Non-Destructive Testing of Fiber Composites

Requirements and Challenges in the Quality Assurance and Monitoring of Modern Lightweight Construction Structures

Fiber-reinforced plastic composites (FRP) have great potential for making the vehicles of the future even more lightweight and economical. It is important to start thinking now about the non-destructive testing (NDT) of the fiber composite parts of tomorrow with the aim of providing reliable, fast and inexpensive evidence of typical material defects before and during service.

Fig. 1. Parts of the outer skin of the A 350 are made of fiber-plastic composites (gray) (figure: Airbus)

Fiber-plastic composites are increasingly being used in a range of engineering systems, in particular in the field of mobility and transportation. The use of such lightweight construction materials can reduce energy demand and therefore fuel consumption due to the lower weight. Besides the economic advantages, this also makes it easier to fulfil the ecological requirements on the automotive technology of the future.

While the use of high-strength materials has so far principally been achieved with optimized steel alloys and lightweight metals, fiber composite materials are increasingly being used in construction. They have great potential thanks to their very low weight together with very high stiffness and strength.

A characteristic feature of oriented reinforcing materials is the directional dependence (anisotropy) of various properties that they introduce. Here, fibers are usually selectively used for improving the mechanical properties. For example, fibers greatly increase the strength and stiffness in the fiber direction, while the elongation is reduced. At the same time, the thermal dimensional stability is increased and shrinkage and creep tendency are reduced.

Aircraft. As the most prominent example, FRPs are increasingly being integrated into aircraft constructions because of their extremely high mechanical properties per specific weight. Thus, challenging fiber-plastic parts are used in the aircraft industry in relatively small series of a few units per month. The composite is chosen highly specialized for each component depending on its requirement. The Airbus A 380, for example, already contains over 22 mass percent of fiber-plastic composites, and the Airbus A 350 X (**Fig. 1**), already over 50 mass percent.

Automotive Engineering. This trend is already emerging in the automotive industry. The continually growing vehicle weights in recent years have been offset by technical improvements in engine technology while fuel consumption has remained the same. However, continually increasing »

Fig. 2. Applications of fiber-plastic composites in automotive engineering (figure: BMW, Mercedes-Benz)

energy prices now promote the opposite trend, namely lower body weights and the associated high-tech composite materials. The production volume of CFRP materials alone is estimated at about 60 to 70,000 t in 2015, and thereby has two-digit growth rates.

The increasing speed of the megatrend towards electromobility and the high weight of rechargeable batteries have for some years been speeding up investments in the field of automotive lightweight construction research. FRPs will pay an even greater role here in future than in the past. The examples of a Mercedes SLR body and the roof module of a BMW M shown in **Figure 2** make it clear that, because of the manufacturing costs, fiber composites have so far only been used in the car for expensive small series.

Fig. 3. Application in regenerative electricity generation: wind farm (figures 3–8, 11: IKT)

However, this situation is currently changing. In 2009, BMW and the carbon fiber specialist SGL Carbon (formerly Hoechst) formed the joint venture SGL Automotive Carbon Fibers. This ensured that BMW and its subsidiaries would be exclusively supplied with carbon fiber-based materials and technologies. At IAA 2013, BMW, with the i3, launched the world's first large series car with a passenger compartment of carbon-fiber-reinforced plastics (CFRP). The chassis is still made of aluminum and the electric motor has 125 kW (170 bhp).

Wind Power. Besides electromobility, the use of fiber plastic composites in wind farms (**Fig. 3**) supports another megatrend in Germany. In sustainable energy production, fiber composites with glass fibers (GFRP) are used. The up to 60 m long rotor blades are manufactured from "endless" glass fiber-reinforced plastics. The fibers and thermosets used are very inexpensive, but the processing is very complicated and expensive compared to other typical plastics processing techniques. Despite the many wind turbines, rotor blades, too, are made by small-series production.

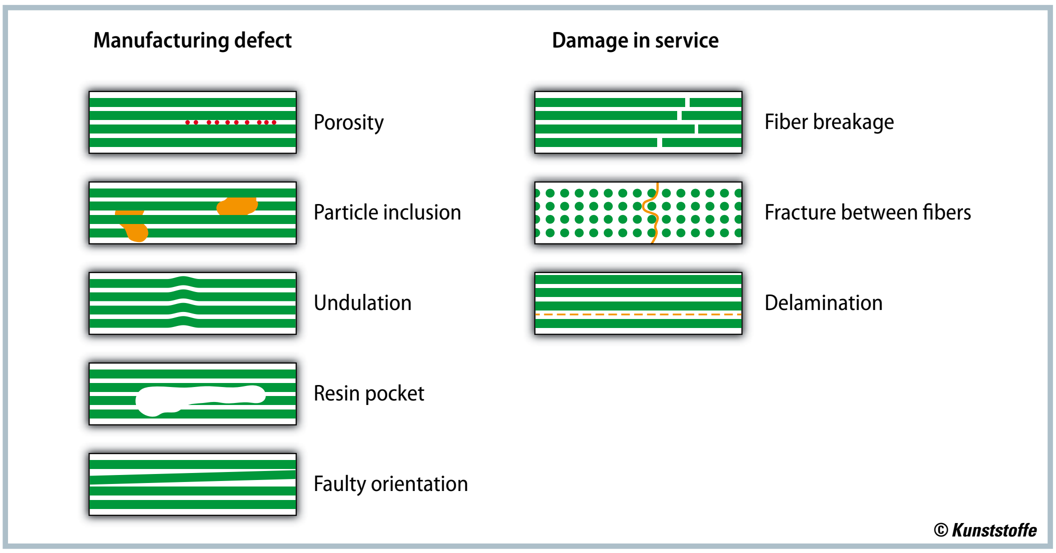

Fig. 4. Defects in fiber-plastic composites – during manufacturing and during service

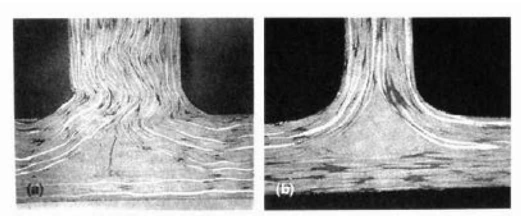

Fig. 5. Undulations in a stringer foot

Defects in FRP and Non-Destructive Testing

The question of what defect types and what defect sizes are only just permissible in a component has not yet been finally settled for all CFRP-based components. For this reason, the requirement profile on non-destructive testing processes is partly still open and, correspondingly, the safety margins to allow for aging and fatigue are very high. The driver of the developments – the occurrence and behavior of the different defect types in dynamically loaded components – is, in the legally regulated field of NDT, clearly aerospace. But in the field of nuclear energy, which is strongly regulated by standards, or in pressure tanks, in which plastics-based materials are increasingly used, (e.g. HDPE pipes or CFRP-jacketed pressure tanks), lively activity in the field of NDT standardization can be seen.

The special anisotropic structure of endless fiber-reinforced composites leads to specific types of defect (**Fig. 4**). First, defects can occur during manufacture, such as faulty orientations and resin pockets, particle inclusions, porosity and undulations of the fibers. On the other hand, damage to the composite can occur during use, including fiber breakage, rupture between fibers (matrix failure) and delamination, i.e. separation of layers.

Figure 5 left shows an X-ray-CT image of unacceptable undulations in the fibers in the lower region of a stringer (stiffening rib in the fuselage). If this defect is compared with an acceptable part (**Fig. 5 right**), it can easily be seen that the undulated fibers transfer the forces more unevenly than those in the acceptable parts.

Delamination, i.e. separation of layers in the fiber-polymer part, is the most widespread forms of damage and, like undulations, cannot be seen from the outside. Such delamination hardly reduces the tensile strength at all, but leads to total loss of shear strength between the detached layers. Excess flexural or impact loading is usually the cause of such delamination.

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While, with fiber-plastic composites, it is possible to adjust the desired lightweight construction properties while maintaining accurate dimensions, because of the more complex hybrid construction, defect detection is significantly more difficult. The use of conventional NDT methods too often fails because of the heterogeneous structure involved in by acoustic, electromagnetic and thermal anisotropies. Damping, scattering and disconnection, for example, are effects that generally play a significant role in analysis of FRPs. As a result, successful modern NDT methods must take into account the material structure, for example »

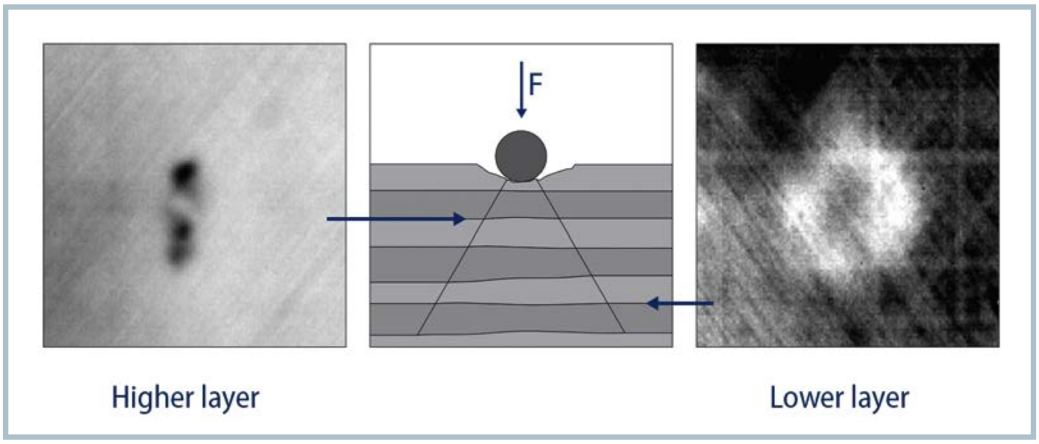

Fig. 6. Thermograph distinguishes between delaminations at various depths

Fig. 7. Measurement set-up of thermography with optical excitation

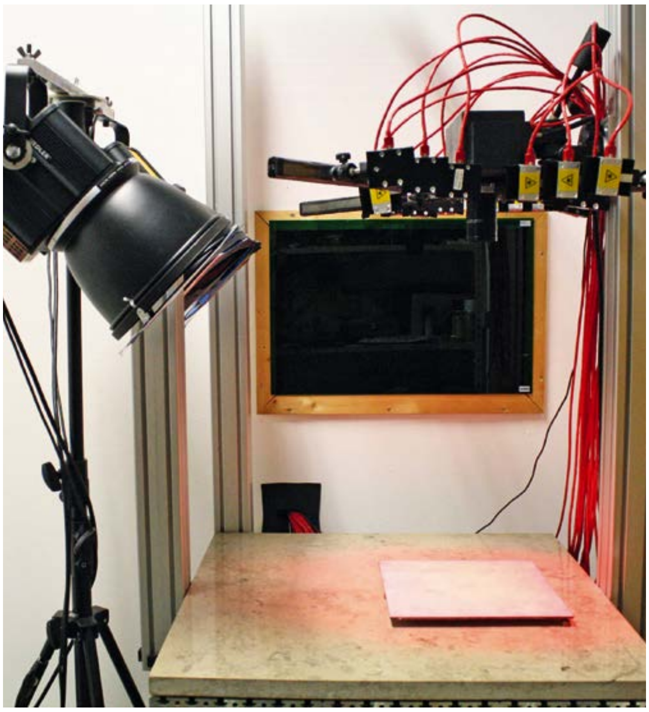

Fig. 8. Measurement set-up of shearography with optical excitation

the number of layers, number of fiber orientations, type of fibers, fiber bundle diameter, etc.

Thermography in the IKT lab allows externally invisible damage, like the above-mentioned delamination, to be very quickly made visible. The image in **Figure 6 left** shows the minor damage near the surface and **Figure 6 right** the much more extensive damage at a deeper layer.

Non-destructive testing by means of thermography is based on the observation of the surface temperature after a pulsed or periodic thermal excitation. The propagation behavior of the introduced heat allows conclusions to be drawn about the internal structure. At a delamination, the heat, for example, cannot dissipate at all, or only to a limited extent, and a hot spot forms on the part surface. **Figure 7** shows the thermograph test set-up in the lab with the example of optical excitation. In this method, the surface of a part is heated by means of strong lighting and is subsequently inspected with the infrared camera.

Figure 8 shows one of the NDT test rigs based on interferometry, principally electronic speckle interferometry (ESPI) and shearography. These processes respond to mechanical properties by comparing the interference patterns on the sample surface at different times. If the sample is under load at a point in time, there is a visible contrast with the unloaded state of the sample. Here, too, excitation by means of light is preferably used, since the heating results in thermal expansion.

Established material testing methods are the so-called "volume methods", which are also known from medicine, and which, unlike the processes mentioned above, can also register parts of large wall thickness in their complete dimensions. X-ray computer tomography (CT), conventional X-ray (transmission testing) and ultrasound.

With ultrasound testing, a sound pulse is usually generated by means of a transducer and transferred via a liquid coupling agent into the part to be tested. The strength of the reflection at damage can be used as a measure of the defect size. There are also more ambitious approaches in which it is attempted, besides the delay and amplitude, to also include the phase information of the reflected sound pulse in the evaluation. This may be performed, for example, by means of matrix ultrasound transducers, which electronically control the sound field in its direction by time-delayed actuation of the transmitter pulse. The comparison in **Figure 9 top** shows the result of a conventional ultrasound measurement on a CFRP reference sample. The C image (**Fig. 9 top, upper part**) and

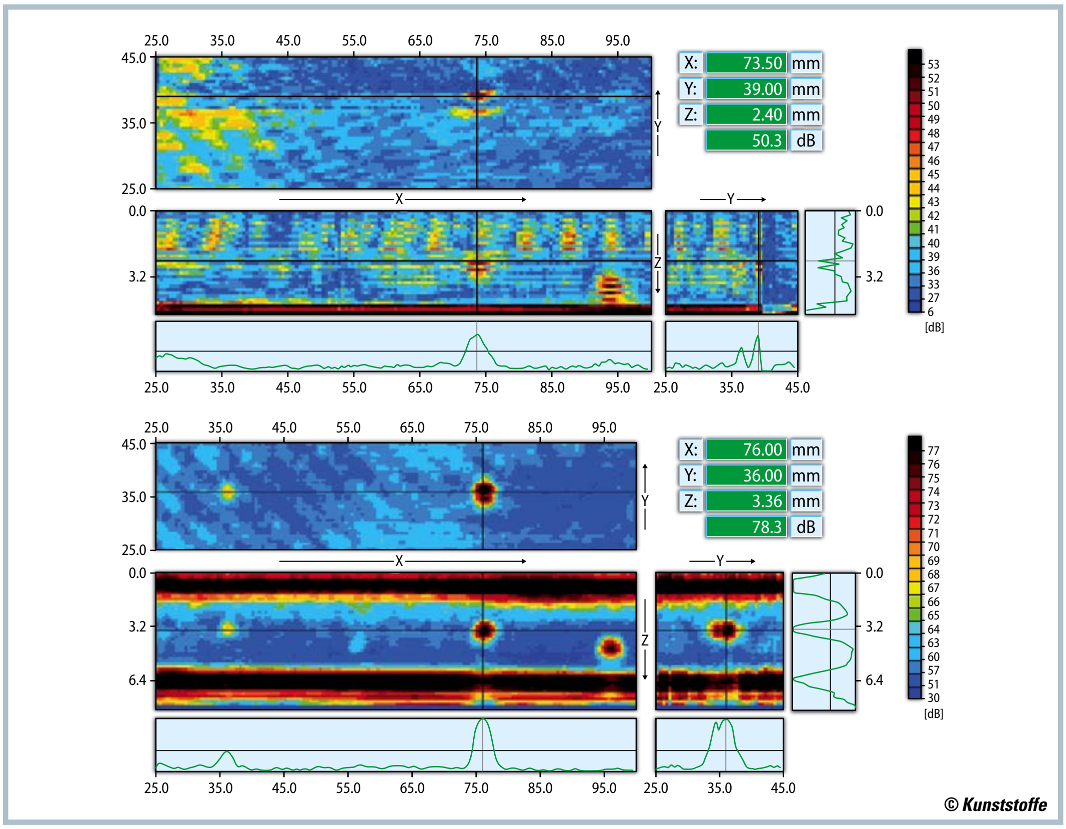

Fig. 9. Top: C scan and B scan by means of a conventional transducer; bottom: Matrix Array (figure: BAM)

the B image (**Fig. 9 top, center**) show strong scattering effects of the fiber bundles. When a matrix array is used (**Fig. 9 bottom**), the sound scattering can be significantly reduced by averaging from different beaming directions and the proof reliability can be greatly improved.

This makes it possible to generate tomography-like images, which significantly facilitate the interpretation of the component state. In **Figure 10**, impact damage on each of two different CFRP samples (bidirectional (**Fig. 10 left**) and unidirectional fiber orientation (**Fig. 10 right**)) is shown by ultrasound tomography. Besides the impact on the surface in the C scan, the conically propagating damage progression is also visible in the side views (B scans). It can also be seen that, in the sample with bidirectional fiber orientation, the inter- and intralaminar defects caused by the impact follow significantly steeper damage angles. The impact energy is thus less laterally scattered due to the orthogonal orientation of the fibers.

A very interesting alternative test method for many test problems is air-coupled ultrasound, since it does not need a coupling agent and the sound pulse is instead transmitted directly into the part via the air. At the IKT, various excitation configurations, such as transmission or pulse echo, are used. Air-coupled ultrasound scans allow the mechanical properties of a part to be positionally accurately imaged. **Figure 11** shows a schematic scan construction and the result of a delamination.

The worse acoustic adaptation between the solid and the air compared to water coupling makes extremely high demands on the sensitivity of the test systems. The field of transducer technology is therefore being intensively researched to make the advantage of contactless testing available for other complex testing applications.

Summary and Outlook

Non-destructive material testing (NDT) plays a key role in ensuring quality in production and during service by diagnosing manufacturing- and service-related damage at an early stage. As a result, NDT contributes significantly to technical safety and also makes a proactive contribution to cost efficiency by, through certified operational reliability, preventing premature exchange of components and system, and can prolong the service life of critical system components. However, the contribution to »

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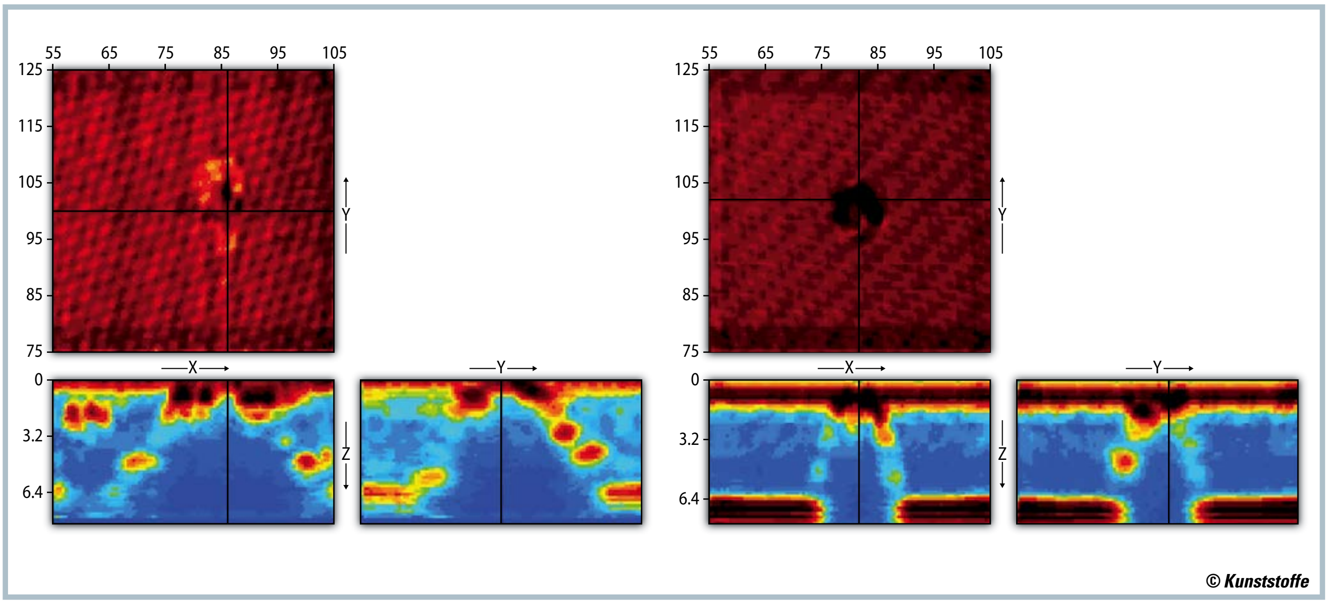

Fig. 10. C scan and B scan with side views from x and y direction (figure: BAM)

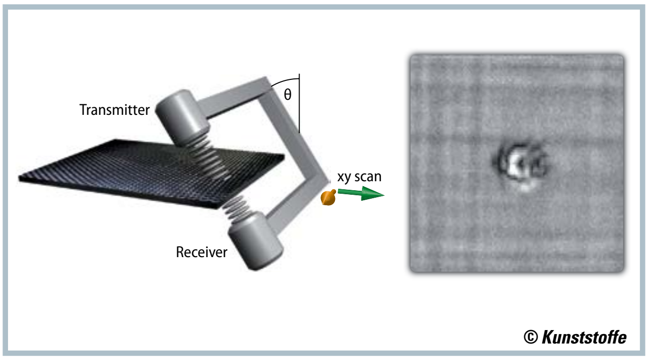

Fig. 11. Air-coupling ultrasound scan in transmission mode and measurement result

quality assurance made by the NDT process has to strike a balance between an additional cost factor during manufacturing and operation, and the degree of reliability that can be achieved in the quality. To be competitive, test methods must therefore not only become faster and more inexpensive In the face of increasing cost and time pressure, but also even more reliable.

Since one standard method does not exist, but processes usually have to be adapted to the test task, flexible handling and a clear range of different methods are necessary when one seeks a successful industrial NDT method. In particular, fiber-plastic composites and metal-plastic hybrid components pose new challenges to NDT, which until now have only been addressed for testing in large quantities. ■

BI-Power VH7000

Heavy-Duty Two-Platen Injection Molding Machine

Negri Bossi SpA, Cologno Monzese, Italy, has recently manufactured the third BI-Power 7000 tonne, the largest size in the popular two-platen series, ranging from 1,000 to 7,000 t and with shot sizes from 2,950 g to 149,799 g PS. This massive machine features a special twin barrel injection unit and co-injection nozzle, allowing a maximum shot size of 149 kg of PS.

To ease the mold change process, the machine is equipped with an automatic tie bar extraction device, which pulls the top, non-operator side tie bar through the fixed platen towards the injection unit. The controller has been upgraded to the new Powerlink Ethernet based system and features an enhanced operator interface that offers easier set up functions and a more intuitive user experience.

The third BI-Power VH7000 will be delivered to a customer in Portugal and used to produce very large containers for the refuse, logistics and agricultural industries. An important customer requirement was to have a machine that has an energy efficient design to allow economical performance. This has been achieved through clever use of hydraulic accumulators and electric screw drives, which also allow simultaneous operation of mold movements and screw recovery.

The third BI-Power 7000 tonne features a special twin barrel injection unit and co-injection nozzle, allowing a maximum shot size of 149 kg of PS (figure: Negri Bossi)

To the manufacturer's product presentation:
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