Composite Structures 107 (2014) 476–481

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Cryogenic characteristics of chopped glass fiber reinforced polyurethane foam

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ARTICLE INFO

Article history:
Available online 30 August 2013

Keywords:
Reinforced PUF
Chopped glass fiber
Cryogenic
Compression test
Tension test
Fracture toughness test

ABSTRACT

Liquefied natural gas (LNG) is mainly carried by membrane type LNG ships, whose cargo containment system is composed of dual tightness barriers and two insulation boards. The insulation board should have not only cryogenic reliability against thermal load, but also high thermal insulation performance for safe and efficient transportation of LNG. Although polyurethane foam (PUF) has been widely used for the insulation board due to its low production cost and relatively good thermal and mechanical properties, the cryogenic reliability of PUF is a remaining concern in marine fields due to its brittleness at cryogenic temperatures.

In this work, the PUF was reinforced with chopped E-glass fiber because of its good dispersion and distribution characteristics. The compression, tension and the fracture toughness test were conducted with respect to the amount of the chopped E-glass fiber both at the room (25 °C) and cryogenic (−150 °C) temperatures. From the experimental results, it was found that the chopped E-glass fiber reinforcement increased the fracture toughness of the PUF much, especially at the cryogenic temperature. Therefore, the PUF reinforced with chopped glass fibers will improve much the reliability of the LNG cryogenic containment system during the voyage of LNG ships.

1. Introduction

Recently, the consumption of natural gas has been increased much, especially due to the increasing concerns for the nuclear power plant safety and developments of unconventional natural gas like shale gas and coal bed gas. Since the natural gas is largely carried by ships in the form of liquefied natural gas (LNG) for efficient transportation, the demand for LNG ships has been increasing as the major carrier of LNG [1–5]. The LNG ship has a special cryogenic containment system (CCS) in order to store the LNG, which is the core technology of LNG ship because LNG is transported generally at very low temperature of −163 °C under the pressure of 1.1 bars. The functional requirements of the CCS are to have cryogenic reliability due to large thermal stresses as well as to have high thermal insulation performance for safe and efficient transportation of LNG [6,7]. Recently the membrane type CCS is generally employed for the efficient transportation of LNG [8]. The membrane type CCS has an octagonal pillar shape whose capacity is generally larger than 39,000 m^3. It is composed of dual barriers against the leakage of LNG and sandwich insulation boards for high thermal efficiency as shown in Fig. 1[9–11].

The polyurethane foam (PUF), one of the widely used core material in sandwich construction, has been generally adopted for the core material of the sandwich insulation board in the CCS due to its good mechanical and thermal insulation performances with relatively low production cost [1–3]. However, the cryogenic reliability of the PUF is a remaining concern in the marine and ship building fields since PUF in the CCS is subjected to various loads such as thermal due to the temperature difference between the LNG and sea water, and mechanical loads due to the weight and flow of LNG during the voyage of LNG ships. Also, the increasing demand for larger capacity as well as higher thermal performance of CCS drums up the significant interest in cryogenic characteristics of the fiber reinforced PUF for higher fracture toughness.

Over the past few decades, there have been many researches for the fiber reinforced polymeric foam. Several authors have reported properties of polyurethane, epoxy and phenolic foam reinforced with glass or aramid fibers. For examples, Cotgreave and Shortall observed that the incorporation of 5 wt.% of fiber into PUF improved the tensile properties up to 56% [12]. The compressive strength of epoxy foam was also improved by 25–34% with fiber reinforcement [13,14]. Shen and Nutt synthesized phenolic foams with 10 wt.% of glass fiber, which improved the mechanical properties up to 60% [15]. However, relatively little attention has been paid to the cryogenic characteristics of glass fiber reinforced PUF.

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http://dx.doi.org/10.1016/j.compstruct.2013.08.017

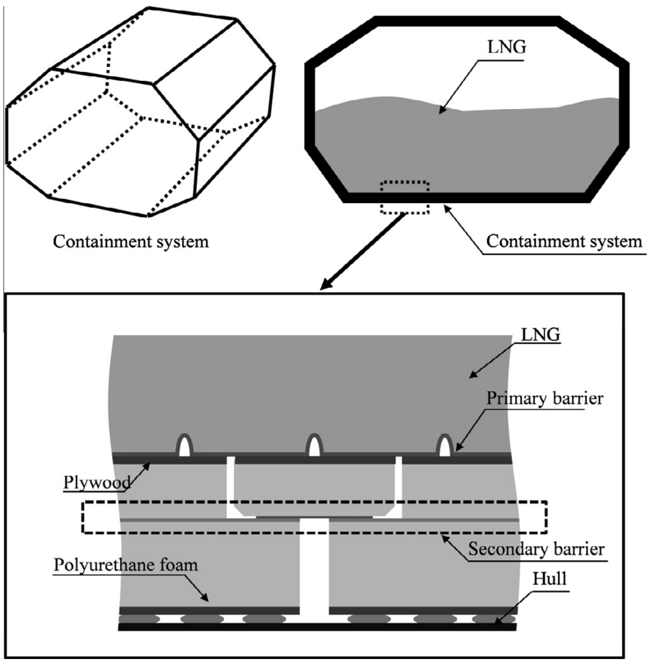

Fig. 1. Schematic diagrams of LNG containment system composed of dual barriers and sandwich insulation boards.

Therefore, in this study, the characteristics of fiber reinforced PUF were investigated at both the room (25 °C) and cryogenic (−163 °C) temperatures. The chopped E-glass fiber was employed due to its good dispersion and distribution characteristics. The fracture toughness test as well as compression and tension test was conducted considering the brittleness of the polymer at the cryogenic temperature.

2. Experimental

2.1. Fabrication of specimen

The characteristics of the materials used in the preparation of PUF were shown in Table 1. Blended polyol (by KPX Chemical Co., Ltd., Seoul, Korea) and polymeric methane diphenyl diisocynate (PMDI) (Huntsman International Pvt., Ltd., USA) were used to fabricate foam specimens. Distilled water was used as a chemical blowing agent. After the blended polyol and the distilled water were thoroughly mixed, then the PMDI was added. The chopped E-glass fibers of 7 mm (Hankook Fiber Group, Miryang, Korea) were dispersed in the mixed sresin. The schematic diagrams of the fabrication process of chopped E-glass PUF are shown in Fig. 2. Firstly, the mixture of polyol and PMDI was cooled to −5 °C in order to prolong the potting time required for the mixing of chopped fibers. The two materials were stirred with an impeller at 2500 rpm for 40 s. Then, the mixture and chopped fibers were mixed using a mixing machine at the room temperature. The final mixture was poured into the mold (80 × 80 × 170 mm) and pressed by steel mesh to align the fibers and eliminate entrapped air bubbles. Finally, as the foaming and curing progressed, the polyurethane foam (PUF) was fabricated in a mold with the density of the neat PUF of 70 kg/m^3. Four different weight percentages of chopped E-glass fibers such as 2.5, 5.0, 7.5 and 10.0 wt.% were mixed to fabricate the reinforced PUF.

Table 1
Characteristics of the materials used in the preparation of PUF.

Materials	Phr[a]	Role
Blended polyol[b]	100	OH value: 380 mg KOH/g
Polymeric methane diphenyl diisocynate[c] (PMDI)	149	NCO content: 31.5%
Distilled water	3.5	Blowing agent

[a] Represents as parts per hundred of polyol by weight.
[b] Supplied by KPX Chemical Co., Ltd., Seoul, Korea.
[c] Supplied by Huntsman International Pvt., Ltd.

2.2. Compression test

The compression test of the reinforced PUF was performed at both the room (25 °C) and cryogenic (−150 °C) temperatures in accordance with the ASTM D1621-1 [16]. The universal testing machine (INSTRON 4206, USA) was used and the experimental setup at the cryogenic temperature is shown in Fig. 3. The shape of the specimen and the experimental setup for the compression test are shown in Fig. 4. The specimen was cut with a band saw to a rectangular brick shape (50 × 50 × 25 mm). The specimen was compressed between the two stainless steel compressive zigs. The sheets of thin PTFE film were placed between the specimen and the compressive zigs in order to minimize the friction between the specimen and the zig. The cross head speed was 5 mm/min and five specimens were tested for each of fiber weight fraction.

2.3. Tension test

The tension test of the chopped fiber reinforced PUF was conducted at both the room (25 °C) and cryogenic (−150 °C) temperatures based on the ASTM D1623-09 [17]. The universal testing machine (INSTRON 4206, USA) was used and the experimental setup for the cryogenic temperature is shown in Fig. 3. The configuration of the specimen and the experimental setup for the compression test are shown in Fig. 5. Since the bonding area of a tab might generate thermal stresses in the specimen at the cryogenic temperature, the dog-bone specimen without tabs, was used for the tension test. The specimen was cut by the water jet process. The length and the width of the specimen were designed for the uniform stress distribution based on the Saint–Venant's principle with enough loading area and enough distance between the grip area and the test area according to the ASTM D1623-09. The cross head speed was 1.3 mm/min and the test results were averaged from the measured results of five specimens.

2.4. Fracture toughness test

The fracture toughness test of the chopped fiber reinforced PUF was performed at both the room (25 °C) and cryogenic (−150 °C) temperatures in accordance with the ASTM E1922-04 [18]. The universal testing machine (INSTRON 4206, USA) with the experimental setup for the cryogenic temperature is shown in Fig. 3. The configuration of the specimen and the experimental setup for fracture toughness test are shown in Fig. 6. The eccentrically loaded, single-edge-notch (ESE) specimen was used. The pre-crack of 16 mm was fabricated by the razor blade tapping method at the center of the specimen [19]. The critical stress intensity factor (K_{IC}) was calculated as follows [18].

$$K_{IC} = \frac{P_Q}{B\sqrt{W}} f\left(\frac{a}{W}\right) \tag{1}$$

$$f\left(\frac{a}{W}\right) = \frac{\sqrt{\frac{a}{W}}\left(1.4+\frac{a}{W}\right)}{\left(1-\frac{a}{W}\right)^{\frac{3}{2}}}\left[3.97-10.88\left(\frac{a}{W}\right)+26.25\left(\frac{a}{W}\right)^2 -38.9\left(\frac{a}{W}\right)^3+30.15\left(\frac{a}{W}\right)^4-9.27\left(\frac{a}{W}\right)^5\right] \tag{2}$$