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Modeling of elasto-viscoplastic behavior for polyurethane foam under various strain rates and temperatures

Tae-Rim Kim [a], Jong Ki Shin [b], Tae Sik Goh [b], Hyung-Sik Kim [a,c], Jung Sub Lee [b], Chi-Seung Lee [a,c,d,*]

[a] School of Medicine, Pusan National University, Busan 49241, Republic of Korea
[b] Department of Orthopaedic Surgery and Biomedical Research Institute, Pusan National University Hospital, Busan 49241, Republic of Korea
[c] Biomedical Research Institute, Pusan National University Hospital, Busan 49241,Republic of Korea
[d] Cryogenic Material Research Institute, Pusan National University, Busan 46241, Republic of Korea

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ABSTRACT

The polyurethane foam (PUF) is one of the most widely used composite materials in industrial and biomedical fields. It is frequently adopted in a wide range of environmental conditions, i.e., from static to dynamic compressive loads, and from cryogenic to high temperatures. Under these various environments, the PUF shows an elasto-viscoplastic behavior including three stages of material characteristics, namely, linear elasticity, a plateau with stress drop, and densification. Hence, the establishment of material model as well as the identification of material characteristics is the key of design and fabrication for PUF-based structures. In the present study, the strain rate- and the temperature-dependent elasto-viscoplastic behavior of polyurethane foam (PUF) which is extensively used in various fields and environments was computationally estimated under static/dynamic compression and the low/high temperature. To depict the three stages of material characteristics such as linear elasticity, a plateau with stress drop, and densification under uniaxial compression numerically, a Frank-Brockman type plastic multiplier and a Zairi type hardening-softening internal stress state variable were introduced. Then, the constitutive model was transformed as an implicit form using algorithmic tangential stiffness (ATS) method and was programmed as a user-defined material subroutine of commercial finite element analysis (FEA) code, namely, ABAQUS UMAT. Through the developed material subroutine, the strain rate- and the temperature-dependent static and dynamic stress-strain behaviors were numerically assessed. In addition, the change of material constants such as elastic modulus, yield stress, and hardening and softening control parameters was investigated quantitatively, and the polynomial multiple regression models were suggested. Consequently, the calculated results considerably correspond to experimental results, and through some supplements, accuracy can be improved. On using the proposed numerical method with some revision, it might be possible to anticipate the nonlinear behavior of the unknown material in various strain rate and temperature environment.

1. Introduction

Polyurethane foam (PUF) is one of the most frequently adopted composite materials in industries, especially in biomedical field since there are many advantages such as easy processing, low density, low thermal conductivity, robust specific stiffness and strength, biocompatible, and hemocompatible [1,2]. In particular, PUF exhibits significant size stability compared with other materials and therefore, depending on various temperature gradients, volume and size variation are considerably difficult to generate [3].

Although there are many advantages of mechanical characteristics of PUF, the material behavior, namely, the stress-strain behavior is strongly dependent on the strain rate and temperature. In other words, three stages of material nonlinear behavior such as linear elasticity, plateau with stress drop, and densification can be drastically changed depending on circumferential environments. Therefore, in order to design and manufacture the robust PUF-based structures, the material features under various strain rates and temperatures should be identified through both experimental and numerical approaches.

For several decades, the material characteristics of PUF under various environments have been experimentally investigated by many scientists and engineers. Yu et al. [4] investigated the impact resistance of the chopped glass fiber-reinforced PUF at cryogenic

* Corresponding author at: School of Medicine, Pusan National University, Busan 49241, Republic of Korea.

E-mail address: victorich@pusan.ac.kr (C.-S. Lee).

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temperature of −196 °C. Ciecierska et al. [5] studied the reinforcement of rigid PUF with carbon nanotubes (CNT) or graphite in order to enhance the mechanical properties, thermal properties, and fire resistance. Park et al. [6] conducted uniaxial compression tests for three types of polymeric foam including PUF at various temperatures from −163 °C to 20 °C and strain rates, 0.0001/s and 0.001/s i.e., static strain rates. In their research, it was found that as the temperature was decreased and strain rate was increased, the yield stress, elastic modulus, and the amount of breakage were increased.

On the other hand, the numerical modeling and simulation of PUF have been introduced by several researchers. Zhang et al. [7,8] investigated the strain rate (from 0.0016/s to 4.60/s i.e., quasi-static and dynamic strain rates), hydrostatic pressure and temperature (from −20 °C to 80 °C) effects of polymeric foams including PUF. In addition, a phenomenological hydrodynamic elastoplastic constitutive law under large deformation was proposed. Chang et al. [9] proposed a unified constitutive model for porous material that can be used for compressive, tension and shear loading with different quasi-static strain rates from 0.004223/s to 0.08466/s. Jeong et al. [10] developed a new constitutive model for PUF to improve the fit of the experimental data at various strain rates from 0.001/s to 100/s, i.e. quasi static and dynamic strain rates.

The aforementioned studies are focused on the experimental investigation or researched under limited loading modes namely, quasi static and low dynamic strain rates load. Recently, Lee et al. [11] proposed a unified constitutive model which depict the mechanical characteristics of PUF. The study was conducted under various compressive loading conditions, 0.003/s to 500/s i.e., covering quasi, dynamic, impact strain rates and a wide range of temperatures, −60 °C to 80 °C. Further, the study applied Gurson-Tvergaard-Needleman (GTN) to constitutive model so as to consider the negative increment of the volume fraction of voids for PUF under compression. In the Fig. 1, the range of the loading modes of the literature reviews is indicated.

However, to be more successfully described on the nonlinear stress-strain behavior of PUF under the dynamic compressive loading such as large amount of stress drops beyond linear elasticity, it is essential to study more numerical modeling and simulation for foam materials containing PUF. Moreover, most of the PUF-based structures can be collapsed/damaged under extreme environments such as dynamic loading and high/cryogenic temperatures. Therefore, researches on numerical models for explaining and predicting the mechanical behavior of PUF ought to be consistently conducted within a range of up to extreme environments. Furthermore, it is positively necessary to provide a numerical computational implementation process that includes a stress update algorithm of the constitutive model in order to apply the numerical model to the analysis of the PUF-based structures under harsh conditions.

Hence, in the present study, the elasto-viscoplastic behavior of PUF under a wide range of strain rates and temperature, from static loading and room temperature to dynamic loading and low/high temperature was estimated computationally. In order to consider the three stages of material features such as linear elasticity, a plateau with stress drop, and densification, a Frank-Brokcman type plastic multiplier and a Zairi type hardening-softening internal stress state variable were adopted. The constitutive model was formulated as an implicit form based on algorithmic tangential stiffness (ATS) method, and coded as a user-defined material subroutine of commercial FEA code, i.e., ABAQUS UMAT. The strain rate- and temperature-dependent material nonlinear behaviors were numerically estimated, and the variation of material parameters such as elastic modulus, yield stress, and hardening and softening control parameters was specifically analyzed. Finally, the polynomial multiple regression models for predicting the unknown stress-strain curve of PUF under arbitrary conditions were suggested.

2. Mechanical features of polyurethane foam

2.1. Experimental condition and test specimen

PUF with a density of 200 kg/m^3 was selected due to obvious appearance of stress drop in stress-strain curve. The size of the specimens used in the experiment was 12 mm × 12 mm × 12 mm (width × length × height) was tested in the study of Marsavina and Constantinescu [12]. A hydraulic MTS testing machine was used to perform the compressive experiments under various conditions: strain rate 0.003/s–500/s and temperatures between −80 °C. and 120 °C where the machine can work in environmental chamber. The selected strain rate for experiments were 0.003/s, 0.075/s, 0.7/s, 83/s. 250/s, 500/s, which be contained in quasi static, dynamic, and high strain rates and temperatures were -60 °C (213 K), 23 °C (296 K), and 80 °C (353 K), as to cover a range of temperatures possible in engineering applications, from aerospace at low temperatures to automotive when an extremely hot environment may appear.

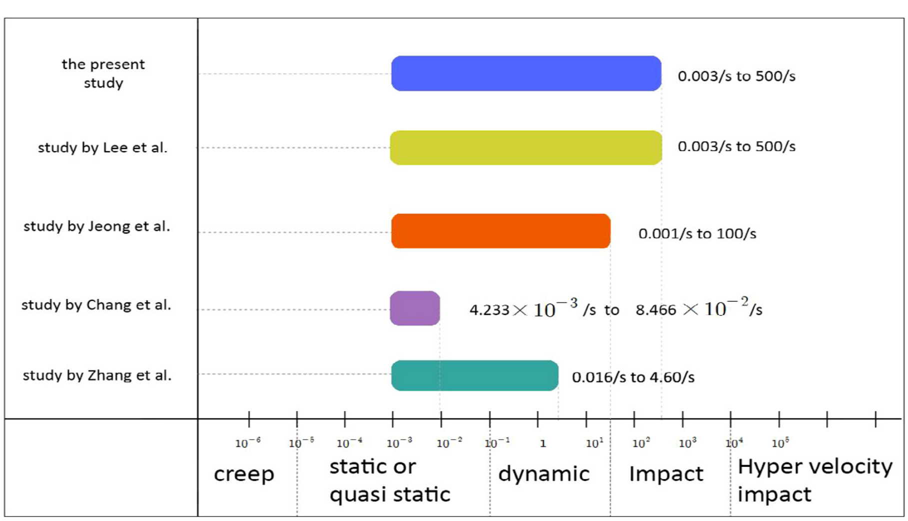

Fig. 1. Ranges of the loading modes of the literature reviews.