COST-OPTIMAL DESIGN AND AUTOMATED PRODUCTION OF SANDWICH STRUCTURES FOR WIND TURBINE ROTOR BLADES

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ABSTRACT

The publicly funded research project BladeMaker aims at industrializing the production of wind turbine rotor blades to achieve a reproducible high quality and cost reductions. Along with other processes it addresses the automated production of sandwich structures through an in-situ foaming process of the core. For the skins, two alternative processes are presented: two-sided infusion of dry non-crimp fabrics and automated tape laying of prepreg tapes.

Manual lay-up of pre-manufactured PVC foam kits is replaced by an automated application of liquid, in-situ expanding polyurethane (PU) foam directly into the mold. The benefits are considerably lower material costs, easier material transportation and the reduction of scrap. This innovative process also brings new challenges in terms of material performance and structural design, since the density-specific material properties of PUs are in general lower than of the typically used PVC-foams. Material properties of PUs depend on the selection of the specific PU system as well as on foaming parameters and especially on the density.

A parameter study for a representative sandwich element has been carried out to make a trade-off between structural performance, weight and costs. Assuming that global buckling of the sandwich plate and skin wrinkling of the sandwich skins are the two dimensioning failure modes, the critical loads were calculated for different core thicknesses and PU densities. The main requirement was to achieve at least the same critical load with a PU-sandwich as with the PVC-sandwich. Finally, the material costs and the structural mass were evaluated to determine the cheapest and the lightest configuration. The contribution of additional flow meshes and resin uptake of the core material was taken into account. Results for the representative sandwich element show that the mass difference is small and that PU sandwich structures allow for significant cost reductions.

1 INTRODUCTION

Wind turbine rotor blades consist area wise mainly of lightweight sandwich structures made of glass- or carbon-fiber reinforced polymer (FRP) laminates and account for approximately 20% of the total cost of an onshore wind turbine. A reduction in the total cost can be initiated by improving the blade design, use of better suitable composite materials and more efficient manufacturing processes. Currently the rotor blade production is still dominated by manual labor, which leads to high tolerances, requiring high safety factors and a less-than-optimal blade design and which reaches its limits with current and upcoming blade dimensions. The size of wind turbines is expected to increase up to 10 MW with rotor diameters up to 180 m within the near future, as the total production cost per kilowatt-hour of electricity decreases with increasing wind turbine size. Automated manufacturing will not only ease the production of large wind turbine blades, it also promises significant improvements leading to higher reliability, higher blade value and ultimately lower cost-of-energy for the entire turbine.
The BladeMaker research project aims at reducing the total blade costs by 10% through industrializing blade manufacturing processes in a consortium of material suppliers, rotor blade and process experts and automation technology suppliers.
The present study introduces an innovative core processing method (in situ foaming), two alternative approaches for manufacturing the sandwich skins along with the intended machine integration. A parametric sandwich design study was carried out to assess the new sandwich manufacturing concept in terms structural performance, weight and cost.

2 STATE OF THE ART: MATERIALS AND PRODUCTION PROCESSES FOR SANDWICH STURCTURES IN WIND TURBINE BLADES

A wind turbine blade consists typically of two bonded shells with integrated spar caps, which are connected by one or more longitudinal shear webs (figure 1). The blade shells and shear webs are sandwich structures due to the high bending stiffness to weight ratio required.

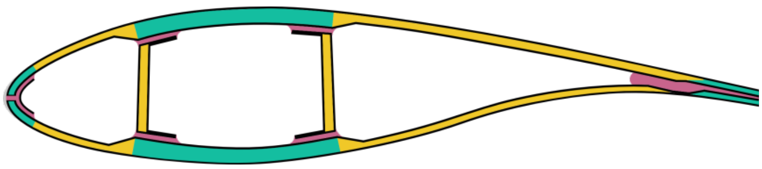

Figure 1: Typical rotor blade topology consisting of spar caps (green), sandwich skins (black), core materials (yellow) and adhesives (red)

For the sandwich skins as well as for the spar caps, different manufacturing technologies are typically used today [1]. The most common technology for the skin laminates is manual lay-up of dry non-crimp fabrics (NCFs) with subsequent vacuum-assisted resin infusion and open mold curing [1, 2]. Hand lamination with manual resin impregnation of the dry NCFs is also still in use [1]. Automated laminate production technologies are mainly applied for the spar caps or for different structural blade concepts.
The primary function of the core is to provide resistance against buckling under compression and shear forces without adding too much mass. Well-established core materials in wind turbine blades are polyvinyl chloride (PVC) and styrene acrylonitrile (SAN) foams selected for their low density (60-80 kg/m³) as well as medium-density end-grain balsa wood (150 kg/m³). PET foams have a lower material cost and are also used in blades, but compared to PVC they have a lower specific shear modulus and they can exhibit a higher resin uptake [3]. Generally, balsa and most polymeric foams come in the form of pre-manufactured core kits which are placed manually in the mold. The kits have a pattern of slits and holes allowing draping into curved molds and serving as infusion channels. This pattern is custom made for the blade manufacturers. During the vacuum infusion process the resin can flow through the infusion channels connecting the top and bottom laminate surfaces.
For the BladeMaker project, a 40 m long reference rotor blade was developed for a 1.5 MW wind turbine, representing the current state of the art in a turbine class that is produced in large series world-

wide. The choice of the core materials is driven by the need to minimize the manufacturing cost and to fulfill the structural requirements in the different parts of the blade. Figure 2 shows the core material distribution within the reference blade. Balsa wood is used in the shell panels near the blade root and at the lifting position at 2/3 of the blade length especially due to its very high out-of-plane shear modulus and out-of-plane Young's modulus. Two different PVC core kits (Airex C70.55 and Airex C70.75 [4]) are used due to their low density. In total, 65% of the total core weight and 75% of the total core costs can be attributed to the PVC core kits.

Figure 2: Core material distribution in the 40 m long BladeMaker reference blade: balsa wood (brown), PVC foam Airex C70.75 (dark yellow) and Airex C70.55 (light yellow)

3 THE AUTOMATED APPROACH

3.1 In situ foaming

The new in situ foaming process allows an automated in-mold application of liquid polyurethane with a multi-axial CNC-controlled gantry system. Rigid foam is formed by the reaction of liquid polyol and isocyanate components. This production method provides a high degree of freedom in terms of the material and geometrical design parameters, which may lead to alternative blade designs. The core thickness can be tapered continuously and the foam density can be changed by modification of the PU formulation.

Compared to the conventional production method with foam core kits, not only the material costs decrease. The in-mold application of liquid PU eliminates all core kitting costs in the value chain and the amount of material scrap will be reduced through the precise production method. Due to the small volume of the two liquid PU components, transportation and storage costs can be significantly reduced in comparison to standard foam kits. Furthermore due to the lack of slits and holes within the foam, the total amount of resin uptake can be reduced, leading to blade cost and weight reduction.

On the other hand, the absence of slits and holes requires a detailed look into the production of the sandwich skin laminates because conventional infusion strategies may come to their limits. Since the envisioned layer-wise application of PU is expected to influence mechanical foam and sandwich properties, final material properties will be thoroughly investigated within the project.

3.2 Adaption of the blade design to the properties of PU foam

Generally rigid polyurethane foams are widely used as thermal and acoustic insulation within the automotive industries, buildings and white goods, such as refrigerators. Due to its relatively low material cost and flexible manufacturability, PU foam can be an economic choice. Density-specific stiffness and strength properties are typical quantities to evaluate the suitability of a material for lightweight structures. Table 1 gives an overview of density-specific properties for PU, PVC and balsa wood. The values of the two PUs for tension and compression are approximately in the range of the two PVC foams. Balsa wood outperforms both polymeric foams in all six categories.

The BladeMaker approach is to adapt the structural blade design of the sandwich panels to the properties of PU foam and to influence the absolute mechanical properties of PU through its density. Since the mass of the core materials has a small share of the total sandwich mass, the additional weight due to an increased foam density is limited and lower resin uptake due to absence of slits and holes is expected to beneficially contribute to the overall sandwich mass compared to a conventional foam kit. The good thermal stability of PU offers the possibility to higher infusion and curing temperatures of the skin laminates and can therefore contribute to a faster overall process.

Due to the very high mechanical properties of balsa, the PU foam will be considered as a core replacement only for the PVC cores in the first step. Missing and assumed properties in Table 1 will be thoroughly measured within the project.

Table 1: Representative density specific out of plane modulus and strength values of PVC foams [4], PU foams and balsa wood [5]

Quantity	Symbol	Units	PVC C70.55	PVC C70.75	PU	PU	Balsa SB.100
Density	ρ	[kg/m³]	60	80	150	500	153
Tensile Young's modulus	E_3^+/ρ	[MPa/(kg/m³)]	0.750*	0.825*	0.470*	1.232*	23.333
Compressive Young's modulus	E_3^-/ρ	[MPa/(kg/m³)]	1.150	1.300	0.381*	0.885*	26.176
Shear modulus	G_{13}/ρ	[MPa/(kg/m³)]	0.367	0.375	0.242	0.462**	1.046
Tensile strength	R_3^+/ρ	[MPa/(kg/m³)]	0.022*	0.025*	0.012*	0.024*	0.086
Compressive strength	R_3^-/ρ	[MPa/(kg/m³)]	0.015	0.018	0.014*	0.040*	0.084
Shear strength	R_{13}/ρ	[MPa/(kg/m³)]	0.014	0.015	0.009	- ***	0.020

*Isotropy assumed, **Assumed relation according to [6]: $G_{13}/\rho = 3/8 \cdot E_3^+/\rho$,
***Value will be determined within the project.

3.3 Infusion

The in situ PU foaming will produce a closed-cell, rigid foam. In contrast to conventional PVC core kits, there will be no slits or holes within the PU foam through which the resin could flow from one laminate side to the other during a conventional vacuum infusion process. This difficulty can be approached through a new infusion concept or through the replacement of dry NCFs with prepregs.

A twofold infusion concept was developed, involving a conventional infusion of the inner sandwich skin and a parallel infusion through infusion channels in the mold surface for the outer skin under one vacuum bag. In order to enhance the resin flow a flow medium is required. The conventional flow mesh cannot be used due to the high surface quality required for the blade shells. Hence, an alternative flow medium is needed, which will allow the infusion process for the outer fiber layers, while not affecting the surface quality or the mechanical performance of the blade structure (see Chapter 4).

3.4 Prepregging and automated tape laying

Within the BladeMaker project an innovative process combination of in-house prepregging and automated tape laying (ATL) is being developed with application especially for the thick unidirectional laminates of the main spar caps. This process can also be used to lay-up the skin laminates of the sandwich panels.

In order to manufacture unidirectional prepreg tapes, a small prepregging unit for in-house application is currently being developed. This approach allows producing prepreg tapes on demand without the need of a cooled storage. Prepregging on demand also avoids scrap, since the prepreg shelf life is not relevant anymore. Prepreg tapes will be made of glass-fiber rovings that allow material cost savings for the fibers of about 50% compared to NCFs. The use of rovings also allows the production of non-rectangular tapes without any significant amount of scrap fibers. An epoxy resin from Hexion is used which allows wide-range viscosity adjustments through control of resin temperature.

Automated contour tape laying will be used to place the prepreg tapes on the mold surface. A flexible compaction unit will press the tape on the mold or on previously placed tapes, respectively while a heating system will change the tack of the prepreg to the required level. After lay-up, the prepregs will be cured under a vacuum bag at 120°C which allows a significant reduction of the curing time in comparison to typical infusion resins that are cured at 70 to 80°C.

3.5 Intended process integration

The intended automated production of sandwich panels for rotor blades will be evaluated on a 1:1-scale with an industrial approach. Additional to material costs, drivers for the total sandwich costs are manual labor costs and mold occupation times. The industrialization of the processes will decrease both significantly.

The required PU mixing and application machine is currently being built and will be integrated into the BladeMaker Demo Center (figure 3). The mixing machine can switch between different polyol components to vary the material properties. The application head will be carried by an innovative, CNC controlled gantry system to apply the PU foam directly into the mold.
The molds will be milled with the same gantry system in a direct process without the need of a master-plug. In the same step, infusion channels will be integrated to test the presented infusion concept. Conductive carbon fibers will be used as the mold heating system which allows shorter heating cycles and a good control of the curing temperature.
The flexible gantry system allows integrating different processes in the same production environment and serves as a universal platform for the evaluation of industrial blade production. The system will have a high working speed of up to 2.5 m/s and a high accuracy in combination with the large working space which is required for blade production. Additionally, advanced offline-programming tools for the different processes will be developed. The optimal application of the PU materials as well as the cost-effective production of the sandwich skins will be researched by simulation and real testing.

Figure 3: BladeMaker Demo Center for the industrialized production of rotor blades equipped with a flexible CNC-controlled gantry system, blade molds, mixing units etc.

4 INFUSION TESTS

When the core material is foamed in the mold, there are no slits or holes in the core which allow the resin to flow through the thickness during the infusion. Therefore, the production of the skins has to be approached in a different way.

4.1 Concept

An infusion concept was developed that allows the impregnation of the outer and the inner sandwich skins with separated infusion channels. The inner skins are impregnated with conventional infusion spirals and flow meshes. The outer skins are impregnated through infusion channels that are integrated into the mold. Multiple infusion channels will be opened one after another to decrease the flow distance (cascade infusion). An additional flow medium is placed directly on the mold. To retain a good surface quality, this flow medium will stay in the laminate.

4.2 Experimental investigation

A flat CFRP test mold with Fibretemp® heating system and two infusion channels was built (figures 4 and 5). In this case the maximum flow distance of 800 mm is given by the distance between the channels.

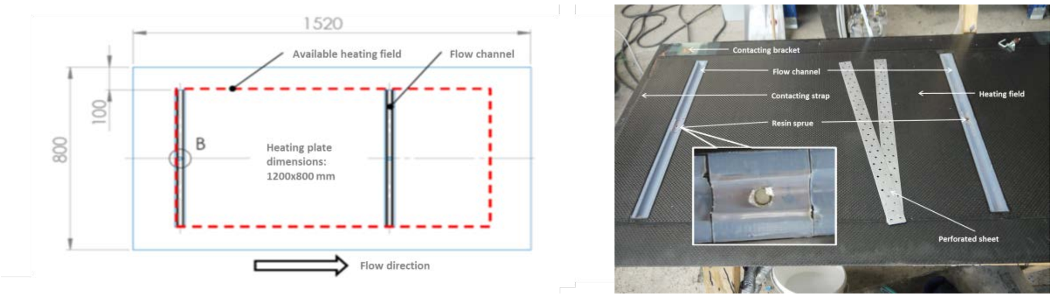

Figure 4 and 5: Dimensions and layout of the infusion test stand

Infusion tests with different flow media are being performed to quantify the infusion time and the achievable flow distance. Figure 6 shows a schematic sketch of the experimental set-up. The laminate lay-up for the outer skin (flow medium plus three plies of tri-axial glass fiber non-crimp fabrics) was derived from the maximum laminate thickness under the PVC foam within the BladeMaker reference blade.

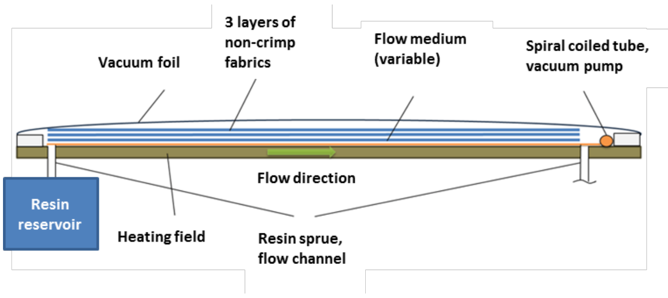

Figure 6: Experimental set up of the infusion tests

Generally, the infusion process can be influenced by a number of different parameters such as: type of fiber material, type of resin system, processing temperature and type of flow medium. The heating table enables infusion at a higher temperature, which first reduces the resin viscosity, but also lowers the resin pot life. The resin system Epikote MGS RIMR 035c with different hardeners from Hexion is used. During the infusion tests the resin flow front is marked continuously (figure 7) in order to determine the time profile of the flow speed and to derive the permeability of the tested textiles. Different textiles made of different materials are currently being tested and evaluated in terms of their infusion speed, resin uptake, dead weight and costs.

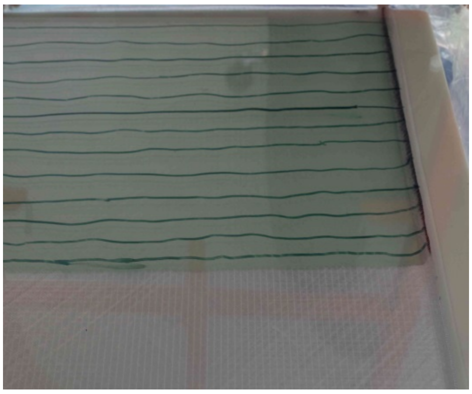

Figure 7: Continuously marked resin flow front in a vacuum infusion test

5 COST-OPTIMAL SANDWICH DESIGN

5.1 Analysis approach

In order to assess the feasibility and cost saving potentials of the proposed in situ PU processing method, a sandwich design tool was created and applied to a flat sandwich plate under uni-axial compressive loading. Global buckling and skin wrinkling are assumed to be the critical failure modes for typical sandwich panels in rotor blades. This is a simplified analytical approach to study the potential of the production concept. For a full assessment, further failure modes should be taken into account in combination with mechanical testing. As a representative reference for sandwich panels in rotor blade shells, a 20 m long and 1 m wide plate with a 20 mm thick PVC foam core (Airex C70.75) and glass fiber reinforced epoxy skins was chosen. Each skin consists of two plies of tri-axial (0°/±45°) non-crimp fabrics with a ply thickness of 0.86 mm. The 0°-layer is aligned in the loading direction.

The design tool allows varying the PU density, the core thickness and the number of plies in the skins. It then compares the critical loads of the competing designs to the reference element with the PVC core. If the minimum of the global buckling load and the skin wrinkling load is higher than the minimum load of the reference element, the PU sandwich element is called viable. The masses and material costs of all viable PU sandwich panels are then compared to the reference PVC panel to identify the most economic design. A parameter study was carried out with core thickness and core density as variables.

5.2 Theoretical background

Failure of a sandwich structure under compressive loading may be caused by failure of the skin laminates, failure of the core material, debonding of the skins and the core as well as buckling. Assuming that the occurring in-plane strains will not change significantly when changing the core material or the core thickness, buckling is taken as the dimensioning failure mode. For the current study, global buckling of the whole sandwich element according to the classic sandwich membrane theory and skin wrinkling according to the extended sandwich membrane theory are investigated (figures 8 and 9), both as described in [7]. As conservative boundary conditions along all sides, the panel is assumed to be simply supported.

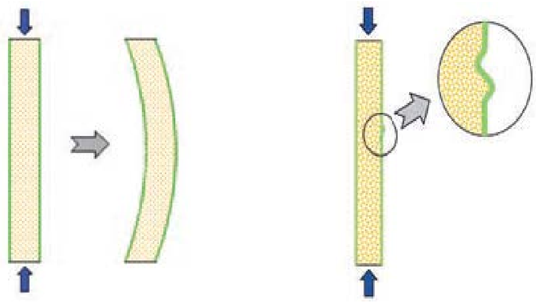

Figure 8 and 9: Global buckling and skin wrinkling of sandwich plates under compressive loading

The stiffness matrix of the skins is defined through the in-plane elastic constants of the skin laminates (Young's modulus E_x, shear modulus G_{xy}, Poisson's ratios ν_{xy} and ν_{yx}) where x is the loading direction:

$$Q_s = \begin{pmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{pmatrix} = \begin{pmatrix} \frac{E_x}{1-\nu_{xy}\nu_{yx}} & \frac{\nu_{yx}E_y}{1-\nu_{xy}\nu_{yx}} & 0 \\ \frac{\nu_{xy}E_x}{1-\nu_{xy}\nu_{yx}} & \frac{E_y}{1-\nu_{xy}\nu_{yx}} & 0 \\ 0 & 0 & G_{xy} \end{pmatrix} \quad (1)$$

The extensional stiffness matrix A and bending stiffness matrix D are sub-matrices of the ABD-matrix of the sandwich element, where t is the thickness of each skin and d is the distance between the skin mid-planes:

$$A = 2tQ_s \tag{2}$$

$$D = \frac{t}{2} d^2 Q_s \tag{3}$$

The stiffness contribution of the core is neglected here. The elements of the matrices A_{ij} and D_{ij} will be used to determine the critical buckling loads. Since the compliance of the core material lowers the critical buckling loads, the out-of-plane shear stiffnesses of the core are taken into account:

$$K_{c,xz} = dG_{c,xz} \tag{4}$$

$$K_{c,yz} = dG_{c,yz} \tag{5}$$

$G_{c,xz}$ and $G_{c,yz}$ are the shear moduli of the core. The critical global buckling load of an orthotropic sandwich plate is given by

$$F_{cr,gb} = \pi^2 k \frac{\sqrt{D_{11} D_{22}}}{b} \tag{6}$$

where b is the panel width. The buckling factor is defined as

$$k = \frac{\left(\alpha + \frac{1}{\alpha}\right)^2 + 2(\eta - 1)}{1 + \frac{\phi_x}{\alpha^2} + \phi_y + (\eta - 1) \frac{\sqrt{\phi_x \phi_y}}{\alpha}} \tag{7}$$

with the effective aspect ratio

$$\alpha_m = \frac{a}{mb} \sqrt[4]{\frac{D_{22}}{D_{11}}}, \tag{8}$$

the panel length a, the number of half sine waves m, the core numbers

$$\phi_x = \frac{\pi^2 \sqrt{D_{11} D_{22}}}{b^2 K_{c,xz}} \tag{9}$$

and

$$\phi_y = \frac{\pi^2 D_{22}}{b^2 K_{c,yz}} \tag{10}$$

and the coupling term:

$$\eta = \frac{D_{12} + 2D_{33}}{\sqrt{D_{11} D_{22}}}. \tag{11}$$

The global buckling load can be increased mainly through increasing the core thickness.

Skin wrinkling can be seen as local buckling of the skin, which is continuously elastically supported by the core material. The critical load which is carried by both skins in equal parts is defined by

$$F_{cr,sw} = b\sqrt{\frac{8E_{c,z}E_x t^3}{3\,d}} \tag{12}$$

where $E_{c,z}$ is the average of the tensile and the compressive Young's modulus of the core in thickness direction [7]. The critical load for skin wrinkling can be increased through thicker skins and a higher Young's modulus of the core in thickness direction. It shall be noted that an increase in core thickness leads to a decrease of the critical load, since a skin wrinkle of a certain height leads to lower out-of plane strains in the core, if the absolute core thickness is higher.
The core thickness can be arbitrarily chosen. For PU foam cores, the core stiffness can be indirectly influenced through the foam density. As a first approximation, a linear relation between density and mechanical performance is assumed over a wide density range between 150 and 300 kg/m³ neglecting any non-linearity. Please note: A careful material characterization taking into account the innovative process of core material application is part of the project. The model described in this paper will be continuously refined based on new findings.

5.3 Parameter study and results

A parameter study was performed to find the lightest and the most cost-effective sandwich configuration with a PU core that can replace the PVC core in the reference element. The core thickness was first varied in a range from 10 to 50 mm and the PU density was varied from 150 to 300 kg/m³. Based on the buckling and wrinkling performance of the PU sandwich designs compared to the PVC reference plate, the core thickness range was then refined between 18 mm and 22 mm for further analysis. As described by the formulas (3) to (12), a higher PU density (and therefore stiffness) increases the critical loads. A higher core thickness d only increases the global buckling load (figure 10) while it reduces the skin wrinkling load (figure 11).
For the reference PVC sandwich panel, the dimensioning failure mode is global buckling. The acceptance criterion for PU sandwich configurations is therefore, that both critical loads for global buckling and for skin wrinkling have to be at least as high as the global buckling load of the PVC reference panel. This design load is shown in figure 10 and 11 by the continuous horizontal line.

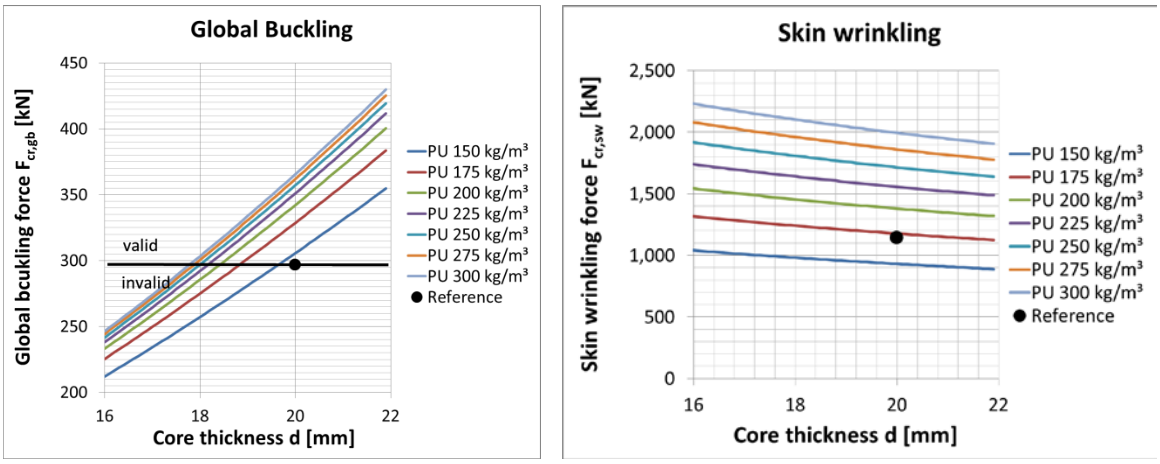

Figure 10 and 11: Global buckling and skin wrinkling loads of PU sandwich panels and the PVC reference. Global buckling is the dimensioning failure mode. Therefore PU panels with a lower buckling load than the reference are termed invalid. PU properties are interpolated based on the density.

In order to find the optimum PU sandwich configuration, all accepted PU sandwich designs are evaluated in terms of their mass (figure 12) and material cost per area (figure 13). Hereby, the mass and costs include core material, glass fibers (2 €/kg) and resin (4 €/kg). For the sandwich designs with PU foam core, the results and costs of an additional resin flow medium from the infusion tests (chapter 4) was incorporated (2.20 €/m²).
The results for the optimum configurations on the black lines show that the mass as well as the costs decrease with a lower core density, but increase with a lower core thickness. This was expected since global buckling is the dimensioning failure mode and the corresponding critical load shows an approximately quadratic dependence on core thickness d in formulas (6) and (3). The shear stiffening effect of an increased core density is much lower. Therefore, reducing the core thickness slightly requires a significant increase in density to reach the same global buckling load.
For the selected, representative sandwich panel, the configuration with the minimum used PU density of 150 kg/m³ and a core thickness of 19.7 mm was found to be the lightest and the most cost-efficient at the same time. As seen in figures 14 and 15, it is slightly lighter than the reference PVC panel, despite the higher core density of the PU. The higher PU mass can be compensated by the estimated lower resin intake due to the new infusion concept. The actual amount of resin intake has still to be verified by experimental tests. A big advantage of the PU sandwich panels are the much lower material costs (figure 15) mainly due to the reduced resin uptake and the lower material cost of PU compared to PVC kits (approximately 14 €/kg).

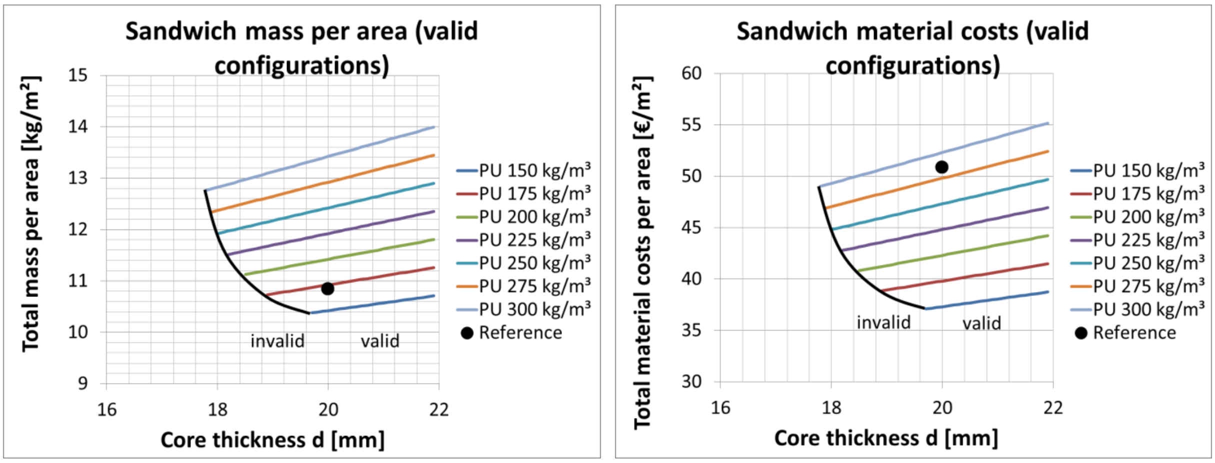

Figure 12 and 13: Total mass and material costs of 1 m² sandwich panel for the valid PU sandwich configurations and the PVC reference

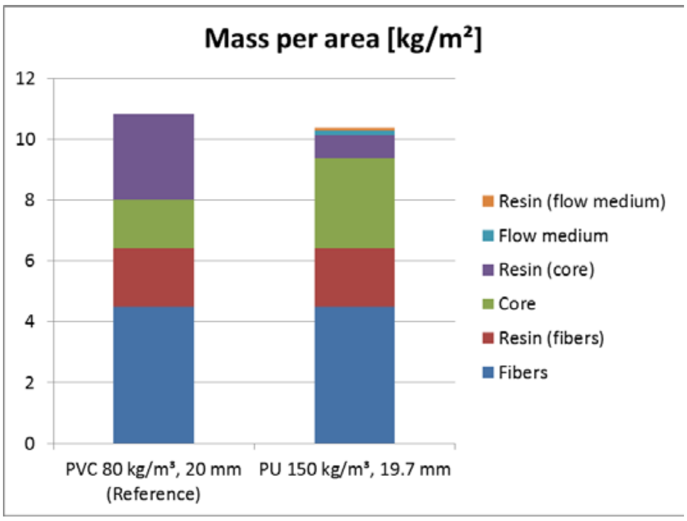

Figure 14: Material mass distributions of sandwich panels

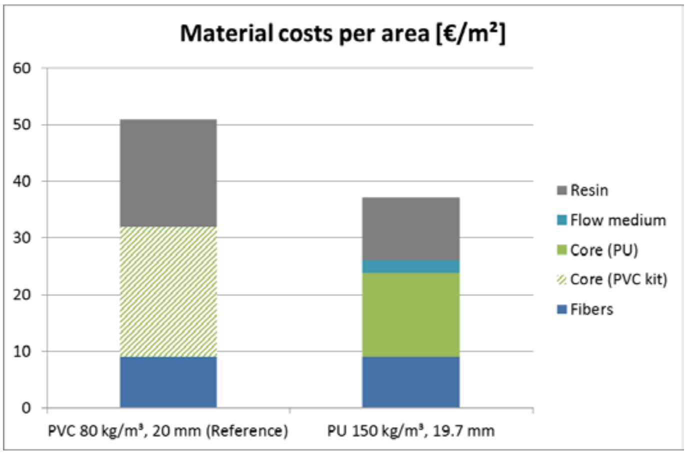

Figure 15: Material price distributions of sandwich panels

6 CONCLUSION

The proposed automated production processes and polyurethane foams have high economic potential in terms of reducing the total material costs for the production of sandwich panels for rotor blades without a weight penalty. In a parameter study, core thickness and core density for simplified planar, rectangular PU sandwich panels were varied. The first analytical results showed that an optimized PU sandwich design can at least partially compensate performance differences compared to the PVC reference. By-passing of necessary kitting steps in combination with the absence of slits and holes in the in-situ generated PU foam could contribute to cost savings of the new process in comparison to classical PVC foam kits. This is complemented by potential savings due to facilitated logistics and a high temperature stability of PU foams enabling faster curing cycles. For the different sandwich panel configurations the dimensioning failure mode is global buckling. Therefore, minimizing the core density to the lowest acceptable value gave the best results in comparison to the decrease of the core thickness (with a significant increase in core density).

In order to cope with the fact that a closed PU foam core will block resin flow through the thickness, an innovative concept for the infusion of non-crimp fabrics under a closed sandwich core was proposed and investigated experimentally. Different flow media were tested to spread the resin from the mold-integrated infusion channels. The flow distance of 800 mm was achieved within the pot life of the resin. The application of additional flow media will affect the resin uptake of the laminate, hence its mechanical properties, and the overall material cost.

Prepregging on demand and automated tape laying are being developed for the production of thick laminates like the rotor blade spar caps, but could also be applied for sandwich skins. The different epoxy system allows faster curing and therefore shorter mold occupation times.

“In-situ foaming” and “automated tape laying” are two of the production processes which will be demonstrated in the BladeMaker Demo Center on a 1:1 scale. The mixing machines as well as the end-effectors are being integrated into a lightweight, CNC-controlled gantry system offering high-speed and high-accuracy production. Directly milled molds with integrated infusion channels offer advanced infusion strategies for sandwich panels with closed foam cores.

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