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X-ray imaging inspection of fiberglass reinforced by epoxy composite

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ABSTRACT

The goal of this work was to study the voids presented in bonded joints in order to minimize failures due to low adhesion of the joints in the industry field. One of the main parameters to be characterized is the porosity of the glue, since these pores are formed by several reasons in the moment of its adhesion, which are formed by composite of epoxy resin reinforced by fiberglass. For such purpose, it was used high energy X-ray microtomography and the results show its potential effective in recognizing and quantifying directly in 3D all the occlusions regions presented at glass fiber-epoxy adhesive joints.

1. Introduction

Much of the existing pipeline infrastructure is constructed from steel. Steel is strong, mechanically robust and relatively inexpensive. However, large sums of money are spent in order to reduce the exposure of steel pipelines to corrosive environments. One way to overcome this problem is to use a material with good corrosion resistance, such as Glass Fiber Reinforced Polymers (GFRPs), instead of steel. GFRPs represent an attractive alternative for pipelines subjected to severe internal or external environments in onshore or offshore applications [1].

Composite material is a combination of two or more separate materials in macroscopic state. Unlike metals, the building constituents of composite materials, namely fiber and matrix, still can be observed without magnification devices. Fibers in composite material act as reinforcement of matrix because fibers are usually stiffer than matrix. Matrix serves as a binder for fibers arrangement and also protects fibers from environmental effect and impact damage [2].

Matrix can be in the form of polymers, metals and ceramics. Two types of polymers are usually used, namely thermoplastic polymers and thermoset polymers. Epoxy, as one variant of thermoset polymer, is commonly used to bind carbon or glass fibers for its good dimensional stability [3].

Fibers act as structural materials to sustain loading since they have higher stiffness than matrix. When they are mixed with matrix, fibers are random in nature. A wide variety of fibers are available. Most common fibers used as reinforcement are glass (E-glass and S-Glass types), carbon (some forms of which are graphite) and Kevlar fiber. Glass fiber in combination with polymeric matrix (GFRP: glass fiber reinforced plastics) is commonly used for storage tanks and pipeworks [4].

The connections between the various parts of the ducts are made by quick lock bounded joints. In ship construction the need to join different materials, such as the bonding of the hull/deck, the sea chest, the portholes, the windshields, the panels of cabins, etc., leads to choosing increasingly the adhesive joints [5].

Adhesive joining is defined as the process of joining parts using a non-metallic substance (adhesive), which undergoes a physical or chemical hardening reaction causing the parts to join together through surface adherence (adhesion) and internal strength (cohesion). The significance of adhesive bonding as structure-joining technology is increasing because of its numerous advantages with other joining methods [6].

The defects which are most often found in Glass Reinforced Epoxy (GRE) pipe systems are lack of adhesive, disbonding and delaminations in bonded joints, which can only be detected through hydrostatic testing or in operational conditions due to induced vibrations. Most of the service failures in composite materials systems are due to mistakes made during the assembly stage [1,5–7].

When the adhesive comes apart or loses its adhesion power, pressure loss on the lines can occur, as well as oil leaks or oil

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contamination, which can result in productivity losses, environmental damages and even lethal accidents. Due to those reasons, there is an urge for inspection methods capable of assessing both the integrity and the quality of the adhesives used in such joints. Due to the difficulties and the high costs implied in interrupting commercial production processes, it is often required that non-destructive methods are employed for joint evaluation [1,5–7].

Currently, several non-destructive tests (NDT) are used in order to inspect bonded joints. General reviews of non-destructive testing of composite materials have been made in detail [8]. The main NDT techniques employed to provide more information about structural integrity, monitoring early stages of degradation and the reasons of failure include eddy current, acoustic emission, liquid penetrant, magnetic particle, X-ray radiography, neutron radiography, ultrasound and thermography. Not only one technology can be applied alone. The exploration of its advantages and disadvantages should be taken into consideration and they may be more or less suitable to a particular investigation depending on its specific questions. Eddy current, for example, can be used to investigate resin content although it is a non-conductive material. Some good correlation between resin content and a chosen eddy current parameter can be obtained [9]. Despite of that, this technique can be applied to detect surface cracks [10]. Many of the microstructural modifications also result in changes in the thermal properties of the material and thermography can be used to inspect polymer composite [11]. Ultrasound is one of the most versatile NDE evaluations. It is a nondestructive testing technique which uses high frequency sound energy to conduct examination and perform measurements. Many defects or microstructural variations result in changes of the acoustic attenuation and the speed of sound in composite materials. Investigation of delaminations, voids or inconsistencies in composite components can be common performed. That is why ultrasonic nondestructive evaluation is currently one the most popular methods used in-field for nondestructive evaluation of polymer matrix composites. Nevertheless this technique require suitable coupling and access both sides of the structures, in the case of transmission method. Another issue related to ultrasonic methods is that linear defects oriented parallel to the sound beam may go undetected as well as reference standards must be established and used to calibrate the ultrasonic equipment. However, no information about the flaw's depth in the specimen or inclusions such as trapped air can be gathered [12]. One of the major limiting factors is the lack of quantitative non-destructive techniques that are able to detect defects in the adhesive bond, such as poor adhesion. This is extremely difficult to detect using conventional ultrasonic techniques due to the fact that the bond strength is governed by a thin, often sub-micron, layer which is many orders of magnitude less than an ultrasonic wavelength [13].

In this context, the purpose of this paper is to develop inspection methodologies through digital imaging techniques capable of identifying and quantifying defects in bonded joints. For such purpose, high energy X-ray Microtomography and Computed and Digital radiographies were used.

A Computed Radiography (CR) system consists of a computer unit, CR scanner and phosphor imaging plate (IP). An imaging plate is a 2D ionizing radiation detector that utilizes photostimulable BaFX:Eu^{2+} (X = Cl; Br, I) in which, after radiographic exposure, latent image is formed. The process that allows images to be acquired by such plates is called photostimulated luminescence (PSL) [7]. When scanning preexposed IP in CR scanner, the latent image is transformed into a radiographic image by a red laser beam (λ = 680 nm), which is used to stimulate the phosphor particles, causing them to release the energy stored within them and convert it into visible light; this is PSL. The intensity of the PSL is directly proportional to the amount of X-ray photons absorbed by the storage phosphor. Such visible photons are collected by a light guide and transferred to the photomultiplier tube, where they are transformed into an electronic signal, which is amplified and forwarded to an analog-to-digital converter. As a result, the digital signals (expressed in pixels) form a radiographic image [14].

Digital radiography (DR) flat-panel systems with integrated readout mechanisms were introduced in the market at the end of the 1990s. Flat-panel systems, also known as large area X-ray detectors, integrate an X-ray sensitive layer and an electronic readable system based on TFT arrays. Detectors using a scintillator layer and a light-sensitive TFT photodiode are called indirect conversion TFT detectors. This electronic readable system allows an active readout process which is called active matrix readout [15].

TFT arrays are typically deposited onto a glass substrate in multiple layers, with readout electronics at the lowest level, and charge collector arrays at higher levels. Depending on the type of detector being manufactured, charge collection electrodes or light sensing elements are deposited at the top layer of this "electronic sandwich" [15].

Large area indirect conversion systems use scintillators such as cesium iodide (CsI) or gadolinium oxisulfide (Gd_2O_2S) as an X-ray detector. When the scintillator layer is exposed to X-rays the beam is absorbed and converted into fluorescent light [16]. The fluorescent light emitted during the X-ray exposure illuminates the photo-diode array freeing charge carriers (electrons or positively charged holes according to the design). The quantity of charge carriers accumulating at each pixel is proportional to the fluency of X-ray photons absorbed at that location [17].

Indirect conversion detectors are constructed by adding a-Si photodiode circuitry and a scintillator as the top layers of the TFT sandwich. The active area of the detector is divided into an integrated array of image elements and each element contains a photodiode and a TFT switch available for the readout process [15]. The output signal is then amplified prior to digitization and transfer to the system computer [17].

X-ray radiography inspection is commonly in the field. It is a versatile, speed and economy for any kind of application. However, computed tomography (CT) is required when becomes important the knowledge of 3D measurements are needed. CT is slow compared with CR/DR, on the other hand offers better accuracy and it is suited for off-line inspections [18].

It was shown that CT is a non-destructive technique that can be used in order to obtain 3D information of materials [19]. This technique is very helpful in material science since relationships between macroscopic properties and material microstructures are often necessary. In this sense, high resolution X-ray 3D computed microtomography (microCT) and CR/DR can be as a non invasive technology and open up a variety of applications.

MicroCT can be used to reconstruct interior structural details with a resolution on a scale of interest for such evaluation [20]. It is a powerful technique used to visualize and characterize the internal structure of objects. It is a non-destructive method that produces images of the internal structure of an object which does not need to be previously modified, i.e., the object inspected does not need to be subjected to a preparation method such as impregnation, thinning or polishing [21]. In this technique, contiguous sequential images are compiled in order to create 3D representations that are digitally processed to obtain relevant quantitative geometric and/or morphologic parameters, depending on the focus of the investigation [22]. The great advantage of microCT is that quantitative information, such as, volume, size, shape, distribution and anisotropy of bonded joints can be obtained through the entire 3D volume of the specimens. In this context, the evaluation of epoxy fiber-glass microstructure of the adhesive joints can be made via microCT in order to obtain a 3D interpretation.