New approach for fabrication of auxetic foam and determination of Poisson's ratio

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Abstract. Conventional foam could 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 is described in this paper. It is evident that the present modified technique in fabricating auxetic foam could be adopted to produce desirable auxeticity characteristics. Moreover, the approach used for determination of Poisson’s ratio has considerably merit with great cost effectiveness. This method is, however, specific to auxetic foam sample under compression loading.

Introduction

Auxetic foam has been known conceptually as material that has negative Poisson’s ratio. Lakes [1] has discovered a process of transferring opened-cell conventional foam to 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 regions of foam specimen are due to the volumetric compression ratio applied during fabrication [2,3]. Chan and Evans [2] have 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]. Nevertheless, the overall principle has remained the same, i.e. volumetric compression followed by heating and cooling [2, 6, 9]. The most possible modifications reported are the multi-phase auxetic fabrication [7, 9], solvent based auxetic fabrication, vacuum-bag auxetic fabrication and dual density auxetic fabrication.

Fabrication of auxetic foam

Despite numerous modification of the auxetic fabrication has been discovered, some of the abovementioned 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 even for more complex shape. Fig. 1 depicts the fabrication technique of auxetic foam and the equipment used. A fabrication technique has been designed to apply pressure tri-axially on the conventional opened-cell foams, resulting inauxetic behaviour. The technique generally needs several equipment namely a hydraulic oil pump (a capacity of 200 bar), a thick-walled aluminum cylinder (both closed-end), a high pressure ball valve, moulds and oven. Inlet and outlet valves on one-end have been devised for inward flow of pressurized oil and air removal, respectively, as shown in Fig. 2. The oil pump is connected to the aluminium cylinder and high pressure ball valve. Firstly, a bulk size of polyurethane foam has previously been cut in a cubic size of 22x22x22 mm. In order to prevent oil absorption into the foam specimen, it is enclosed with a layer of plastic and two layers of special
silicate glue as shown in Fig. 1 (a). The specimen is then placed inside the thick cylinder and compressed at a distinct pressure of 10 - 65 bar. Upon compression, the specimen is 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 is then closed using a cap and placed inside an oven. Finally, after heating up the mould for 20 – 55 minutes just over the softening temperature of the foam (130 – 170°), it is later removed and cooled down to room temperature. The auxetic foam is now ready to be tested.

Fig. 1: (a) Cubic size of auxetic foam (b) Hydraulic oil pump (c) Thick-walled aluminum cylinder (d) Aluminium mould

**Determination of Poisson’s ratio**

Poisson’s ratio of material is of 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] have previously used a complicated laser system for measuring Poisson’s ratio. Moreover, 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 is initially subjected to a uniaxial compression test. Fig. 3 shows the compression test set-up. A high speed camera is used to capture the elastic deformation at different compression stages. Using image processing technique and MATLAB programme, all images are converted to black and white colour.

![Schematic diagram of auxetic foam fabrication](image)

Fig. 2: Schematic diagram of auxetic foam fabrication
Theoretical basis of Poisson’s ratio is provided to enhance understanding of this proposed technique. In particular, compression test is 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 \( i \)th 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 Fig. 4. The average value of \( b \) for \( i \)th step is obtained from the following equation.

\[
\bar{b}_i = \frac{\int_0^{h_i} b(y) dy}{h_i} = \frac{A_i}{h_i}
\]  

(1)

\( A_i \) is the cross-sectional area for \( i \)th 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 \( i \)th step are expressed as follows:

\[
\begin{align*}
(\varepsilon_x)_i &= \frac{h_i - b_0}{b_0} \\
(\varepsilon_y)_i &= \frac{h_i - h_0}{h_0} 
\end{align*}
\]  

(2)

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

\[
\begin{align*}
\varepsilon_x &= \frac{\sum_{i=1}^{n} (\varepsilon_x)_i}{n} \\
\varepsilon_y &= \frac{\sum_{i=1}^{n} (\varepsilon_y)_i}{n}
\end{align*}
\]  

(3)

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

\[
\nu_{yx} = -\frac{\varepsilon_x}{\varepsilon_y}
\]  

(4)
Table 1: Poisson’s ratio for various hydraulic pressure, heating time and heating temperature

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Hydraulic Pressure (bar)</th>
<th>Heating time (min)</th>
<th>Heating temperature (°C)</th>
<th>Poisson’s ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>30</td>
<td>140</td>
<td>0.18</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>20</td>
<td>140</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>30</td>
<td>150</td>
<td>-0.08</td>
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<td>4</td>
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<td>150</td>
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<tr>
<td>5</td>
<td>30</td>
<td>30</td>
<td>160</td>
<td>-0.22</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>20</td>
<td>160</td>
<td>-0.26</td>
</tr>
<tr>
<td>7</td>
<td>40</td>
<td>30</td>
<td>170</td>
<td>-0.28</td>
</tr>
<tr>
<td>8</td>
<td>40</td>
<td>20</td>
<td>170</td>
<td>-0.31</td>
</tr>
</tbody>
</table>

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 increasing of the volumetric compression ratio.

Conclusion

It is evident that the auxeticity of foam specimens strongly depends on the fabrication parameters namely hydraulic pressure, heating temperature and heating time. In particular, the hydraulic pressure which causes a volumetric compression showing significant influence on the auxeticity. However, there are some limitations on these parameters which restrict them to be in a special domain. Increasing heating temperature or heating time may cause the specimens melting. The new proposed auxetic foam fabrication method and determination of Poisson’s ratio have proved advantageous over the existing approach for structural mechanics applications with cost reduction and acceptable level of accuracy.

References