EFFECT OF THE COVER FACTOR OF 2D BIAXIAL AND TRIAXIAL BRAIDED CARBON COMPOSITES ON THEIR IN-PLANE MECHANICAL PROPERTIES

Frieder Heieck[1], Peter Middendorf[1]

[1]Institute of Aircraft Design, University of Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany
Email: frieder.heieck@ifb.uni-stuttgart.de, Web Page: http://www.ifb.uni-stuttgart.de

Keywords: braiding, cover factor, mechanical properties, image processing

Abstract
The effect of the cover factor on the in-plane mechanical properties of biaxial and triaxial braided carbon fiber composites is investigated. Low braid coverage occurs if the mandrel circumference exceeds a specific length for a given braid setup, so that gaps occur in between the different yarn systems.
Braids are manufactured on different mandrel sizes with a braid angle of ±45°. The cover factor is calculated analytically and measured by means of gray scale analysis of scanned samples. Mechanical test results are presented for the thermoset resin systems EPIKOTE MGS® RIM 235 and HexFlow® RTM6. The results show that there is a significant influence of decreased cover factors on the tensile properties, especially in case of triaxial braids tested in axial direction. The influence of different resin systems is observed for matrix-dominated tensile properties of biaxial braids, where the composite failure strain is in the range of the neat resin failure strain.

1. Introduction

In recent years, 2D-braided carbon-fiber composites have been becoming increasingly popular due to their potential of realizing parts with complex hollow geometries and high load bearing capacities. A common technique used for manufacturing braided composites is the circular braiding process with radial braiding machines. By robotically guiding a mandrel through the center of the machine with a defined speed, the fiber architecture can be adjusted along the axis. The braid pattern evolves from a complex interaction of the yarn movement along the circumference of the machine, the yarn configuration, the mandrel geometry and the robot-controlled path of the mandrel.
The textile fiber architecture created during this process mainly determines the mechanical properties of the composite part. Most of the visual braid attributes, such as the braid angle and braid coverage, are directly linked to each other within the process. For certain geometries it is thus often necessary to use a compromise between different parameters, so that it is crucial to know their potential impact. The influence of different braid architectures (e.g. braid angle variations) on the composite performance has already been investigated in several studies ([1], [2]). Typically, full braid coverage has always been desired for braided components in order to avoid any reduction of the mechanical properties without knowing the exact magnitude of this effect.

Consequently, this paper highlights the braid coverage as one of the major influence parameters of braided composite materials. First, a theoretical background is provided to understand the connection between the process parameters, the mandrel geometry and the resulting fiber architecture. Second, a method for determining the braid cover factor based on image processing techniques is introduced and

Excerpt from ISBN 978-3-00-053387-7

compared to analytical results. Finally, mechanical properties of tensile tests are presented and a statistical Welch test is performed to demonstrate the significance of the results.

2. Theory

There are different types of braids which can be produced with braiding machines, which are mainly categorized by the amount of yarn systems and the braid pattern. For the presented work, a radial braiding machine is used which - if fully mounted - produces 2D-braids with a 2:2-1 weave pattern according to Koysev's notation rule [3]. This means that one yarn alternatingly floats over and under two yarns of the opposite direction. The pattern thus equals a 2:2 twill weave. This basic braid is also known as regular braid. In this work all braids are of this type, however both biaxial and triaxial braids are produced. The latter consists of three yarn systems, whereas a third fiber orientation is introduced by stationary yarns which are incorporated in axial direction (see figure 1).

The fiber architecture of a braid is mainly determined by the interaction of process parameters, the mandrel geometry and mandrel trajectory. For a cylindrical mandrel which is guided through the center of the braiding machine with constant speed, the braid exhibits a uniform braid architecture with a specific **braid angle** γ between the longitudinal axis of the mandrel and the braiding yarns, which is calculated as:

$$\gamma = \arctan(\frac{2\,\pi\,\Omega\,D}{v\,n_{hg}}), \tag{1}$$

where Ω is the rotational frequency of the horn gears, D the circular mandrel diameter, v the advance speed of the mandrel and n_{hg} the number of horn gears of the braiding machine.
The equation shows that by increasing the mandrel diameter, the advance speed has to be increased equally in order to keep a constant braid angle. However, the amount of yarns deposited on the mandrel is limited by the bobbins mounted on the machine, so that gaps occur in between the yarns for higher mandrel diameters. This effect is directly linked to the cover factor of a braid, which is defined as the area covered by the braid with respect to the total mandrel area.
Rosenbaum [4] presented a formula to calculate the **cover factor** cf for a biaxial braid based on the width of the braiding yarns:

$$cf = \frac{b_f\,n}{\pi\,D\,\cos(\gamma)} - (\frac{b_f\,n}{2\,\pi\,D\,\cos(\gamma)})^2, \tag{2}$$

where b_f is the yarn width of the braiding yarns and n the number of yarns.

As it is shown in section 4, the equation allows for calculating the cover factor in good accordance with experimental results for biaxial braids. However, the variation of yarn width has to be taken into consideration for higher mandrel diameters, as the yarns tend to spread with increasing gap sizes. For triaxial braids, it is difficult to analytically calculate the cover factor, as the axial yarns are often distributed unequally. Therefore the cover factor has been measured optically to later correlate the mechanical properties with real fiber architecture parameters. The method is further described in section 3.
For triaxial braids, another important parameter is the **axial yarn content**, which describes the ratio of axial yarn weight and the total areal weight of the braid. The axial yarn content is given by:

$$C_a = \frac{1}{1 + \frac{n_b\,tex_b}{n_a\,tex_a\,\cos\gamma}}, \tag{3}$$

Excerpt from ISBN 978-3-00-053387-7

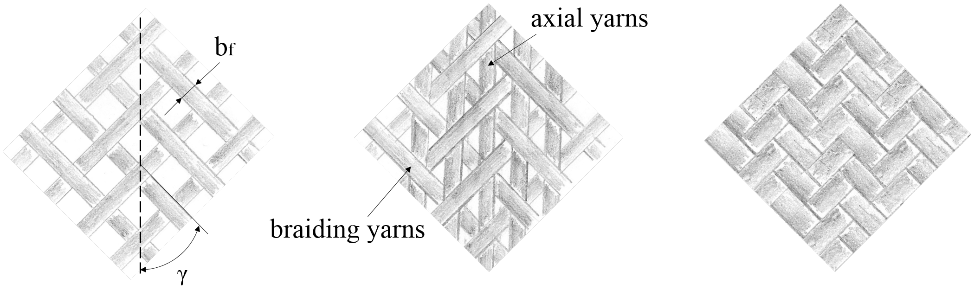

Figure 1. Regular biaxial (left) and triaxial (middle) braids with cover factor smaller than 1 and braid with full coverage (right)

where n_b is the number of braiding yarns, tex_b the linear mass density of the braiding yarns and n_a, tex_a the equivalent parameters for the axial yarns. It can be seen that the axial yarn content is independent from the mandrel diameter for a given braid angle. Thus, it is possible to produce braids with the same axial yarn content on different mandrel sizes. This is important, as the axial yarn content mainly determines the in-plane mechanical properties of the triaxial braid in axial direction.

3. Material and Methods

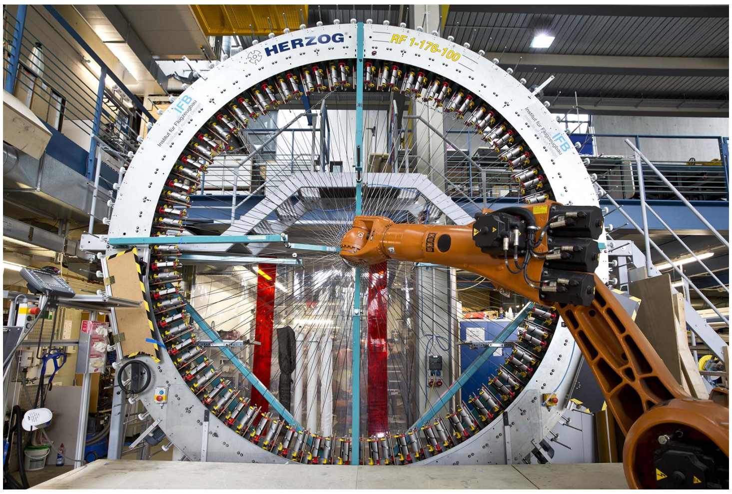

Figure 2. Radial braiding machine RF 1-176-100 at the Institute for Aircraft Design used for the production of braid samples

In order to investigate the effect of the cover factor on the in-plane mechanical properties of braided composite laminates, 6 different types of braid are manufactured.
Biaxial and triaxial braids are produced on three different mandrel sizes on a radial braiding machine of the type Herzog RF 1-176-100. The machine can mount a total number of 176 bobbins for the braiding yarns and additionally 88 stationary axial yarns on the outer side of the machine. Cylindrical mandrels with diameters of 120 *mm*, 160 *mm* and 190 *mm* are overbraided with an industrial robot with different advance speeds to obtain a braiding angle of ±45° for all braids. The circular braid sleeves are cut along the mandrel axis and uncoiled to obtain flat layers which can be further processed to manufacture specimens for mechanical testing. The braids which are shown in figure 3 all consist of Toho Tenax® high tensile strength (HTS 40) fibers with 12.000 filaments, 800 tex and zero twist.

Excerpt from ISBN 978-3-00-053387-7

Two different infusion resin systems are used to investigate the influence of the matrix with decreasing cover factor: The two-component resin system EPIKOTE MGS® RIM 235 with EPIKURE MGS® RIMH 237 curing agent (Resin A) and the aircraft certified monocomponent resin HexFlow® RTM6 (Resin B).

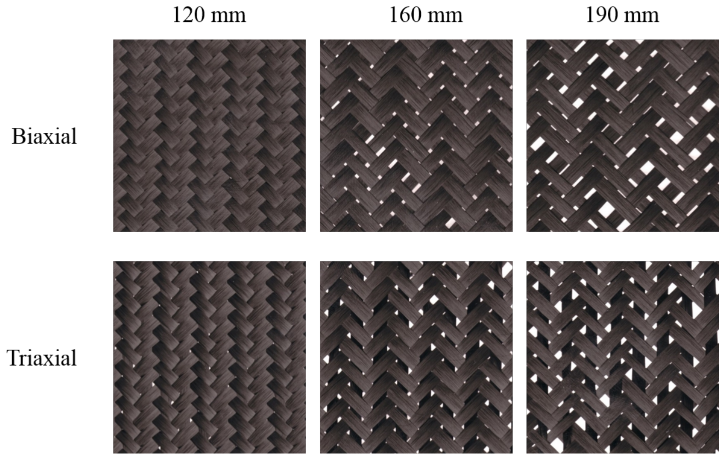

Figure 3. Investigated biaxial and triaxial braids with ±45° braid angle on different mandrel sizes (the given value is the mandrel diameter)

The mandrel diameters have been chosen to obtain full braid coverage for the smallest mandrel diameter and reduced cover factors in a range which is realistic for braided components.
The cover factor for biaxial braids is calculated analytically. In order to validate the calculation and obtain values for triaxial braids, an optical measurement method is used. Therefore, flat samples of each braid are scanned with a standard hand-held scanner to create high resolution images. The image data is evaluated with a Matlab-Code which counts pixels within a gray scale range between 0 and 255, where 0 is 100% black and 255 white. All pixels below a calibrated threshold value are assigned to the braid. The cover factor is then calculated as the ratio of braid pixels to the total amount of pixels. All scans are performed on a white background to reach a high contrast.
Results of the analytical cover factors calculated with equation 2 and measured cover factors are given in table 1. Deviations of analytical and measured cover factors tend to increase with lower coverage, which is mainly due to the increasing variation of the yarn width used for the calculation.

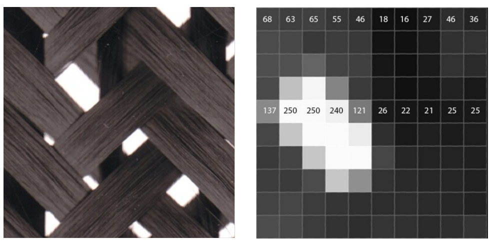

Figure 4. Original scanned image and local greyscale matrix

Test plates with several braid layers are manufactured with Vacuum Assisted Resin Infusion (VARI). In case of the resin system RIM 235, the resin is infused at room temperature and cured for 24 hours. Afterwards, a heat treatment at 70°C for 12 hours is performed to reach optimum mechanical properties. Plates with RTM6 are infused at 120°C in an industrial oven and cured at 180°C for 2 hours.

Excerpt from ISBN 978-3-00-053387-7

Table 1. Cover factors of different braids

Braid	D $[mm]$	$\bar{b}_f$ $[mm]$	cv analytical [%]	cv measured [%]	deviation [%]
Biax	120 mm	3,2	99,7%	99,9%	0,31%
Biax	160 mm	3,5	98,2%	97,9%	0,37%
Biax	190 mm	3,7	94,8%	92,9%	1,99%
Triax	120 mm	-	-	99,4%	-
Triax	160 mm	-	-	95,7%	-
Triax	190 mm	-	-	93,3%	-

Test specimens for tension tests are cut with a diamond-coated wet saw according to DIN EN ISO 527-4 with 250 mm length and 25 mm width.
The number of layers for all specimens is 4 which results in laminate thicknesses of $2,2\,mm$, $1,8\,mm$ and $1,6\,mm$ for the biaxial braids and $3,0\,mm$, $2,5\,mm$ and $2,2\,mm$ for triaxial braids. The thickest laminates are obtained on the smallest braid mandrel due to an increased areal weight.

Strain measurements are performed on one side of the tension specimens using longitudinal strain gauges. All tests are conducted on a Schenck-Trebel RM250 universal testing machine shown in figure 5.

Figure 5. Universal testing machine Schenck-Trebel RM250

4. Experimental Results and Discussion

Tensile test results in 0° (the direction of production) of the braids according to DIN EN ISO 527-4 are presented to illustrate the effect of the cover factor on the in-plane mechanical properties of the braids. The tensile modulus E_x is derived from the stress-strain curves between strains of 0,05 and 0,25. Tensile moduli and strengths presented in figure 6 and 8 are given as direct values from the tests as well as normalized results based on a fibre volume fraction of $\varphi = 0,6$.
Normalized values are calculated for a parameter P by

$$P_{\varphi_2} = P_{\varphi_1}\frac{\varphi_2}{\varphi_1}, \tag{4}$$

Excerpt from ISBN 978-3-00-053387-7

with $\varphi_2 = 0,6$ and φ_1 being the measured fiber volume fraction of the test laminates. It is important to note that for biaxial braids tested in axial direction, a linear correlation of φ and the mechanical properties is not strictly given. Therefore, both normalized and not normalized values are presented. All error bars shown are standard deviations of the test series plotted in positive and negative direction. Results are shown for all three measured cover factors given in table 1.

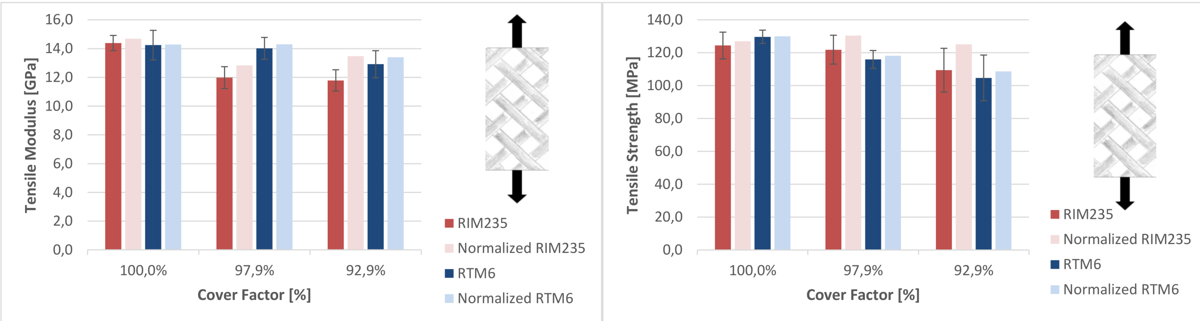

Figure 6. Tensile moduli and strength of biaxial braids

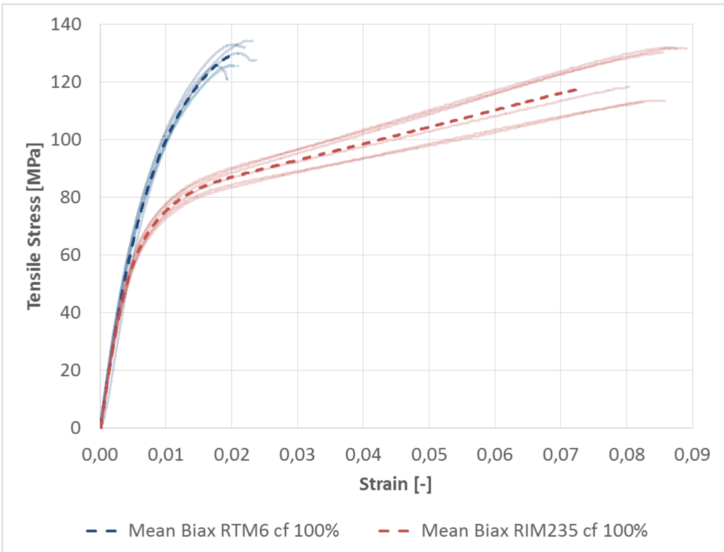

Figure 7. Stress-strain curves of biaxial braids with RTM6 (blue) and RIM235 (red) matrix with full coverage. Dashed lines represent mean values of all data sets of a test series.

Figure 7 shows the stress strain curves of two biaxial braids with full coverage and different resin systems RTM6/RIM235 with dashed lines representing the mean values of the test series. It can be seen that the failure strain is significantly lower for RTM6, which is a direct result of the neat resin failure strain given in the data sheets ($3,4\%$ for RTM6 vs. $8-12\%$ for RIM235).
Normalized stress-strain curves ($\varphi = 0,6$) of triaxial braids are shown in figure 9 for full and low coverage ($99,4\%$ and $94,0\%$, respectively) with the resin system RIM235. A decrease of the tensile modulus at higher strains and a strong reduction of the mean tensile strengths occur for lower coverage. As the axial yarn content is theoretically not affected by the varying braid architecture, there are other effects to be taken into consideration. One potential impact is an increased fiber misalignment of the axial yarns due to the lower coverage, which nest into the adjacent layers. Morever, figure 8 shows that there is a strong correlation of laminate thickness and mechanical properties, which is directly linked to the areal weight and the cover factor of the braids.

Excerpt from ISBN 978-3-00-053387-7

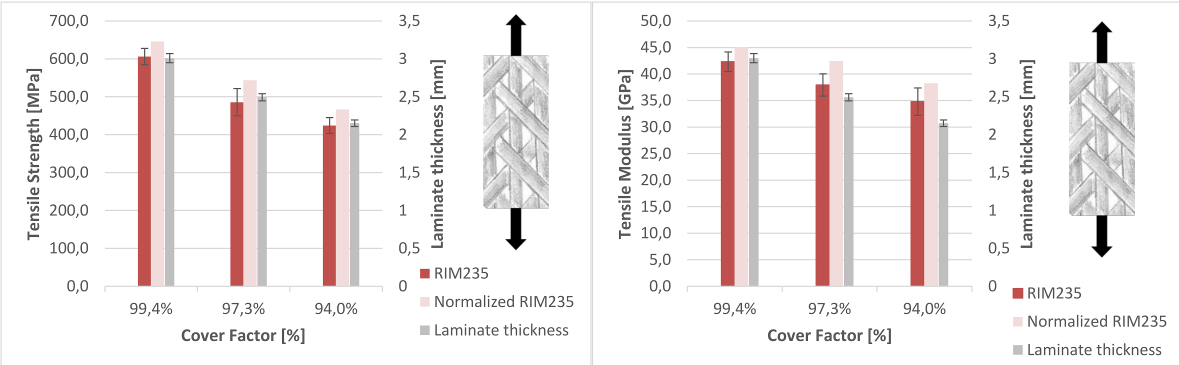

Figure 8. Tensile moduli and strength of triaxial braids

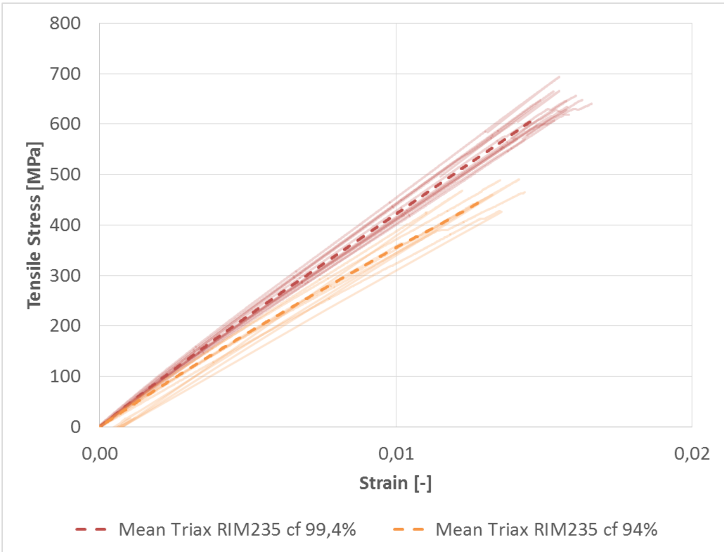

Figure 9. Stress-strain curves of triaxial braids and RIM235 matrix with full and low coverage (normalized to $\varphi = 0,6$)

In order to prove the significance of the obtained results, a two-tailed Welch test (an unpooled type of the Student's t-test) is performed for braids with highest and lowest coverage. The Welch test is used for test series with different variances and determines if two sets of data are significantly different with a certain probability P. Significance levels are $\alpha = 5\%$ ($P > 95\%$) for significant results and $\alpha = 1\%$ ($P > 99\%$) for highly significant results. Input parameters are $\overline{E}_x$ or $\overline{\sigma}_{max}$ (the mean values of the tensile modulus and strength of the test series), n (the number of specimens tested) and s (the standard deviation). Table 2 shows the results of the t-test. Significance levels are "'o"' for being not significant, "'+"' for being significant and "'++"' for being highly significant.

Excerpt from ISBN 978-3-00-053387-7

Table 2. Results of the two-tailed Welch test ($\alpha = 5\%/1\%$) with normalized mean values of tensile modulus and strength. A=RIM235, B=RTM6. Sign. levels: o = not significant, + = significant, ++ = highly significant.

Test series		cf [%]	$\overline{E}_x/\overline{\sigma}_{max}$ $[GPa]/[MPa]$	n [−]	s $[GPa]/[MPa]$	$\Delta\overline{E}_x/\Delta\overline{\sigma}_{max}$ [%]	P [%]	sign. level
Biax A	$\overline{E}_x$	100	14,7	6	0,5	−8,2	98,3	+
		92,9	13,5	6	0,8			
	$\overline{\sigma}_{max}$	100	127,0	6	8,3	−1,5	20,3	o
		92,9	125,1	6	15,2			
Biax B	$\overline{E}_x$	100	14,3	7	1,0	−6,1	85,5	o
		92,9	13,4	6	1,0			
	$\overline{\sigma}_{max}$	100	130,0	7	4,1	−16,5	98,6	+
		92,9	108,6	6	14,5			
Triax A	$\overline{E}_x$	99,4	42,9	12	1,7	−10,7	99,1	++
		94,0	38,3	6	2,8			
	$\overline{\sigma}_{max}$	99,4	656,5	12	23,4	−28,9	100,0	++
		94,0	466,5	6	23,1			

5. Conclusion

The mechanical test results show that the cover factor has a strong influence on the in-plane mechanical properties of braided composites, depending on the type of braid. While an effect is measurable for biaxial braids tested in axial direction, a more significant reduction of both tensile modulus and strength is observed for triaxial braids. Since the theoretical axial yarn content is not affected by the mandrel diameter, there are other effects which have to be taken into consideration. One potential reason is an increased fiber misalignment caused by the gaps occuring with lower braid coverage. Further investigations are still required to investigate the failure mechanisms caused by lower cover factors and reduced laminate thicknesses. Transferring the results to a component level, both the reduction of laminate thickness and the additional decrease of mechanical properties should be considered for dimensioning.

References

[1] Markus Wolfahrt, Gerald Pinter, Swen Zaremba, and Tjark von Reden. Effect of preform architecture on the mechanical and fatigue behavior of braided composites for generating design allowables. 30th SAMPE EUROPE, Paris, 2009.

[2] K. Birkefeld, M. Röder, T. von Reden, Martina M. Bulat, and K. Drechsler. Characterization of biaxial and triaxial braids: Fiber architecture and mechanical properties. *Applied Composite Materials*, 19:259–273, 2012.

[3] Y. Kyosev et al. *Braiding Technology for Textiles*. Woodhead Publishing Series in Textiles. Woodhead Publishing, 2015.

[4] Jens Ulrich Rosenbaum. *Flechten: Rationelle Fertigung faserverstärkter Kunststoffbauteile*. Dissertation, Technische Hochschule Aachen, 1991.

Excerpt from ISBN 978-3-00-053387-7