

The effects of glass fiber reinforcement on the mechanical behavior of polyurethane foam[†]

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Abstract

In this paper, the mechanical properties of polyurethane foam (PUF) reinforced with glass fiber (RPUF) and non-reinforced PUF were investigated and compared to evaluate their structural applicability and failure criteria. The effects of glass fiber reinforcement were analyzed by tensile, compression, and repetitive impact testing. In the compression test, the differences of compressive response were analyzed by specimen directions, and tensile tests were carried out to evaluate the strain rate sensitivity of two materials in the low strain rate regime ($\dot{\epsilon} < 0.1/s$). Structural impact tests were carried out using dry drop tests and custom-made equipment. The dimensions of the test PUF specimens were 340 mm × 340 mm × 270 mm. Reaction forces were measured at the bottom of the specimen using impact load sensors with the capacity to measure up to 100 ton. Deformation due to impact load was measured using a high-speed camera system. The time histories of the impact load versus displacement behavior during repetitive impact loading were analyzed. This study presents a comprehensive understanding of the effect of fiber reinforcement on the mechanical behavior of PUF.

Keywords: Failure criterion; Glass fiber reinforcement; Mechanical behavior; Polyurethane foam (PUF); Reinforced polyurethane foam (RPUF)

1. Introduction

Polyurethane foams (PUFs) are mostly used as the core of sandwich structures in conjunction with two face sheet materials. Face sheet materials are usually strong and stiff, and carry most of the structural load, whereas the core is usually weak and makes the sandwich lighter and stiffer. In addition to these structural properties, they are also excellent insulators. Owing to their fascinating mechanical and thermal properties, PUFs are applied in various insulation systems.

PUFs can be reinforced using glass fibers. In a Liquefied Natural Gas Carrier (LNGC) with Mark III system, glass fiber reinforced polyurethane (RPUF, Reinforced Polyurethane Foam) is used for thermal insulation from exterior temperatures in accordance with Gaztransport & Technigaz (GTT) standards. Although PUF foams are widely used in insulation systems, few studies on the effects of glass fiber reinforcement on the mechanical behavior of PUF have been conducted.

From a design viewpoint, due attention should be given to

the sloshing impacts of LNGC. When the natural frequency of loaded LNG is the same as that of ship motion, sloshing loads amplify and may cause significant damage to cargo holds. In the design of LNGCs, PUF materials are the main component of the insulation system; mechanical characteristics and failure modes are important considerations in the system when considering reinforcement effects.

PUFs are commonly used structural members for impact absorption; therefore, the impact responses of PUFs have been studied by typical drop tower tests [1, 2]. In relation to the shipbuilding fields, Lee et al. studied the dynamic failure problems of RPUF insulation systems by performing dry drop tests and a series of finite element analyses. They showed that the cracks or delaminations within the insulation could occur under a certain loading level [3]. Crack initiation and propagation characteristics of the LNG insulation system under repeated impact loads were analyzed by Chun et al. However, these studies were focused on RPUF [4]. Therefore, in this study, the structural responses of the PUF were investigated by a well-known experimental method to investigate the effect of glass fiber reinforcement of PUF and mechanical failure criteria. The compressive and tensile test specimens were fabricated using GTT's recommendation, and impact test specimens were made of a partial LNG insulation system.

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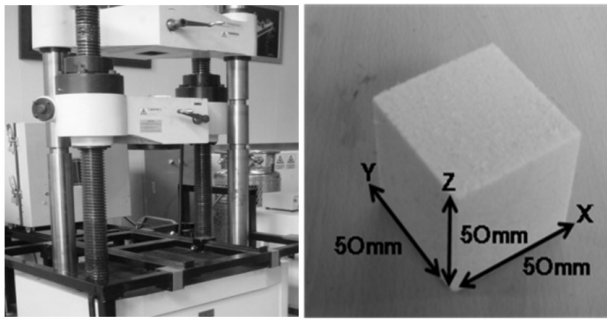


Fig. 1. Compression test equipment and specimen (GTT's recommendation)

2. Experiments

2.1 Materials

PUF and RPUF were used in this study. They were supplied by several companies certificated by GTT to produce an LNG insulation system. The testing PUF are classified as I-grade PUF with a density of 115 kg/m³, and the material density varies with the amount of reinforcing glass fiber. For the reinforcement of glass fiber, the density of PUF is increased to 133 kg/m³, and the weight content of the glass fiber is 15%. To evaluate the quantitative influence of the glass fiber reinforcement on PUF, these materials were selected as test specimens without any special fabrication process.

2.2 Compression test

Fig. 1 shows the test equipment and the dimensions of the compression test specimen. A universal testing machine with 100-ton capacity was used. To characterize the directional variations of compressive responses, all compression specimens were extracted along the coordinate where the PUF and RPUF materials were paralleled and tested by X (length), Y (breadth), and Z (depth) with 5 mm/min of crosshead speed.

The test was terminated manually when the planed displacement was observed on the force-displacement data from universal testing machine (UTM). Force-displacement data were obtained from the quasi-static tests and were converted to stress-strain data using the specimen dimensions.

Figs. 2 and 3 show the results of the compression tests. The glass fiber reinforcement not only causes an anisotropic response but also increases the yielded stress of PUF.

As shown in Fig. 3, PUF shows an almost identical compressive behavior depending on the test direction with a coefficient of variation (COV) of 0.029. Conversely, the yield stress of RPUF has a strong association with the test directions because the glass fibers are piled layer upon layer along the Z-direction.

2.3 Tensile test

Tensile tests focused on the strain rate dependence of the reinforcement effect on PUF rather than on the directional varia-

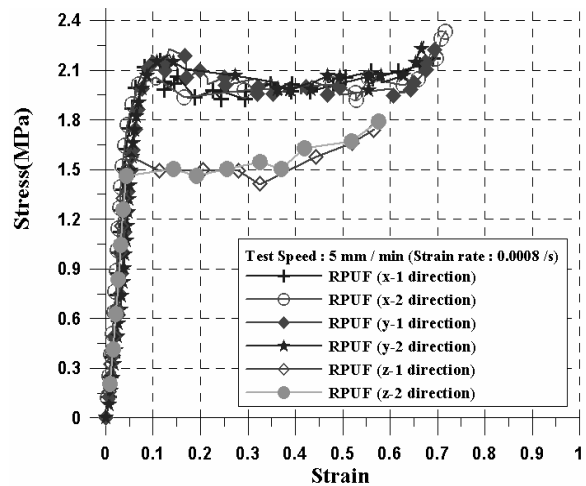


Fig. 2. Compression test results of the RPUF.

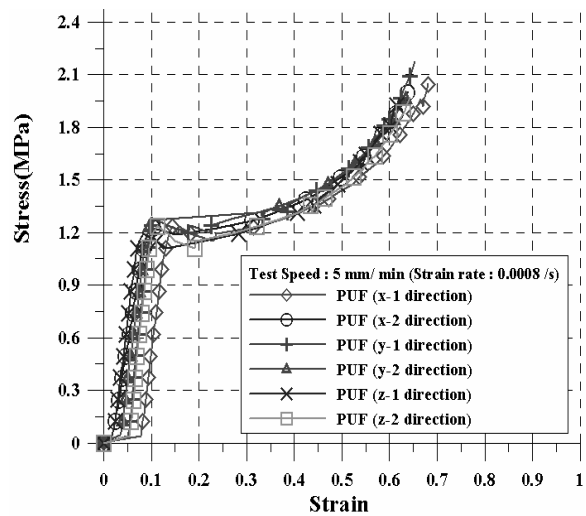


Fig. 3. Compression test results of the PUF.

tions. All tensile specimens were made of X-direction PUF and RPUF materials, and the test crosshead speed ranged from 6-2,400 mm/min. The schematic of the tensile specimen and test setup is shown in Fig. 4.

Generally, applying the conventional contact-type extensometer is difficult when the specimens are large. Due to the initial gauge length (100 mm), a high-speed digital camera was adopted to calculate the resultant strain. The digital images obtained using high-speed digital cameras were analyzed using commercial software (TEMA) to determine the position of the marks as a function of time during a test.

Figs. 5 and 6 represent the tensile test results at a test speed of 6 mm/min corresponding to the specimen strain rates of 0.0006/s and 0.00029/s, respectively.

Although these specimens have the same dimensions and test speed, the strains at the gauge length are different from each other due to the differing material reinforcement. Table 1 summarizes the differences in measured strain rate at a constant test speed.

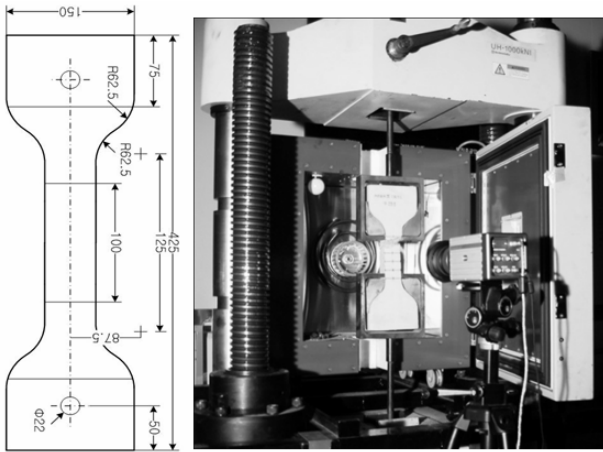


Fig. 4. Tensile test specimen (thickness: 50 mm) and test set-up (GTT's recommendation).

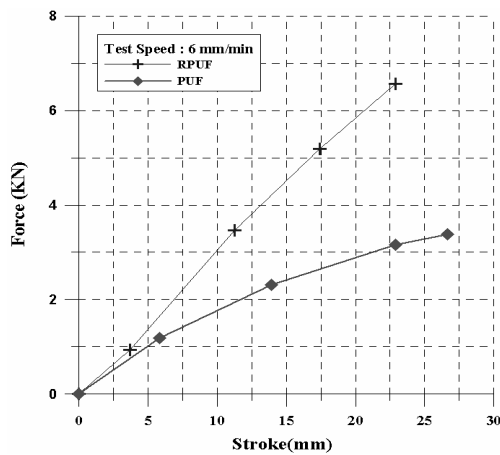


Fig. 5. Tensile test result for 6 mm/min (force-stroke).

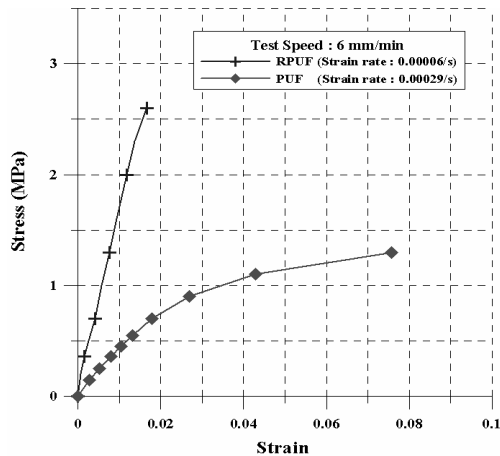


Fig. 6. Tensile test result for 6 mm/min (stress-strain).

The other difference between the two sets of data is shown in Fig. 7, which expresses the tendencies of the fracture stress and fracture strain of RPUF and PUF. In contrast to RPUF, PUF shows a higher level of fracture stress and strain at very low strain rates (0.0029/s and 0.003/s). Except for this result,

Table 1. Strain rates at the gauge length.

Test speed (mm/min)	6	60	600	1200	2400
Strain rate (RPUF)	0.0006	0.0007	0.0068	0.018	0.033
Strain rate (PUF)	0.00029	0.003	0.026	0.04	0.1

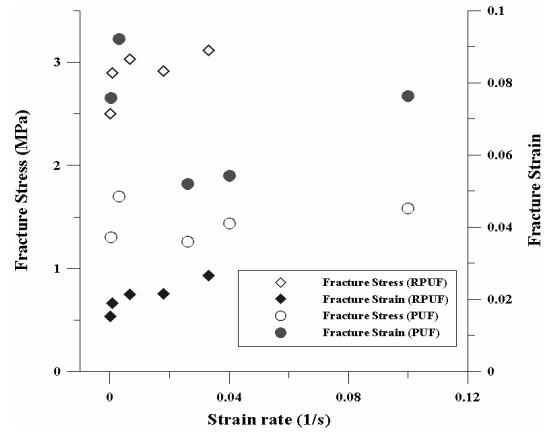


Fig. 7. Fracture stress and strain versus strain rate of RPUF and PUF.

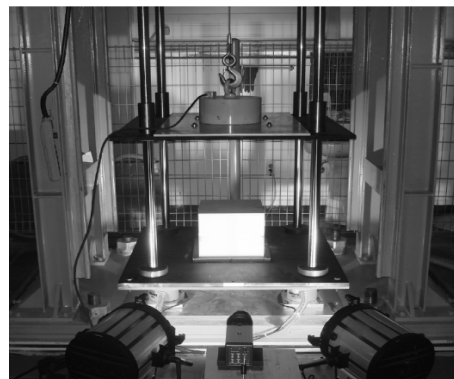


Fig. 8. Impact test specimen (340*340*270) and drop test set-up.

the overall trend of fracture strain and stress increases with increasing strain rate.

2.4 Dry drop test

When considering the structural applicability of a PUF material, it may be useful to evaluate impact performance. For this purpose, dry drop towers were designed to perform impact tests, as shown in Fig. 8. A specimen was fixed at the bottom, and a drop weight consisting of iron plates was dropped from a chosen height.

Time history of the reaction forces during impact loading was measured by a custom-built reaction force measurement system that uses four impact load sensors and a dynamic strain logger system. All signals of the time history of the reaction forces were recorded and analyzed in an automated manner. Dry drop tests were conducted repeatedly until the specimens were completely fractured.

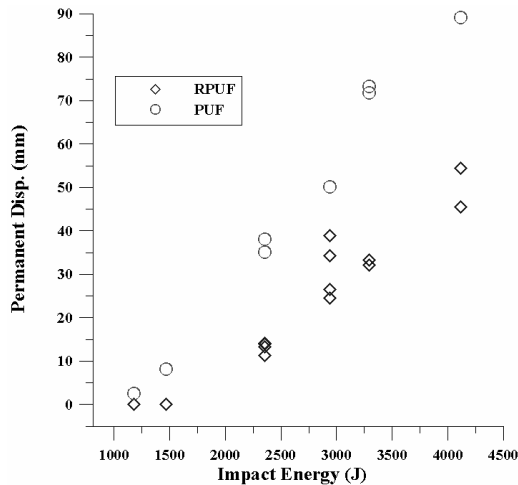


Fig. 9. Comparison of permanent displacement after 18th impact loading.

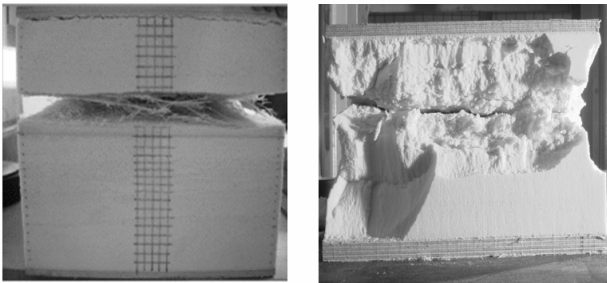


Fig. 10. Fracture shape of impact specimen (left: RPUF; right: PUF).

Fig. 9 represents the result of the permanent displacement of the two materials after the 18th impact for various impact energies (loading conditions).

From the repetitive impact tests, it seems reasonable to conclude that the glass fiber reinforcement increases the cohesion of PUF. Fig. 10 shows that the crack propagation of reinforced material occurs along the fiber glass layers, whereas other cases have no directional characteristics. These results present useful ideas for structural guidelines and practical limitations for the deformation of RPUF and PUF against impulsive loads in various environments.

3. Conclusions

The effects of fiber reinforcement on PUF mechanical properties are summarized below.

- The compressive yield stress of PUF was increased by 70% in the X, Y direction with a COV of 0.043 in RPUF. In the case of the Z direction, a 20% strength improvement and 0.023 of COV were observed in RPUF.
- Under tensile tests, the average fracture stress increased by over 20%, and fracture strain showed a decrease in all test cases due to a stiffening effect.

- The results of a series of impact tests show that the reinforcement induces improved impact resistance against permanent deformation and crack initiation and propagation. Fracture phenomenon caused by impact and their quantitative characteristics could be further investigated.

The results of this study provide a useful basis to understand the effect of glass fiber reinforcement on the mechanical behavior of PUF.

Acknowledgment

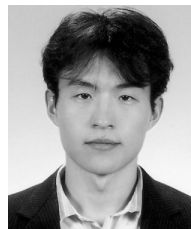
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