Nonwoven-Based Composite Sheets with Constant Areal Weight as Fuselage Skin Material for Light-Aircraft Applications

M. Nuño[1], M. Krause[1], P. Abel[2], K.-U. Schröder[1]

[1] Institute of Structural Mechanics and Lightweight Design (SLA), RWTH Aachen University, Germany

[2] Institut für Textiltechik Augsburg gGmbH, Germany

Abstract

This study investigates the properties of nonwoven fabrics as well as their application as secondary structures in aircraft applications. For this, the mechanical properties, manufacturing process and suitability for use as aircraft skin material are discussed. First, the manufacturing of the hybrid nonwoven-based composite sheets by ITA Augsburg is described. Later, experimental tests with constant-areal-weight nonwoven composite sheets with different degree of consolidation and thicknesses are performed. The test results are then used to evaluate the suitability of using nonwoven-based sheets as skin-material for truss structures.

Keywords

Nonwoven-based composites, Composite Structures, Composite Recycling

1 INTRODUCTION

Nonwoven fabrics are generally the most cost-efficient textiles to produce and also one of the most versatile textiles with regard to their structure, thickness, aerial weight and the degree of fibre orientation. For the use of secondary carbon fibres – be it production waste or recycled carbon fibre from prepreg waste or end-of-life composites – nonwovens offer the only possibility to produce a 2D-textile in a one step process, skipping the costly process steps of spinning and weaving.

Hybrid nonwovens made of recycled carbon fibres and thermoplastic polymer fibres can be easily processed to thermoplastic carbon fibre reinforced composites through simple hot-pressing processes, in which the nonwoven is heated above the polymers melting temperature and then cooled under pressure. Hereby, the polymer fibres form the thermoplastic matrix of the composite.

With a local variation of the consolidation pressure it is possible to locally tailor the material properties: high local pressure results in thin blanks with low thickness and a relatively high tensile modulus. Lower pressure leads to a higher thickness and correspondingly a lower density, also resulting in a lower tensile modulus. However, regarding the bending stiffness, this loss in modulus is overcompensated by the gain in thickness, making partially consolidated web based composites especially suitable for those applications, where a high bending or buckling stiffness is required, while mechanical loads are generally low and weight saving and cost efficiency goals shall be met at the same time.

In this study, the previously described effect is investigated to gain a quantitative insight into the mechanical properties of these fabrics. The production process of such sheets as well as a the application potential as skin for truss structures is discussed.

2 WEB-BASED COMPOSITES AND PRODUCTION OF NONWOVENS

Web-based composites – a type of composites made of either a thermoset or thermoplastic matrix polymer and a nonwoven-based reinforcement

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textile – are gaining importance in many cost-sensitive applications such as the automotive industry. A main driver for their application is the use of recycled carbon fibres for the nonwoven production and the resulting low price. Different nonwoven production routes can deal with fibre lengths from approx. 5 mm up to more than 100 mm. Typical fibre lengths of production cut-off from the composite industry between 40 mm and 80 mm are well suited for the production of carded nonwoven.

Web-based composites offer a large versatility as to the thickness, the degree of (3D)-fibre orientation and to the types of fibres combined within a single textile. Unlike in short fibre compounds for injection molding, the fibre length of the secondary carbon fibres is largely preserved in nonwovens, giving them a significantly higher reinforcement potential.

2.1 Production of Hybrid Nonwovens for Thermoplastic Composites

While 100 % carbon fibre nonwovens can be produced and find their applications as reinforcement textiles in thermoset routes like the resin transfer molding process, hybrid nonwovens made of reinforcing carbon fibres and thermoplastic fibres offer significant economic and technical advantages in many cases.

For the production of the hybrid nonwovens used in the present study, the carding line shown in Fig. 1 has been used. Recycled carbon fibres and thermoplastic fibres (polypropylene or polyamide 6) are premixed and fed into the bale opener (1). After passing the opening line (2) where the mixture is homogenized, a thin veil is formed in the carding machine (3). In a cross lapper (4) several layers of veil are stacked in order to obtain the desired areal weight. The stack is then mechanically consolidated to a nonwoven textile in the needle loom (5) and finally wound up (6).

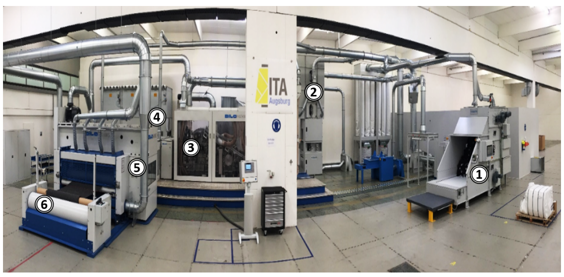


Figure 1: Carding line used for producing the tested composites. Numbered parts are explained in the text

Through a heating and pressing process, the thermoplastic fibres are first molten, then the nonwoven is compressed and cooled down under pressure with the solidifying polymer forming the matrix embedding the reinforcement fibres. For the production of samples used in the present study, a variothermal process has been applied. Both heating and cooling were performed in a double belt press with different temperature zones. The thickness of the consolidated composite sheet was defined by setting the adjustable gab between the upper and lower belt of the press to the desired value.

A fully consolidated reference sample for each fibre mixture has been produced by setting the gap between the belts lower than the calculated thickness of a fully consolidated plate of the given mixture and areal weight. In this case, the final thickness is defined by the maximum pressure of the press.

From that starting point, sample sheets of different consolidation grades have been produced. The consolidation grade is defined as the ratio between the thickness of the fully consolidated sheet and the measured thickness of the partially consolidated sheet of the same areal weight.

2.2 Thermoplasic Nonwoven-Based-Composites with Locally Adjusted Consolidation Degrees

Through different degrees of consolidation, materials with different thickness, density and mechanical properties can be produced from the same hybrid nonwoven with constant areal weight. Mechanical properties of the obtained material vary largely depending on the degree of consolidation. A lower consolidation grade implies lower strength and modulus due to the higher content of voids and the consequently poorer embedding of the fibres. On the other hand, the higher resulting thickness increases the weight-specific bending stiffness due to the greater area moment of inertia.

It is therefore possible to locally tailor the desired properties to the expected loads, by simply varying the grade of compression during the pressing process. In Fig. 2 the unconsolidated hybrid nonwoven as well as the three consolidation concepts (partial consolidation, full consolidation and locally adjusted consolidation) are shown.

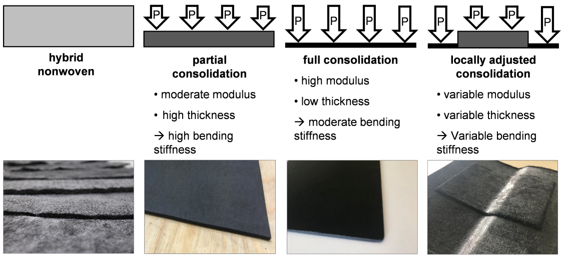


Figure 2: Schematic cross section, properties and photos of the different consolidation concepts for hybrid nonwovens.

Much like in sandwich structures the higher bending stiffness of partially consolidated web based composites is gained from an increase in the structure's thickness. However, panels are of a homogenous, mono-component kind, eliminating any de-bonding issues. Production and shaping of areas with local reinforcements, locally adjusted thickness or scarfed transitions is largely facilitated.

3 MECHANICAL CHARACTERIZATION

To characterize the main mechanical properties of the consolidated nonwoven-based plates, in-plane tensile and 3-point bending tests are performed. All specimens are tested under quasi-static conditions using a universal electric testing machine INSTRON 5567, which logs both the applied force and deformation of the specimens.

3.1 Specimens

For the research presented in this paper, five different plates made of rCFRP (recycled carbon fiber reinforced polymers) with a polypropylene (PP) and polyamide (PA 6) matrix are produced. Their characteristics are listed in Table 1.

Table 1: Main characteristics of the tested nonwoven-based composite plates

Plate	Matrix material	Thickness [mm]	Areal weight [kg/m^2]
1	PA	3.2 ± 0.1	1.54
2	PP	4.4 ± 0.1	1.78
3	PP	2.5 ± 0.2	1.77
4	PA	4.0 ± 0.2	1.56
5	PA	2.3 ± 0.1	1.66

To cut the specimens a circular table saw is used. Specimens are taken from a distance of at least 5 cm from the production edges to guarantee more homogeneous material properties. For each test, at least five specimens are used. All specimens are cut in the production direction of the plate, marked in Fig. 3 as **1**.

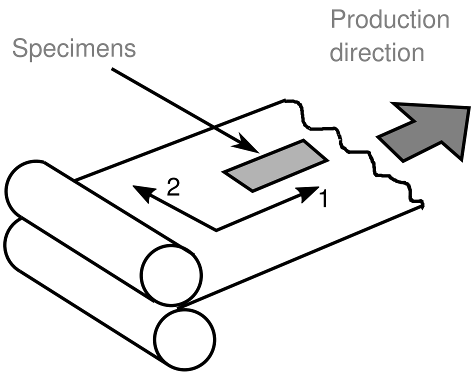


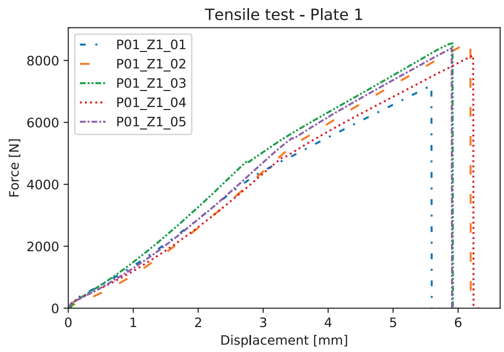
Figure 3: Coordinate system definition

3.2 Tensile Tests

The tensile tests are performed according to the standard ISO 527-4, with 50 mm wide and 250 mm long specimens clamped to the clamping jaws of the testing machine. The initial distance between the jaws is 150 mm and the testing speed is 2 mm/min. In Fig. 4 the test arrangement used for the tensile tests is shown.

Figure 4: Test arrangement for the tensile tests

The load-displacement curves obtained in the tensile tests are shown in Fig. 5. Bilinear characteristics can be observed in all five plates, with a higher gradient difference between the two linear zones at the plates with PA matrix. The breaking loads of the tested specimens are between 6 kN and 14 kN, and the elongation at break is between 4 mm and 8 mm. The inflexion point between the first and second linear zone is at displacements between 2 mm and 3.5 mm.



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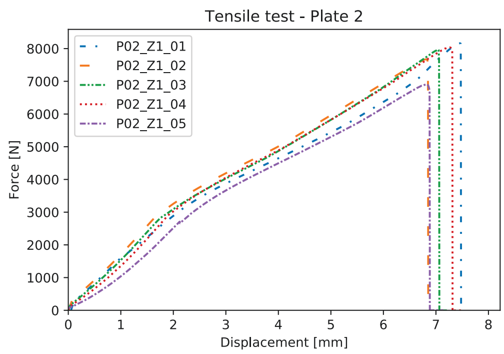

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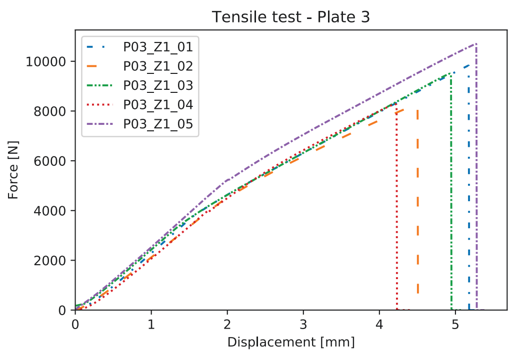

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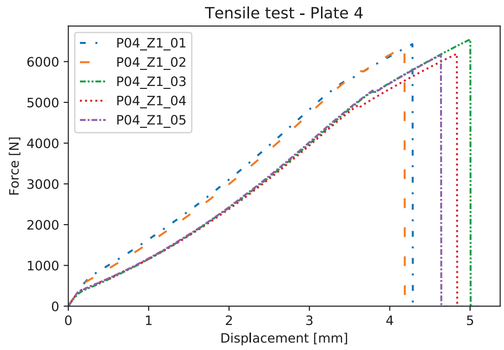
Figure 5: Load-displacement curves of the tensile tests



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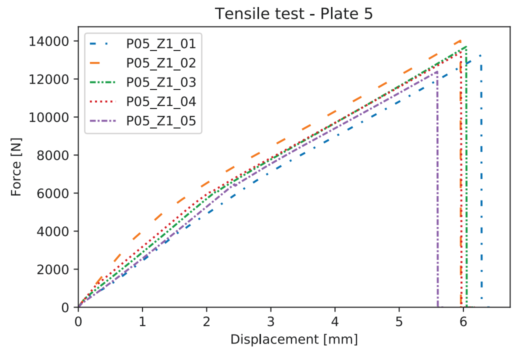


(e)

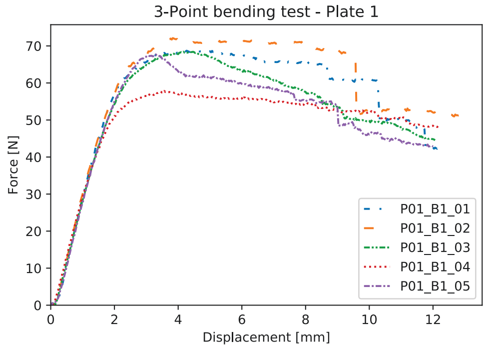
Figure 5: Load-displacement curves of the tensile tests

3.3 Bending Tests

The bending tests are performed according to the standard DIN EN ISO 14125, with 25 mm wide and 80 mm long specimens. The outer span of the supports is 64 mm and the testing speed is set to 2 mm/min. In Fig. 6 the test arrangement used for the bending tests is shown.

Figure 6: Test arrangement for the 3-point bending tests

The load-displacement curves obtained doing the bending tests are shown in Fig. 7. All curves show linear characteristics at the beginning, followed by degressive behaviour. After the maximum load is reached, a plateau with constant or slightly decreasing load follows. The extension of this plateau is smaller on the thinner plates (Plate 3 and 5). The maximum loads measured are between 50 N and 150 N at elongations between 2 mm and 8 mm. The linear range is not longer than 2.5 mm in any of the tested specimens.



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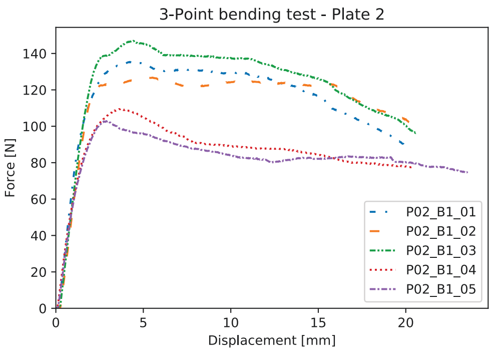

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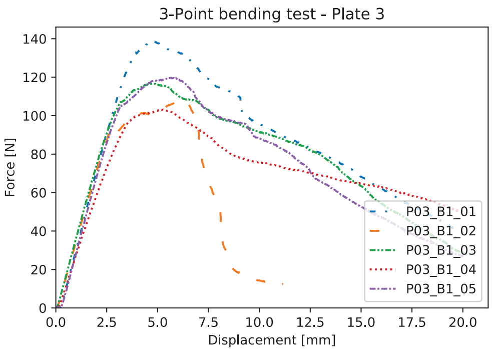

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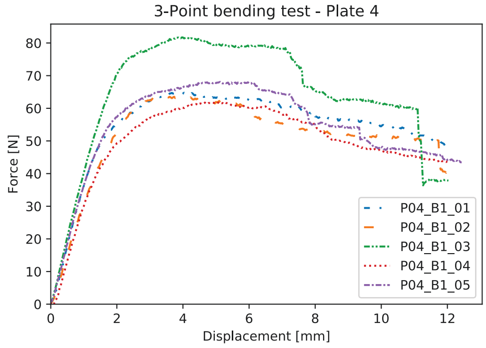
Figure 7: Load-displacement curves of the 3-point bending tests



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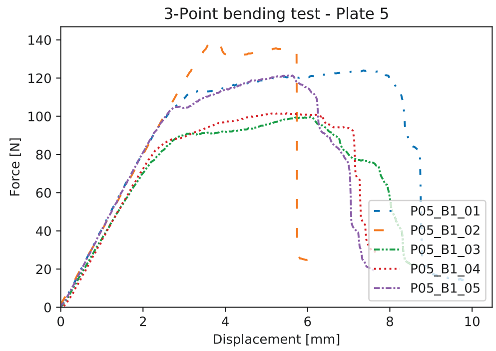

(e)

Figure 7: Load-displacement curves of the 3-point bending tests

3.4 Results and Discussion

Using the data measured in the tensile and bending tests several properties can be calculated. The ultimate normal stress σ and ultimate bending stress σ_b are calculated using Eq. (1) and Eq. (2). The used symbols are $A = bh$ for the sectional area, F_max for the maximal measured force, L the distance between the supports, b the width of the specimen and h the thickness.

$$\sigma_\mathrm{max} = \frac{F}{A} \tag{1}$$

$$\sigma_\mathrm{b,max} = \frac{3F_\mathrm{max}L}{2bh^2} \tag{2}$$

To calculate the axial stiffness EA and bending stiffness EI, Eq. (3) and (4) are used. For the axial stiffness u_1 and u_2 are chosen to be 0.5 mm and 2 mm, while the bending stiffness is calculated linearizing the curves between $u_1 = 0.3$ mm and $u_2 = 0.6$ mm.

$$EA = \frac{F(u_2) - F(u_1)}{u_2 - u_1} \cdot L \tag{3}$$

$$EI = \frac{L^3}{48} \cdot \frac{F(u_2) - F(u_1)}{u_2 - u_1} \tag{4}$$

The values calculated using these equations are presented in Fig. 8 to 11. Error bars delimit the 95% confidence interval assuming a normal distribution. In Fig. 8 and 9 the ultimate strength for tension and bending of the tested specimens is shown. The results correspond to the qualitative expectations. At higher consolidation degrees (smaller thicknesses) the strength increases. Thus, the tensile load a thin plate can carry is higher than the load carried by a thicker plate with the same aerial weight. This can be confirmed looking at Fig. 5, where the load-carrying capability is increased about 50%. The ultimate axial strength of the specimens with PP matrix is almost equal to their ultimate bending strength, while in the specimens with PA matrix larger differences are observed.

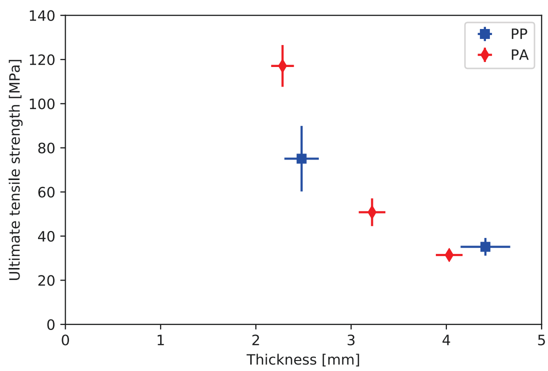

Figure 8: Ultimate strength of the tested specimens

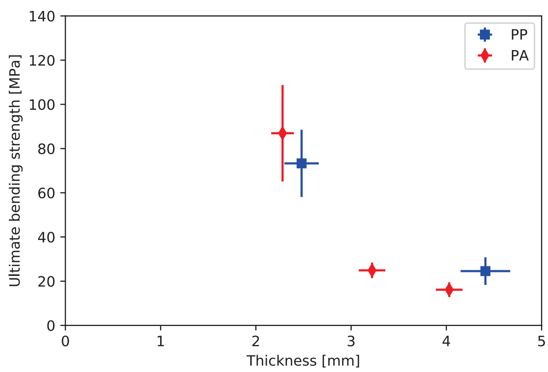

Figure 9: Bending strength of the tested specimens

The same qualitative trend can be observed in Fig. 10: thin plates have a higher axial stiffness than thicker plates with the same aerial weight. The axial stiffness of the tested thin plates is twice as large as the stiffness of the thick plates.

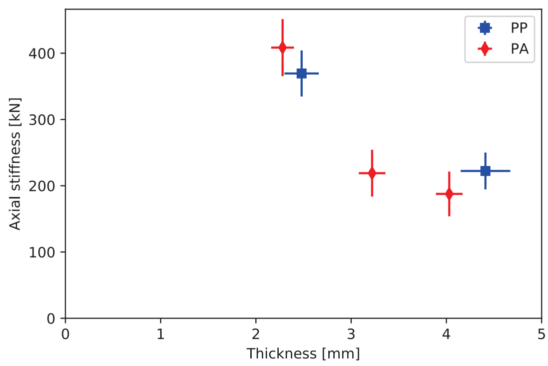

Figure 10: Axial stiffness of the tested specimens

On the contrary, thicker plates are expected to have a higher bending stiffness. This can be seen in Fig. 11, where the 4.4 mm thick PP specimen has a bending stiffness two times larger than the stiffness of the 2.5 mm thick PP specimen. However, on the PA specimens, no stiffness increase can be seen. For all thicknesses ranging between 2.3 mm and 4.0 mm, the bending stiffness is more or less constant. The reason for this behaviour is unknown to the authors and more tests with different consolidation degrees are needed. A possible reason could be that some process parameters during production, such as the temperature of the moulds or the pressing force, were too low.

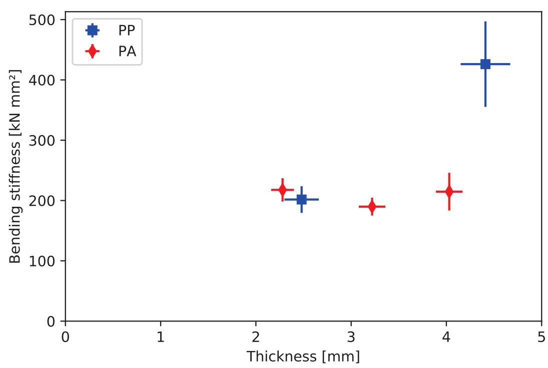

Figure 11: Bending stiffness of the tested specimens

4 APPLICATION IN TRUSS STRUCTURES

To analyse the potential of nonwoven-based composite sheets for applications where a high bending stiffness is required, an application scenario of an aircraft skin in the general aviation sector is chosen. The main structure of the aircraft is a truss structure carrying the main loads of the aircraft. For aerodynamic purposes an aerodynamic fairing is essential. At the nodes of the truss structure the aerodynamic fairing is fixed, see Figure 12.

Figure 12: Truss structure with aerodynamic fairing

4.1 Performance of nonwoven fabrics

It is assumed that between four nodes the aerodynamic fairing can be expressed as a simply supported plate with the plate length a equalling the node distance, see Figure 13.

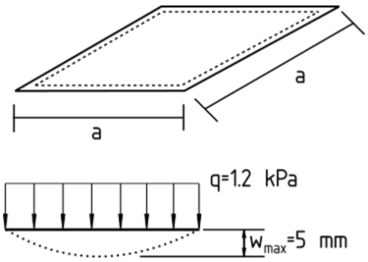

Figure 13: Structural model

The plate is loaded by a surface load of 1.2 kPa. This surface load corresponds to the mean dynamic pressure on a fuselage of a general aviation aircraft flying at 300km/h at FL100. Under this loading a maximum allowed deflection of 5 mm is defined. The node distance a is chosen to be 300mm.
The 66% consolidated fabric denoted with plate 3 is compared to different materials: Two plastics, one without reinforcements (ABS) and one reinforced with glass fiber (PA6GF30), and aluminium (Al 2024-T3). The material properties are given in Table 2. The required thickness of the plate for the above given conditions is calculated and the areal weight recorded. The calculation is done analytically using Timoshenko[1].

Table 2: Material properties

Material	E-Modulus [N/mm^2]	Density [g/cm^3]
66% PP fabric	5773	0.72
37% PP fabric	2170	0.40
ABS	2300	1.07
PA6GF15	4200	1.22
Al 2024-T3	70000	2.7

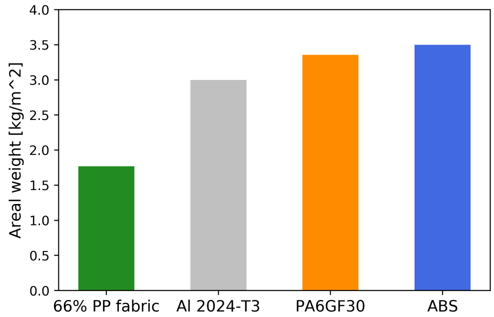

Figure 14: Comparison of areal weights

Figure 14 shows the areal weights for all analysed plates. Plates made out of plastic have nearly the same areal weight, whereas aluminium as the material leads to a somewhat smaller value. The case with the nonwoven fabric stands out with a value of about fifty percent of the areal weight of ABS. It can be seen that by using a "standard" fabric material type with 66% consolidation a high mass saving can be achieved.

But the full potential of the fabric material is not used sufficiently at this point. This potential can be exploited by lowering the consolidation ratio, thus increasing the thickness and bending stiffness. Two ways are seen for the application at hand.

Firstly, for a constant node distance and therefore bending stiffness a different fabric with less material (areal weight) can be used and the consolidation ratio adjusted to achieve the required bending stiffness. This would lead to a further mass reduction for the aerodynamic fairing itself.

Secondly, by using the same fabric the consolidation degree can be lowered to achieve a greater bending stiffness without changing the mass of the aerodynamic fairing. With a higher bending stiffness the node distance of the fuselage truss structure can be increased, thus leading to a lighter truss structure. Figure 15 shows the required node distance if a consolidation of 37% is used. It shows that by using a lower consolidation the node distance can be increased by 20% for the application at hand.

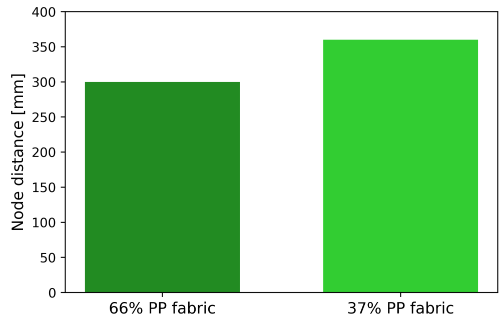

Figure 15: Required node distance for different consolidation degrees

4.2 Adaptability of nonwoven fabrics

The examples in Figure 14 and Figure 15 show that nonwoven fabrics are more flexible in their application in comparison to other materials resulting from the additional gained degree of freedom being the consolidation ratio. In contrast to other materials the bending stiffness and the strength of the nonwoven fabric can be adjusted without adding or removing mass. Figure 16 shows the specific bending stiffness vs the specific strength of aluminium and non-woven fabrics for a constant areal weight. The specific bending stiffness corresponds to the bending stiffness divided by the probe width, i.e. the plate bending stiffness of the respective plate. Whereas aluminium is represented by one specific point (an increase in plate bending stiffness always leads to an increase in weight) the non-woven fabric covers a wide area. The tested materials with PP matrix are included as calculated points, whereas the area which could be covered with the non-woven fabrics is estimated. Further tests with different consolidation ratios need to be made to confirm and narrow the illustrated area.

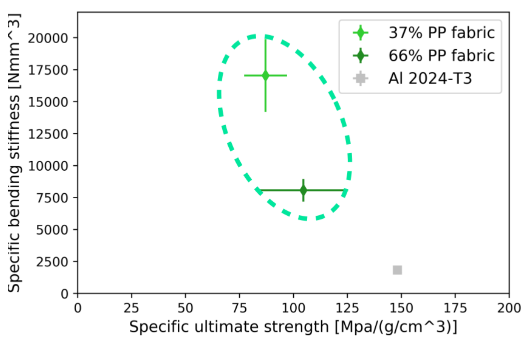

Figure 16: Plate bending stiffness vs specific strength

The consolidation ratio enables the designer to locally tailor the material based on the specific requirements. Figure 17 shows the chosen example of a truss structure with an aerodynamic fairing. The aerodynamic fairing needs to have a high bending stiffness in the "far off field" but also a high material strength at load introduction points. This rather contradicting requirements can be fulfilled by the non-woven fabric. A low consolidation ratio is chosen in the far off field and a high consolidation ratio at the introduction point. This leads to an aerodynamic fairing with adjusted stiffness and strength manufactured in one process.

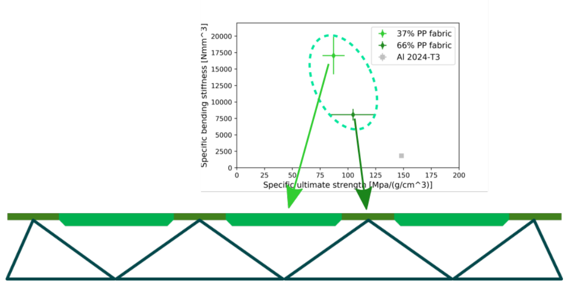

Figure 17: Local tailoring due to different consolidation ratios

5 SUMMARY AND OUTLOOK

This paper discusses nonwoven-based composites with different consolidation degrees. After production, the mechanical tensile and bending properties of rCFRP specimens with a PA 6 and PP matrix were experimentally determined. The tests show that the bending stiffness of partially consolidated sheets can be increased at the cost of diminishing tensile strength, bending strength and tensile stiffness. In the specimens considered, the stiffnesses changed by a factor of two and the strength by almost four while keeping the areal weight of the sheets constant. For a subset of specimens with PA matrix, no change in bending stiffness could be observed. While probably attributable to production defects, further tests should be performed.

In future investigations, a material model to calculate properties depending on the consolidation degree and chosen materials of the sheets should be developed. For this, a larger amount of experiments and specimens will be needed. Considering a larger range of consolidation degrees will also help determine the point from which a thickness increase doesn't improve the bending stiffness.

References

[1] Stephen P. Timoshenko and Sergius Woinowsky-Krieger. *Theory of plates and shells*. 2. ed., reissued. McGraw-Hill classic textbook reissue series. New York: McGraw-Hill, 1987. ISBN: 0-07-064779-8.