Characterization and Damage Assessment of Polyurethane Foams Subjected to Compression Testing

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Closed cell polyurethane foams with densities of 100, 140 and 325 kg/m³ were tested in compression at speeds from 0.6 to 500 mm/min. Digital image correlation (DIC) is used to determine the engineering characteristic curve, modulus of elasticity, maximum stress, and the deformation bands that appear during deformation and prior to the final failure of the specimens. By using this procedure both global and local phenomena are observed and analyzed. While each specimen is compressed, the damage behaviour of the foams is directly observed in different stages.

Keywords: polyurethane foam, compression, speed of testing, digital image correlation, recovery

Polyurethane (PUR) foam materials are widely used as cores in sandwich composites, for packing and cushioning. They are made of interconnected networks of solid struts and cell walls incorporating voids with entrapped gas. The main characteristics of foams are lightweight, high porosity, high crushability, and good energy absorption capacity. Foams are characterized by energy absorbing capabilities combined with a low weight and are used as core materials in structural sandwiches and as absorbers of impact energy in typical applications. Foam materials have a cellular structure and hence behave in a complex manner, especially under conditions of progressive crush. Besides their excellent ability for energy adsorption, good damping behaviour, sound absorption and excellent heat insulation, they have a high specific stiffness combined with a low weight. A good knowledge of the behaviour of different grades of foams is important for being able to design high performance sandwich composites adapted to the special needs of a particular application [1,2].

When testing a closed-cell aluminium alloy foam [3] three stages in the deformation response have been identified: l) localized plastic straining at cell nodes; 2) bands of concentrated strain containing cell membranes that experience plastic buckling, elastically constrained by surrounding cells – new bands appear in the neighboring regions; 3) one of the bands exhibits complete plastic collapse.

In [4] the foam material of interest was a rigid closed-cell polyurethane foam with a nominal density of 320 kg/m³. The deformation of foam specimens was obtained using the 3-dimensional digital image correlation (3D-DIC) technique. These experiments confirmed that the 3D-DIC technique is able to obtain accurate and full-field large deformation of foam specimens, including strain concentrations. The full-field surface displacement and strain distributions obtained with this technique provided detailed information about the inhomogeneous deformation over the area of interest during compression.

The capabilities of DIC to capture the heterogeneous deformation fields which appear during the compression of ultra-light open-cell foams were discussed in [5]. The present algorithm is formulated in the context of multi-variable non-linear optimization where a merit function based on a local average of the deformation mapping is minimized implicitly. Quantitative characterization of these fields is of importance to understand the mechanical properties of the collapse process and the energy dissipation patterns in this type of materials. The main conclusion is that the collapse of light open-cell foams occurs as a phase transition phenomenon.

Other complexities in the constitutive behavior of foams also occur. The post-collapse behavior is influenced by the air pressure enclosed in the closed cell foam which is compressed. Properties for polymeric foams are viscoelastic and hence time dependent. Recovery after loading is also time dependent, and matters are further complicated if foam damage has occurred.

In this paper careful observations of the foam behaviour are done in the linear elastic domain, in the plateau region, and in the densification region. Several observations, characteristic for each foam density are discussed. As damage mechanisms are different, DIC allows the direct monitoring of the formation of the deformation bands and their propagation till the final failure of the foams, as long as calculations of the local strains are possible. Maps of the vertical displacements and local Mises strains are presented and comments on the characteristics of the deformation bands are done.

Experimental part

Tested materials

The polyurethane foam is an anisotropic material due to the fact that on the direction onto which the rising process of the foam takes place induces a certain geometry to the cell of the material that may prove to be helpful when it is subjected to compressive loading. It is a known fact, [1], that on this direction the materials exhibits superior mechanical properties with respect to the other directions.

The samples have been subjected to compressive loading using eight test speed, reaching a value of 500 mm/min, using a Zwick-Roell two column testing machine of 1 tf capable of ensuring the necessary rigidity to perform compressive tests.

Three different foams have been considered, produced by Necumer, having the densities of 100, 140 and 325 kg/m³. All the samples had a cubic like shape; the ones cut from the materials with the highest density 325 kg/m³ had a side of 25 mm, while the other samples have the size of the cube equal to 50 mm. These dimensions are the result of the fact that the manufacturer delivered the materials in the form of sheets having the thicknesses of 25 mm (325 kg/m³) and 50 mm (100 and 140 kg/m³).

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Testing procedure

Polyurethane foams have a unique behaviour when subjected to compression testing, and the engineering characteristic curve is divided in three different zones (fig. 1). At the beginning of the test, in the elastic region, stress and strain variation is mainly linear until it is reached a first maximum stress value, considered as being the upper yield limit of the material or named also for simplicity yield limit; afterwards the foam starts to exhibit plastic deformation entering in the plateau region. The material will keep on deforming plastically until it transforms into the solid material out of which it is fabricated, and the so-called onset of densification starts. Passing this point densification will continue till the damage of the cells leads to the formation of the deformation bands, plastic collapse appears, and the final failure of the tested specimen is produced.

In our testing procedure the complete testing cycle consisted of two different stages. The first stage represented the loading cycle, up to a strain equal to 0.8 (for the convenience of the graphical representation the stress-strain variation till this strain value is not represented), performed with a prescribed speed (as mention before, from 0,6 to 500 mm/min), while the second stage represented the unloading cycle where for all the tests the speed was equal to 0.6 mm/min until a force of 15 N was reached. This testing procedure was used to determine the viscoelastic behaviour of the material by analyzing the influence of the loading speed and the unloading effect, known as foam recovery.

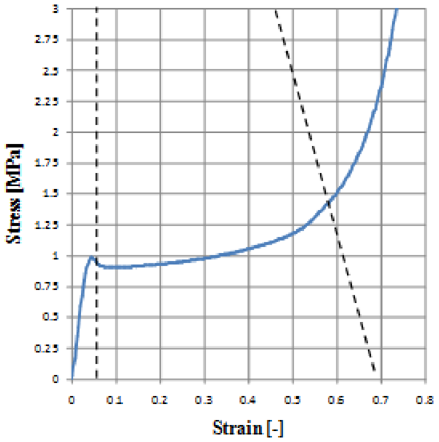

Fig. 1. Engineering stress-strain curve of a polyurethane foam

Results and discussions

The characteristic curves shown in figure 2 suggest the fact that the mechanical properties increase with respect to the speed of testing.

It is a general rule to say that all materials exhibit a viscoelastic behavior. In table 1 one can see the obtained results for the maximum stress and Young's modulus established in compression, and how these values vary with respect to the testing speed. Foams with the density of 100 and 140 kg/m^3 have a short decrease in stress after the maximum stress value, this being the effect of the gas tearing the walls, gas which was encapsulated inside the cells of the materials.

It is important to mention and to understand that all the results that are presented hereby are obtained on the rise direction of the foam. As polyurethane foams are anisotropic, the mechanical properties on the other directions may (and will be) different.

The maximum stress and the Young's modulus are increasing with respect to the testing speed for all analyzed densities.

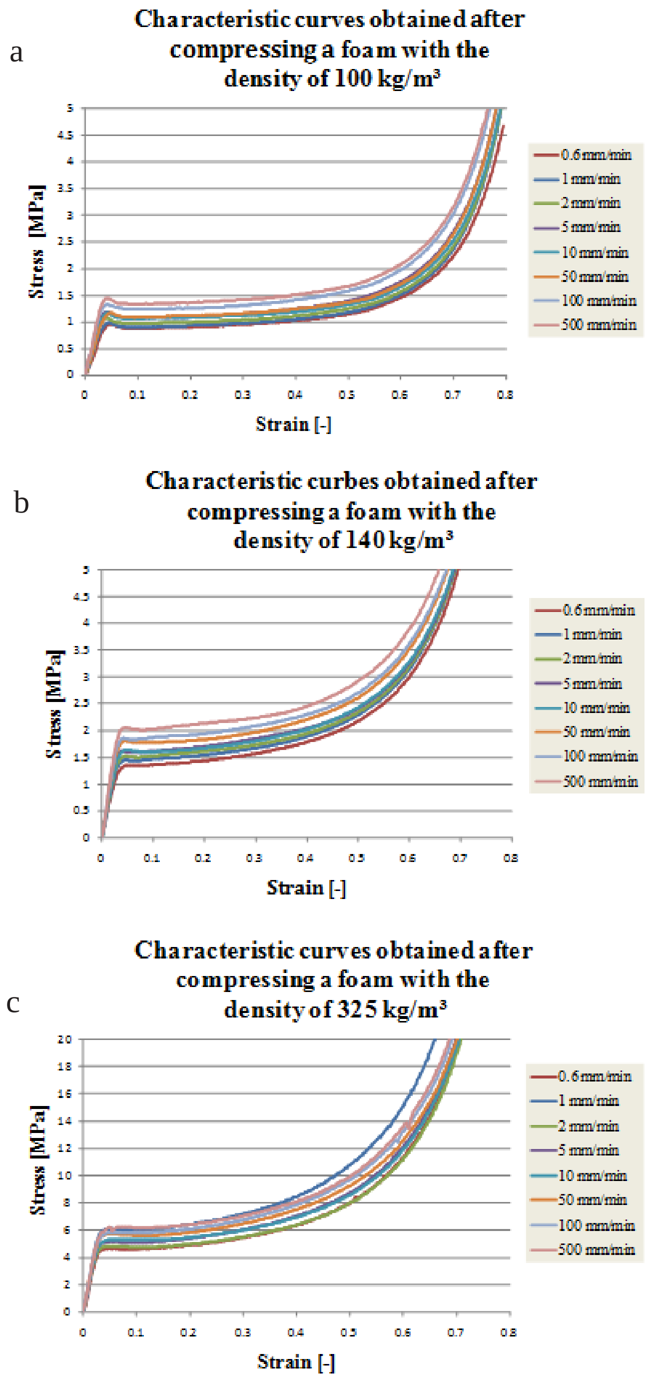

Fig. 2. Effect of the speed of testing on the stress-strain curves for the densities; a) 100 kg/m^3; b) 140 kg/m^3; c) 325 kg/m^3

The approximated densification point is around the strain value of 0.65. It is clear that these materials can be considered cellular materials bellow this limit.

Damage assessment

PUR foams are used in sandwich structures because of their ability to provide high stiffness coupled with light weight. Because of this, sandwich panels are often used in applications where weight saving is critical: in aviation applications in recent years, for isolations, helicopter rotor blades, tail and wing components. The core of such structures is often made of plastic foams: polyurethane (PUR), polyvinylchloride (PVC), polymethylmethacrylate (PMMA).

Failure of sandwich structures occurs due to:

- the yielding or fracture of the faces, [1,6];

- the compressed face may *wrinkle* by local buckling of the skin into the core, or it may *dimple* by a local buckling of the compression face, [7];

Density [kg/m³]	100		140		325	
Testing speed [mm/min]	Maximum Stress [MPa]	Young's Modulus [MPa]	Maximum Stress [MPa]	Young's Modulus [MPa]	Maximum Stress [MPa]	Young's Modulus [MPa]
0.6	0.98	22.40	1.38	39.71	4.58	172.33
1	1.01	25.26	1.49	49.22	5.75	237.67
2	1.12	31.69	1.65	58.85	5.27	208.22
5	1.15	30.48	1.61	53.77	5.61	223.50
10	1.17	34.87	1.65	51.67	5.85	230.05
50	1.18	30.95	1.74	55.22	6.44	240.84
100	1.29	38.68	1.83	63.36	5.89	211.72
500	1.45	44.45	2.03	71.39	6.25	214.77

Table 1
VARIATION OF MECHANICAL PROPERTIES WITH THE SPEED OF LOADING FOR THE THREE DENSITIES

- the core can fail, usually in shear, [8], but tensile, compression or local crushing can also occur;

- the bond between the face and the core can fail; and since resin adhesives are usually brittle, debonding is by brittle fracture, [9, 10];

- the sandwich beam can fail by indentation of the faces and core at the loading point, [11].

That is why the complete mechanical behaviour of the foams is crucially important.

The damage of the foams was studied in this research in two ways: by determining the recovery of the foam from the mechanical testing and by using the 3D-DIC ARAMIS system manufactured by GOM GmbH.

The foam recovery represents the difference between the maximum strain considered here as being 0.8, moment at which the specimen starts to be unloaded, and the one determined at a force equal to 15 N.

In table 2 the values calculated for the foam recovery are given for all speeds of testing and the three densities. For each density foam recovery decreases when the speed of loading is increased.

Table 2
2 FOAM RECOVERY FOR THE TESTED PUR FOAMS

Testing speed [mm/min] \ Density [kg/m³]	100	140	325
0.6	0.147	0.141	0.074
1	0.143	0.141	0.075
2	0.135	0.137	0.074
5	0.136	0.135	0.071
10	0.133	0.133	0.067
50	0.117	0.128	0.059
100	0.119	0.124	0.056
500	0.115	0.113	0.043

For the lower foams densities (100 and 140 kg/m³) the foam recovery values are quite similar, while the values obtained for the density of 325 kg/m³ are almost 50% lower than the ones determined for the smaller densities.

Using the ARAMIS system it was easy to assess the way the foams deformed plastically under the compression load. The method is quite simple: a white layer of paint is sprayed on the surface, followed by spraying a random speckle of black paint. Using the software the surface is then split into different smaller areas, called facets, each such facet being unique and identified throughout the whole test, calculating the surface displacements. In order to fully correlate the strains with the loads, we connect a

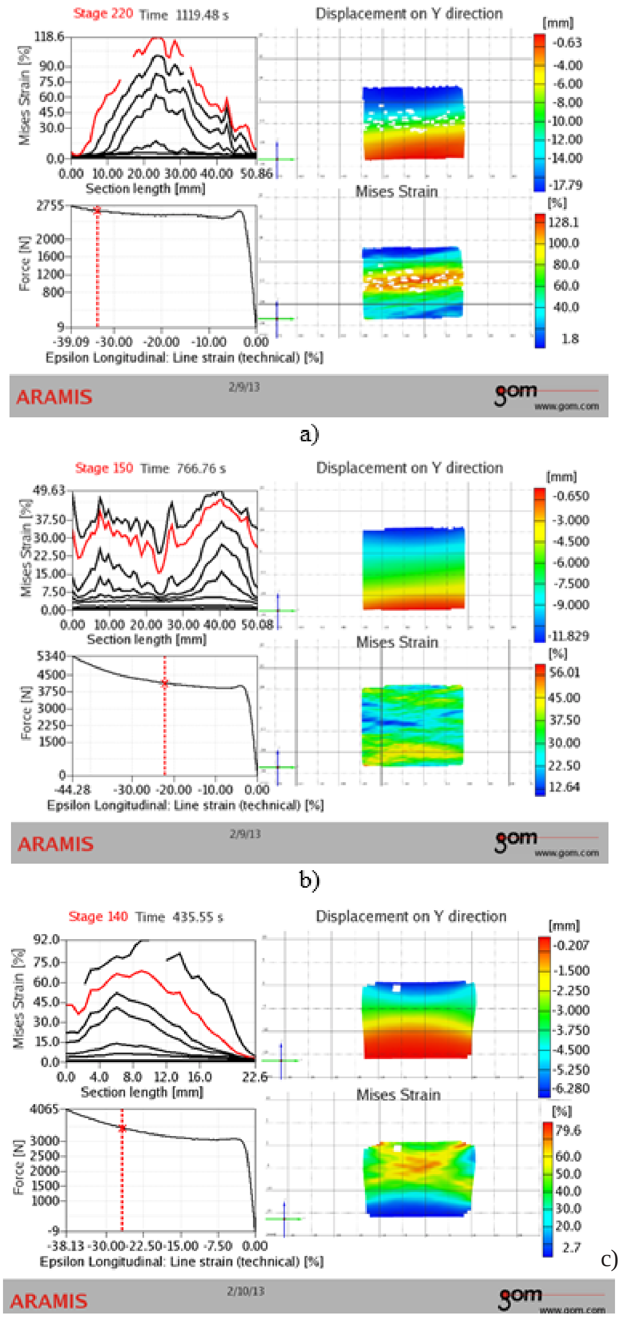

Fig. 3. Deformation bands obtained in compression for PUR foams with densities: a) 100 kg/m³; b) 140 kg/m³; c) 325 kg/m³

data acquisition system produced by Höttinger (HBM GmbH).

In figure 3 a complex report generated with the help of the ARAMIS software is presented for the three densities. For the presented results the speed of testing was 1 mm/min.

In all the analyzed foams one can observe a band like surface, which is also known as a deformation band. Usually, when the materials deform, the strains localize in such bands while the rest of the materials remains in at a quasi-constant strain value until it reaches the vicinity of the band. The contact between the compression plateaus and the specimen produces localized strains in the close vicinity even if we use oil to reduce the friction.

There are areas in the strain images where some pixels are missing (especially at higher strain values, when damage is generalized), this being produced by the fact that the material has been damaged enough and, therefore, the facets cannot be recognized by the software.

Conclusions

Careful mechanical testing in compression can give a complete characterization the PUR foams and the influence of the loading speed on their mechanical properties. As speed of testing is increased the Young's modulus and the maximum stress (yield stress) also increase for all the three densities. The foam recovery is also analyzed indicating that it is almost twice higher for the lower densities.

After densification starts and crushing of the cells is produced, deformation bands appear as being horizontal, inclined with about 45°, or in an X-shape, depending on the density, speed of testing, and level of damage. When speed of testing is increased one may observe less evident tendencies of the formation of inclined deformation bands. All these experimental observations on the formation of deformation bands indicate 3D-DIC as a powerful full-field tool to monitor the local damage behaviour, being capable to account for the influence of the foam density and speed of testing.

Mechanical considerations on the polyurethane foams were studied in [12].

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