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Automated detection and quantification of hidden voids in triplex bonding layers using active lock-in thermography

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ABSTRACT

This paper presents an automated hidden void detection and quantification technique for inspecting triplex bonding layers in liquefied natural gas (LNG) carriers using active lock-in thermography. Hidden voids are first detected and visualized by an amplitude image and a series of binary image processing. Then, the sizes of the detected voids are quantified using an empirical mapping function, relating the detected void sizes to the void sizes obtained by an independent X-ray testing. The performance of the proposed technique is blind tested using two triplex specimens. The experimental results reveal that the hidden voids can be successfully detected and quantified.

1. Introduction

Liquefied natural gas (LNG) has been playing a significant role in global energy markets due to its ease of storage and transportation as well as its eco-friendly nature. Along with such trend, there are also increasing demands for building highly robust insulation structures for LNG carriers [1–3]. Among various carrier types, Mark III type membrane LNG carrier is one of the most popular LNG carrier types, of which storage tanks are protected by several sealing barriers as shown in Fig. 1 [4–6]. The primary barrier made of stainless steel (SUS) is directly in contact with LNG containment in cryogenic conditions ($-162\,^{\circ}$C) and resists contraction stresses and sloshing loads. The secondary barrier, called triplex bonding layer (hereafter, triplex), is composed of three composite layers: (1) a flexible secondary barrier (FSB), (2) an epoxy/urethane-based bonding layer and (3) a resin-based rigid secondary barrier (RSB). The thicknesses of FSB and RSB layers are both 0.72 mm, and the thickness of the glue bonding layer varies from 0.2 mm to 1.2 mm. FSB layer further consists of a 0.63 mm-thick weaved glass cloth, a 0.07 mm-thick aluminum sheet and a 0.02 mm-thick rubber bonding film between them. In RSB layer, the same types of an aluminum sheet and a glass cloth used in FSB layer are bonded to each other within the resin in a pre-impregnated state. Due to the variation of the thickness of the glue bonding layer, the total thickness of the triplex system varies from 1.64 mm to 2.64 mm. The exact components and details of the layers are not revealed due to the confidentiality of the triplex. Because liquid adhesives are used to attach these triplex layers, voids can be easily formed within the bonding layer. The hidden voids can compromise the tightness of the secondary barrier [5,8,9], and result in catastrophic explosions if not properly mended. Therefore, it is critical to inspect and control the tightness and quality of triplex during its installation process. The current industry guidelines require any triplex section including voids larger than 8 mm to be repaired [5,7].

Currently, inspectors need to examine every single triplex manually by rubbing the surface of triplex with a metal round stick to find hidden voids inside the glue of the bonding layers [5]. The round stick is rubbed on the surface of FSB with sufficient pressure so that the void profile can appear on the FSB surface. This manual inspection has several limitations: (1) It is labor intensive and highly time-consuming for large area inspection including vertical walls and ceilings; (2) The manual inspection results are highly subjective depending on individual inspectors, and many of these trained inspectors are retiring and/or getting close to their retirement; (3) Additional surface defects can occur while the manual inspection because of its contact nature (rubbing with high pressure); (4) It is difficult to quantify the void size although it is absolutely necessary to meet the industrial

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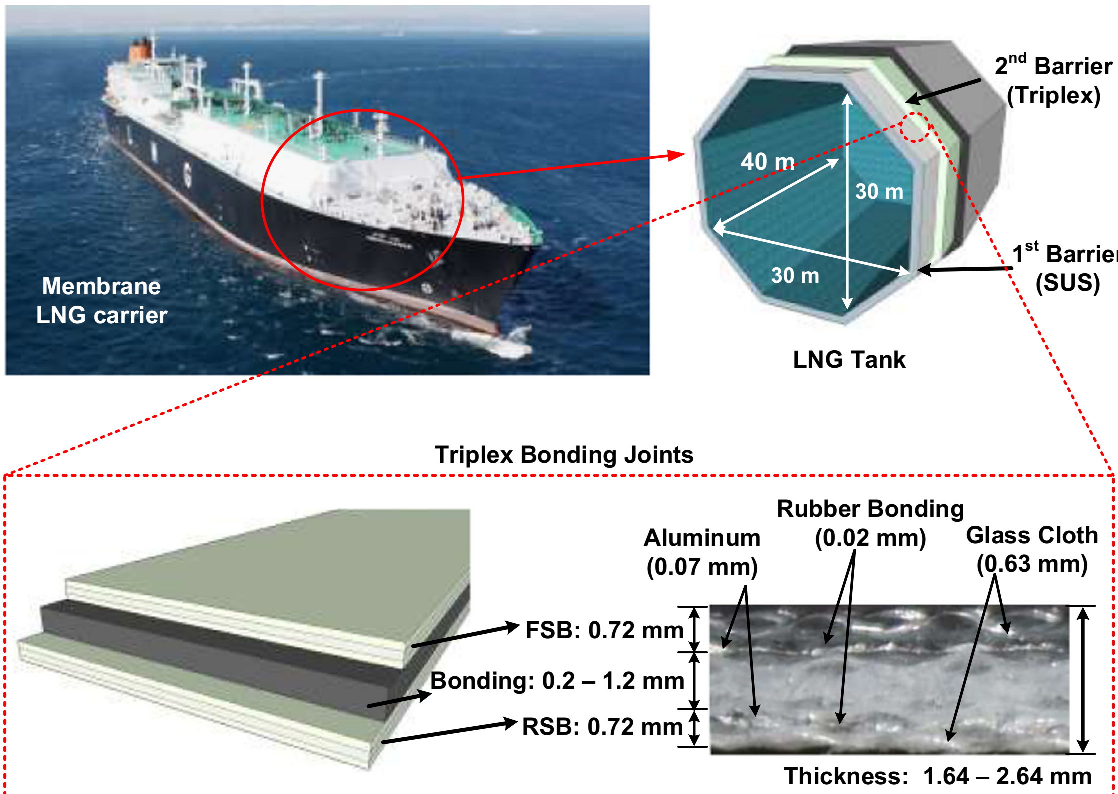

Fig. 1. A membrane LNG carrier [6] and the schematics of a Mark III type LNG cargo tank and triplex bonding layers. A single membrane LNG carrier normally contains 4 LNG tanks.

guidelines. These shortcomings of the current manual inspection necessitate the development of an automated hidden void detection and quantification technique.

To date, active infrared (IR) thermography technique is proven to be a promising tool for detecting defects in composite structures owing to their noncontact, nonintrusive and rapidly deployable natures. Pulsed, lock-in and frequency modulated thermography techniques are among the most widely accepted active IR thermography techniques [10–14]. These active IR techniques use external heat sources such as halogen lamps to create thermal waves through the thickness direction of target structures, thus making it possible to distinguish differences in heat transfer characteristics between defect and intact areas. However, the halogen lamps tend to non-uniformly heat the target surface, resulting in false alarms around unevenly heated regions [15]. Furthermore, the application of the conventional active IR thermography techniques to the triplex is challenging. The heat exposed on the top FSB layer cannot easily propagate through the thickness direction of the triplex because of the significant mismatch of thermal impedance and thermal contact resistance between two triplex layers.

In this study, an improved active lock-in thermography is applied to the inspection of a newly developed triplex system so that hidden voids in the triplex can be automatically detected and quantified. First, an improved amplitude image is extracted from raw thermal images after compensating the non-uniform heating of triplex caused by halogen lamps. Second, a series of binary image processing is performed to clearly discern defects from the intact areas in triplex and to remove unwanted noise components. Then, the void size is estimated using an empirical mapping function obtained by matching the void size initially estimated by the proposed detection technique to the void size validated by an X-ray. Finally, only the voids, whose final estimated sizes are larger than 8 mm, are visualized as defects.

The uniqueness of the proposed technique lies in that (1) a fully automated lock-in thermography technique is developed for detecting and quantifying hidden voids in triplex, which are extremely difficult to detect using conventional thermography techniques; (2) only hidden voids larger than the allowable void size are quantified and visualized; (3) because of the noncontact and nonintrusive natures of the proposed technique, large areas can be rapidly inspected without damaging triplex; (4) the inspection unit can be potentially mounted to the automated installation vehicle, which is currently in use for triplex installation, for real-time inspection and reduce the inspection time and costs substantially.

This paper is organized as follows. First, the working principle of the active lock-in thermography technique is described in Section 2. Then, the proposed hidden void detection and quantification algorithm is developed in Section 3. In Section 4, real void defects in two triplex specimens are detected and quantified using the proposed technique. This paper concludes with a brief summary and discussions in Section 5.

2. Active lock-in thermography

Here, the basic working principle of the lock-in thermography technique is described. First, a heat source periodically modulated at a single frequency component, so called “lock-in” frequency, is used to heat the surface of a target structure [10,11]. Then, thermal waves propagate through the thickness direction of the specimen based on a temperature gradient-induced heat conduction phenomenon. Eq. (1) represents the resulting temperature profile $R_i(t, z_i)$ at the ith layer of a multi-layer plate structure with a finite thickness, when the top surface is repeatedly heated with a lock-in