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Crushing Characteristic of Rigid Polyurethane Foam as Shock Absorbing Material for Transport Cask

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Abstract

In this study, crushing characteristics of rigid polyurethane form (R-PUF) were obtained, and applicability of R-PUF as shock absorbing material for transport cask was verified. Firstly, the stress-strain curves of R-PUF under constant strain-rate conditions were obtained using constant deformation rate testing machine by varying R-PUF density between 0.1 to 0.8 g/cm^3, strain-rate between 1.25×10^{-3} to 1.25×10^1 /s, and temperature between 20 to 80 °C. Then, the material crushing data collection to apply design and numerical analysis was accumulated. Secondly, side and 10°-declined 9m drop tests of 1/3 scale model cask that had impact limiter designed using material data obtained in this study were conducted. As the result showed the shock-absorbing performance obtained in the test was superior to as designed, applicability of designing R-PUF impact limiters based on the material data collection in this study was verified. Moreover, the 9m drop tests were numerically simulated in LS-DYNA using material data considering the strain rate dependency obtained in this study. As impact acceleration was estimated effectually in the numerical simulations, the validity of the strain rate dependency in the material data was confirmed. Finally, drop weight tests were conducted by varying R-PUF density between 0.1 to 0.65 g/cm^3 and temperature between -20 to 80 °C to valid applicability of extrapolation of the dependencies of temperature in the material data collection.

Introduction

In general, wood is applied as a shock absorbent material for impact limiter of transport cask. However, because wood is a natural material, there is a difficulty of material management, such as insufficient of the wood species suitable for the cask impact limiter, or cost for controlling moisture content. Previously, in Japan, imported wood has been used as a shock absorbent material in most cases. Therefore, to improve constant availability and to easily manage costs and quality, the shock absorbent material which could be an alternative to wood is desired.

We had chosen R-PUF as an alternative material to wood, because its characteristic of crush strength is adjustable and R-PUF can be prepared at low cost which is almost the same as low-priced wood [1,2]. In recent study, stress strain curves of three densities (0.1, 0.3, 0.5 g/cm^3) of R-PUF under each temperature condition (between -40 to 100 °C) were obtained by drop weight tests [2].

However, in the dynamic events such as 9m drop test, to evaluate the behavior of the cask, it is important to properly evaluate the strength increase due to the deformation rate of the material (strain rate dependency). Therefore, it is necessary to obtain stress strain curves under constant strain rate conditions. In this study, stress strain curves of R-PUF of several kind of density were obtained under constant strain rate, by varying strain rate and temperature to accumulate material data considering the strain rate and temperature dependency. Moreover, the applicability of the data obtained in present study was verified by 9m drop test of 1/3 scale model cask and drop weight test.

Cosntant Deformation Rate Tests

Test Method

To obtain the crush characteristics of various densities of R-PUF under constant deformation rate, the column shaped specimens were cut out as shown in Figure 1. Note that skin layers of relatively high density R-PUF on the surface were removed. In general, shock absorbing material in impact limiter of transportation cask is under restrained condition filled in steel cover plate. In this test, to restrain a specimen, a specimen was inserted in a filler block made of same material as each of the test specimen.

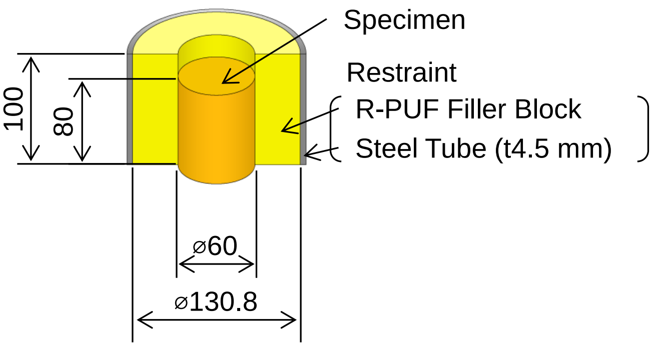


Figure 1 Specimen Assembly.

The experiments were performed at constant deformation rates using an 800 kN electro-hydraulic servo rapid load testing machine. The equipment allows a maximum velocity of 1000 mm/s and has stroke length of ±125 mm. Figure 2 shows an overview of the constant deformation rate test equipment.

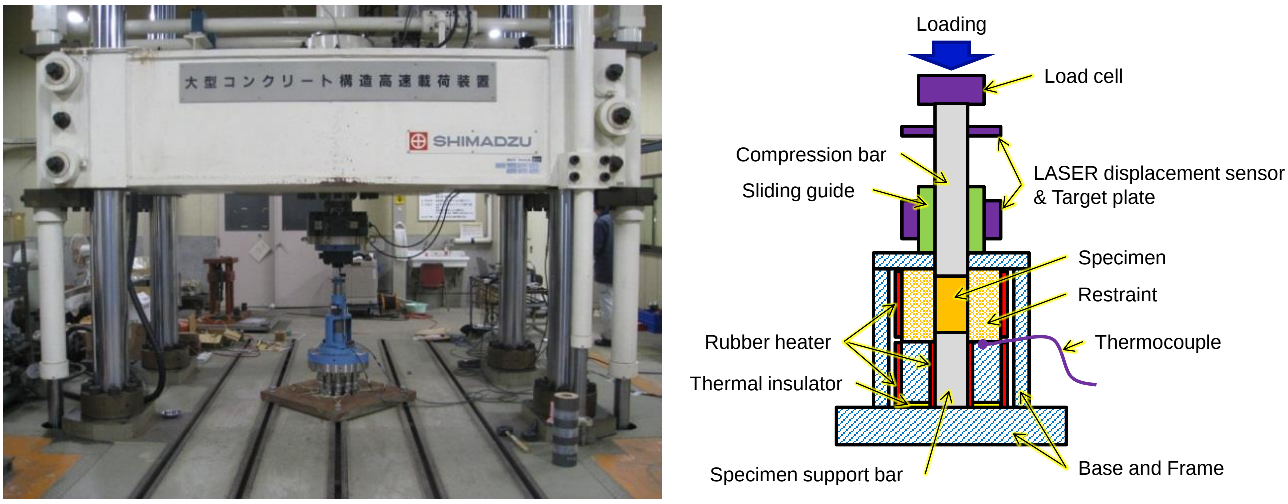


Figure 2 Overview of Constant Deformation Rate Test Equipment [3].

By letting the compression bar move down with constant velocity, a specimen was deformed under constant strain rate. Then, reaction force and displacement of compression bar were measured. Three conditions of crushing velocity were 0.1, 10, and 1000 mm/s. In these condition, strain-rate was to be 1.25×10^{-2} s^{-1} (static-rate) , 1.25×10^{0} s^{-1} (dynamic-rate), and 1.25×10^{1} s^{-1} (impact-rate).

The crushing characteristic of R-PUF depends on density and temperature. Tests were conducted for four density as 0.1, 0.3, 0.5, and 0.8 g/cm^3, and three temperature as 20(Room Temperature), 50, and 80 °C.

Measurement Method

Reaction forces were measured using load cell having a maximum capacity of 500 kN with a resolution of 125 N (NCX-500KN, Nippon Tokushu Sokki Co., Ltd.). Displacements of the target on compression bar were measured using LASER displacement sensor has a resolution of 20 μm (LK-H155, Keyence Corp.) as deformation of specimen. They were measured with sampling frequency of 10 kHz in static-rate, 50 kHz in dynamic-rate, and 100 kHz in impact-rate. The specimen temperature was conditioned in thermostatic chamber. On testing, the specimen and jigs were heated with silicone rubber heater, and temperature was verified with a thermocouple under the bottom support of the restraint.

Test Result

Figure 3 shows stress-strain curves and absorbed energy-strain curves that calculated from deformation-force curves obtained in the experiments. Note that engineering stress (σ_c), engineering strain (relative deformation) ε, and absorbed energy per unit mass E_a are calculated from equations as follows:

$$\sigma_c = \frac{F}{A_0} \quad , \quad \varepsilon = \frac{\delta}{H_0} \quad , \quad E_a = \frac{1}{m}\int F\, d\delta.$$

F : Reaction force

δ : Deformation

A_0 : Initial cross section of specimen

H_0 : Initial height of specimen

m : Mass of specimen

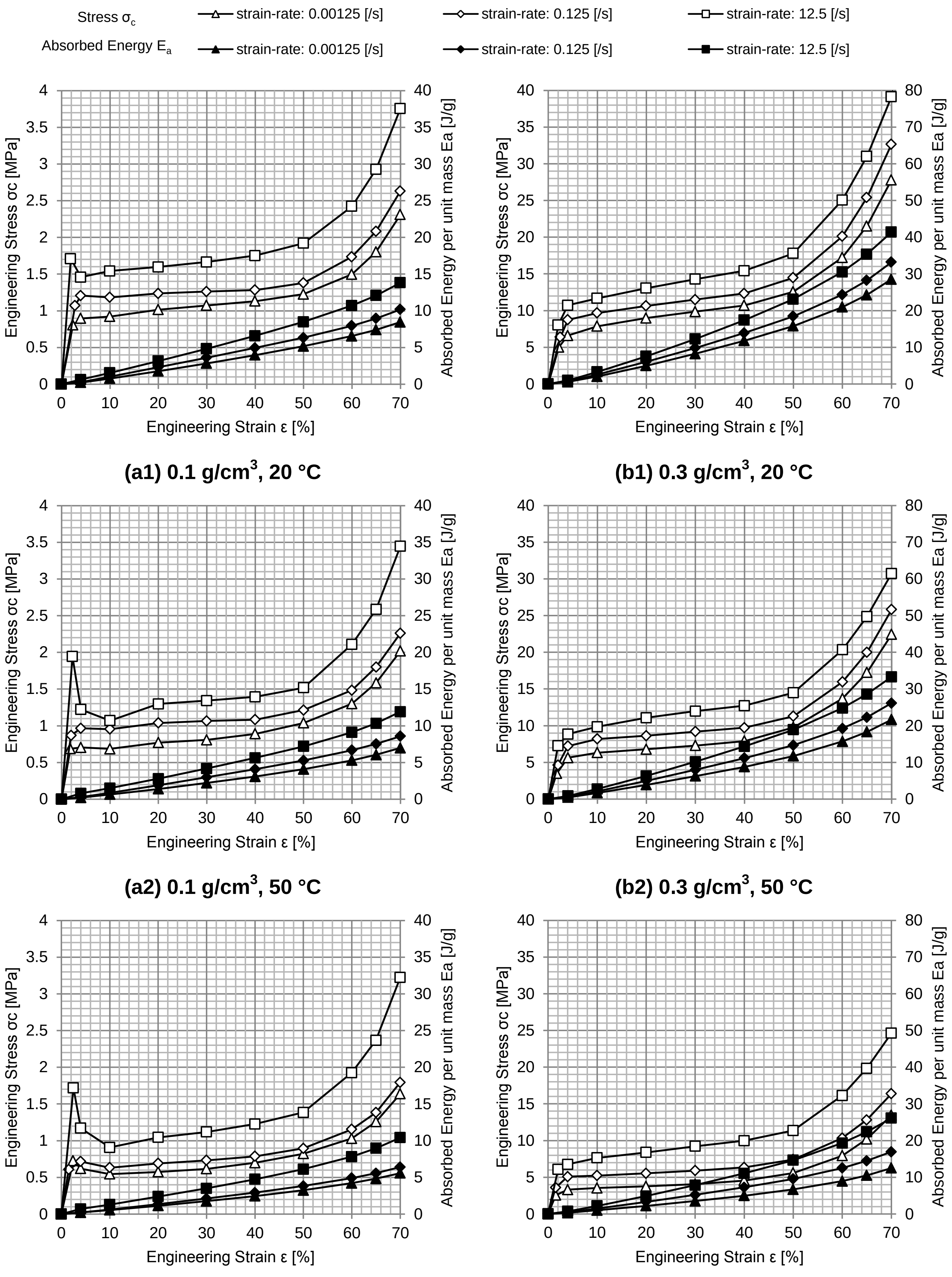
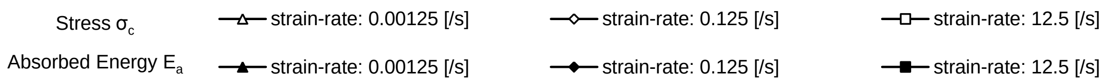
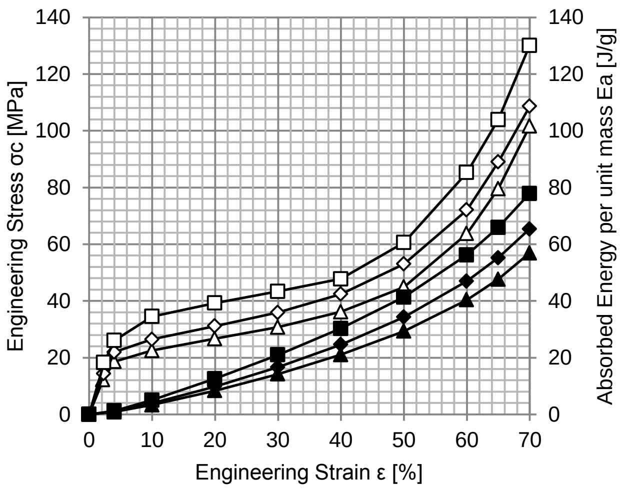
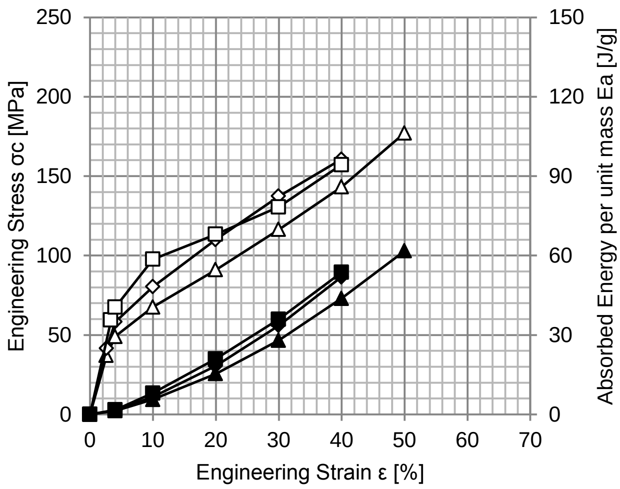


Figure 3(1/2) Stress-Strain Curves and Absrobed Energy-Strain Curves [3].

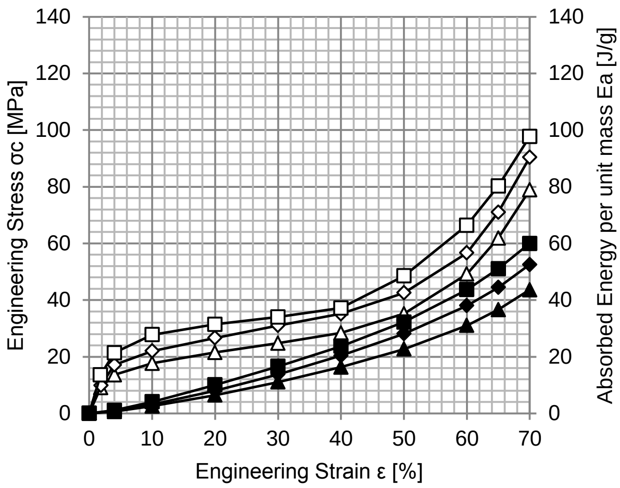




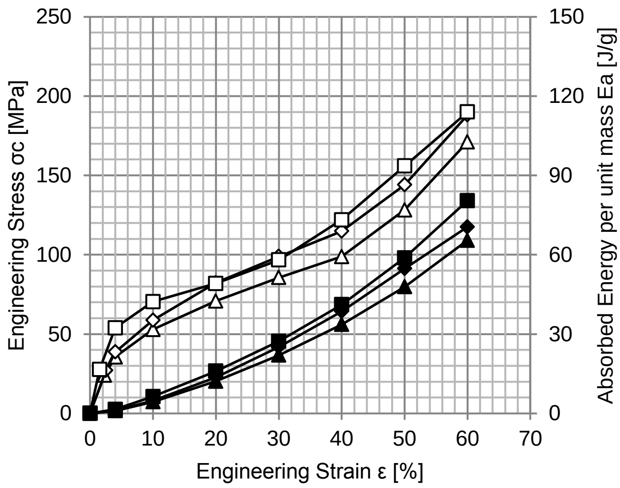
(c1) 0.5 g/cm³, 20 °C



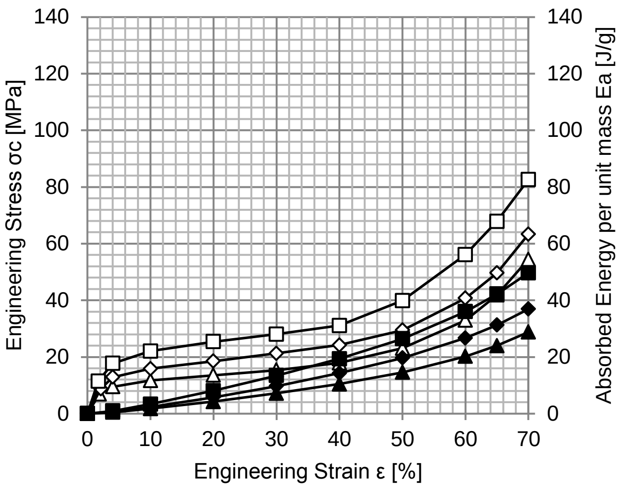
(d1) 0.8 g/cm³, 20 °C



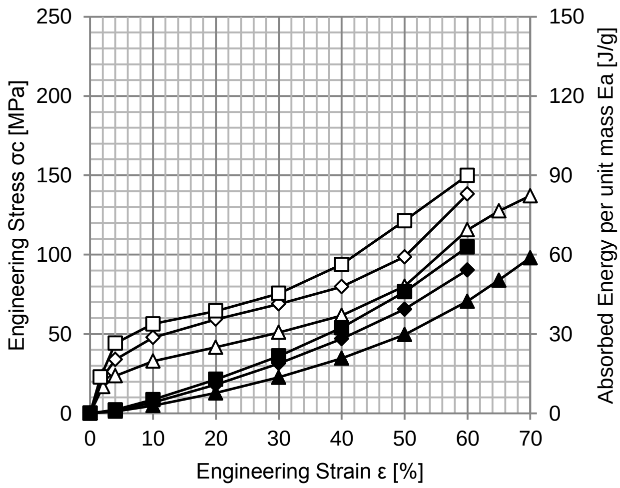
(c2) 0.5 g/cm³, 50 °C



(d2) 0.8 g/cm³, 50 °C



(c3) 0.5 g/cm³, 80 °C



(d3) 0.8 g/cm³, 80 °C

Figure 3(2/2) Stress-Strain Curves and Absrobed Energy-Strain Curves [3].

9m Drop Test of 1/3 Scale Model Cask

Test and Measurement Method

Figure 4 shows 1/3 scale model cask and measurement points of impact acceleration. Impact limiters were designed using stress-strain curves obtained above ((b1) and (c1) in Figure 3). As shown in Figure 5, the impact limiter was composed of both densities of 0.3 g/cm^3 of R-PUF and 0.5 g/cm^3 of R-PUF to limit the impact acceleration under side drop condition to 2265 m/s^2 or less. Total model length including impact limiters was 2.3 m. Total mass was 4972 kg including the mass of impact limiters (465 kg) and the content (dummy basket, 1198 kg) of the cask. The side and 10°-declined drop tests of the cask from 9 m in height (impact velocity is 13.4 m/s) were carried out.

Acceleration data were measured using strain gauge accelerometers (ASA-A-1K/ASDH-A-2KV, Kyowa Electronic Instruments Co., Ltd.). Measured data processed with the low path filter of 544 kHz.

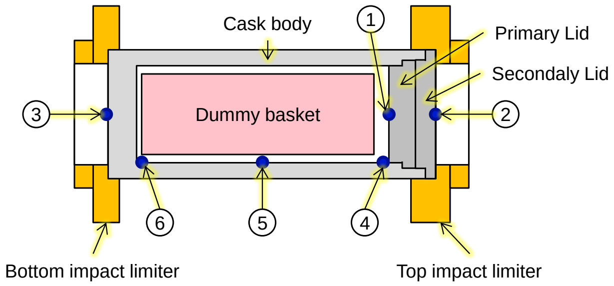


Figure 4 Specimen and Acceleration Measurement Points.

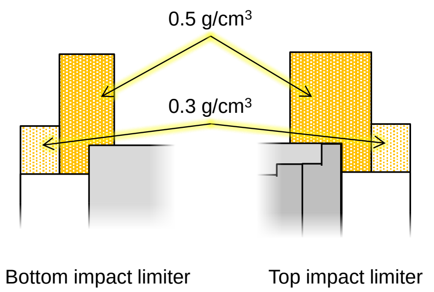


Figure 5 Construction of Impact Limiters.

Numerical Analysis

The numerical simulation of these 9m drop tests were carried out by finite element method (LS-DYNA) using material data obtained in this study ((b1) and (c1) in Figure 3) considering the strain rate dependency as linear to the logarithm of strain rate.

Test Result

Figure 6 shows maximum accelerations measured and simulated in these tests. The measured maximum acceleration in side drop test shows the accelerations were less than designed acceleration limit. Furthermore, the numerical analysis by LS-DYNA showed the good agreement with the test result.

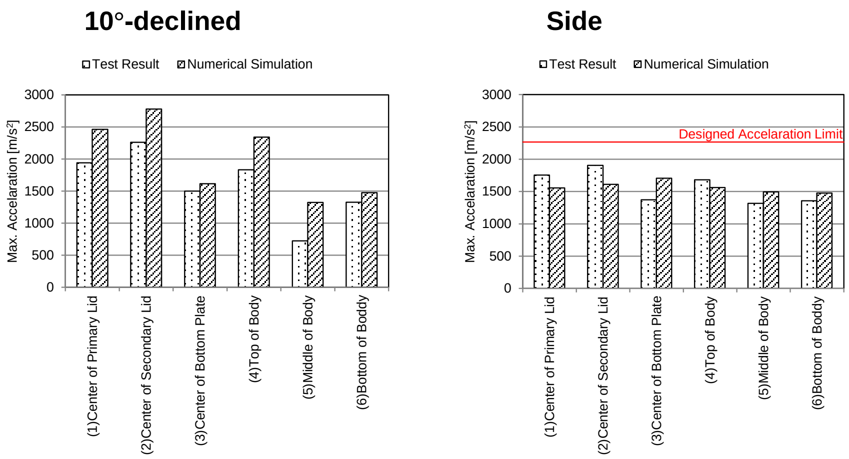


Figure 6 Maximum Acceleration [3].

Drop Weight Test and Estimation of Stress-Strain Curve from Material Data

Test Method and Measurement Method

Drop weight tests were conducted to verify the reproducibility of stress strain curves in the material data collection by another experiment system, and to obtain crushing characteristic of R-PUF of other density than contained in the data collection. Specimens of R-PUF (density between 0.1 to 0.65 g/cm^3) were cut out in ⌀25×H70 mm cylinder shape, restrained by restraint made by the same material as specimen. Figure 7 shows drop weight impact tester (IM10-30T, IMATEK Ltd.) and specimen. To condition of temperature between -20 to 80 °C, the specimens put in thermostatic chamber.

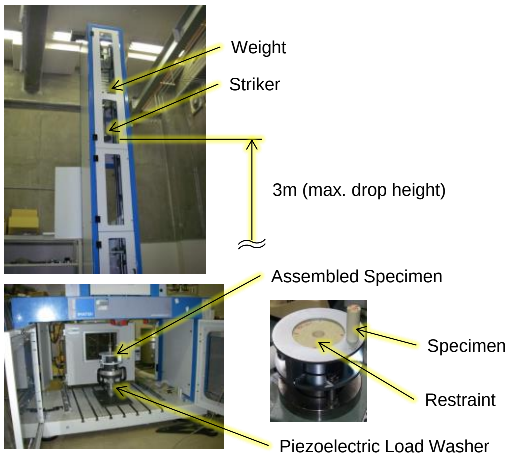
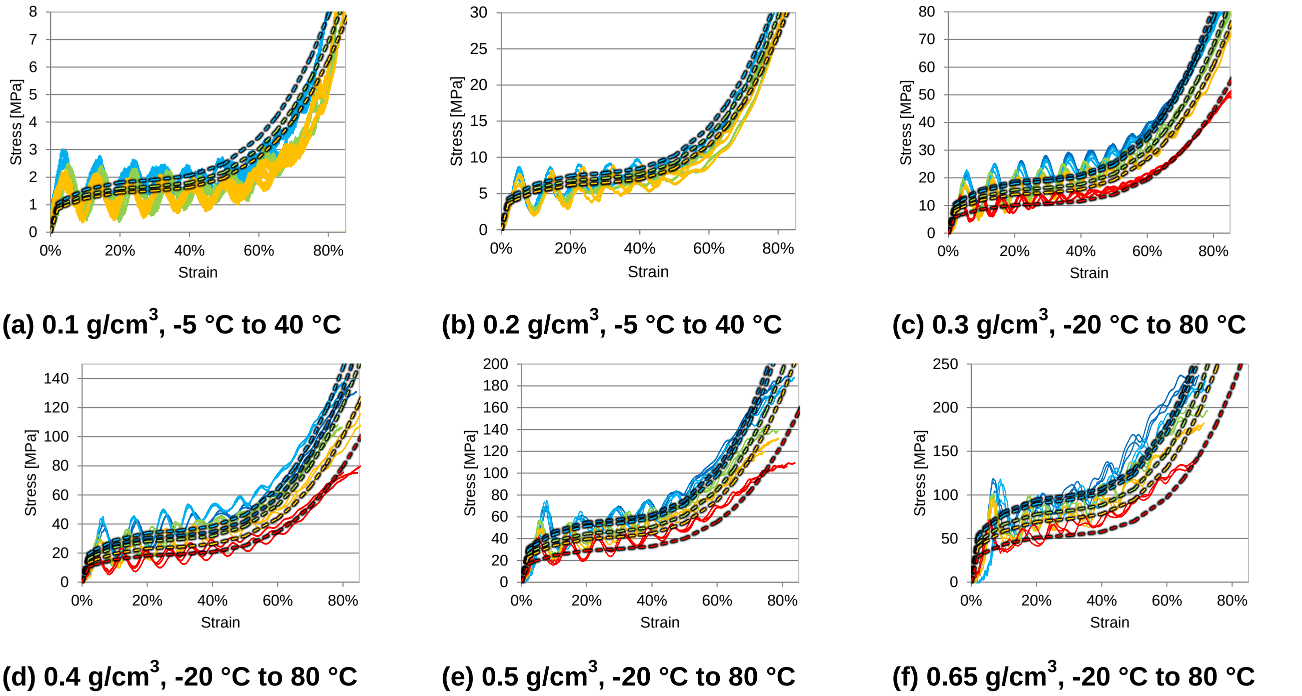


Figure 7 Overview of Drop Weight Test.

Estimation of Stress-Strain Curve

The predictor equation of absorbing energy-strain curve was determined by making a polynomial regression of the relationship between absorbing energy and strain under representative condition (0.3 g/cm^3, 20 °C, 1.25×10^1 s^{-1}), and multiple nonlinear regression of the magnifications of absorbing energy under high strain region (40% or higher) of the material data collection.

Dotted line: Estimated curve; --- -20 °C, --- -5 °C, --- 20 °C, --- 40 °C, --- 80 °C,



(a) 0.1 g/cm^3, -5 °C to 40 °C **(b) 0.2 g/cm^3, -5 °C to 40 °C** **(c) 0.3 g/cm^3, -20 °C to 80 °C**

(d) 0.4 g/cm^3, -20 °C to 80 °C **(e) 0.5 g/cm^3, -20 °C to 80 °C** **(f) 0.65 g/cm^3, -20 °C to 80 °C**

Figure 8 Comparison of Measured Stress-Strain Curves with Estimated.

Test Result

Figure 8 shows test results and estimated curve. The estimated curves were good agreement with test results in range between -20 to 80 °C.

Conclusions

(1) Stress strain curves under constant deformation rate condition were obtained by varying the density, strain-rate, and temperature. Therefore, the collection of crushing characteristics of R-PUF considering the strain rate and temperature dependency was accumulated to apply design and numerical analysis.

(2) 9m drop tests of scale model cask with R-PUF impact limiter designed using material data obtained in this study were carried out. The performance of impact limiter was superior to as designed.

(3) Using material data obtained in this study, 9m drop tests were simulated numerically by LS-DYNA. Because the maximum response acceleration measured in the test was able to be properly evaluated in numerical simulation, it is confirmed that the effectiveness of the currently acquired material data.

(4) Dynamic physical property data of R-PUF of density between 0.1 to 0.65 g/cm^3 were obtained by drop weight test varying the temperature between -20 to 80 °C. By comparison with the estimated curves by analyzing the material data collection, in a temperature range between -20 to 80 °C, availability of estimation of the shock absorbing property of R-PUF was confirmed.

Acknowledgments

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