Materials and Design 84 (2015) 163–172

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/jmad

A temperature- and strain-rate-dependent isotropic elasto-viscoplastic model for glass-fiber-reinforced polyurethane foam

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ARTICLE INFO

Article history:
Received 9 January 2015
Received in revised form 14 June 2015
Accepted 15 June 2015
Available online 26 June 2015

Keywords:
Glass-fiber-reinforced polyurethane foam
Cryogenic temperatures
Constitutive modeling
Finite element analysis
ABAQUS user-defined subroutine UMAT

ABSTRACT

The primary aim of the present study is to provide a new constitutive model and its computational procedure for a glass-fiber-reinforced polyurethane foam (RPUF) subjected to various cryogenic temperatures and compressive loading rates. A Frank–Brockman-type isotropic elasto-viscoplastic model was introduced to describe the hardening and softening phenomena of RPUF under compressive loads. In addition, the increase of the yield strength and plateau according to the change of temperature and strain rates was demonstrated using the given constitutive model. The introduced numerical model was transformed as an implicit form and was implemented into a user-defined subroutine of commercial finite element analysis (FEA) code, i.e., ABAQUS UMAT. Based on the developed material library, the complex elasto-plastic behavior of RPUF under various cryogenic temperatures and strain rates was numerically estimated. The variation of material internal variables, such as hardening and softening control parameters, was quantitatively investigated, and the temperature- and strain-rate-dependent empirical formulae, namely, a polynomial multiple regression model, were proposed. Finally, the simulation results were compared with a series of compressive test results to validate the proposed method. On using the developed numerical method, it might be feasible to predict the unknown stress–strain behavior of RPUF under arbitrary severe environments.

1. Introduction

Recently, many types of insulation materials—such as vacuum insulation, multilayer insulation, perlite, and polymeric foams—have been invented in low/cryogenic temperature industries. Among these, polymeric foams, especially glass-fiber-reinforced polyurethane foam (RPUF), have been widely adopted. There are many advantages of polymeric foams: low thermal conductivity, low density, low water absorption, low water permeability, and dimensional stability. In particular, volume and size changes are extremely difficult to generate in polymeric foams, depending on various temperature gradients; namely, polymeric foams exhibit significant size stability [1].

Numerous studies in the literature related to the thermal performances were published from the viewpoint of material and chemical sciences. Kuhn et al. [2] inspected the thermal transport of an insulation system consisting of polystyrene foam (PSF) and polyurethane foam (PUF) using a calorimetric measurement device. In their study, the authors employed the linear superposition formula consisting of three types of equations, namely, solid, gaseous and radiative conductivity equations. Then, the researchers measured some material parameters for each equation using experimental facilities. Tseng et al. [3] experimentally investigated the thermal conductivity of PUF under various temperature ranges. An experimental facility was prepared based on the Japanese Industrial Standards (JIS) A1412, and the thermal conductivity of the PUF was specifically measured under temperatures of 300 K to 20 K and various pressures. In their research, it was confirmed that the thermal conductivity of the PUF could be reduced up to 70% by evacuating the gases in the foam cells. Placido et al. [4] proposed a predictive model for the thermal properties of insulating foams based on the analysis of different foam insulation morphological structures. In their study, a geometrical cell model was developed for application to the prediction of radiative and conductive foam insulation properties based on electromagnetic theory and the theory of conduction through a porous material.

Although it is important to identify the precise mechanical behavior of polymeric foams prior to the design and fabrication of an insulation system, there is limited literature on their elasto-plastic behavior under temperature- and strain-rate-dependent environments. Instead, studies have mostly focused on the property of thermal conductivity.

Only a few studies regarding the failure peculiarity and nonlinear material behavior of polymeric foams, in particular RPUF, have been reported. In the authors' previous studies, the aforementioned material characteristics of RPUF and RPUF-based insulation system were experimentally/numerically investigated using uniaxial monotonic/cyclic tests and structural impact tests. Chun et al. [5] performed a series of

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http://dx.doi.org/10.1016/j.matdes.2015.06.086
0264-1275/

impact tests for a GTT Mark-III-type LNG insulation system, which consisted of RPUF, plywood, an adhesively bonded plate, and mastic, to estimate the crack initiation cycles and dynamic strengths. Kim et al. [6] investigated the fatigue strength and life of the RPUF contained within the GTT Mark-III-type LNG insulation system through a set of fatigue tests at room temperature. Lee and Lee [7] proposed an anisotropic elasto-viscoplastic-damage model to identify the nonlinear material behavior and crack initiation/growth of RPUF; they applied the developed mechanical model to the dynamic failure of a GTT Mark-III-type LNG insulation system under room temperature and dynamic cyclic loads.

However, there are some limitations in these authors' research, for example, in Ref. [5,6], the experimental measurements of the dynamic and fatigue behavior of RPUF were presented; however, there was no constitutive modeling considering various temperatures and strain rates. In Ref. [7], the procedure of constitutive modeling for RPUF was introduced; however, the proposed model was excessively complex, and there were numerous material parameters needing identification, since the numerical model was derived accounting for material anisotropy. Moreover, the effects of various temperatures and strain rates were not considered during the constitutive modeling.

Therefore, in the present study, an isotropic Frank–Brockman type elasto-viscoplastic model for the RPUF considering the effect of strain rates and temperatures was introduced. In addition, the proposed numerical model was transformed as an implicit form and was implemented into a user-defined subroutine of commercial finite element analysis (FEA) code, i.e., ABAQUS UMAT. Then, the temperature- and strain-rate-dependent elasto-plastic deformation of the RPUF subjected to cryogenic temperatures and compressive loads was computationally evaluated based on the developed UMAT. Furthermore, the variation of material internal variables, such as the hardening/softening control parameters, was quantitatively estimated, and the temperature- and strain-rate-dependent empirical formulae, i.e., a polynomial multiple regression model, were proposed. Finally, the simulation results were compared with a series of compressive test results to validate the proposed method.

2. Experimental investigation

2.1. Test facilities and specimens

In the present study, a series of compressive tests of RPUF at various cryogenic temperatures and strain rates were performed to investigate the temperature- and strain-rate-dependent material features. Fig. 1 presents a schematic diagram of the test facilities for compressive testing at cryogenic temperatures. As observed in this figure, a cryogenic-

Fig. 2. Photograph of RPUF test specimen for compressive test.

chamber-embedded universal testing machine (UTM) and liquid nitrogen inlet–outlet equipment were adopted to achieve the cryogenic temperature environment. Based on these custom-built facilities, target temperatures from room temperature to 77 K can be maintained during the test.

In the compressive tests, RPUF consisting of 15 wt.% chopped glass fibers was employed as a test specimen, and the density of the RPUF was 133 kg/m^3. Fig. 2 presents a photograph of the RPUF test specimen for the compressive testing. The dimensions of length, width and height are all 50 mm.

In the RPUF fabrication process, the chopped glass fibers were spread onto an XY-plane perpendicular to the Z-direction, and the foam was foamed in the Z-direction. Thus, the fiber effect such as the increase of the elastic modulus and yield/plateau stresses can be identified in the X- and Y-directions under compressive loads, whereas this material response cannot be observed in the Z-direction (or foaming-direction).

During the compressive test, the test specimen was pre-cooled for approximately 2 h to reach thermal equilibrium between the inside and surface of the RPUF. The test specimen was then compressed using two cylinder-type stainless steel jigs, as observed in Fig. 1.

2.2. Test scenario

Table 1 presents the test scenario for the compressive test considering the four temperatures and three strain rates to investigate their effect. The four temperatures, namely, 293 K, 223 K, 163 K and 110 K, were selected based on the operating condition of polymeric foam-

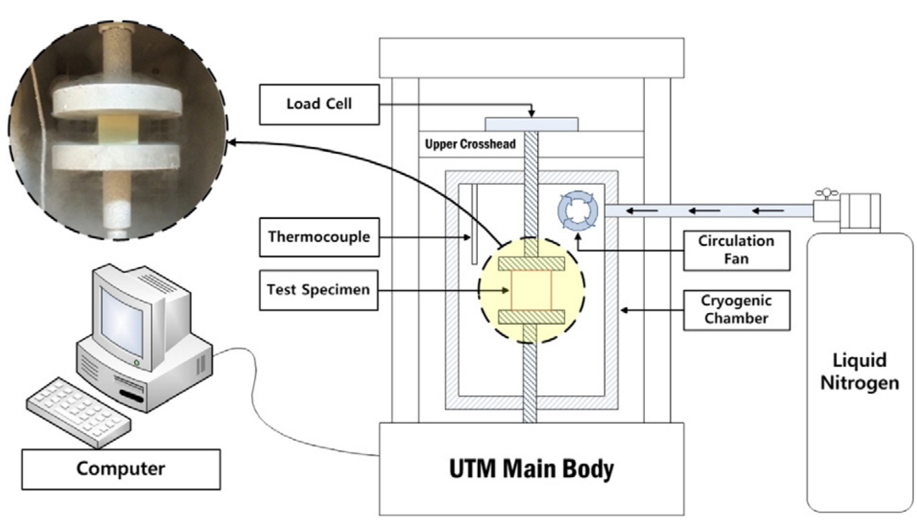

Fig. 1. Schematic diagram of test facilities for compressive testing at cryogenic temperatures.