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Poisson's Ratio and Energy Absorption of Auxetic Foam under Dynamic Loading

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Abstract – *Conventional foam can be converted to auxetic foam under auxeticity process. A new and simple technique to fabricate auxetic foam and to further determine its Poisson's ratio and energy absorption capacity are described in this paper. It is evident that the present modified technique in fabricating auxetic foam can be adopted to produce desirable auxeticity characteristics with considerable value of energy absorption performance. Moreover, the approach used for the determination of Poisson's ratio has considerable merit with great cost effectiveness. However, this method is specific to auxetic foam sample under dynamic loading. The auxetic foam is anticipated to be advantageous compared to conventional foam in energy absorption application.*

Keywords: Auxetic, Poisson's ratio, Compression, Fabrication

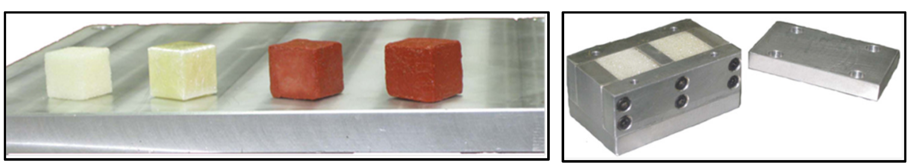
1.0 INTRODUCTION

Auxetic foam has been conceptually known as a material that has negative Poisson's ratio. Lakes [1] discovered a process of transferring open-cell conventional foam to the auxetic one. The process comprises of three steps: i) Compression of the foam specimen tri-axially, ii) Heating the foam specimen up to just above softening temperature, and iii) Cooling down at room temperature. However, there are some drawbacks of such process. One of them is a long-term instability, which causes samples reverting back to their original shape, severe surface creasing, inability of isotropic auxetic production, and limitation of complex shapes. In particular, the surface creasing and wrinkles observed in any deformable region of foam specimen are due to the volumetric compression ratio applied during fabrication [2, 3]. Chan and Evans [2] proposed an applicable solution to surmount the formation of wrinkles on the sample surface by applying volumetric compression in several stages. It is evident that more homogeneous auxetic foam may be produced by using this technique. For decades, this production process has been applied by numerous researchers, and a number of modifications have been reported [2, 3, 4-7, 8, 10, 11]. Nevertheless, the overall principle has remained the same, i.e. volumetric compression followed by heating and cooling [2, 6, 9, 10]. The most possible modifications reported are the multi-phase auxetic fabrication [7, 9, 12-14], solvent-based auxetic fabrication, vacuum-bag auxetic fabrication, and dual density auxetic fabrication.

This present study treats the determination of Poisson's ratio using a new approach in conjunction with the numerical and theoretical methods. The use of a high-speed camera system and falling weight system are described concisely to manifest the technique used in order to obtain the energy absorption capacity of auxetic foam. The influence of heating temperature, hydraulic pressure and heating time are highlighted appropriately to aid in designing auxetic foam for energy absorption applications.

2.0 FABRICATION OF AUXETIC FOAM

Despite numerous modification of auxetic fabrication has been discovered, some of the above-mentioned drawbacks still exist. In this present study, a new modification method has been proposed to enhance the stage of volumetric compression and fabrication of isotropic auxetic that can be conducted even for more complex shape. Fig. 1 depicts the cubic samples of auxetic foam and Al mould used in this fabrication technique. A fabrication technique was designed to apply pressure tri-axially on conventional opened-cell foams, resulting in auxetic behaviour. The technique generally needs several equipment, namely a hydraulic oil pump (with the capacity of 200 bar), a thick-walled aluminum cylinder (both closed-end), a high pressure ball valve, moulds and an oven. The inlet and outlet valves on one end were devised for inward flow of pressurized oil and air removal respectively, as shown in Fig. 2. The oil pump was connected to the aluminium cylinder and high-pressure ball valve. First, a bulk size of polyurethane foam was cut in a cubic size of 22 x 22 x 22 mm. In order to prevent oil absorption into the foam specimen, it was enclosed with a layer of plastic and two layers of special silicate glue as shown in Fig. 1 (a). The specimen was then placed inside the thick cylinder and compressed at a distinct pressure of 10 - 65 bar. Upon compression, the specimen was removed from the cylinder and placed inside an aluminium mould with a zero clearance in order to prevent foam expansion. Four different mould sizes are available due to varied pressure magnitudes. The mould was then closed using a cap and placed inside an oven. Finally, after heating up the mould for 20 – 55 min just over the softening temperature of the foam (130 – 170°), it was later removed and cooled down to room temperature. The auxetic foam is now ready to be tested.



(a) (b)

Figure 1: (a) Cubic size of auxetic foam, (b) Aluminium mould

3.0 DETERMINATION OF POISSON’S RATIO

Poisson’s ratio of material is an important mechanical property that can be determined by using strain gauging method. However, due to the flexibility of foams, this method is not reliable and accurate for such material. Thus, exploring a method for calculating this parameter accurately is of great importance. Brandel and Lakes [9] previously used a complicated laser system for measuring Poisson’s ratio. However, such method is very expensive. In this present study, a simple novel approach in calculating Poisson’s ratio has been discovered to evaluate the auxeticity of foam material. An auxetic foam specimen was initially subjected to a uniaxial compression test. Fig. 3 shows the compression test set-up. A high-speed camera was used to

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capture the elastic deformation at different compression stages. Using image processing technique and MATLAB programme, all images were converted to black and white.

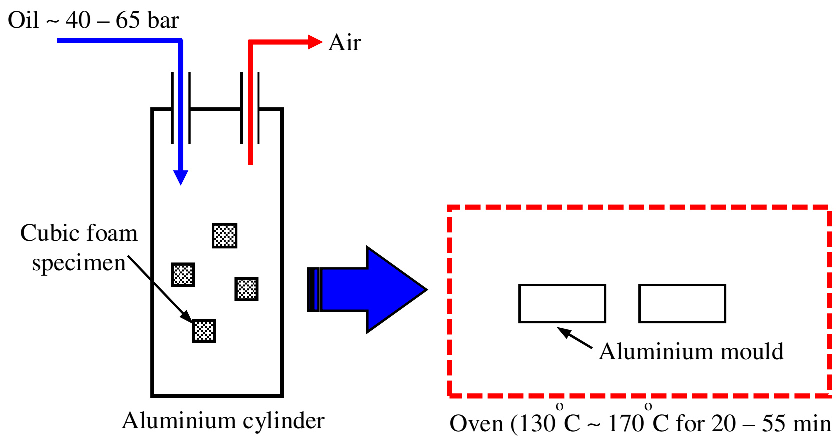

Figure 2: Schematic diagram of auxetic foam fabrication

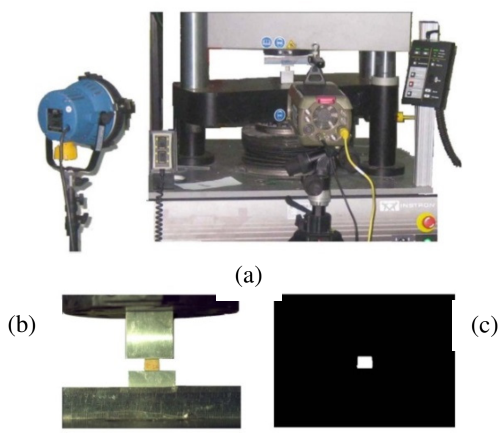

Figure 3: Compression test set-up (a) High speed camera, (b), Tested sample, (c) Processed image

The theoretical basis of Poisson's ratio is provided to enhance understanding of this proposed technique. In particular, compression test was carried out on typical auxetic foam in n steps. The initial height and width of the specimen are denoted by h_0 and b_0 respectively. The height of the specimen at the end of ith step is denoted by h_i. It is noteworthy that the width, b_0 of the specimen is not uniform during the compression due to the flexibility effect. From a global coordinate system, the width, b_0 of the foam is a function of y, as detailed in Figure 4. The average value of b for ith step is obtained from the following equation.

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$$\bar{b}_i = \frac{\int_0^{h_i} b_i(y)dy}{h_i} = \frac{A_i}{h_i} \tag{1}$$

A_i is the cross-sectional area for ith step. A_i and h_i are obtained using image processing method for all specimens in different compression steps. Strains along x and y for ith step are expressed as follows:

$$\left.\begin{aligned} (\varepsilon_x)_i &= \frac{\bar{b}_i - b_0}{b_0} \\ (\varepsilon_y)_i &= \frac{h_i - h_0}{h_0} \end{aligned}\right\} \tag{2}$$

By averaging the above strains for all steps, the normal strains of the specimen can then be expressed:

$$\left.\begin{aligned} \varepsilon_x &= \frac{\sum_{i=1}^{n} (\varepsilon_x)_i}{n} \\ \varepsilon_y &= \frac{\sum_{i=1}^{n} (\varepsilon_x)_i}{n} \end{aligned}\right\} \tag{3}$$

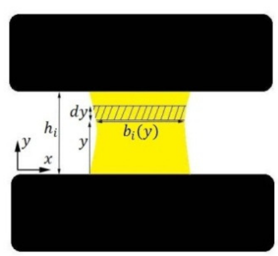

Figure 4: The auxetic foam specimen under *i*th compression stage

By dividing the negative perpendicular strain with longitudinal strain, Poisson's ratio can finally be calculated as follows.

$$v_{yx} = -\frac{\varepsilon_x}{\varepsilon_y} \tag{4}$$

Table 1: Poisson's ratio for various hydraulic pressure, heating time and heating temperature

Specimen No.	Hydraulic pressure (bar)	Heating time (min)	Heating temperature (^oC)	Poisson's ratio
1	10	30	140	0.18
2	10	20	140	0.21
3	20	30	150	-0.08
4	20	20	150	-0.06
5	30	30	160	-0.22
6	30	20	160	-0.26
7	40	30	170	-0.28
8	40	20	170	-0.31

Table 1 shows the results of Poisson's ratio for varying hydraulic pressure, heating time and heating temperature. It is evident that auxeticity increases as the hydraulic pressure and heating temperature increase. In other words, Poisson's ratio is significantly influenced by the volumetric compression ratio. The volumetric compression ratio is calculated from the ratio of initial volume and final volume. Overall, the auxeticity of material increases with the increase of volumetric compression ratio.

3.1 Energy absorption capacity of auxetic foam

Since the fabricated foam is of interest for energy absorption application, some of the samples have initially been tested to evaluate their energy absorption capacity. Two different methods, namely falling weight and high speed camera systems, have been used in the determination of energy absorption performance of such foam.

By using the falling weight system, the energy absorption capacity was determined based on the Newton's second law, particularly the analysis for the impactor. Fundamentally, the following theoretical formulation has been adopted in such analysis.

$$F(t) - mg = ma(t) \quad (5)$$

From Equation (5), the imposed impact load was then calculated and incorporated with the displacement, thus resulting in energy absorption capacity. The initial acceleration of the impactor was captured by the attached accelerometer. The acceleration data was then integrated to obtain the velocity and displacement. Figure 5 depicts the schematic diagram of the falling weight system used in this present study.

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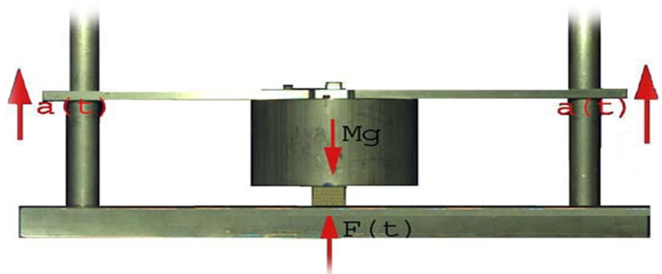

Figure 5: The schematic diagram of the falling weight system

As abovementioned, the energy absorption capacity was also determined by using a high-speed camera system. The system used is similar to the approach conducted in determining Poisson's ratio as shown in Figure 3. In contrast to the preceded approach, this system was used to capture the displacement data. This data was then only derived to obtain velocity and acceleration. As the acceleration was obtained, the force could later be calculated. From this test, force-time and displacement-time functions have been cooperated to evaluate the energy absorption capacity of the auxetic foam.

Table 2 tabulates the results of energy absorption capacity obtained from both methods. By comparing the experimental results with the preliminary results of numerical models, it is agreeable that the high-speed camera system may produce more accurate and reliable results.

Table 2: Energy absorption capacity of auxetic foam obtained from two different methods

Specimen No.	Energy absorption, mJ/cm^3 (Falling weight)	Energy absorption, mJ/cm^3 (High-speed camera)
1	14.35	10.21
2	14.65	10.64
3	14.92	10.35
4	14.73	10.14
5	14.7	10.23

In addition to this, the effects of heating temperature and hydraulic pressure on the energy absorption of auxetic foam have also been researched in this present study, as illustrated in Figure 6. It is obvious that the energy absorption performance increases as the heating temperature and hydraulic pressure increase. In particular, hydraulic pressure has more influence in the energy absorption capacity compared to heating temperature. These results may be useful in predicting the performance of auxetic foam in the early stage of auxetic foam fabrication, in which controlling hydraulic pressure is more significant.

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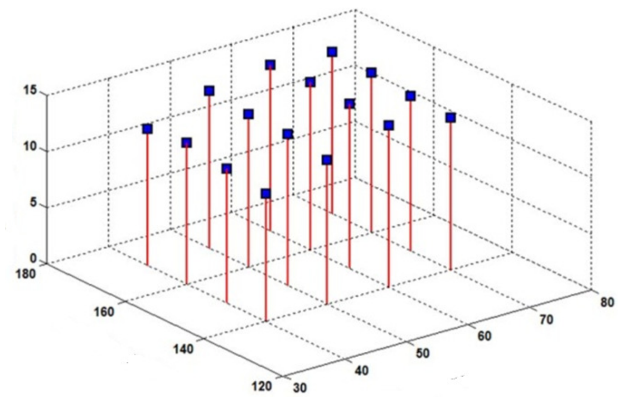

Figure 6: The influence of heating temperature and hydraulic pressure on the energy absorption of auxetic foam

4.0 CONCLUSION

It is evident that the auxeticity of foam specimens strongly depends on the fabrication parameters, namely hydrostatic pressure, heating temperature and heating time. In particular, the hydrostatic pressure that causes volumetric compression shows significant influence on the auxeticity. However, there are some limitations on these parameters that restrict them to be in a special domain. Increasing heating temperature or heating time may melt the specimens. The new proposed auxetic foam fabrication method and the determination of Poisson's ratio have been proven to be advantageous over the existing approach for structural mechanics applications with cost reduction and acceptable level of accuracy. From energy absorption point of view, the auxetic foam may be advantageous to the conventional ones since it can mitigate higher impact energy with respect to the same volume of foam. It is also clear that the hydraulic pressure needs to be controlled accordingly in fabricating great performance of auxetic foam for energy absorption applications.

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