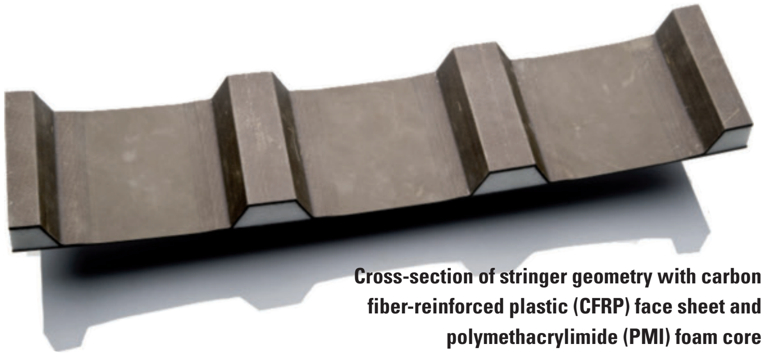
PMI Rigid Foam. Lightweight solutions are sought for many applications today, but rarely is it a matter of "lightweight at any cost". Instead, a balance of manufacturing costs, process reliability and part weight is usually the rule.



Cross-section of stringer geometry with carbon fiber-reinforced plastic (CFRP) face sheet and polymethacrylimide (PMI) foam core

A Delicate Balance

FELIX GOLDMANN

In many applications, the subject of lightweight construction is becoming increasingly important. For this reason, composite structures are employed in not only aircraft, but also sports equipment, the automotive industry, for highly-accelerated components in machinery and many other fields.

Depending on the requirements placed upon a component in terms of geometry, load and design criterion, continuous fiber-reinforced plastics are ideal for different designs: usually only high rigidity is required, and monolithic structures are suitable. If, on the other hand, good rigidity and excellent flexural properties, as well as high buckling resistance, are required, then sandwich construction usually turns out to be the optimal choice. Here, a distinction is drawn between full sandwich, skin sandwich and shell construction stiffened with stringers. **Table 1** provides an overview of the aforementioned variations.

The core material is designed so that it transfers the shear stresses between the face sheets at the sandwich layer and the compression stresses perpendicular to the sandwich layer. Typically, the core material in these constructions plays the role of the principal structural element. In the noted stringer construction, a thin monolithic shell is provided with stiffening elements, primarily to improve buckling resistance. This principle can be found in the pressure bulkhead of the Airbus A340. The A-shaped monolithic structure is largely responsible for the stiffening effect. Because of this design, it is possible to consider the construction of this core as purely an aid to production.

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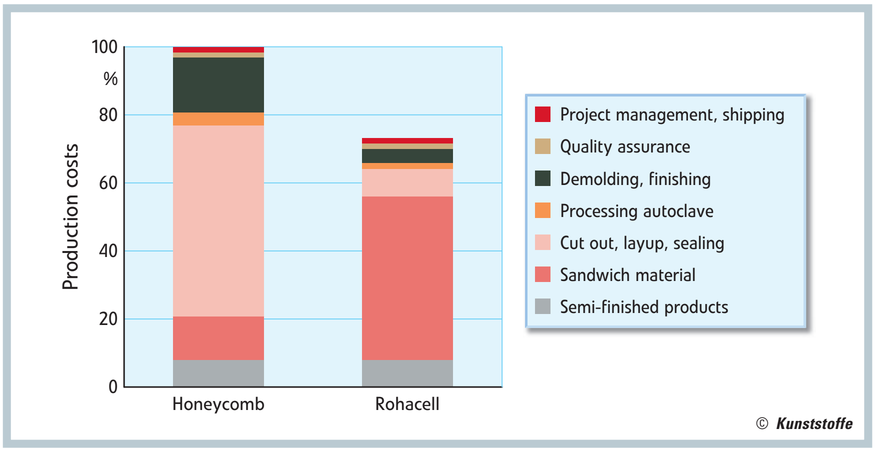


Fig. 1. Savings potential of foam-filled stringer construction versus honeycomb sandwich

Integral Design

In addition to optimized component weight, it is also important to keep the cost of raw materials, semi-finished material, the manufacturing process, and subsequent work in mind. In demand are system solutions that take these factors into account and simultaneously combine minimized weight with optimized stiffness and strength.

Different materials come into consideration as the core material for sandwich construction. Most frequently, honeycomb structures and polymeric foams are used. Rarely are folded-honeycomb cores, metal foams, and natural materials (such as balsa wood) used. In view of the production costs, plastic foam cores prove the most attractive alternative. The reasons for this are especially process-driven: components with foam cores can often be made in one step (Co-Curing). This reduces the layup effort significantly and enables efficient production with maximum process reliability. In contrast, shells reinforced with honeycomb sandwich structures or monolithic structures usually have to create stiffening elements in one additional step and then be bonded through use of an adhesive. Inevitably, measuring inaccuracies are present; these must be corrected before joining the parts. The increased production costs of this so-called differential design compared to the integral design significantly outweigh the possible savings from lower-cost semi-finished material. Moreover, by using honeycomb cores, filling opened honeycomb cells at the edges and in the drilling areas using so-called potting materials is necessary. This increases both the manufacturing cost and component weight. **Figure 1** shows the potential savings in a typical foam-filled, integrally manufactured aeronautical component with stringer construction compared to a conventional sandwich construction with a honeycomb core. The costs of various items relative to the total production →

Construction concept	Layout	Rigidity	Weight	Layup costs	Assembly costs
Full sandwich		++	+	++	++
Skin sandwich		+	++	+	o
Stringer stiffening		+	+	o	+

Legend: Rohacell Face sheet, e.g. CFRP ++ = very good; + = good; o = satisfactory

Table 1. Overview of sandwich construction

costs are shown. The material costs of a foam-filled sandwich construction are significantly higher, but may be more than compensated through substantial savings in labor during sandwich structure preparation and reduction of subsequent work.

Furthermore, excellent surface qualities can be realized through the use of rigid foam cores, since the core has no inhomogeneous structure which can pull on the component surface (the so-called telegraphing effect of honeycombs). If the foam, such as the polymethacrylimide (PMI) foam discussed here (manufacturer: Evonik, grade: Rohacell), further exhibits excellent mechanical properties and thermal stability then economics and low component weight are combined in an optimal manner. **Table 2** provides an overview of the typical material properties of the foam.

It should be further noted that the cycle time can be reduced by increased curing temperatures in many cases. In turn, higher production rates are achievable, which then often compensate for the higher cost of the semi-finished core material with better process reliability.

Property		Rohacell 51 RIST	Rohacell 71 RIST	Rohacell 110 RIST
Density	[kg/m³]	52	75	110
Compression strength	[MPa]	0.8	1.7	3.6
Tensile strength	[MPa]	1.6	2.2	3.7
Shear strength	[MPa]	0.8	1.3	2.4
Elastic modulus	[MPa]	75	105	180
Shear modulus	[MPa]	24	42	70
Elongation at break	[%]	3.0	3.0	3.0
Heat deflection temperature	[°C]	205	200	200

Table 2. Typical material properties at the nominal density for the example of PMI grade Rohacell RIST

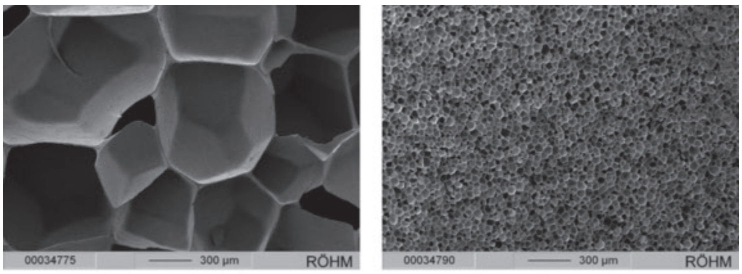
The Right Foam Core Material

In addition to the above properties, additional characteristics are important when it comes to achieving the best possible part quality. These include, among others, the creep resistance against pressures and temperatures encountered in the hardening process, pore structure, and cell size. With these characteristics, it is particularly important to adapt the foam used to the current process conditions and the type of sandwich construction.

From process pressure, curing temperature, process duration and acceptable creep value, it is possible to derive the best core type and density for the process. Generally, with higher foam quality, lower densities are needed in order to withstand the process conditions. With respect to the pore structure, the highest possible percentage of closed cells provides an advantage: the face sheet resin penetrates only open cells on the surface when cutting and shaping the core. This creates a reliable connection between the core and skin layers without resin penetrating to the depth of the core, ultimately reducing excess component weight. All Rohacell foams have a 100 % closed cell structure **(Fig. 2)**. In addition, the product exhibits a homogeneous and isotropic structure, which is also an advantage for most applications.

The ideal choice of cell size depends on the viscosity of the resin system used and the requirements placed on the component. Thus, in prepreg processing, where the resin system often displays a high viscosity, a relatively coarse cell structure is normally required. This facilitates the penetration of resin into the outer surface pores and allows a form-fitting and integral connection between the foam and fiber composite. If an infusion process is used, in which the viscosity of the matrix is usually much lower, a smaller cell size is sufficient for reliable filling of the cells cut at the foam's surface.

In this case, by choosing a properly matched foam type, the amount of resin retained at the surface, and thus the component weight, can be reduced. **Figure 3**



Rohacell 71 WF   Rohacell 71 RIMA

Fig. 2. REM images of cell structures in Rohacell WF and RIMA PMI foam

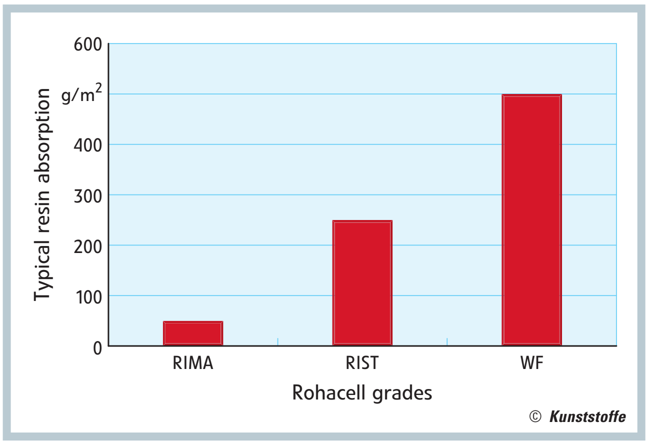


Fig. 3. Comparison of typical resin absorption by surface for various Rohacell grades as a function of cell size

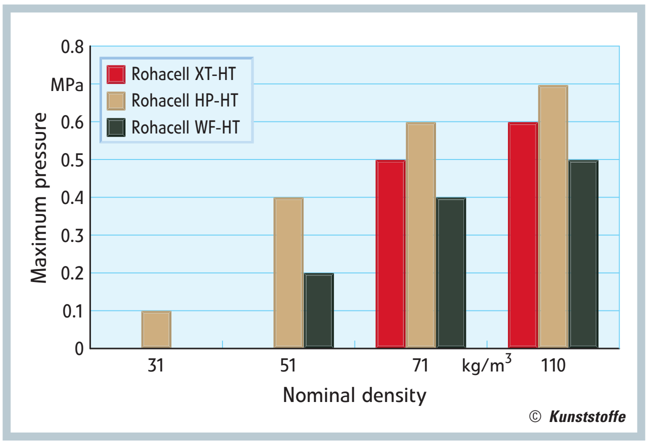


Fig. 4. Process pressures withstood by Rohacell HP compared to other Rohacell grades (after hot-temperature treatment) at 180 °C over a time span of two hours

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shows the typical resin absorption of various PMI foams (grade: Rohacell) as a function of cell size.

Another point that should be considered when selecting the core material is the compatibility with the resin system used. Many foams are chemically incompatible with certain resins, which can lead to the collapse or disintegration of the foam during the process. Due to its chemical structure, the PMI foam can be combined with all of the usual matrix systems, e.g. with hot- and cold-curing epoxy resins, unsaturated polyester resins, and vinyl ester resins. It is also available in high-heat formulations that allow the use of a thermoplastic matrix.

Foam Core as a Production Tool

In some cases, the foam core is used only as a production tool for easy and inexpensive production of the desired sandwich structure in one shot and remains in the component after the curing of the layers. This example is derived from the widespread stringer construction found in the aircraft industry and in various applications in the range of sports equipment. The **Title picture** shows an example of the cross-section of the stringer geometry.

The use of a lost core is often inevitable, because the usual methods for producing a hollow fiber composite body, such as the film bubble process or the subsequent removal of a reusable core from the component structure, are not always presentable as a good idea for economic and/or technical reasons.

If the foam is seen only as a lost core and its contribution to the mechanical component properties is neglected, it is important that the core be able to bear process loads while possibly leading to a small increase in component weight. Evonik has designed the new PMI Rohacell HP foam specifically to meet this requirement profile. Even at a nominal density of 31 kg/m³, it is able to withstand a pressure of 0.1 MPa (1 bar) at a temperature of 180 °C. At lower curing temperatures, an appropriate increase in process pressure is possible. It also has a very fine cell structure, which reduces the amount of resin absorbed on the surface to a minimum. **Figure 4** compares the pressures that can be withstood by Rohacell HP at 180 °C and at different nominal densities with Rohacell grades.

Because of these properties, the final weight of a sandwich construction when using the new type of foam as a lost core is often marginally increased when compared to a hollow structure. However, the efficiency increases significantly thanks to an improved manufacturing process, even if the pure semi-produced material costs initially increase **(see Figure 1).** ■

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