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Ultrasonic Evaluation of Interconnecting Pipe Adhesive Joints in Glass Fiber Reinforced Polymer Pipelines

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Abstract
Steel pipeline structure is a proven technology for reliable transportation of oil and gas. Steel structures suffer several major disadvantages: corrosion, high costs of pipeline assembly procedure and time consuming expensive testing of welded sections. Pipelines made by glass fiber reinforced polymer (GFRP) composite materials on the other hand are relatively recent innovation and in the last few years have been found in an increasing number of pipeline structures built in. The present paper ultrasonic testing technique is developed in order to evaluate adhesive bonded joints of GFRP pipelines. Experimental samples containing artificial defects have been manufactured. Experimental set-up and the main results after evaluation are presented and discussed. Validation of the results show that the proposed technique is an attractive tool for the in-field quality assessment and structural integrity evaluation of adhesively bonded GFRP pipelines.

Keywords: glass fiber reinforced polymer, pipes, filament winding, pipe joints, ultrasonic testing, immersion technique

1. Introduction

Millions of kilometers of pipelines in Europe transport hazardous fluids. Over half of them are carrying gas, oil and oil derivatives. The majority of these pipelines are fabricated from steel pipes joined together by butt welds. Steel pipelines suffer corrosion over a period of time and are likely to leak hazardous products into the environment. Additionally, pipeline production costs are high and a very precise and costly welding procedure should be carried out in every 12 meters, followed by even more expensive radiography testing of many billions of but welds. In case of underwater transportation where corrosion is an important factor, stainless steel is used and the investments are much higher. Up-to-date solution to the problem is the use pipes made of corrosion resistant glass fiber reinforced polymer (GFRP) materials. Their corrosion and chemical resistance makes them particularly well-suited for general industrial service and chemical processing applications. Fiberglass pipes also provide environmental protection benefits [1 – 3]. However, the interconnecting pipe joints of GFRP pipelines also should be inspected by using non-destructive testing (NDT) methods [4, 5]. Inspection of the interfacial region of the adhesive bonded matched joints has significant practical importance by giving indirect indication for the adhesion strength and ability to reveal defects in the interface both during the production process and in-service. A number of methods are used for evaluation of the adhesive joints in GFRP products [6 – 8], but automatic ultrasonic inspection is one of the most promising methods because of high level of confidence, relatively low costs and possibility of in-field application.

Unfortunately, ultrasonic testing of adhesively joined composite laminates is much more complicated than the inspection of other adhesively bonded materials. The main problem is the high attenuation of the material and the scattering of the ultrasonic beam from the fiber reinforcing layers. The ultra-high level of porosity, typically found in GFRP lay-ups additionally increases the attenuation [9 – 11]. This necessitates the use of lower frequencies which leads to poor spatial resolution. At low frequencies the interpretation of the signals is

complicated because of the fact that the small thickness of the adhesive layers leads to overlapping of successive echoes. All these factors suggest that the right inspection parameters must be chosen in every specific case.
The aim of this study is to develop novel ultrasonic testing technique that is capable of assessing the quality and structural integrity of GFRP pipe adhesive bonded matched joints during the installation process and subsequently "in-service".

2. Experimental samples and equipment

For the current experiments two samples were tested. The samples are in the form of joined pipes with nominal outside diameter 159 mm, interconnected with adhesive bonded coupling. The pipes and the coupling are manufactured using filament winding technology using epoxy resin reinforced with glass fibers. The dimensions of the samples are presented on fig. 1. During the joining process some artificial defects were inserted in the adhesive layer of the samples. Type, size and position of the defects were unknown to the research team in order to carry out a blind test. A specially marked tape was fixed on the samples in order to establish the circular position of any indication registered during the inspection.

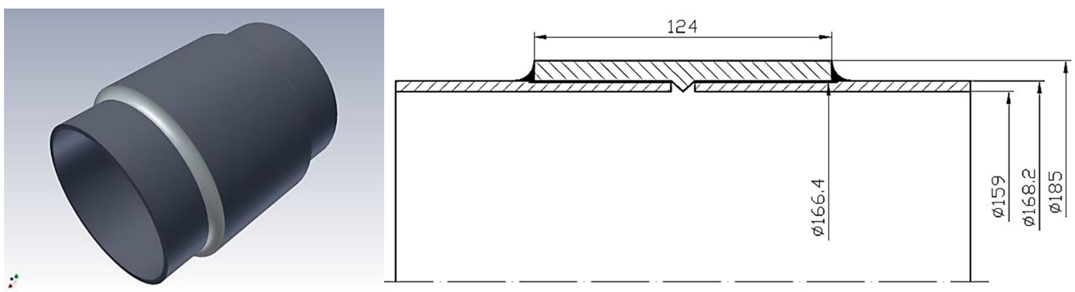

Fig. 1. 3D-view and drawing of experimental samples

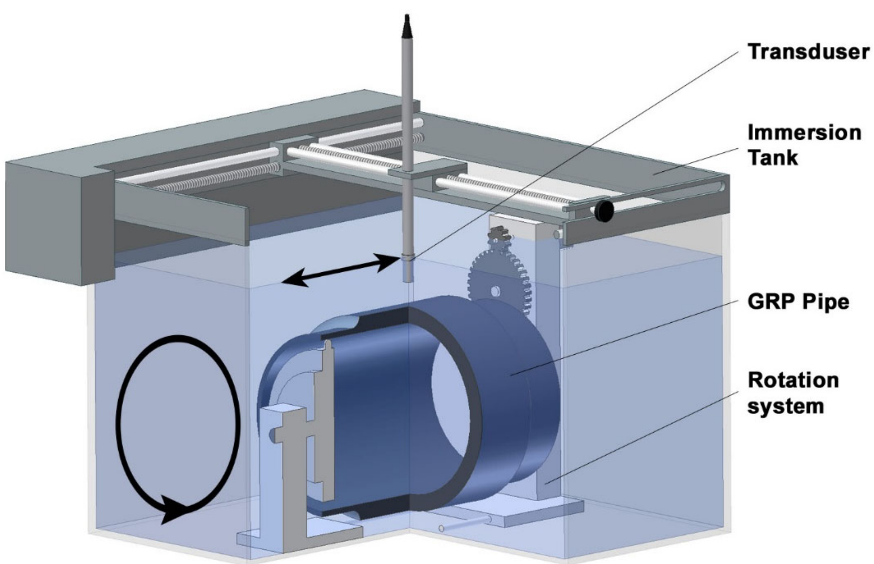

Fig. 2. Experimental set-up

The adhesive bonded area was tested using pulse-echo ultrasonic immersion technique. For the purpose a special pipe rotation mechanism was designed. The sample is mounted on the rotation system and both are placed in an ultrasonic immersion tank. Acoustic image of the whole bonded area was recorded by combining the rotation of the sample and the longitudinal movement of the transducer along the pipe's longitudinal axis. The resolution in longitudinal direction is 500 dpi and in circumference at the given pipe diameter is 100 dpi. The experimental set-up is presented in fig. 2.

The measurements were made using the following equipment: Ultrasonic Pulser/Receiver and 100MHz Analog to Digital Converter Board, Model PCIUT3100 (Manufacturer: US Ultratek, Inc., USA) and 1 MHz, 5 MHz and 10 MHz single element longitudinal wave immersion transducers with a 1/4 wavelength layer acoustically matched to water, spherically focused at 75 mm in water (Manufacturer: Panametrics, USA). From the recorded ultrasonic data A-, B- and C-Scans at different positions and time intervals were extracted. For all experiments the focal point was positioned at the outer surface of the coupling. The transducers were aligned to the normal of the pipe's surface to ensure maximum reception of the ultrasonic energy.

3. Results and discussion

After analyzing the preliminary results for all used frequencies it was concluded that at 5 MHz and 10 MHz only a portion of the coupling can be penetrated by the ultrasonic waves because of the very high attenuation of the material. At these higher frequencies no reliable results for the inspection of the adhesive layer were obtained. That is why the present work is concentrated on the results from a 1 MHz transducer only. On the other hand the use of frequencies below 1 MHz will greatly reduce the spacial resolution.

On fig. 3 is presented typical A-Scan of the zone where the pipe is bonded with the coupling. The first echo observed at time about 4 μs is from the top surface of the coupling. The second echo at time about 10 μs is from the adhesive layer. The third echo at time of about 16 μs is the second reflection echo from the adhesive layer. Echo from the inner surface of the pipe cannot be observed at the chosen gain of the receiver but at a greater amplification it can be registered.

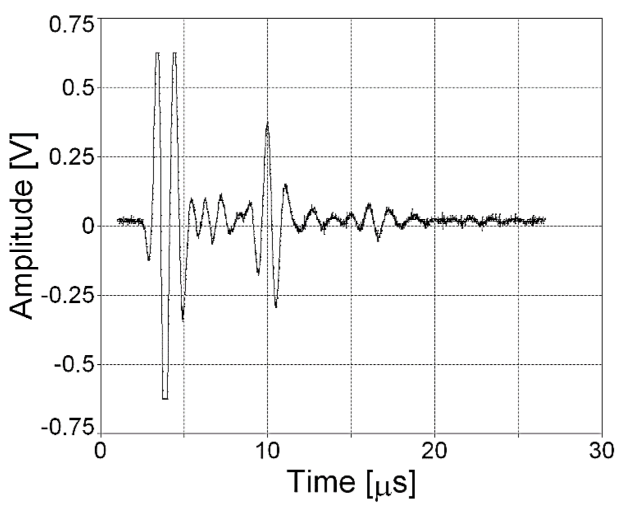

Fig. 3. A-Scan from the adhesively bonded area

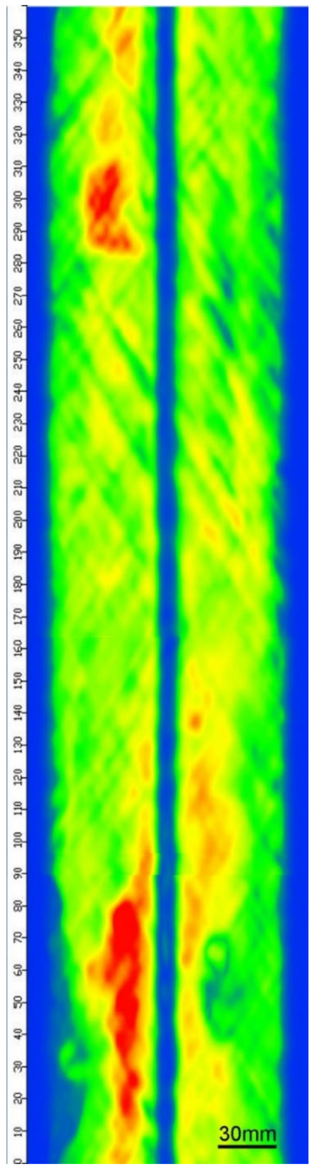

Fig. 4. Amplitude C-Scan of adhesive layer in sample 1

The velocity of longitudinal ultrasonic waves in the glass reinforced material of the pipes was measured and was estimated to be about 3200 m/s. Knowing the time of each echo and the velocity of the waves, the exact distance of every reflected echo can be determined. The distance between the echo from the upper surface and the echo from the adhesive layer is about 9 mm and the distance between the adhesive layer and the inner surface of the pipe is about 4 mm. These results correspond to the data given by the manufacturer.

For the experiment special software was developed in order to partly compensate the surface roughness and deviations of the geometrical shape and dimensions of the samples. Using this software the data in the C-Scans, extracted from the ultrasonic database becomes much clearer and reliable.

C-Scan was extracted for the first sample (Fig. 4). The vertical axis of the C-Scan shows the envelope of the sample with degree marks from 0˚ to 360˚. The horizontal axis corresponds to the longitudinal axis of the coupling. The amplitude of the reflected signals is color coded, red color corresponds to high amplitude and blue color corresponds to low amplitude. The blue colored central line is due to the triangular shape of the coupling at the center of its inner surface (see fig. 1). Practically, no reflected signal was received from this area. The prevalent green color of the C-Scan corresponds to the nominal bonding between the coupling and the pipes.

The amplitude of the red colored zones in the C-Scan is 16 to 18 dB higher than the amplitude of the green colored zones. Another specific area located between 40 and 70 degrees, predominantly colored in blue, is more complicated to interpret. In this area the Time of flight (TOF) C-Scan of the adhesive layer was extracted (Fig. 5). The change of the time of flight can be clearly observed.

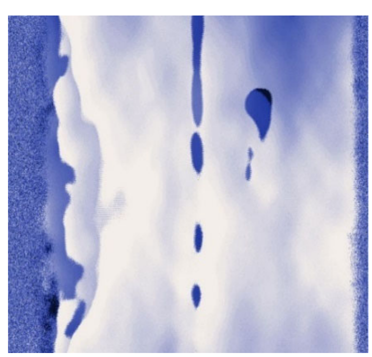

Fig. 5. Time of flight C-Scan of the same area in sample 1

For a precise evaluation of the time of flight intervals, a B-Scan at 65 degrees from the pipe circumference was extracted (Fig. 6). This B-Scan crosses both zones having anomalies – the red colored and the blue colored on the C-scan (Fig. 4). The horizontal axis of the B-Scan represents the longitudinal axis of the coupling. The vertical axis represents the ultrasound propagation time. The series of colored stripes at the top of the image corresponds to the surface echo. The two specific areas observed on the C-Scan are marked as "A" and "B". The area "A" is the red-colored area on the C-Scan, and "B" is the blue colored area.

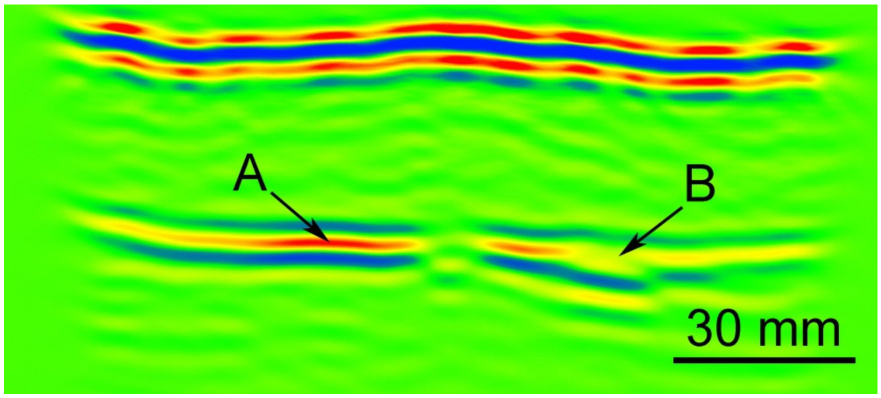

Fig. 6. B-Scan at 65 degrees mark of sample 1

For area "A" the TOF of the reflection corresponds to the inner surface of the coupling. Considering the high amplitude of this reflection, it can be concluded that this is due to the lack of bonding between the coupling and the adhesive layer. For zone "B" the TOF has higher value and thus the reflector must be positioned deeper in the adhesive layer.
After the ultrasonic experiments, sample 1 was cut into several sections for visual validation of the results. A microscopic image of section at 80 degrees of the pipe is presented on Fig. 7. In the C-Scan this section was visible as red-colored area with a high amplitude of the reflection. A complete lack of bonding can be observed on the image. The visually measured length of the debonding is 22.3 mm which corresponds to the length of the indication in the C-Scan image (21.8 mm).

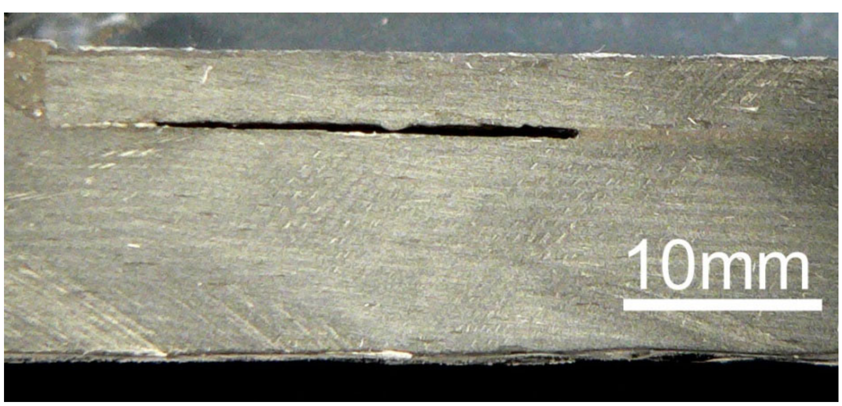

Fig. 7. Lack of bonding at 80 degrees

Another section from the pipe was cut at 65 degrees, the area shown on the B-Scan (Fig. 6). For a better presentation 12 photos were taken from different parts of the defect and combined mosaic picture was constructed. Fig. 8. shows presented a microscopic mosaic of the lack of bonding defect which corresponds to the area "A" in the B-Scan.

Fig. 8. Lack of bonding at 65 degrees

Fig. 9 shows a microscopic mosaic of the section shown as area "B" in the B-Scan. An image with larger magnification was acquired at the area marked with an arrow (Fig. 10).

Fig. 9. Foreign object between the adhesive layer and the pipe

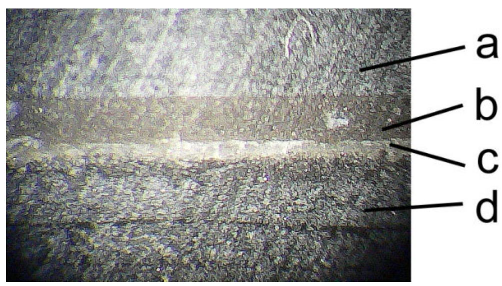

Fig. 10. Magnified picture of the foreign object

Four distinctive layers can be observed. Zone "a" is the parent material of the coupling. Zone "b" is the adhesive layer, zone "c" is some foreign material, and zone "d" is the parent material of the pipe. The layer in zone "c" may be some thermoplastic polymer or some rubber type polymer. The visually measured length of this layer is about 20 mm and the thickness is about 0.1 mm. The length corresponds to the ultrasonically measured dimensions. Ultrasonically measured TOF exactly corresponds to the position of this foreign material between the adhesive layer and the pipe material. Later the manufacturer confirmed that the conjectures were correct.

4. Conclusions

Immersion pulse-echo ultrasonic technique was used for quality inspection of adhesive joints in interconnected GFRP pipes. The results provided by the ultrasonic testing are confirmed by microscopic observations of the defective areas. The results obtained prove the applicability of the proposed technique for the registration of areas with poor adhesion or complete lack of adhesive as well as some installation process lapses. The sizes of the indications obtained ultrasonically and the optically measured defects coincide to a large extent.

For in-field application this technique can be developed further using phased array transducers which will increase additionally detection and sizing accuracy. For this purpose a special manual scanner equipped with integrated water manifold for couplant delivery has to be developed in order to perform circumferential inspection of the coupling. Furthermore, a dry contact phased array wheel probe could be used. Last solutions in this field guarantee high-quality, immersion-like ultrasonic testing. They require minimal couplant and pressure and provide excellent coupling and a strong signal, even in difficult scanning positions.

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