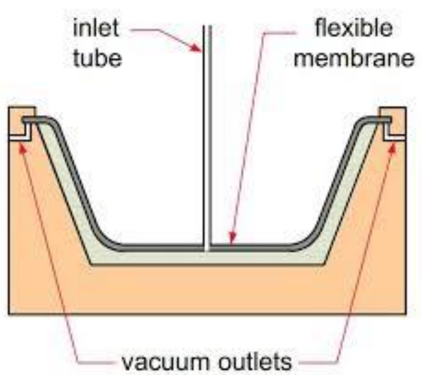
Measurement of Fibre Undulations in unidirectional GFRP by Microwaves

Johann HINKEN[*,***], Felix KÖSTER[**], Christian ZIEP[*]
[*] FI Test- und Messtechnik GmbH, Breitscheidstr. 17, 39114 Magdeburg, Germany
E-mail: johann.hinken@fitm.de
[* *] Fachhochschule Flensburg, Postfach 1561, 24905 Flensburg, Germany
[* * *]Hochschule Magdeburg-Stendal, Breitscheidstr. 2, 39114 Magdeburg, Germany

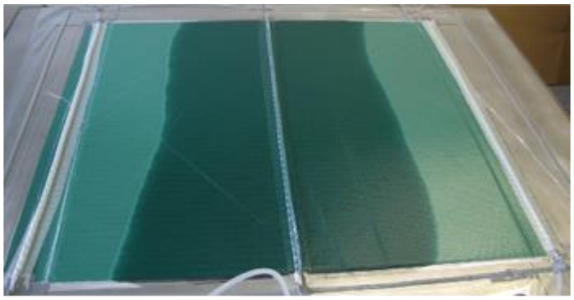
Abstract: During the manufacture of components from glass-fibre reinforced plastic (GFRP) out-of-plane fibre undulations may originate. After covering with paint these undulations can no longer be seen visually. However, they considerably impair the strength of the component. This paper reports about a feasibility study which shows that a proper microwave system can detect such undulations and measure their profile quantitatively.

1. Introduction and problem

During the manufacture of components from glass-fibre reinforced plastic (GFRP) often the vacuum infusion method and unidirectional glass fibre mats are used. Fig. 1 shows that at first the fibre material, enclosed by a hermetic bag (flexible membrane), is deposited into the smooth mould. The bag is evacuated and temperate liquid resin is sucked by the vacuum through the inlet tube into the fibre mats. After cooling down and hardening the glass material is rigid within the laminate. Fig.1b is a photo of a component during the infusion of the liquid resin, which as dark regions propagates to the left and to the right.



a)

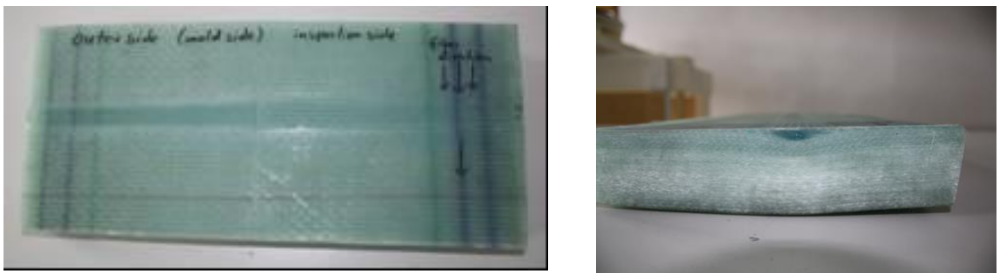


b)

Figure 1: Vacuum infusion method for the manufacture of components from glass-fibre reinforced plastic (GFRP). a) Schematic, after ETH Zürich, IMES-ST. b) Photo during injection of resin, after BaltiCo GmbH

The bottom side of the laminate is smooth like the mould, the top side is less smooth. Occasionally at the bottom side of the component resin enrichments arise, together with fibre undulations which are perpendicular to the surface. At the latest when the component is coated with paint and/or gelcoat these undulations cannot further be seen visually. However, they significantly impair the strength of the component. So the problem arises to detect and to determine the strength of the undulations.

The feasibility study for the detection and measurement of such undulations is described in the following and performed at the sample of fig. 2.



a) b)

Figure 2: Sample with artificial fibre undulation. a) Top view. b) Side view

In fig. 2b at the top side one can see the dark resin enrichment with the fibre undulation adjacent to it at its bottom side. On the top side a thin cover layer of biaxial GFRP is added. In the top view of fig. 2a the resin enrichment lightly shows through the biaxial GFRP layer.

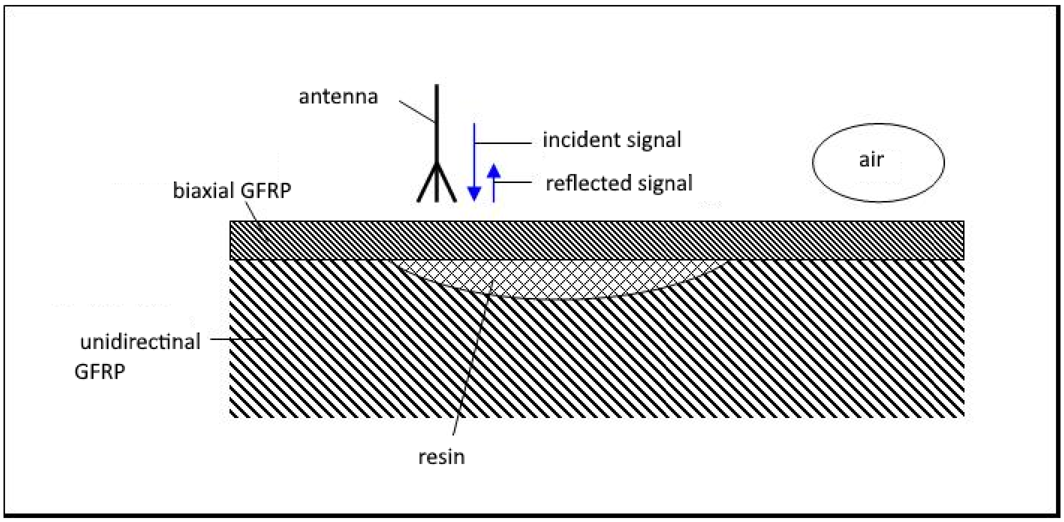
2. Concept to solve the problem

On the top side of the component, fig. 2a, from an antenna a microwave is irradiated into the component. This microwave passes regions with different permittivity (dielectric constant), e.g. air 1; epoxy resin 3.0; E glass 6.5. Therefore these different regions can be modelled by transmission lines with different impedances and phase constants. Reflections occur at each surface between the regions. The total reflection is measured and evaluated.

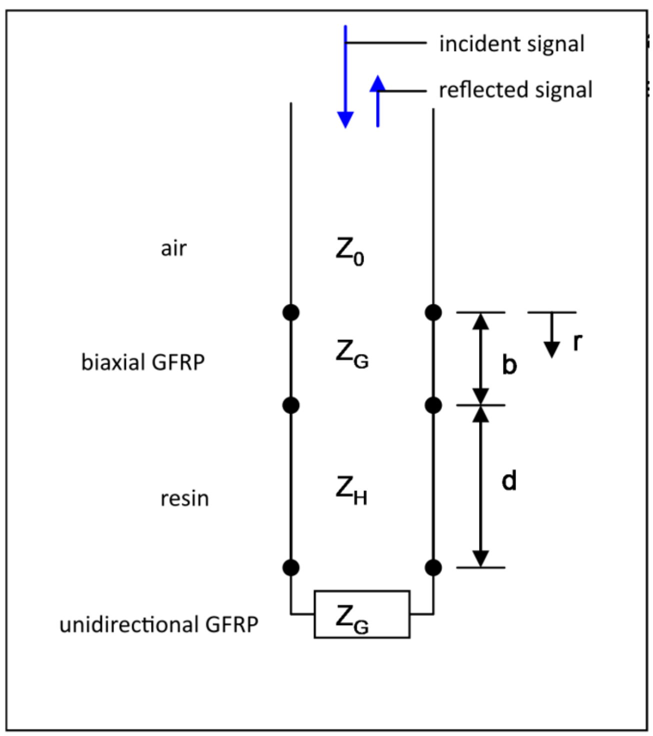
More specifically, for the non-destructive measurement of the fibre undulation the sample is scanned in several parallel lines, vertical in fig. 2a. A momentary situation is sketched in fig. 3a. From a transmitter via the antenna a signal is incident onto the sample. A reflected signal is received by a receiver and then evaluated. This reflected signal consists of several single signals, which are determined by the single layers: the outside air, the biaxial GFRP, the resin region, and the very thick unidirectional GFRP.

Fig. 3b shows the approximate high-frequency equivalent circuit of this structure. The single regions are characterized by their different wave impedances Z_0, $Z_{G,}$ and $Z_{H,}$ respectively. The nearly infinitely thick unidirectional GFRP is characterized by the load $Z_{G.}$ The constant thickness of the biaxial GFRP is b, the variable thickness of the resin is d.

For the calculation of the wave impedances and phase coefficients the formulas for the field wave impedance and the phase coefficient in free space with the respective permittivity from above were used. For the permittivity of GFRP the value of 4.7 was used which is the weighted average of resin and glass at an assumed fibre-volume-ratio of 50% and which is fairly consistent with direct measurements of the unidirectional GFRP.



a)



b)

Figure 3: Structure and calculation model of fibre undulation. a) Structure of momentary situation. b) high-frequency equivalent circuit with sections of transmission lines

The complex reflection coefficient r is the ratio of the reflected signal to the incident signal. It was calculated for this structure. The result, with variable resin thickness d = 0…6 mm, is sketched in fig. 4 as a locus curve in the complex plane. The thickness of the biaxial GFRP layer is assumed to be 1.2 mm. According to the calculation model the locus curve is a circle which for the present values is repeatedly passed about 1 ½ times. Strictly speaking, parts of the locus curve would coincide. But in fig. 4 they are sketched a little bit apart for a better understanding. This idealized calculated curve was used as the basis for the data evaluation of the measurements which are described in the following.

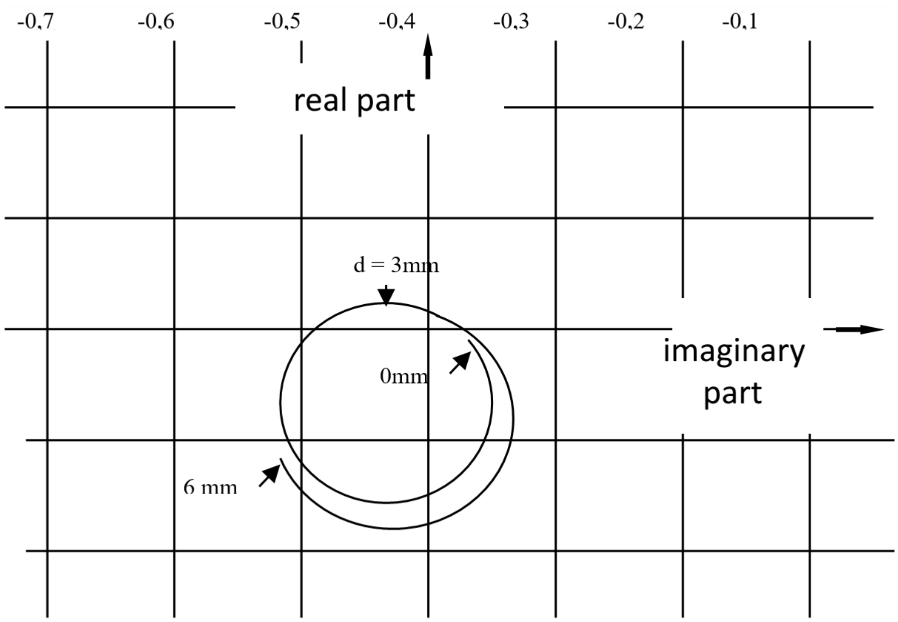


Figure 4: Locus curve of reflection coefficient r with variable resin thickness d

3. Measurements and data evaluation

Fig. 5 shows a top view of the sample with 4 scan lines added in red colour.

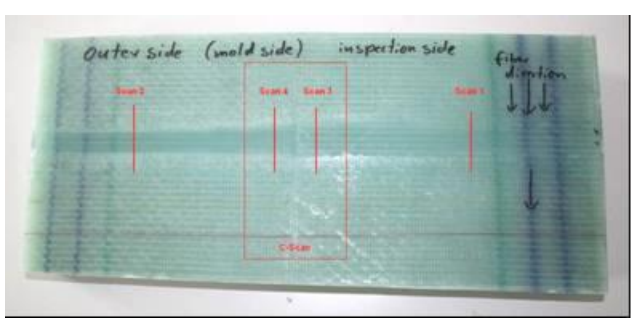


Figure 5: Sample with 4 scan lines in red colour

Fig. 6 shows a part of the 24 GHz measurement setup with positioning stage. The blue cable on the right hand side leads to a network analyzer to measure the reflection coefficient. The antenna is an open waveguide with flange and located about 1 mm above the sample.

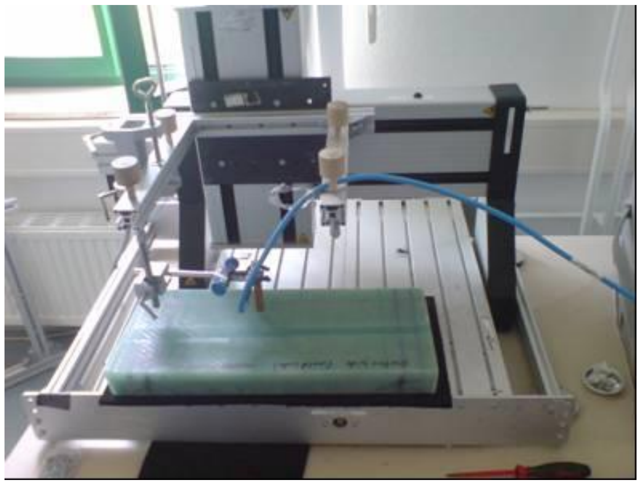


Figure 6: Measurement setup with positioning stage

Fig.7 on the right hand side shows the measured locus curve of the complex reflection coefficient. The knot on the right results from passing regions outside the resin enrichment: inhomogeneities of the material are the reason for the widening of a dot in theory to this knot in practice.

When the antenna is passed across the surface in the region where the resin enrichment is below the surface, in fig.7 at first the circle is passed in clockwise direction until the thickest part of the resin enrichment is reached. This is the end at the lower left of the white curve. When further moving the antenna over regions with decreasing resin enrichment the curve is passed again, but anticlockwise, until it ends in the mentioned knot. The clockwise and anticlockwise plots are not completely congruent because of asymmetries in the resin enrichment.

On the left hand side of fig. 7 the imaginary part of the reflection coefficient as a function of the length coordinate of the scan is shown. From this curve one can determine the width of the resin enrichment region or fibre undulation, respectively. This width is marked by the green horizontal lines. On the right hand side of fig. 7 in the locus curve two auxiliary lines are added. These originate from the centre of the circle. The one auxiliary line tending to above right passes the knot and therefore represents the resin thickness zero. The other auxiliary line tending to the lower left through the end of the curve represents the maximum resin enrichment. The angle range between these green auxiliary lines is evaluated using fig. 4 and results in the maximum thickness of the resin enrichment.

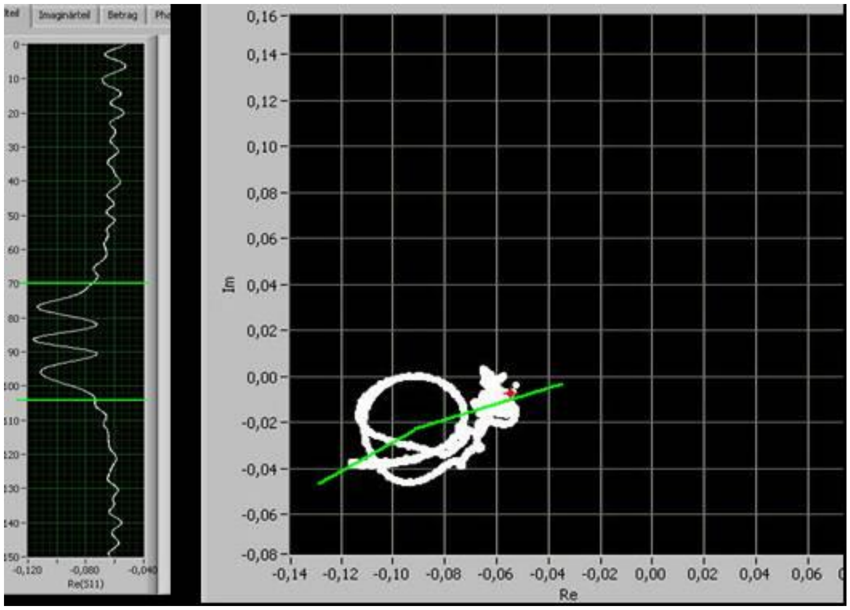


Figure 7: Imaginary part (left) and locus curve (right) of scan 2

The calculation model has some drawbacks. For example the attenuation of the field strength of the incident wave by widening of the radiation beam and scattering at the glass fibres is not taken into account. This and further effect can lead to a deformation of the locus curve, for example like in fig. 8 which shows scan 1.

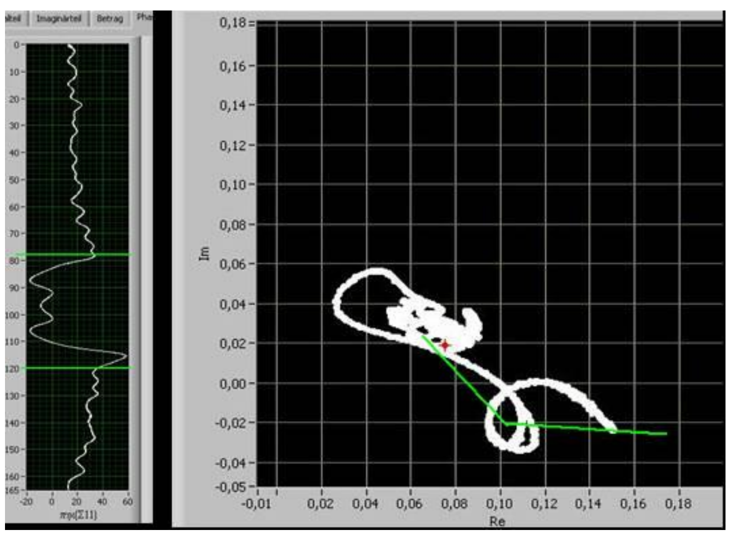


Figure 8: Imaginary part (left) and locus curve (right) of scan 1

However, because in spite of attenuation the phase relations are largely saved, the resin thickness can still be calculated from such a deformed curve. The green auxiliary lines in fig. 8 still correspond to the positions with resin thickness zero and maximum, respectively.

This method can be applied not only to determine the maximum resin thickness but also to determine the thickness variation along the whole scan line. Fig. 9 shows this evaluation of scan 2.

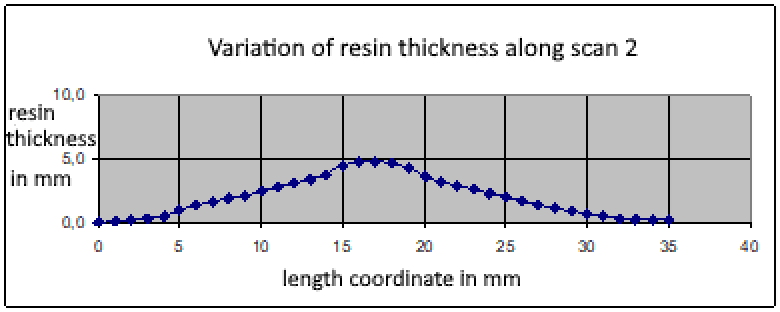


Figure 9: Measured profile of resin thickness along scan 2

Table 1: From line scans evaluated characteristic values of the fibre undulation

No. of scan	Length of resin enrichment l in mm	Height of resin enrichment d in mm	Slope m_{linear}	Maximum slope m_{trigon}
1	42	4.9	13.4 ^{o}	21 ^{o}
2	34	5.3	17.9 ^{o}	28.2 ^{o}
3	39	4.9	14.4 ^{o}	22.7 ^{o}
4	32.5	5.5 4.6 average: 5.1	19.5 ^{o} 16.3 ^{o} average: 17.9 ^{o}	30.5 ^{o} 25.6 ^{o} average: 28.1 ^{o}

Table 1 shows the most important measuring results of the four line scans, namely the length l of the resin enrichment in scan direction, the maximum thickness of the resin enrichment and, derived from these values, the slope m of the surface between resin enrichment and unidirectional GFRP. More specifically, m_{linear} is the slope resulting from an assumed triangle shaped profile and m_{trigon} the slope resulting from an assumed sine shaped profile. However, using the above described procedure such an interpolation is not necessary, because the maximum slope can be found directly from figures like fig. 9. Such maximum slopes are critical values to determine the strength of GFRP material.

4. Conclusion

This feasibility study shows

- Fiber undulations in GFRP can be detected and measured with a proper microwave test method.
- This is also possible if they are located below insulating layers like biaxial GFRP, gelcoat or paint.
- This holds for fibre undulations which are located not too far from the surface of the component. In practice this mostly is the case.