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Effects of cryogenic thermal cycle and immersion on the mechanical characteristics of phenol-resin bonded plywood

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ABSTRACT

The main objective of the present study is to investigate the performance degradation of the plywood used in a liquefied natural gas (LNG) cargo containment system (CCS). A plywood sheet features an odd number of thinly layered wooden plies bonded perpendicularly to the previous layer to give it a very strong and durable structure. Owing to this strong point, plywood is applied to a variety of interior and exterior applications. Above all, it is widely adopted as insulation panels in an LNG CCS owing to a high stiffness with low density and its superior mechanical capabilities. As an insulation material of an LNG CCS, plywood is constantly exposed to repeated wave-induced thermal variations caused by the loading (−163 °C) and unloading (20 °C) of LNG during general operating periods of 25 years on average. Therefore, the effects of cryogenic-level thermal loads on the material characteristics of plywood must be analyzed with respect to the design and safety aspects of LNG CCSs. In the present study, the influences of the estimated thermal load, testing temperature, and grain orientation on plywood adopted in an LNG CCS are investigated. In terms of safety and design, the repeated thermal loads in a LNG CCS must be considered because the modulus of elasticity (MOE), tensile strength (TS), and modulus of rupture (MOR) are degraded by thermal treatments, such as cyclic thermal-shock and cryogenic immersion.

1. Introduction

Compared to other carbon-based energy resources, such as crude oil and coal, natural gas (NG) has become favored as an environmentally friendly fuel for reducing the problems caused by greenhouse-gas-induced global warming because of its low levels of greenhouse-gas emission. Greenhouse gases, such as carbon dioxide, water vapor, and methane, stop heat from the Earth escaping into space. If the effects of greenhouse gases continue to increase, it could lead to global warming and climate change. The combustion of NG emits almost 30% and 45% less carbon dioxide than crude oil and coal, respectively. In past decades, however, the NG market was regionally isolated with limited technical facilities for transporting significant amounts of NG across oceans because the storage and transport of NG in a gaseous state requires an enormous amount of space [1–3]. However, liquefying technology for NG has enabled its cost-effective commercialization on the global energy market with reasonable prices because liquefied natural gas (LNG) takes up to 630-times less space than other gaseous states [4–6]. Therefore, this clean energy has become the world's fastest-growing fossil fuel with a consumption of 3200 billion cubic meters in 2010, which is expected to increase to 5239 billion cubic meters in 2040 [7]. Increasing demand for NG has led to an increase in demand for LNG carriers used in the shipping industry. LNG vessels have specialized cryogenic handling equipment and cargo containment systems for carrying LNG cooled to −163 °C. Generally, LNG carriers are classified into membrane tank systems and independent tank systems depending on the shape, capacity, and type of insulation system used for cargo containment [8]. Recently, membrane type LNG carriers have become preferable owing to their reasonable prices and practical use for cargo containment space.

Fig. 1 shows the two main cargo storage systems used for a membrane-type LNG tank with regard to the insulation materials and structures, i.e., MARK III and NO96. These two kinds of cargo containment systems consist of three different parts: a primary barrier, an insulation panel, and a secondary barrier. For MARK III, the primary barrier, which is in direct contact with LNG, is composed of a corrugated stainless steel membrane with a 1.2 mm thickness for preventing thermal deformation caused by the loading (20 °C) and unloading (−163 °C) of LNG. In addition, the insulation panel is composed of adhesively bonded polyurethane foam and plywood to create a light-weight structure. Polyurethane foam

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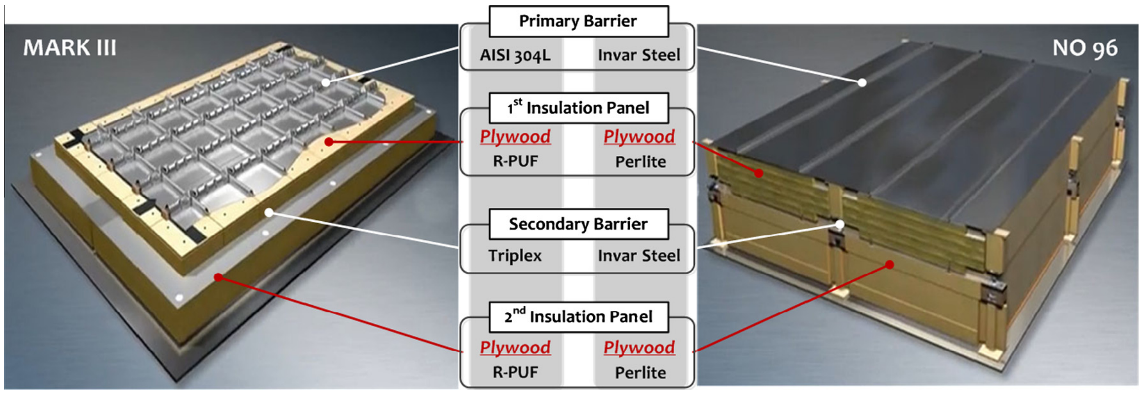

Fig. 1. Schematic diagram of MARK III- and NO96-type LNG insulation systems (www.gtt.fr).

and plywood have a low thermal conductivity and high stiffness with a low density, respectively. In addition, the secondary barrier, called a triplex, is composed of a metal composite sheet located between two-layered insulation panels, and plays an inevitable role in keeping the liquid tight for a period of 15 days in the event of a primary barrier failure. For the NO96, the primary and secondary barriers are based on two identical membranes made of 36% nickel steel alloy (Invar steel) with a very low shrinkage coefficient of approximately ten-times less than that of general steel. The insulation panel consists of a grillage structured plywood box filled with perlite, which is an insulation material based on expanded silica. In summary, MARK III and NO96 adopt different structural materials to insulate the cargo containment system in an LNG vessel. However, there is only one type of insulation material used for both MARK III and NO96 LNG cargo containment systems, i.e., plywood.

Plywood is the main structural material used in a variety of interior and exterior applications, and is created by an odd number of thinly layered (from 1 to 3 mm) wooden plies perpendicular to the grain orientation of the previous layer, which makes it a very strong and durable structure [9]. With such features, the mechanical properties of plywood, such as the force–displacement, stress–strain relationship, and failure mechanism, are dependent upon the surface-grain orientation [10,11]. Therefore, the grain orientation must be considered when investigating wood or wood-based composite materials. In an LNG cargo containment system, the plywood used is constantly exposed to cryogenic environments because it is in direct contact with the primary barrier. It experiences repeated temperature variations along with the loading (−163 °C) and unloading (20 °C) of LNG for a ship's general operating period of 25 years. For this reason, the operating conditions of LNG-based applications, such as cyclic thermal-shock and cryogenic immersion, should be considered when investigating the material characteristics and performance degradation of plywood-based composite materials.

Over the past few decades, several studies have reported the effects of thermal treatments on the characteristics and performance degradation of wood-based materials. Koretelinen et al. investigated the effects of the heat-treatment temperature (from 70 to 230 °C) on the water-absorption behavior of wood-based composite materials. Their results showed that the moisture content of the specimens was increased with increasing exposure time and decreasing heat-treatment time [12]. Wang and Cooper investigated the moisture content of woods treated with palm oil, soy oil, and slack wax for different processing times and temperatures. The thermal-treatment temperatures and times ranged from 100 to 220 °C and 2 to 4 h, respectively. They found that the thermal treatment time decreases the moisture-absorption equilibrium and increases the dimensional stability [13]. Bengtsson et al. performed bending tests on heat-treated wood that was treated in a steam chamber, which has a maximum temperature of 220 °C. The results of the bending tests showed that the heat-treatment of wood beams reduces the bending strength and bending stiffness by approximately 50% and 3.5%, respectively [14]. Winandy and Krzysik evaluated the effects of heat treatments on the moisture absorption, mechanical properties, and durability of wood composites. For most of the mechanical properties, very little degradation occurred until the temperature exceeded 150 °C [15]. Arriaga-Martitegui et al. investigated the mechanical properties of radiata pine plywood that was fabricated in accordance with European procedures for structural use. The strength and elasticity modulus of the plywood layers were determined under bending, tension, and compression. In addition, they proposed a calculation method for estimating some of the mechanical properties of plywood [16].

Although a significant amount of useful research results can be found from the literature, most have focused on the ambient or high-temperature effects of plywood composite materials [17]. However, for an LNG insulation system, plywood should be exposed to cryogenic temperatures. Moreover, considering the LNG transport route of an LNG carrier, typical mechanical loading conditions such as a bending or tension of the plywood used in the insulation system might occur during a voyage. Therefore, investigating the effects of cryogenic conditions on the material performance of the plywood at the temperature of LNG applications (−163 °C) is crucial for safety and design aspects.

In the present study, a series of tensile and bending tests under cyclic thermal-shock and cryogenic immersion were conducted at various temperatures and with multiple grain orientations. These tests were performed with the aim of generating data on some of the basic properties of plywood-based composite materials and observing the thermal-treatment-dependent performance of such materials. The experimental results, such as the general material behaviors and material properties, are quantitatively reported in this manuscript for further use in finite element (FE) analysis. Finally, the grain-orientation-dependent failure mechanisms of the plywood composites were evaluated.

2. Experimental details

2.1. Materials and methods

Plywood is composed of an odd number of thinly layered wooden plies that are perpendicular to the adjacent layers to reduce shrinkage and improve the mechanical strength. In the present study, the plywood tested was composed of birch wood, which is widely used in LNG insulation systems. To bond each wooden ply