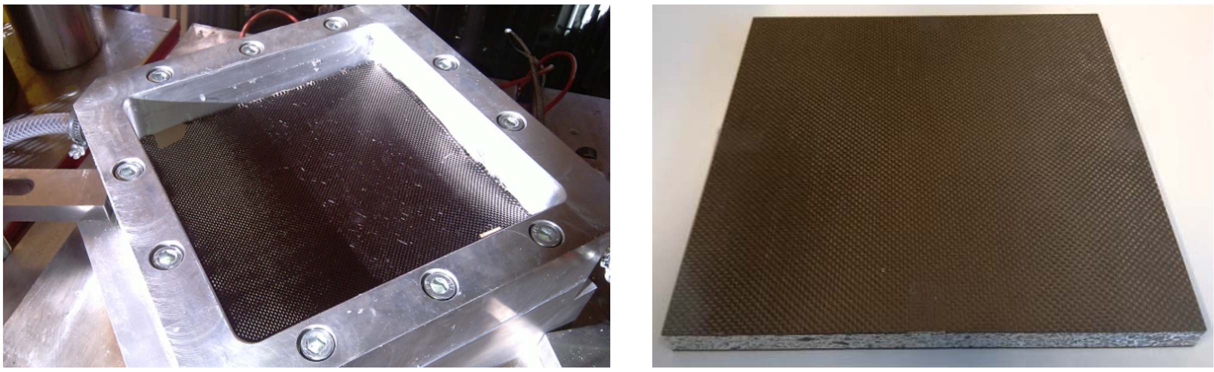

Figure 8: Dry CF preforms with AF plate in the RTM mold before injection (left) and cured CFRP/ AF hybrid composite plate (right)

Table 3 lists the measurement results of the performed preliminary tests. The density of the manufactured CFRP/ AF plates is in the range of 1.51 to 1.66 $\frac{g}{cm^3}$.

Table 3: Measurement results for preliminary tests

measured variable	unit	test 1	test 2	test 3
mass of the injected ER resin	g	276	314	309
mass of the CFRP/ AF plate	g	725	760	799
density of the CFRP/ AF plate	$\frac{g}{cm^3}$	1.51	1.58	1.66

The amount of injected resin cannot be used as an indicator for the resin penetration depth, because of the inhomogeneity of the foam structure.

6. CONCLUSIONS

This paper can demonstrate, that the production of CFRP/ AF hybrid material by means of the RTM process is feasible. The first manufactured specimens exhibit a smooth surface, dimensional accuracy, no displacement of the fibers as well as almost no air inclusions. The simulation of CFRP/ AF hybrid material could be implemented. The anisotropy of the CFRP layers can be simulated with the ANSYS® fiber fracture software ACP. The structure of the AS core can be mapped with great computational effort. The next step is the execution of the developed experimental plan with an especially designed and manufactured RTM mold for sandwich composites.

REFERENCES

[1] S. Torsakul, Modellierung und Simulation eines Verbunds von Sandwichplatten zur Entwicklung einer mechanischen Verbindungstechnik, Dissertation, Rheinisch-Westfälische Technische Hochschule Aachen - Fakultät für Maschinenwesen, Aachen, 2007.

[2] M. Koch, Skript Faserverbundtechnologie, Technische Universität Ilmenau - Fachgebiet Kunststofftechnik, Ilmenau, 2012.

[3] L. Gibson, M. Ashby, Cellular Solids – Structure and Properties – Second Edition, Cambridge University Press, Cambridge, 1997.

[4] T. Hipke, G. Lange, R. Poss, Taschenbuch für Aluminiumschäume, Aluminium Verlag, Düsseldorf, 2007.

CONTACTS

M. Sc. R. Hartmann	robert.hartmann@tu-ilmenau.de
Univ.-Prof. Dr.-Ing. M. Koch	michael.koch@tu-ilmenau.de