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Assessment of test methods for a cryogenic liquid containment system

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ABSTRACT

This paper presents a study demonstrating the selection and use of adhesive joint test methods for the design and validation of an adhesively bonded, foam-composite membrane, cryogenic insulation system for the marine transportation of liquefied natural gas (LNG). The study considered the performance of epoxy and polyurethane adhesives under ambient and sub-zero operating temperatures. Double-lap, sandwich panel and double cantilever beam (DCB) joint tests, essential in "calibrating" the interpretation of finite element analysis (FEA), were performed along with FEA in order to assess the stress states (in-plane, peel and shear stress) in the adhesive layer that, under defined loads and extensions, are comparable with the stress levels in the LNG container under service conditions.

The study reinforces the view that the presence of barrier film substrates has a major effect on performance, and that the critical state of stress for the integrity of the flexible composite barrier film (FSB) to rigid composite barrier film (RSB) bond in the cryogenic containment system is the tensile peel stress at the ends of the joint. Sandwich panel tests conducted using the two adhesives indicate that failure tends to occur when the peel stress exceeds the tensile strength of the bulk adhesive with the polyurethane adhesive exhibiting more robust adhesion properties than the epoxy with consequences for future design of LNG containers.

1. Introduction

Transportation of liquefied natural gas (LNG) is recognised as an efficient means of distributing energy over long distances, however the relatively high cost associated with production, and the need for expensive cryogenic containment systems for storage and transportation has until recently hindered the widespread commercial use of LNG [1]. Storage and transportation of LNG requires large and energy efficient containment systems (i.e. low energy loss) that can withstand a cryogenic temperature of −161.5 °C under atmospheric pressure. The emergence of new technologies, such as membrane containment systems (adhesively bonded), for storage and transportation purposes has enabled LNG to become more competitive as a means of energy distribution [2,3]. The membrane containment system used in carrier ships (sea tankers) is designed to protect the ship's hull from the low temperature of the LNG by providing a seal to contain the LNG, support the pressure from the cargo or ballast, and adapt to the wave induced deformation of the ship. Membrane containment systems employed in sea tankers consist of two insulation barriers (prevention of LNG boil-off caused through heat ingress through the ship hull) and two tightness barriers (protection of the ship hull from low-temperature brittle damage) [4–9]. The insulation barriers consist of a primary barrier (directly in contact with the LNG) and a secondary barrier designed to prevent the LNG from contacting the ship hull in the case of failure of the primary barrier (see Fig. 1) [8]. Both the primary and secondary barriers experience severe thermal stress variations during loading and unloading of LNG with the temperature of the secondary barrier on cooling extending below −100 °C (or −161.5 °C in the event of primary barrier failure) and rising to ambient temperature after unloading.

The insulation system has to be able to contain the cargo while sustaining the displacements and stresses arising from large temperature changes (on filling and emptying the tank) and wave motion transmitted from the hull (via mastic pads). The International Gas Carrier (IGC) code [10] recommends that the secondary barrier should be designed to contain a leakage of liquid for a period of at least 15 days (N.B. Containment systems used for transporting LNG in sea tankers can contain thousands of cubic metres of liquefied gas). Adhesively bonded joints offer many benefits for applications, such as membrane containment systems for LNG. The major advantages for the application are: (i) capability of joining dissimilar materials, (ii) distribution of load across a relatively large area reducing the risk of damage to substrates, (iii) facilitating the flexing and extension of joints to accommodate thermal expansion, (iv) adhesive provides a liquid tight seal to contribute to the barrier, (v) adhesive can be used to

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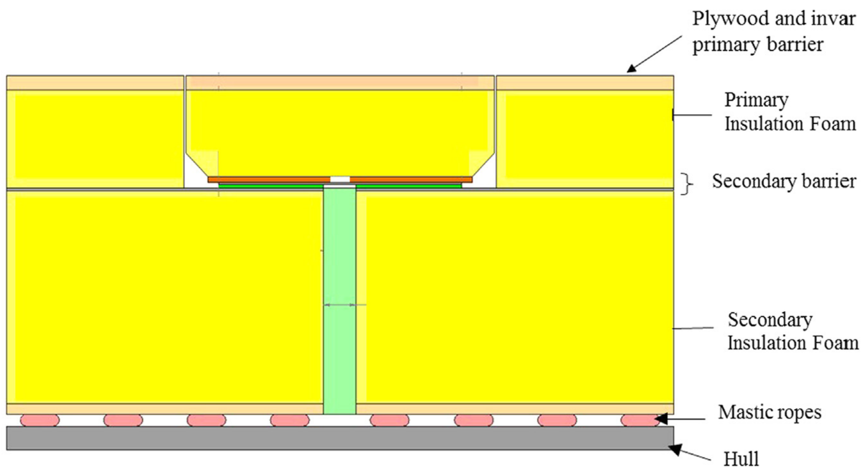

Fig. 1. Schematic of insulation membrane system (courtesy of GazTransport & Technigaz).

fill gaps in order to create smooth and level surfaces and (vi) provision of good fatigue resistance. As with all structural joint technologies, there are some disadvantages and risks arising from adhesive bonding that need to be understood and managed. A high degree of quality control is required. The key risks include: (i) poor joint design – failing to account for the adhesive performance, (ii) surface contamination and poor surface preparation resulting in low adhesion strength, (iii) poor joint manufacture and (iv) loss of joint performance through extended exposure to hostile chemicals and/or long-term loading. It is essential that design and manufacturing procedures for the bonded system should consider and minimise these risks (see [11–17]).

The manufacture of a cryogenic containment system for transporting liquefied gases presents many challenges in design and fabrication. The process through materials selection, design validation and quality assurance testing demonstrates the need for different types of adhesive joint testing to meet different requirements (i.e. repeated thermal shock, fatigue loading and subcritical impact loads) [8,9,18]. Prototype testing of full-scale components is desirable to validate designs, but often may not be possible owing to the size of the structures. In such situations, representative joint tests are used in combination with finite element analysis (FEA) to validate the design. This paper presents a study demonstrating the selection and use of adhesive joint test methods for the design and validation of an adhesively bonded, foam-composite membrane, cryogenic insulation system. Double-lap, sandwich panel and double cantilever beam joints were mechanically tested and three-dimensional (3-D) FE analyses were undertaken in order to assess stress states (in-plane, peel and shear stress) in the adhesive layer that, under defined loads and extensions, are comparable with the stress levels in the LNG container under service conditions. The study, undertaken by the National Physical Laboratory (NPL) for GazTransport & Technigaz (GTT), considered the performance of room temperature curing epoxy and polyurethane structural adhesives under ambient and sub-zero operating temperatures.

2. Design and FEA modelling of membrane insulation system

The membrane insulation system consists of two layers of insulated foam (rigid polyurethane foam) separated by a rigid composite secondary barrier film (RSB) Triplex bonded to the bottom layer of the foam and subsequently for most of the membrane to the top foam layer (see Fig. 1). The top surface of the foam is bonded to plywood that is attached to an invar layer that provides the primary barrier. At regular intervals there are expansion gaps between the panels to allow for movement – these gaps are bridged by a top-bridging pad (TBP), to which a flexible (rubber-based) composite barrier film (FSB) Triplex is bonded. The TBPs are spaced at regular intervals (approximately every metre) along the container wall. The bonds between the flexible layer covering the TBP and rigid layer covering the lower layer of foam are critical to the structural performance. The secondary barrier film provides a back up to the primary invar barrier film and needs to contain the liquid gas in the unlikely event of primary barrier failure. The assembly is attached to the inner hull of the vessel by mastic ropes.

Global FE models of the ship and insulation system, and representative bonded joint elements, were analysed at GTT to provide predictions of temperature distributions and local forces/deflections acting on the bonds. Stress analyses and material property data measurements were repeated at NPL, at the behest of GTT, as part of a study to investigate the effect of more realistic boundary conditions and provide more accurate descriptions of materials behaviour. Although the repeat analyses produced slightly different stress and strain levels in the bonded layer, the stress states calculated in the various bonded joints were very similar to the findings of GTT. These predictions formed the boundary conditions for more detailed analyses of the bonds, thus enabling the stress in the adhesives and barrier films to be calculated.

Stress in the adhesive layer results from differential thermal contractions of the different materials used in the insulation system and deformations resulting from the deflections (hogging and sagging) of the hull. Consequently, stress analysis of the membrane containment system was carried out to determine the stresses produced by service loading, which included ballast loading and loading from wave action. Calculations have shown that wave action is the harshest loading condition and can be represented by the application of a specific tensile displacement to the FE mesh in the direction of the vessel length. The container wall is cooled to -100 °C and a remote displacement is applied to simulate service conditions.

In order to ensure safe operation of the bonded region under these stress levels (i.e. container wall values) measurements have been carried out on joint specimens in which the stress states (i.e. in-plane, peel and shear) that, under defined loads and extensions, are comparable with the stress levels encountered in the bonded region of the container walls under service conditions. The joints chosen were the sandwich panel and double-lap joint. The double-lap joint, which produces a stress state comparable to the