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An experimental study of high-velocity impact on elastic–plastic crushable polyurethane foams

Ali Taherkhani, Mojtaba Sadighi *, Ali Sadough Vanini, Mohsen Zarei Mahmoudabadi

Mechanical Engineering Department, Amirkabir University of Technology, Tehran, Iran

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The mechanical behavior of elastic–plastic polyurethane foams was studied experimentally under high-velocity local impact loading in normal and oblique directions, in particular, the energy absorption and the situation of damage zone were investigated. In order to obtain the mechanical properties, at first quasi-static compressive global loading was performed on the foams. Then, several samples of rigid polyurethane with different thicknesses (between 10 and 80 mm) and densities (between 40 and 320 kg/m^3) were prepared and subjected to high-velocity normal impact loading (with projectile velocity range between 30 and 140 m/s). The results showed that the foam with density of 320 (kg/m^3) at thickness of 40 (mm) has the highest energy absorption between them and also increasing the density and thickness of the foam increases the energy absorption and the area of the damage zone on rear side of the foam. Furthermore, it was found that the damage area consists of two different cylindrical and frustum-like zones. It was shown that the absorbed energy was dependent on both density and thickness; therefore, it was attempted to statistically formulize the relationship between absorbed energy on the one hand and thickness and density on the other hand based on experimental data. The effect of projectile nose including the five shapes such as flat-ended, hemi-spherical, semi-elliptical, right-conical and sharp-conical was investigated on penetration depth of projectile into the target. The results have revealed that the penetration depth increases with decreasing in the curvature radius of projectile nose cross-section; hence, the foams were too weak against sharp noses. On the other hand, performing the oblique impacts showed that increasing the oblique angle increases the damage area and changes the shape of rear side from ellipsoid-like to triangle-shape.

1. Introduction

Properties such as cellular structure, low density, high resistance against corrosion and decay, waterproofness, absorbing harmful sunlight rays, and easy and controllable production process have made foams one of the most common cellular solids with vast applications in industry, especially in energy absorption, thermal insulation, acoustics technologies, electromagnetic wave attenuator, and also in packing industry [1].

Among the various applications of foams, utilizing them as a core in sandwich panels is increasing every day [2]. For a typical sandwich panel, face sheets are responsible for flexural rigidity, while the core provides shear load tolerance. In addition to stiffness required to keep the face sheets apart, the core must have enough shear resistance to prevent slippage relative to each other between face sheets and maintain structural continuity. Hence, foams are one of the best materials for this purpose, which considering their cellular structure does not add much to total weight of the structure [1,2].

Bois et al. [3] categorized polymers into uncrushable elastomers, crushable foams and thermoplastic materials and studied their mechanical behavior under impact loading. They employed hyper-elasticity theory and metals plastic properties in order to study elastomers and thermoplastics, respectively. Tu et al. [4] studied plastic deformation modes of rigid polyurethane foams under static compressive loading in order to experimentally assess their mechanical behavior in raise direction of the foam as well as its lateral direction. Avalle et al. [5] studied the mechanical models of cellular solids based on stress-strain behavior. They performed the uni-axial compression tests on several types of foam (such as: EPP, PUR, EPS and PPO/PS) at different density levels and comparing the experimental results with some available models (such as: the Gibson model, the Rusch model, a modified version of Gibson model and the new empirical model). Marsavina et al. [6] investigated the role of impregnation on mechanical properties of polyurethane foams in room temperature under static and impact

* Corresponding author. Tel.: +98 21 64543448; fax: +98 21 66419736.
E-mail address: mojtaba@aut.ac.ir (M. Sadighi).

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three-point bending loading, experimentally and analytically. Analysis of static loading on different types of polymeric foams and comparing its results with those of impact loading is a common subject of studies in this field [7,8].

Some of the works about the strain-rate effects have been done by researchers. Chakravarty [9] investigated the mechanical characterizations of the foams at varying strain-rates from 10^{-3} s^{-1} to 10^{3} s^{-1}. He found that the compressive strength and energy absorption capacity increase with the increase in both strain-rate of loading and density of foams, but decrease with the increase in surrounding temperature. Also, Luong et al. [10] tested PVC foams at different densities under compression loading at a wide range of quasi-static and high strain-rates and obtained the same result. They understood that the mechanical properties depend on the foam density and are strain-rate sensitive; also the compressive strength and modulus increase with the foam density. The mechanical behavior of common foams (such as: EPS, HDPE and PU) has been studied at strain-rates in rang of 0.0087 to 2500 s^{-1} by Ouellet et al. [11]. In that paper, the results shown that the strain-rate effects become more pronounced at rates above approximately 1000/s; so, at above of this range the relationship between stress and strain becomes distinctly non-linear. At another work, Iannace et al. [12] investigated the linear and non-linear behavior of PP foam at a wide range of strain-rate and the correlation between strain-rate effects and viscoelastic properties of the foam was obtained using viscoelasticity theory and separating strain and time effects.

Numerical and experimental analysis of 2-D response of crushable foams under low-velocity impact loading was performed by Shim et al. [13]. They employed strikers with different cross-section geometries (cubical, cylindrical and wedge-shaped) and analyzed the effects of reducing speed of the strikers and dissipated energy on the mechanical behavior of foam. Johnson and Li [14] continued the work on effects of rigid impactor nose on penetration in other kinds of foams in order to assess the penetration resistance dependency to geometry of the impactor and density of the foam. On the other hand, Rizov [15] studied local low-velocity impact on two different densities of elastic–plastic PVC foams and analyzed their dynamic response and kinetic parameters such as contact force, load-time curve, striker speed and energy and post-impact creep response. With a more practical attitude, Yang et al. [16] assessed energy absorption capacity of polymeric foams that were used in bumpers of vehicles under different cyclic loads, including uniaxial pressure, biaxial pressure and three-point bending.

High-velocity (H-V) impact is mostly noted for scientific and research approaches especially in aerospace technology. Hedayati et al. [17] investigated the differences in bird-strike studies. They attempted to find out where the difference on pressure readings between the experimental, theoretical and numerical values come from and what the true values are. The behavior of GFRP laminates investigated by Venkatanarayanan and Stanley [18] experimentally. In their work, composite and nano-composite panels were characterized experimentally in intermediate impact response and vibration damping characteristics. Nasirzadeh and Sabet [19] attempted to assess effect of core density on ballistic resistance of sandwich panels and studied changes in the microstructures of foams. Also, Uddin et al. [20] studied experimentally the improving ballistic performance of the polyurethane foam by reinforcing with nanoparticle in projectile speed that leads to complete penetration of the target. On the other hand, Kang et al. [21] used another kind of cellular solids, honeycomb, as a core of the sandwich panel and modified the projectile diameter with considering the channeling effect in hyper-velocity impact. Improving resistance of sandwich panels with foam cores has become an interesting subject in this field; hence, Ghalami-Choobar and Sadighi [22] investigated the H-V impact response of sandwich panels with FML face sheets and polyurethane foam core experimentally and numerically.

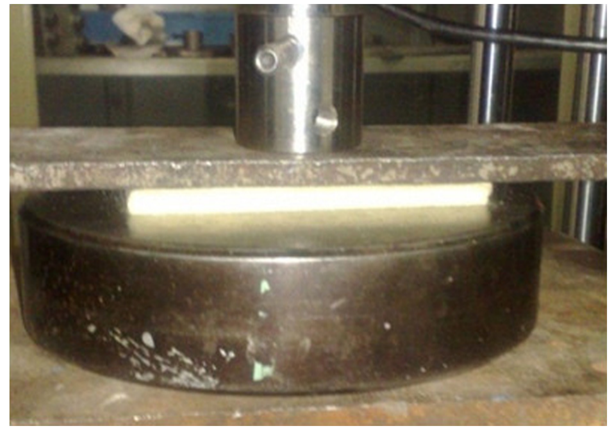

Fig. 1. Quasi-static uni-axial loading on elastic–plastic polyurethane foam.

Table 1
The results of uni-axial compression tests for utilized PU foams.

ρ (kg/m^3)	E (GPa)	σ_y (MPa)	E_{pl} (MPa)	ε_d	W (kJ)
40	3.01	0.21	0.175	0.86	29.2
80	14.61	0.96	0.63	0.79	59.5
140	39.89	2.04	2.14	0.76	148.2
180	47.63	4.22	4.63	0.73	182.9
320	114.05	6.33	8.18	0.61	340.7

As discussed above, several studies were done on different types of foams under local and global conditions of quasi-static and low-velocity dynamic loadings; some of them were experimental tests while others presented numerical and analytical models. Hence, this research is dedicated to study response of crushable polyurethane foams to the H-V impact loading. In this outline, obtaining the residual velocity of the projectile leads to gain the absorbed energy in each of foam samples. Effects of the density and thickness of the foams on damage mechanisms, absorbed energy and its effective parameters are also discussed in this paper for normal and oblique impact tests. For better evaluation, the effect of projectile nose on foam's response and penetration depth studied for five of different projectile nose shapes with equal mass and same initial velocity.

2. Materials and methods

2.1. Material properties

In order to assess the energy absorption of elastic–plastic crushable polyurethane (PU) foams under H-V impact, samples with different densities were prepared and cut in various thicknesses to study the effects of the two parameters (density and thickness) on behavior of the foams. Hence, the density of 40 (kg/m^3) with thicknesses of 1, 2, 3, 4 and 8 (cm), the densities of 80 and 180 (kg/m^3) with thicknesses of 1 and 2 (cm), and the densities of 140 and 320 (kg/m^3) with thicknesses of 1, 2, 3 and 4 (cm) were prepared. Each sample is addressed with "PU X–Y" where X and Y represent thickness (in centimeter) and density (kg/m^3), respectively.

To get the better assessment of mechanical properties, the quasi-static global compression loading at speed of 5 (mm/min) by Zwick screw machine done on each sample (Fig. 1) and the stress-strain curves of the specimens plotted (Fig. 5); the results are summarized in Table 1.