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Cryogenic impact resistance of chopped fiber reinforced polyurethane foam

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ABSTRACT

Liquefied natural gas (LNG) is primarily carried by a membrane type LNG ship, which has a cryogenic containment system composed of dual tightness barriers and insulation boards. The insulation board should have cryogenic reliability as well as high thermal insulation for the safe and efficient transportation. Sandwich construction and fiber reinforced polyurethane foam (PUF) are generally used for the insulation board and the core materials, respectively. During the operation of the LNG ship, cavitation and sloshing could generate an impact load on the PUF, which is an ongoing concern in the ship building industry.

Therefore, the cryogenic impact resistance of the chopped E-glass fiber reinforced PUF was investigated with respect to the amount of chopped fibers. The drop weight impact test was conducted at a cryogenic temperature of −196 °C using liquid nitrogen. The applied maximum impact pressure, permanent strain and damage factor were measured to assess the damage caused by the impact test, from which the critical impact energy was investigated. From the experimental results, a criterion was suggested to assess the cryogenic impact resistance of the PUF and it was determined that the chopped fiber reinforcement significantly increased the impact resistance of the PUF at the cryogenic temperature.

1. Introduction

Recently, the consumption of natural gas has significantly increased, especially due to the increasing concerns of nuclear power plant safety and the development of unconventional natural gas, such as shale and coal bed gas [1–5]. Because natural gas is largely carried by ship in the form of liquefied natural gas (LNG) for efficient transportation, the demand for shipping LNG has increased for the primary LNG carriers [6–9]. The LNG ship contains a special cryogenic containment system (CCS), which is the core technology of the LNG ship, to store and transport the LNG at an extremely low temperature of −163 °C under a pressure of 1.1 bar [10–12]. The functional requirements of the CCS are to maintain cryogenic reliability and a high thermal insulation performance for the safe and efficient transportation of LNG [13–15]. Recently, a membrane type of CCS has been generally used for the efficient transportation of LNG [16]. The membrane type of CCS has an octagonal pillar shape, whose capacity is generally larger than 39,000 m^3, and is composed of dual tightness barriers to prevent the leakage of LNG as well as two insulation boards for high thermal insulation performance, as presented in Fig. 1 [17–20].

Polyurethane foam (PUF), one of the widely used core materials in sandwich construction, has been generally used for the core material of the sandwich insulation board in the CCS due to its good mechanical and thermal insulation properties and relatively low production cost. However, the cryogenic reliability of the PUF is a remaining concern in the marine and ship building industry because the PUF in the CCS is subjected to the cavitation impact load caused by the flow of LNG during the voyage of the LNG ship, as indicated in Fig. 2 [21–25,9,26].

Over the past few decades, there have been several studies on the mechanical properties and impact responses of fiber reinforced polymeric foam. A few researchers have reported the mechanical properties of polyurethane, epoxy and phenolic foam reinforced by glass or aramid fibers. Cotgreave and Shortall reported that the incorporation of 5 wt.% fiber into the PUF improves the tensile properties up to 56% [27]. The compressive strength of epoxy foam has been reported to increase by 25–34% with fiber reinforcements [28,29]. Shen and Nutt synthesized phenolic foams with 10 wt.% of glass fiber, which improved the mechanical properties up to 60% [30]. Also, some researchers have reported the impact response

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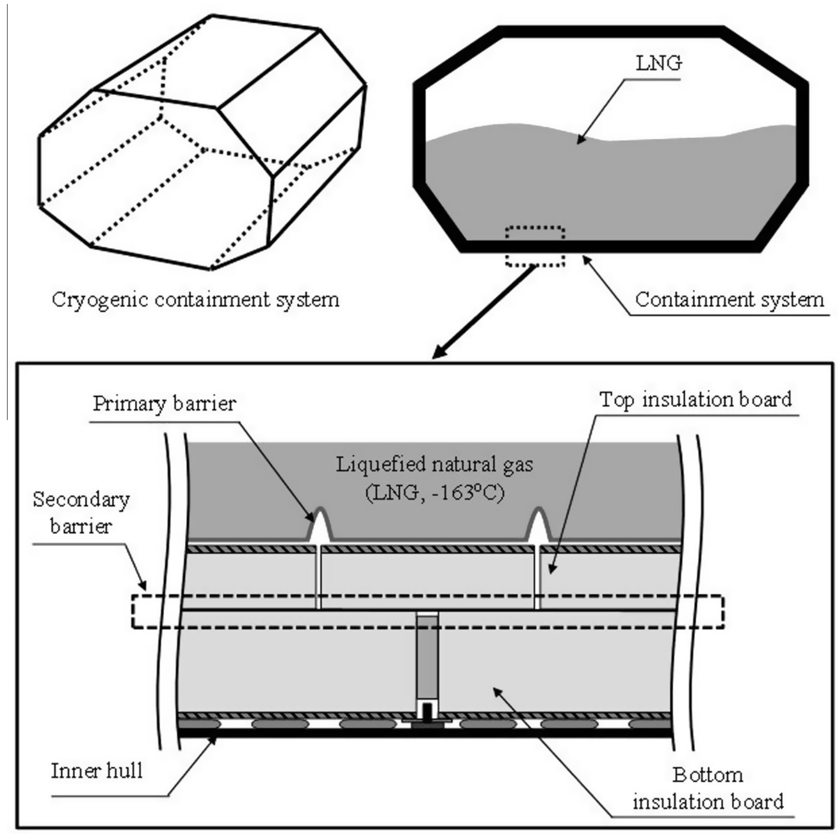

Fig. 1. Schematic diagrams of the cryogenic containment system composed of dual tightness barriers and two insulation boards.

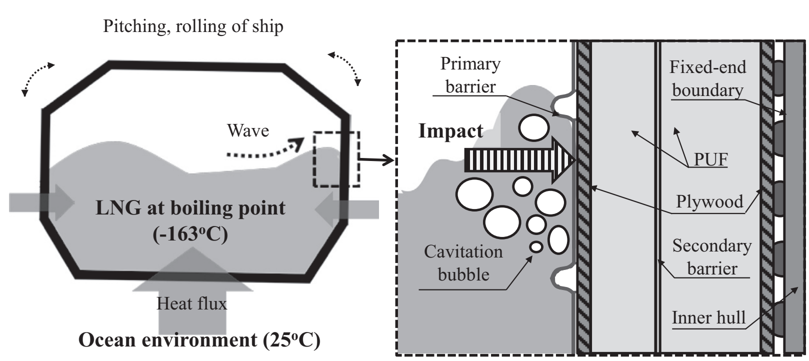

Fig. 2. Schematic diagrams of the impact load to the polyurethane foam in the cryogenic containment system during the voyage of the LNG ships.

of foam based composite structure. Akil et al. and Zhang et al. reported the low velocity impact response of foam based sandwich structures [31,32]. Bull and Edgren measured the compressive strength after impact of CFRP-foam core sandwich panels in marine applications [33]. Tekalur et al. and Xia et al. reported the impact response and properties of through thickness stitched foam core sandwich structures [34,35].

However, few studies have been conducted for the impact resistance of fiber reinforced polymeric foam at cryogenic temperature, where the polymeric foams exhibits very different mechanical behaviors in compressive, tensile strength and fracture toughness compared to those at the room temperature [1]. Also, few researches have been performed for the reliable criterion to assess the impact resistance of polymeric based on parameters like impact pressure, permanent deformation and residual strength.

Therefore, in this study, the cryogenic impact resistance of chopped E-glass fiber reinforced PUF was investigated w.r.t. the weight percent of glass fiber with newly developed cryogenic experimental set-up using liquid nitrogen of −196 °C. Also, the reliable criterion to assess the impact resistance of PUF at cryogenic temperature was suggested based on the three parameters such as maximum impact pressure, permanent deformation and residual tensile strength. To measure the impact resistance, the cryogenic impact test and tension test after impact were performed and three parameters were measured with respect to the weight percent of glass fiber and the applied specific impact energy.

2. Experimental

The impact resistance of the chopped glass fiber reinforced PUF was investigated at the cryogenic temperature with respect to the weight percent of chopped fiber. The drop weight impact test was conducted at the cryogenic temperature of −196 °C using liquid