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Damping Effect of Reinforced Polyurethane Foam under Various Temperatures†

Tak Kee Lee[1*], Myung Hyun Kim[2], Chae Whan Rim[3], Min Sung Chun[4] and Yong Suk Suh[4]

[1] *Dept. of Naval Archi. and Ocean Eng., Marine Industry Institute, Gyeongsang National University, Tongyoung, 650-160, Korea*
[2] *Dept. of Naval Archi. and Ocean Eng., Pusan National University, Busan, 609-735, Korea*
[3] *Korea Institute of Machinery & Materials, Daejeon, 305-343, Korea*
[4] *Samung Heavy Industries, Co., Ltd., Geoje, 656-710, Korea*

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Abstract

Reinforced polyurethane foam (RPUF) is one of the important materials of Mark III type insulation systems used in liquefied natural gas (LNG) cargo containment systems. However, RPUF is the most difficult material to use with regard to its safety assessment, because there is little public and reliable data on its mechanical properties, and even some public data show relatively large differences.

In this study, to investigate the structural response of the system under compressive loads such as sloshing action, time-dependent characteristics of RPUF were examined. A series of compressive load tests of the insulation system including RPUF under various temperature conditions was carried out using specimens with rectangular section. As a result, the relationship between deformation of RPUF and time is linear and dependent on the loading rate, so the concept of strain rate could be applied to the analysis of the insulation system. Also, we found that the spring constant tends to converge to a value as the loading rate increases and that the convergence level is dependent on temperature.

Keywords: Reinforced polyurethane foam (RPUF), insulation system, compressive load, liquefied natural gas (LNG) cargo containment system, strain rate, spring constant

1. Introduction

Recent continuous increase of the demand for liquefied natural gas (LNG) has led to the seamless construction of the LNG carrier. Over the next 10 years, the demand for LNG is expected to double the demand seen in 2005 [1]. The portion of LNG comprising the world energy consumption reached about 24% in 2003 from about 18% in the 1980s, and it is going to comprise a larger portion in the future [2]. This trend will continue for several decades, since LNG is more environmentally friendly than oil and coal. The major oil companies worldwide have developed many gas fields and will continue harvesting gas and improving cost competitiveness by reducing production costs.

As a result of these developments, many new LNG carriers (LNGC) have been built in recent years, and the trend is larger ship and larger cargo to achieve its less fuel consumption. The operating area of LNGC has also been broadened even to arctic area. As means of dealing with the larger size ship and operating conditions, the safety assessment of LNGC cargo containment system has became one of main research themes [3-5].

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* Corresponding author. Tel.: +82-55-772-9193, Fax.: +82-55-772-9199.
E-mail address: tklee@gnu.ac.kr.

Reinforced polyurethane foam (RPUF) is the most important material in the Mark III type insulation systems used in LNG cargo containment systems. It has excellent heat shielding capacity and its stiffness is better than other insulation materials in bulk condition. As a result, it is a popular insulation material in various fields including shipbuilding. It is also known that RPUF has better mechanical properties at very low temperature than those at room temperature, so it seems to be the best choice for insulation at very low temperatures. However, RPUF is a most difficult material to deal with in the numerical approach for the structural safety assessment of LNG cargo containment system, because there is little public and reliable data on its mechanical properties, and even some public data show relatively large differences [6].

One of the characteristics could be treated as a kind of damping, because RPUF plays the role of damper against the compressive load as shown at Fig. 7 in Ref. [7]. Some authors [7] have investigated the damping effects of the insulation system by applying compressive loads at room temperature. As a result, it was found that the strain-rate is constant because the change of displacement over time is almost linear. It also was found that the spring constant tends to converge to a value as the strain rate increases.

In this study, to investigate the damping effect of the insulation system under compressive loads such as sloshing action in LNG cargo containment, a series of compressive load tests of a Mark III type insulation system including RPUF under various temperature conditions was carried out using specimens with rectangular section.

2. Previous works

When the insulation system including RPUF is subjected to impact loads due to sloshing, the RPUF becomes deformed and much of the impact energy is absorbed by the deformation. Thus, decreased impact load is transferred to the hull structure by so-called damping effect of RPUF. Bang et al. [8] conducted a free drop impact test of Mark III system to collect basic information and investigate the structural behaviours of the LNG cargo. They focused primarily on the cushioning and damping effects of the insulation system using an experimental approach. Here, the cushioning effect indicates the buffering action of the air between the LNG and the corrugated cargo hull under the sloshing motion.

Bang et al. [8] reported that they tried to measure the strain on RPUF in the drop test to examine the damping effect, but they could not obtain reliable data due to bad bondage between the strain gauges and the RPUF. However, they were able to define a damping factor using the ratio of pressures measured at the RPUF top and bottom. The maximum damping factor was 2.4 for a 5° incident angle, and the factor at a 0° incident angle was approximately 2.1. Despite this, they could not find a relationship between impact velocity and damping factor.

Lee [9] reported that the insulation system response can be divided into the structural damping effect and the cushioning effect. Using the results of the sloshing impact tests, he calculated the pressure damping ratio in a similar manner as Bang et al. [8]. According to the result, the maximum damping ratio was 2.28 for the 0° incident angle and the larger the incident angle was, the smaller the ratio was. Finally, he demonstrated that the ratio was almost constant when the incident angle was over 4°.

Nam et al. [10] investigated the structural response of the membrane type insulation system to the fluid sloshing impact load using the fully coupled hydro-elastic model, including the RPUF damping effect. They used a reduced visco-elastic shear model to simulate viscous damping. This model consists of a damper and two springs with a long-term shear modulus and a shear modulus defined by a short-term shear modulus minus the long-term shear modulus. According to their comparison of the bending stress of plywood and hull plate, the maximum stresses in cases with damping were about 5% less than those in cases without damping. Based on these results, they concluded that the damping effect of RPUF on the structural response of both cargo containment system and hull is not significant.

Meanwhile, Lee et al. [11] examined the dynamic strength characteristics of the LNG cargo containment system under sloshing impact loads in both a numerical and an experimental manner. They carried out a series of impact tests of a full-scale Mark III insulation system using a custombuilt drop test facility with various heights and weights of the drop object. In the tests, they measured strains inside the insulation system including RPUF using two embedded fiber brag grating sensors to monitor various failures inside the LNG insulation panels due to the sloshing impact actions. However, they did not examine the damping effect of RPUF.

3. Experiment and discussion

A series of compressive load tests of the Mark III type insulation system including RPUF under various temperature conditions was conducted using the specimen with a rectangular section on a universal test machine with a 500 kN capacity (Fig. 1). The dimension of the specimen in Fig. 2 is 340 mm × 340 mm in section and 270 mm thick. Figure 3 gives the test loading history. A compressive load of -6 to -66 kN (stress range = 0.519 MPa) was applied. The load was maintained for 5 minutes at the maximum and minimum loads to obtain stable strain values. The loading and unloading times were 0.33, 1.0, 10.0 and 100 sec. Temperatures of -40, -80 and -110℃ were applied. The minimum temperature of -110℃ is considered the temperature in the second barrier area from a heat distribution analysis when the cargo tank is filled with LNG at -163℃.

Fig. 1. Overview of the universal test machine

Fig. 2. Test specimen with a rectangular section

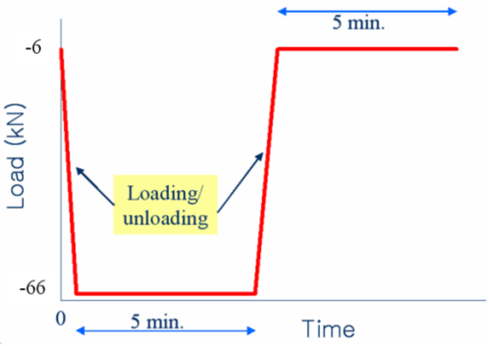

Fig. 3. Loading history for the tests

Displacements in case of loading and unloading time of 1.0 sec. are shown in Fig. 4, the room temperature in which is from the previous test [7]. Displacement at the maximum load decreases as the temperature decreases, and it returns to the initial status after unloading. The phenomenon that the material becomes stiffer at lower temperature is natural. This figure shows the difference in stiffness according to temperature changes of the insulation system including RPUF. The difference in stiffness can be described as the strain value at the maximum load (Table 1). The strain shown in the table is calculated from the displacement at the maximum load and specimen height (270mm).

Figure 5 shows the displacement change during loading at various temperatures with a loading time of 0.33 sec. The tendency of the response against the compressive load in Fig. 5 is similar to that in Fig. 4, i.e., the lower the temperature, the smaller the displacement. It can also be found that the strain rate is constant because the change in displacement over time is almost linear.

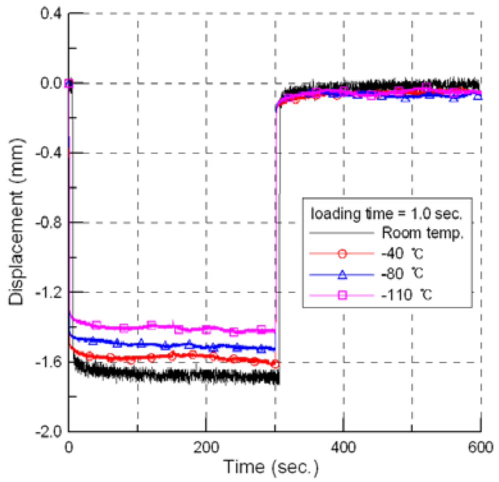

Fig. 4. Measured displacements (loading time =1.0 sec.)

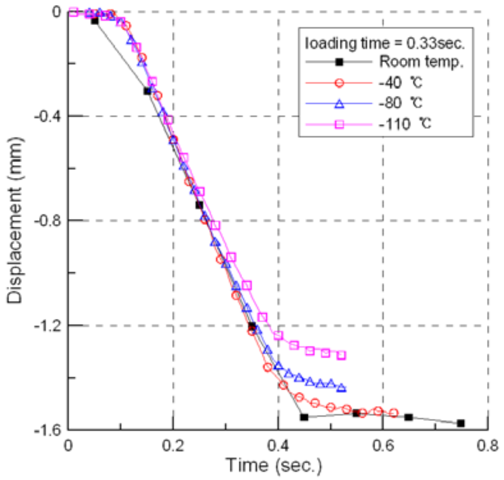

Fig. 5. Displacement change during loading

Table 2 gives the strain rate and spring constant calculated from the test results of various loading times under the four temperature conditions. According to Chun et al. [12], the strain rate of RPUF under the impact loading calculated using the drop test results was in the range of 7.4 - 14.8 (1/sec.). Comparing the present results with those of Chun et al., the strain rates of the present test (Table 2) are much lower [12].

Finally, the spring constant was calculated from the compressive load and displacement in Table 2. Figure 6 shows the relationship between the spring constant and the strain rate. The figure shows that the lower the temperature, the higher the spring constant. As the strain rate increases, the spring constant tends to converge to a value of 40,000 - 50,000 N/mm depending on temperature. As mentioned above regarding the strain rate range, the loading rate range in the present tests seems to be much lower than those of full-scale sloshing impact tests. Therefore, additional investigations are required to obtain more realistic data of higher strain rates.

Table 1. Calculated strains according to temperatures

Temp. (°C)	Loading time (sec.)	Disp. (mm)	Strain (micro-strain)
Room temp.1)	0.33	-1.740	-6,443
	1.0	-1.734	-6,422
	10.0	-1.648	-6,104
	100.0	-1.642	-6,083
-40	0.33	-1.656	-6,132
	1.0	-1.617	-5,990
	10.0	-1.617	-5,990
	100.0	-1.587	-5,877
-80	0.33	-1.541	-5,708
	1.0	-1.541	-5,708
	10.0	-1.534	-5,680
	100.0	-1.503	-5,567
-110	0.33	-1.419	-5,256
	1.0	-1.434	-5,312
	10.0	-1.419	-5,256
	100.0	-1.404	-5,199

1) Data from [7]

Table 2. Test data summary

Temp. (°C)	Load time (sec.)	Load rate (mm/s)	Strain rate (1/sec)	Spring const. (N/mm)
Room temp.1)	0.33	3.806	0.014096	39,686
	1.0	1.545	0.005721	39,022
	10.0	0.158	0.000585	38,058
	100.0	0.016	0.000061	36,559
-40	0.33	4.997	0.018508	41,679
	1.0	1.613	0.005973	41,581
	10.0	0.165	0.000612	39,858
	100.0	0.016	0.000061	40,445
-80	0.33	4.521	0.016745	42,550
	1.0	1.536	0.005689	43,738
	10.0	0.145	0.000538	45,213
	100.0	0.015	0.000055	44,389
-110	0.33	4.272	0.015824	46,600
	1.0	1.418	0.005253	46,076
	10.0	0.140	0.000520	46,771
	100.0	0.014	0.000051	48,294

1) Data from [7]

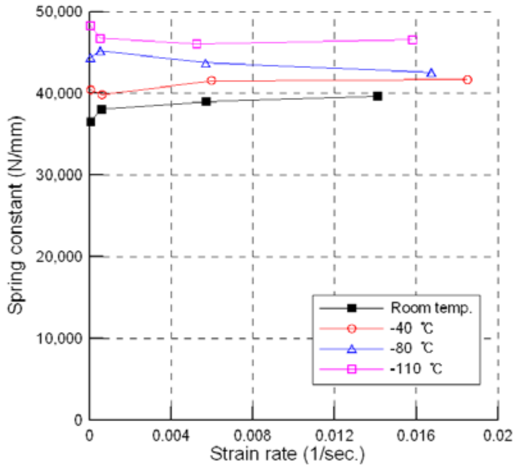

Fig. 6. Relationship between spring constant and strain rate under various temperature conditions

4. Conclusions

In this study, to investigate the structural response of Mark III type insulation systems against sloshing motions under various temperatures, a series of compressive load tests was carried out in the low strain rate range. The load and displacement of the insulation system including RPUF were measured during the tests.

The results showed that the lower the temperature, the smaller the displacement under the same pressure because the stiffness of specimen increases as the temperature decreases. This indicates that the damping effect of insulation systems including RPUF decreases as the temperature decreases. Also, the concept of strain rate should be applied to the analysis of the insulation system since the relationship between displacement and time is dependent on the loading rate, which is linear. The damping effects of RPUF were analyzed using strain rate, loading rate, and spring constant. Finally, it also was found that the spring constant tends to converge to a value as the loading rate increases and the temperature decreases.

The strain rates of the present tests cover only the very low strain rate range compared with the result of the full scale drop test. Therefore, to simulate numerically the structural response of the insulation system with RPUF in LNG cargo containment subjected to a sloshing impact load, it needs to investigate the impact behaviour of each component including RPUF on the higher strain rate.

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