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Novel tests and inspection methods for textile reinforced composite tubes

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Methodology of research

ABSTRACT

Purpose: This paper describes innovative lightweight applications of fiber and textile reinforced polymers in aircraft, automotive and chemical industry.
Design/methodology/approach: This paper deals with modern test methods of braided composite tube specimens as basic elements of modern composites. The tubes subjected to strength tests under superposed compressive, tensile and internal pressure loadings, and tested by the acoustic emission method for damage detection.
Findings: For the quality assessment and here, especially for the verification of fibre orientations after manufacture, the X-ray method is an advantageous inspection method. For the identification of fracture modes, after uni- and biaxial mechanical test under tensile, compressive and torque loads as well under inner pressure loading the computer tomography CT is used. The acoustic emission to assess for damage detection in braided composite pipes, and mechanical loading. Moreover, from the applied techniques the information concerned quality of a manufactured specimen, damage propagation and determination the types of damages can be obtained.
Research limitations/implications: Those three methods assure very good and promising results having one limitation in case of volume of a tested sample, e.g in the CT device, an allowable diameter of an investigated tubular specimen amounts to 150mm.
Practical implications: Use of the methods resulted in improved efficiency of test process and analysis of GFRP tubular specimens.
Originality/value: The paper describes the new implicated test and inspection methods for textile reinforced composite tubes.
Keywords: Methodology of research; Braiding; Filament winding material characterization; Multi-axial state of stress; Composite tube

1. Introduction

Fiber reinforced polymers (FRP) offer a high lightweight potential for innovative applications. One of the most frequent problem encountered within the practical utilization of fiber reinforced materials is the verification of the manufacturing quality, which has a large influence on the mechanical properties of the material and thus on the structural behavior of lightweight components.

This problem increases even more in the case of hand made products, were man made mistakes are not always easy to overcome. The braiding technology offers here a very efficient, automated method for repeatable manufacture. For the quality assessment and here, especially for the verification of fibre orientations after manufacture, the X-ray method is an advantageous inspection method. Moreover, for the inspection of safety relevant components on-line inspection methods are required.

Especially, in the case of piping elements, which are applied in chemical industry, certain additional requirements must be considered, such as increased working temperature and aggressiveness of the interacting medium [1]. Some applicants of composite pipes already use inspection methods based on acoustic emissions (AE) to investigate the process of defect appearance and growth in pipelines made by winding technology. Those efforts are specially seen in the nuclear power plant industry as well as in oil extraction platform installations, were safety issues play a major role. In this paper the AE is used and assessed for damage detection in braided composite pipes, and mechanical loading [2].

For the identification of fracture modes after uni- and biaxial mechanical test under tensile, compressive and torque loads as well under inner pressure loading the computer tomography CT was used.

The experimental investigations have been performed on tubular specimen made of glass fibre reinforced polymers (GFRP) with a braided reinforcement structure. Tubular specimen has been chosen on the one hand because the braiding manufacture technology is similar to the industrial application and on the other hand because tube specimen does not show any edge effects, during testing known from flat specimen.

2. X- ray method for reinforcement analysis

X-Ray Radiography belongs to the Non-Destructive post-analysis techniques and is used to investigate the internal structure of the composite materials. It operates on the principle of dissimilar transmission of X-Rays through different materials, as it can be seen in figure 1. X-rays are also a form of electromagnetic radiation with 10^{-8} m – 10^{-12} m wavelength.

The output energy J_1 of an undamaged material is compared with the energy J_2 of a damaged specimen, giving indications of the damage surface size. The energy wave equations for J_1 and J_2 are depicted below[3]:

$$J_1 = J_0 e^{-\mu h}$$
$$J_2 = J_0 e^{-\mu(h-1)} \tag{1}$$

with J_1, J_2, J_0 energy of waves, and h- material thickness, and μ-damping coefficient, which depends on the density of the material and the atomic number.

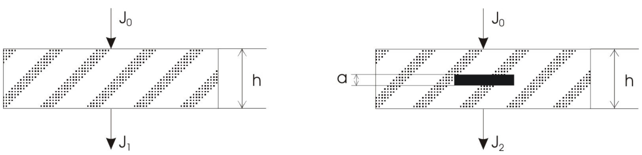


Fig. 1. Schematic illustration of energy radiation within the X-ray method

Figure 2 depicts the set up used X-ray to the examination of the specimen. One can clearly see the transducer, which_is used to convert the distribution of X-rays field intensity into a light image.

In the production process of braided GFRP tubular specimen, the textile material is put on a cylindrical core using braided sleeves method. In the following step, reinforcement structure is impregnated with heat-hardening resin. Here undesired fiber orientation might occur. After hardening of the resin in the drier, the fiber orientation lay-up and the porosity of the structure was investigated via X-ray analysis. The proper prepared pipes with fiber arrangement of ±45° have been placed on the radiological stand and few exposures were performed to verify the fiber arrangement.

Figure 3 shows two pictures of tubular samples with fiber orientation of ±45°. It can be seen that this tube is correctly fabricated and the desired fiber arrangement was retained after infiltration.

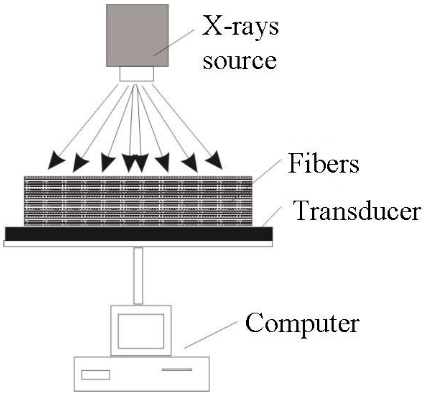


Fig. 2. Schematic illustration of experimental test stand for X-ray examination

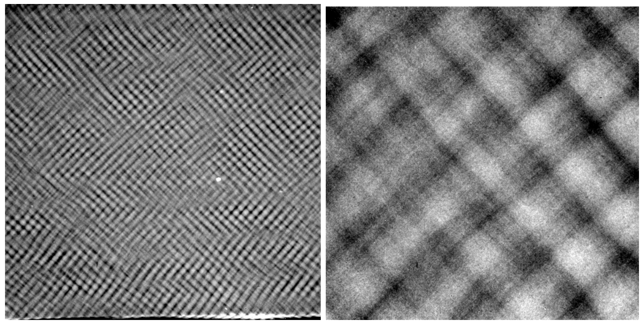


Fig. 3. Fibers arrangement of ±45°

3. Acoustic emission analysis of damage processes

For the acoustic emission analysis of the damage process in braided tubes internal pressure tests were performed with the help of rubber spheres acting as working medium. A heap of rubber spheres with a height of 100 mm was installed in the pipe. The rubber heap was then pressed bilaterally by steel pushers fixed in the clamped support of the test machine (Fig. 4). During this investigation, the machine imposed displacement as well as the gauge force at the clamp was recorded. Acoustic emission analysis was used to identify the degree of damage of the specimen.

The AE method measures the sound energy produced during the microstructure damage in the composite due to load increase. This damage is as composition of microcracks in the polymer matrix, adhesion and cohesion damage on the fiber-matrix interface, fiber breakage as well as local delamination caused by internal defects[4-6].

An example of the test set up with internal pressure for a tubular specimen is shown in Fig. 4. In this figure, the machine pistons can be seen compressing the rubber filling inside of the specimen as well as four acoustic sensors placed at the specimen ends. The heap of rubber spheres were coated with talc. Other lubrication methods were also tested, like silicon, suds, etc. The lubricant friction influence was found to be negligible.

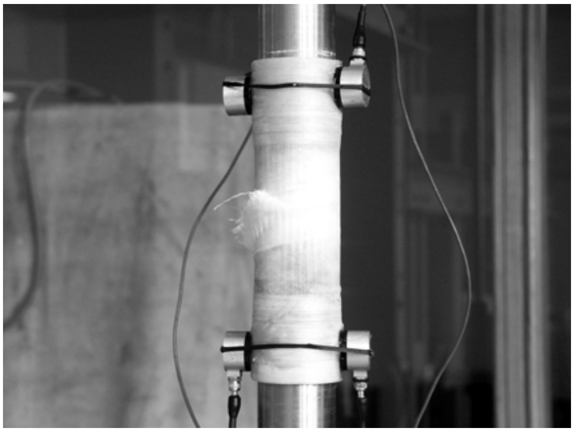
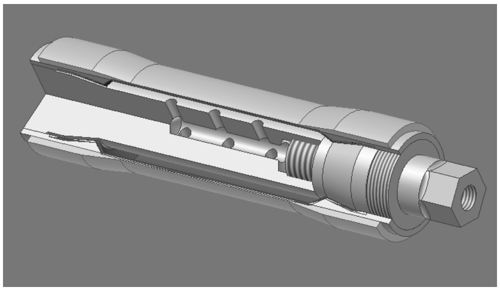
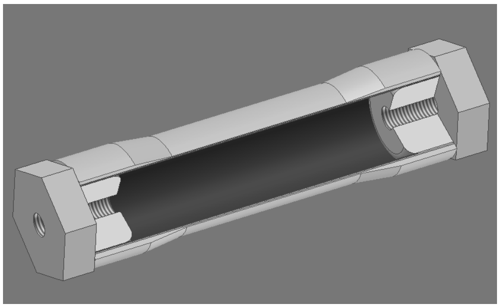


Fig 4. Tube specimen during tests with installed AE-system



MOD II



MOD III

Fig. 5. Sketch of internal pressure chamber for oil

Furthermore, tests were carried out using oil as working medium. The schemes of the used chambers used to produce internal pressure with oil are shown on figure 5. The pure internal pressure chamber configuration, MOD II, was characterized by the possibility of applying internal pressure without additional combined tensile and compressive loads. Further enhancements of this configuration enabled the application of internal pressure together with superposed compressive or tensile loads, as well as torque moments (MOD III). Here, all specimens being investigated with oil as working medium were tested with the chamber configuration MOD III [7,8].

Fig. 6 shows results of the acoustic emission analysis of a tubular specimen. The load was induced by a displacement controlled test (displacement over time, Fig. 6.3). The other diagrams are related with data measured from EA. Diagram 6.1, presents the amplitude of acoustic events over time, diagram 6.4 and 6.5 show the amplitude of acoustic events over specimen position. Diagram 6.6 shows RMS (Root Main Square) an indication of the measured signal. Based on the first investigations basic agreement of acoustic emissions and damage events were found. A more detailed analysis is currently performed[9,10].

4. Computer tomography for fracture mode analysis

X-ray computer tomography (CT) is a non-destructive testing method for diagnostic purposes. The basic principle bases on the examination of local differences in density of different materials. As well as in X-ray microscopy, the information about the sample's interior are obtained from the damping of the X-ray radiation transmitted thought the specimen. Such attenuated radiations are recognized by the detector. In contrast to the X-ray microscopy, CT analysis do not deliver a plain image, but after a filtered back-projection, a 3-dimensional space view of the examined specimen. Using the so called *cone beam tomography,* the incident X-ray has a 3D cone shape differently than the classic tomography beam, with its 2D triangular projection. It enables to collect data from more than a few square centimeters of area without moving the target object.

A cone-beam CT system mainly consists of four functional units, as a micro-focus X-ray tube, a precise sample manipulator, a flat panel digital detector and a computer for data acquisition and reconstruction. A schematic CT system is shown on Figure 7.

The tested specimens, with visible cracks, were subjected to the CT analysis, as shown in figure 8. The CT analysis was faster to perform and less complicated than the classic microscopic analysis. To reconstruct the 3D volume image it is necessary to use visualization and rendering software. Thanks to a virtual cutting, it is possible to carry out a detailed investigation of selected transverse longitudinal sections, as well as to visualize delamination between single layers.

Figure 8b shows a visible surface of inner tubular sample and the failure occurred during the strength tests. In the case of cylindrical samples, the analysis of microsection inside an object is difficult due to its small diameter.

Using CT, it is possible to analyze a section of the sample without physical contact. For example, slices of the specimen can be visualized without any additional cutting, which could induce further damage to the specimen. Fig. 9 shows delaminations on a cross section of the specimen. The specimen depicted in figure 9 was subjected to torsion loading, which caused considerable damage on the internal without much failure occurring at the outer layers. The internal layer cracks of the sample are well visible.

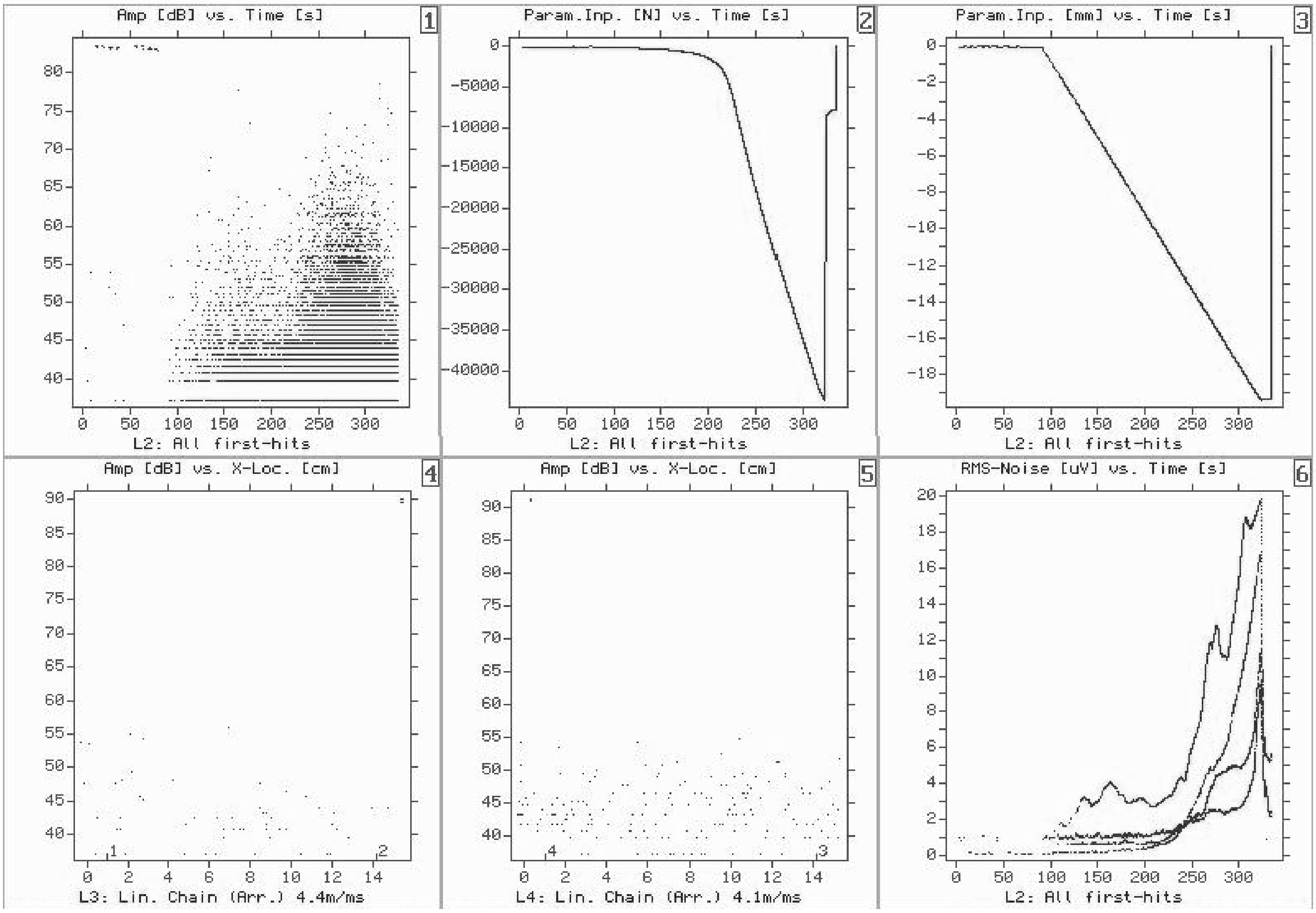


Fig. 6. Results of acoustic emission: 1) amplitude of acoustic events – time relation, 2) force, 3) displacement, 4) and 5) amplitude of acoustic events in specimen, 6) RMS

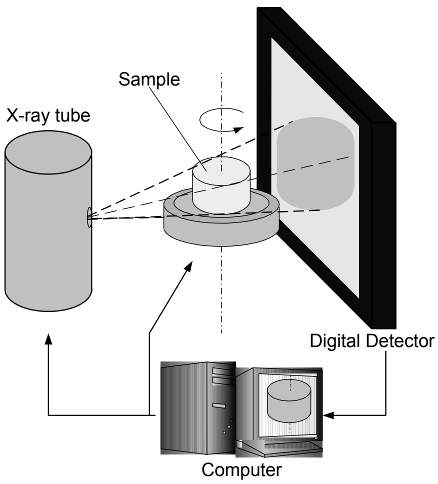


Fig. 7. Scheme of cone-beam CT set-up

Since the microscopic analysis is time and resource consuming and leads to additional damage of the investigated specimens, CT method arises as a very attractive alternative method to investigate damage after loading tests.

To evaluate the manufacturing quality and final damage of the composite tubular specimens, the following criteria have been used:

- visual evaluation inspection,
- evaluation of microsections in tubular sample cross-section (magnification 200 X),
- evaluation of fiber orientations using X-rays,
- measured AE during tests (amplitudes comparison, RMS and rejection of signal),
- comparison of breaking loads, gauge force (fracture loads),
- microsections analysis of tested samples applying the computer tomography.

5. Summary

It was found that the investigations under uni- and biaxial torsion, tension, compression and internal pressure loads on tubular specimens did deliver less results deviation than tests performed on flat specimens to the avoidance of edge and

a) b)

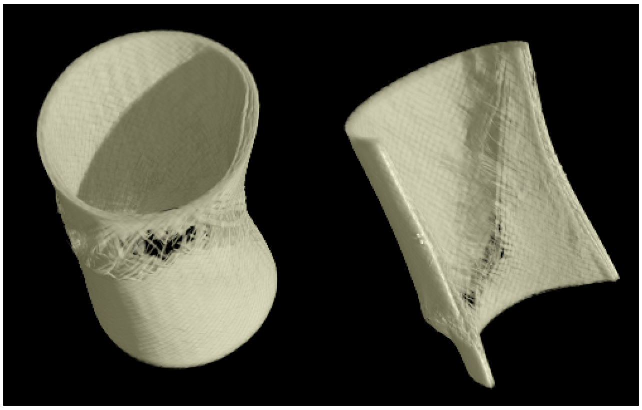


Fig. 8. Result of tubular sample reconstruction of a) sample b) view on the inner surface

clamping effects. The X-ray methods for the analysis of fibre orientations of reinforced tubular specimens delivered good results. A comparison of different test methods for internal pressure loading in tubular specimens was performed. The results showed that the kind of working medium has low influence on the damage and strength results. The AE analysis is an applicable method to detect different damages during testing. The computer tomography allows to accurate analyse virtual cross and longitudinal sections without the necessity of further damaging the specimens. The CT method helps to find defects on internal layers of composite materials. Further work shall be concentrated on the simulation of the tested specimens and on the comparison with the experimental obtained data.

References

[1] W. Blazejewski, P. Chmielarczyk, A. Langkamp, Pressure investigation of the composites pipes under complex load, XIX Sympozjum of Experimental Mechanic of the Solid Body, Jachranka 18-20 October 2000.

[2] W. Hufenbach, W. Blazejewski, L. Kroll, R. Böhm, M. Gude, A. Czulak, Manufacture and multiaxial test of composite tube specimens with braided glass fiber reinforcement, Jurnal of Materials Processing Technology 162-163 (2005) pp.65-70.

[3] S. Ochelski: Experimental methods for composite mechanics. WNT, Warsaw 2004.

[4] W. Hufenbach, L. Kroll, Laminated cylindrical shells under mechanical and hygro-termal loads., Advances in Engineering Software 23: PP. 83-88, 1995.

[5] W. Hufenbach, L. Kroll, R. Böhm, A. Langkamp, A. Czulak: Piping elements from textile reinforced composite materials for chemical apparatus construction. 12th International Scientific Conference "Achievements in Mechanical & Materials Engineering", Zakopane, 7.-10. 12. 2003, pp. 391-398.

[6] W. Hufenbach, L. Kroll; R. Böhm, A. Langkamp: Braided composite pipe elements for applications in chemical apparatus engineering. Chemie Ingenieur Technik, Vol. 76 (7), 2004, pp. 898-902.

[7] P. Zajac, W. Blazejewski, A. Czulak, R. Böhm: Investigation of composite pipe specimens for evaluation of the composite material properties. Polymer materials „Pomerania-Plast" 2004, Miedzyzdroje, 2.6.-4.6. 2004.

[8] L. Kroll, W. Hufenbach, Physically based failure criterion for dimensioning of thick-welled laminates Applied, Composite Materials, 4: 321-332, 1997.

[9] W. Blazejewski, Non-destructive pressure investigation of composite pipes, VI National Scientific Conference of Failure Mechanics, Kielce University of Technology, 62, Kielce – Ameliówka 22-24 September 1997, pp. 43-50.

[10] W. Chmielowski, Determination of material properties of long-fibre reinforced polymers, Master Thesis, ImiMT, Wroclaw University of Technology 2002.